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碩士學位論文

Department of Interaction Design

Master Thesis

易動板塊：探索在房間規模的替代實境中之動態傢俱的全身互動設計

MovableBlocks: Exploring Dynamic Furniture for Whole-body Interaction in Room-scale Substitutional Reality

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ABSTRACT

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Substitutional Reality (SR) is one of the emerging areas in the spectrum of virtuality continuum investigated by some researchers with the aim of providing a greater variety of immersive experience in virtual environments based on the physical environment. However, in most of the existing research the cost of substitution is quite high in terms of low variety of substitution for each prop, thus requiring more props to expand the overall variety of substitution. Besides, there are few related works explored in whole-body interaction but lacking interaction such as standing or jumping on the objects. This could be worth investigating in the area of Encountered-Type Haptic Displays (ETHDs) to create a device to achieve higher load tolerance to support fierce interaction with humans' weight. This work tried to overcome the above issue using approach from Modular Tangible User Interface with inert modules, which are used based on their physical capability such as weight, shape, and softness instead of embedded sensors and microprocessor.

Thus, MovingBlocks is proposed. It is a system using mobile base to create dynamic furniture in Substitutional Reality, to inform the possibility of using modular TUIs to form a variety of larger objects for whole-body interaction in room-scale range for the future VR application.

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Chapter 1 Introduction

With the advancement of Virtual Reality (VR) technology, there are many VR head-mount devices (HMDs) rolling out in the consumer market in recent years, leading to the accessibility of VR technology and application to the general public. Accompanied by the COVID-19 pandemic, it greatly changes the ways of living for most people, including working, communication, and entertainment via the Internet and VR technology. There is also increasing discussion and investigation in the possible application of VR technology with the objective to help users in various aspects of life in an immersive virtual environment. One of the goals in this work is to investigate how VR technology can help to elevate the users' experience in the context of Substitutional Reality (SR), an umbrella concept under the VR which would be further explained in the next Chapter.

VR HMDs impressed most users by offering a realistic immersive 3D virtual environment which takes the visual approach to "fake" users they are immersed in another different environment. However, humans perceive the world in a multi-modal way including smell, touch, hear, taste, etc. The research in haptic devices for VR embarks emerging experiences with not merely realistic graphics, but also assists users to perceive the virtual environment in a multi-modal way, hence increasing the immersiveness of VR experience. In this work we would like to investigate to include whole-body and more fierce interaction such as standing and jumping from height, which lacks discussion in the previous research.

Tangible User Interfaces (TUI) could be one of the feasible solutions. "Tangible Bits" [1] is one of the earliest visions related to TUI which states "allowing users to grasp and manipulate bits in the center of users' attention by coupling the bits with every physical object and architectural surfaces" with the goal to bridge the gaps between virtual environment and physical environment. To narrow down the issue, we opt to investigate the area of modular TUI, which emphasizes the combination of TUI to offer functional adaptability and flexibility to users. There have been quite a number of works focusing on investigating the application of “smart” modules, which consists of sensors or microprocessors, towards tangible interaction. However, we believe that “inert” modules, which is merely based on its physical capability such as weight, shape and texture, could lead to more low-cost but also flexible tangible interaction for users in virtual environments, particularly with the aid of advanced computer graphic technology nowadays such as object recognition and tracking technology.

Thus, we proposed MovableBlocks, an interactive solution with modular blocks to form dynamic furniture in SR, to offer a more immersive and realistic experience for users by allowing whole-body interaction in a virtual environment via interaction with the physical props. In this work we would discuss the design consideration of the proposed solution. User studies are also included to assess the functional flexibility, ease of learn and use, and overall usability experience.

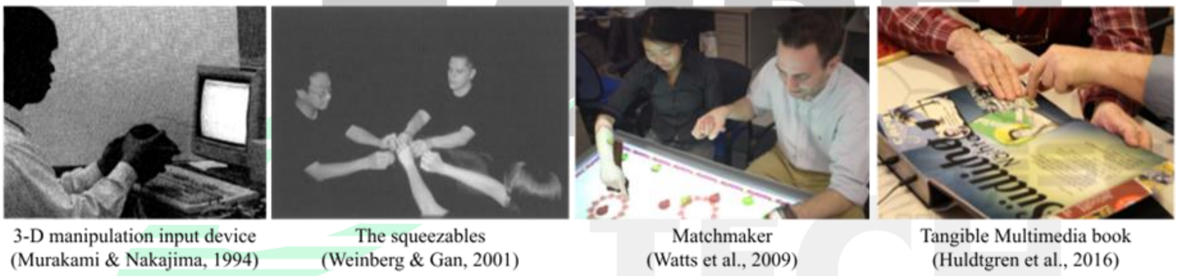


Figure 1.1 Examples of previous researches in TUIs.

Chapter 2 Related Works

Our research focuses mainly on utilizing the existing technology to explore the interaction design of room-scale substitutional reality experience, which requires extensive knowledge and technology in various areas such as Substitutional Reality, Encountered-type Haptics, and Modular TUI. Our research would like to explore more possibilities and breakthroughs in all these areas, and to obtain the insights to create emerging experiences with technologies.

2.1 Substitutional Reality

The concept of "Substitutional Reality" (SR) was firstly raised in 2012 [2] with the intention of substituting participants' "live reality" with "alternative reality" without noticing the change. This implication tried to create a replica of the real environment and to merge it fully to participants' reality to fake their perception. It was not designed to have any interaction between the participants and the systems. It became more relevant to HCI research until [3] attempted to define it as a "class of Virtual Environments where every physical object surrounding the user is paired, with some degree of discrepancy, to a virtual counterpart". Such description of SR is very close to the Mixed Reality (MR) which is defined as "merging of real and virtual worlds" and included in "Virtuality continuum" suggested by [4] (Figure 2.1).

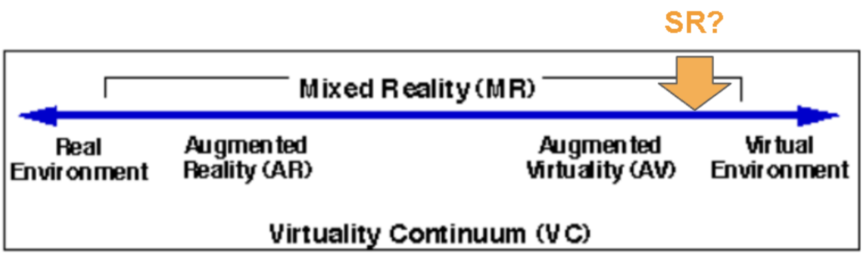


Figure 2.1 The position of SR in "Virtuality continuum". [4]

Stepping into the concept of MR, SR could be easily confused with other MR types such as Blended Reality (BR), Augmented Reality (AR), etc. The key characteristics of SR can be pinpointed using the "virtual continuum" as in the figure 2.1; SR should be located closer to the end of "Virtual Environment" (VE) as the concept of SR is allowing the user being in the VE which is formed based on the real environment. The sense of presence from users' perspective is based on the VE instead of Real Environment (RE).

Regarding the existing research in SR, we attempted to create a design space for the SR work by categorization based on two factors as the following:

1) Level of Interaction - the human body part(s) that are used for interaction in the work (finger, hand, whole-body)

2) Variety of functionality (per substituting prop) - the ability of each prop to substitute into different virtual prop to offer range of functionality to users

We consider level of interaction is one of the key factors in SR application because we found that most previous works focus on the interaction using finger and hand; Haptic Retargeting [5] suggests a solution of visual illusion to allow a single physical prop providing passive haptics for multiple virtual objects to users' hand. [6] proposed a similar idea of visuo-haptic illusions to increase users' finger perceived resolution of the shape display. [7] explores the technique of redirected position to resize the user's virtual grasping in VR while interacting with the same physical object. However, these works limit the users' interaction in SR by only using hands, which could hardly offer an immersive experience for the whole-body. There are few works explore possibility of whole-body interaction in VR, but still limited in the range of interaction, especially for more fierce interaction; RoomShift [8] attempt to support limited range of whole-body interaction such as physically moving objects and walking in the room for touching different furniture,

Another key factor in SR application would be the variety of functions (per prop), which is the flexibility of a physical prop to substitute into different objects offering different functions in VE. “Per” is keyword because it is related to the cost efficiency and usability, it is possible for a work that can substitute many different virtual objects by including more physical props such as Annexing Reality [9] but this kind of 1-to-1 matching between virtual and physical props offer low variety of functions (per prop) and lead to low scalability as the expansion cost is high. We considered it is critical because we found that it is related to the cost efficiency and usability and the variety of functions is not high in many previous works during literature review; Haptic-go round [10] offer different functions in a standing position for users to achieve different function by attaching several props on circular ring. MoveVR [11] explores to simulate different objects by attaching structure on swarmbot and providing prop for users to interact. VRRobot [12] utilizes the board to simulate the surface of different objects for users to interact and also support touching the users but changing into different prop is required.

Among the works we found, TilePoP [13] seems to be achieving high in both level of interaction and variety of functions (per props); it can offer a wide range of whole-body interaction such as laying, sleeping, riding, sitting, etc. but currently it cannot support users standing on it. In terms of a variety of functions, it uses a fixed number of air-inflated cubes to simulate different virtual objects, but air-inflated cubes are prone to some fierce interaction. It also does not offer mobility which limits the range of functions for moving objects.

In our proposed work, we would like to push further in both aspects to explore more possible applications of SR; supporting a wider range of interaction between simulated objects and users like standing on, punching on, walking along, etc. The investigation of substitutional technique to increase the variety of functions (per prop) to lower the prop cost of substitution.

Figure 2.2 Design Space (Substitutional Reality).

2.2 Encountered-type Haptics Display

Haptic feedback is one critical area upon the discussion of VR-related technology to offer touch sensation for immersive experience. In recent years, the investigation in Encountered-type Haptics Display (ETHD) is popular among researchers. The concept of ETHD was rooted from 'robotic graphics' by [14] and the name was first mentioned in work by [15] with the presentation of a system tracking users' hands and placing the haptic display in the location that users can access it. ETHD is defined by [16] as "a device capable of placing a part of itself or in its entirely in an encountered location that allows the user to have the sensation of voluntarily eliciting haptic feedback with that environment at a proper time and location". In short, ETHD aims at providing the sensation of feedback to users at the right time and right place. It is one of the popular technologies used in VR application as the virtual environment in visual display devices allow the robotic actuator to hide its presence to offer touching surface for contact with the users, thus providing natural and voluntary interaction in VE.

Focusing in the current research of ETHDs, we also come up with 2 key factors for investigation in this area:

1) Mobility

2) Weight and Force

Mobility refers to the movement ability of the ETHD. It impacts the users' space available for VR interaction. Grounded and fixed devices provide lowest mobility as they limit user experience in fixed locations with either sitting or standing stance; Snake Charmer [17], Haptic-go-round [10], HapticBots [18]. There are some grounded devices with XY movement to allow users to explore larger areas of interaction; CoVR [19], ZoomWalls [20], Reach+ [21]. Wearable device such as EncounteredLimbs [22] can allow users to explore the virtual environment without considering the space requirement of a haptic prop/device as it is attached on the users' body part. With the invention of drone, ungrounded device is also becoming more common for the ETHDs with its ability to move freely in XYZ; BitDrones [23], SlingDrone [24], Beyond the Force [25]

Weight and Force would be of importance in ETHD as it could affect the limit of the amount of force feedback or intensity of interaction to users. Quite a number of the previous work focus on providing light force and weight feedback to users such as touching by hand or fingers; HapticBots [18], Snake Charmer [17], EncounteredLimbs [22]. Some previous works explore the application of applying mild force such as pushing, stretching and holding light-objects; ZoomWall [20] and MoveVR [11].

With these categorizations, it is not hard to tell that in some extent these two factors are interrelated in existing works; For the ungrounded works, they cannot bear with heavy weight or sustain with strong force from fierce interaction due to the nature of drone which is light and mobile but its structure is fragile to support weight and strong force. For the wearable device, it is convenient for user to explore the virtual environment with least restriction in physical space but the weight and force is limited to the bearing ability of average human - the device is designed to bear the weight and force limit which the users can withstand. It is because all the weight and force would be exerted on the users' body as the wearable device is equipped by the user. Some of the grounded devices can support heavy weight but also sacrifice part of its mobility by fixing its movement along the trail such as CoVR [19] or can support heavier weight and stronger interaction but giving up all its mobility such as TilePOP [13].

A challenging question comes into our mind: "Is it possible to provide an ETHD with both mobility and also stronger weight and force endurance?". Our work would like to explore its possibility to offer a wider range of interaction and immersiveness to the users.

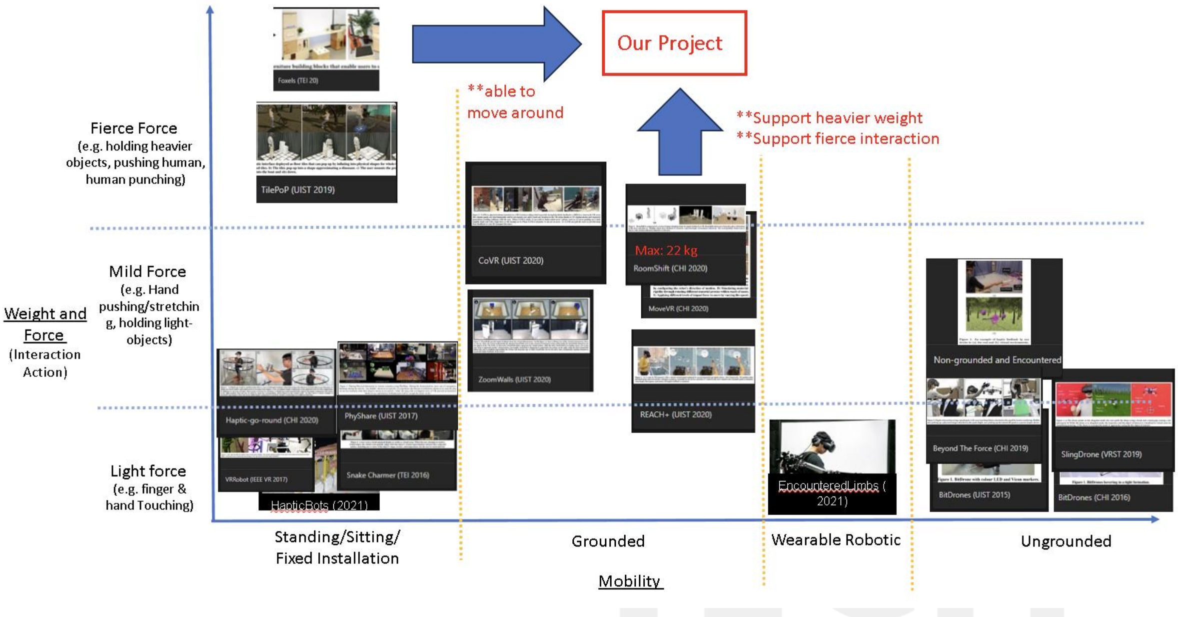


Figure 2.3 Design Space (Encountered-Type Haptic Display).

2.3 Tangible User Interface (TUI)

There are plenty of investigations and discussions about the field of Tangible User Interface (TUI) in a great variety of applications and platforms. The size of the TUI is also varying. For the larger one like PSyBench [26] explore the possibility for remote users to collaborate in a shared physical workspace by using TUI, and also DiamondTouch [27] utilizes multi-user touch technology with tabletop front-projected displays to enables users to manipulate the interface on the same table. The smaller TUI includes Bricks [28] as graspable user interfaces composed of physical handle and a virtual object, and Learning Cube [29] built by microcontroller with acceleration sensors for orientation and movement detection and support the display on each side of the cube. Tangible Bots [30] explores the interaction on tabletop interfaces with the active and passive tangibles via different combinations of commands.

There are also some discussions of TUI in the field of XR such as Mediate [31], a display to render 3D physical geometry based on the virtual objects that the user is interacting with in the virtual environment, and also the discussion of hybrid 2D-3D tangible VR interface [32] that combines smartphone and VR controller to interact with the surrounding environment. Tangible VR Book [33] to explore the marker-based tangible interfaces in VR settings. However, it seems that the works are mainly focus on the single-user usage and lack of discussion of TUI for multi-users interaction in co-located environment for VR applications.

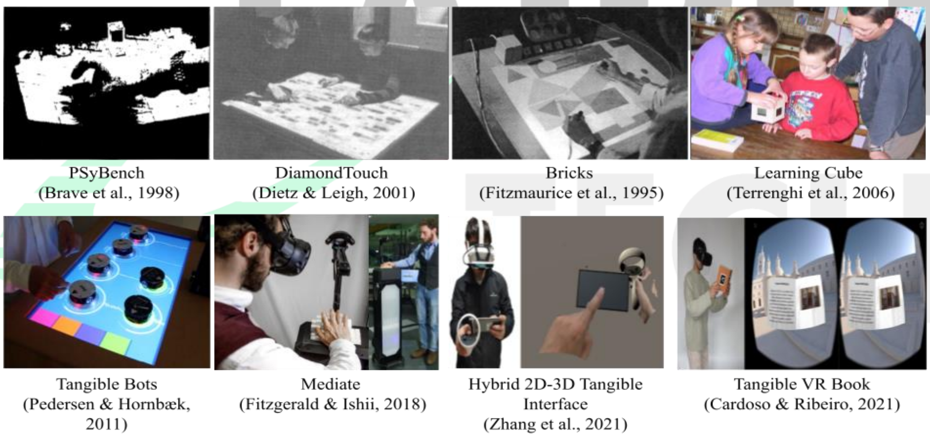


Figure 2.4 Related works in TUI.

In response to the previous session 2.1 about the variety of functionality of a prop in SR, we believe that modular TUI is one of the research areas that is worth investigation and discussion. The concept of Modular TUI is rooted from Graspable User Interfaces raised by [28] that uses physical artifacts “bricks” to operate the Graphical User Interface on table-top screen. Due to the advancement in technology of microprocessor and sensors, it is more possible to create smaller blocks as different modules and combine them for higher scalability in design of TUI such as Blockjam [34] used modular blocks embed with sensor and motherboard to manipulate interactive music systems and TUImod [35] to build modular system for a block with different features.

With the popularity of the concept of virtual reality in 2010s, there has been some researches started to investigate how the TUI can be beneficial to the user experience in the spectrum of virtuality continuum; [36] propose the integration of TUI and Augmented Reality to blend the real and virtual objects on the tabletop surface to enrich the user experience.

Adapting the similar approaches as the previous session, we create a design space for Modular TUI to facilitate the discussion of the current research gap and to explore how our work can be contributed in this related area. We categorized the works on the following two factors:

1.) Internal ability (per module)

2.) Interaction flexibility

Internal ability (per module) refers to the functionality of the individual module of TUI that can offer. Such a concept can be further subdivided into either “inert” or “smart”. The latter one means that the individual module contains a sensor and/or microprocessor while the former one only offers the form of shape and weight. Due to technological advancement, there are many research works focused on making the modules smarter to explore tangible interaction in different fields; Siftables [37] consists of wireless sensors inside the modules for manipulation in groups to interact with digital information and media. LineFORM [38] adopts the ideas from robotics to use a chain of servo motors with sensors for direct manipulation. Inert modules such as Urp [39] using physical architectural models without any embedded sensor inside for urban planning.

The second factor Interaction flexibility refers to the possible variety of interaction with the combined modules. One module may offer only a few ways of interaction, but the combined modules could trigger more possibilities in interaction. Base on the previous researches we found, quite a number of works using smart modules indeed do not offering very high interaction flexibility even when combined as a system; Blinky blocks [40] was intended for an ensemble of large number of modules but did not expand for more functionality and interaction with combined modules. Foxel [41] allows users to build furniture by utilizing modular, smart blocks with different features, though the interaction flexibility is still restricted by the function of the individual modular blocks. In recent year there are some works that offer a wider range of simulation of objects thus expanding the interaction flexibility such as TilePOP [13] and LiftTiles [42].

Regarding the concepts of internal ability and interaction flexibility, it seems that the investigation of modular TUI is mainly focusing on the smart modules rather than inert modules with the rapid growing technology in hardware such as sensors and microprocessors. It could also mean that an individual module is usually customized for one function and so the interaction flexibility of a work would be restricted by how many types of modules it has. For the project requires high interaction flexibility, it might require lots of different types of blocks, which means higher development cost and manufacturing cost, but also higher learning cost to users as they need to spend time to learn and to distinguish the modules.

In the area of inert modules, Urp [39] uses physical models and lightbulb to build a luminous simulation system for urban planning was one of the early examples. TurkDeck [43] shows the possibility of using the surface of coffee tables to build foldable structures to arrange into different shapes physically for more flexible interaction. With the help of 3D printing technology, it is also possible to create more detailed inert module for haptic interaction such as in VRtefacts [44], but it also limits the flexibility of interaction as the shape is customized for specific artifact instead of the general one.

It seems that there is a research gap to study if inert modules could be utilized for higher interaction flexibility with the assistance from the current computer graphics technology such as object recognition or tracking, especially for larger inert modules that can be easily assembled and for wider range of interaction to users.

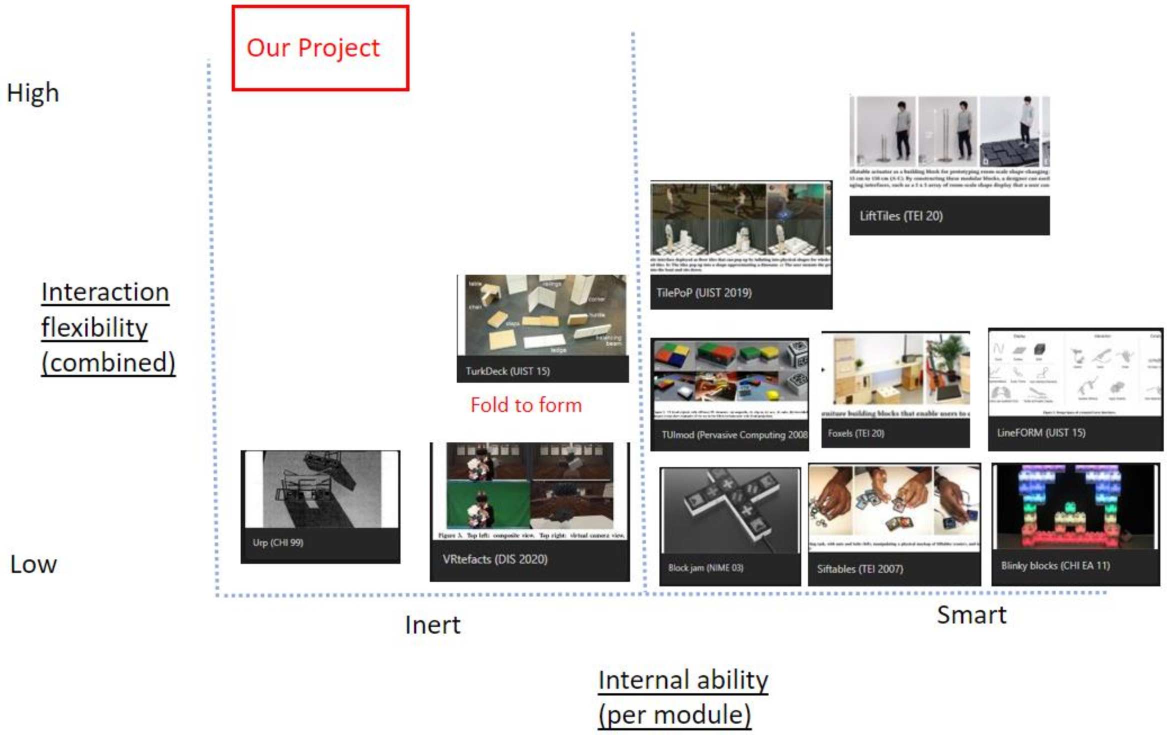


Figure 2.5 Design Space (Modular TUIs).

Chapter 3
Design Considerations and Implementation

3.1 Design Considerations

This paper aims at exploring the design of multi-robot to have more realistic and immersive whole-body experience via the use of props in SR context. With this goal and the related works in the previous chapters, the design considerations can be primarily wrapped up as the following:

3.1.1 Load Tolerance for Human Weight and Force

One of the goals of this work is to create an immersive whole-body experience, which means that the load tolerance of the device should be able to bear the human weight and force. Regarding the human weight, [45] suggests the average Newton force with the world average body mass (62kg) would be around 608N. However, the amount force from human interaction could be varied in different scenario; In case of laying the bed, the newton force would be around 1200N for the user' weight of 110kg and it is suggesting that the strength of the lying area should be have around 1400N (Reh R, 2019). In case of jumping, the landing force could be ranging from 5 to 7 times of the body weight in jumping from 0.45m. In the case of punching, the professor boxer can give punching forces ranging from around 800N to 2300N, based on the type of punches. [46]

3.1.2 Mobility

Referring back to the limitation of the existing ETHDs research in previous sessions, our work would like to explore the possibility for the fierce force of whole-body interaction with higher mobility of the grounded device to offer an immersive experience for users in room-scale settings. In this case, the design of device structure requires the attachment of the motor. And the motor power should be strong enough to support the load tolerance mentioned in the above session and to sustain a certain speed while moving with load on the device. High mobility is critical to reduce the setup time for each scenario and objects to avoid long waiting time to users.

3.1.3 Prop Efficiency

In tangible interaction and SR, users have to deal with props or proxy to complete the certain action. We have raised the concern about the variety of functionality per props in session 2.1, with internal ability and interaction flexibility in session 2.3; The existing research is able to provide a wide range of substitution but at the cost of offering more prop, or providing a smart module with specialized function for user to interact. However, these approaches may hinder the prop efficiency at the cost of production to designers and also the cost of learning to users. In our work, we would like to explore using the inert module with primitive shapes for users to build different combinations of form for whole-body interaction.

3.1.4 Ergonomic Factors and Prop Formation

When considering the whole-body interaction, the ergonomic factors are of high importance in terms of height, weight, and other types of body measurements. Our work is currently focused on the formation of furniture and so we refer the relevant anthropometric measurement from other researchers as reference for our design. [47] give recommended chair and desk dimensions for users in Asian countries as the following:

- Height of desk: 55.5 – 75.9cm
- Height of chair: 33.8 – 45.8cm
- Width of chair: 37.1 – 63.1 cm
- Depth of chair: 34.4 – 47.6cm

These data could help us to determine the appropriate dimension of the modular blocks used in our work by subdividing the recommended dimension with different combination of width, height and depth.

3.2 Implementation

With the above design considerations, we proposed MovableBlocks, a multi-robots solution as modular blocks to form dynamic furniture for whole-body interaction.

3.2.1 Hardware

To differentiate single robotic device from our multi-robot solutions titled "MovableBlocks", the single robotic device is named "M-Block" as a single modular unit in our work . Each M-Block is made of following key components: 1) Aluminum extrusion designed in octagonal shape for structural stability and connectability between multiple M-Blocks(Figure 3.1) ; 2) Controlling system to actuate M-Block by two brushless hub motors (24V) powered by lithium-ion battery pack via the Raspberry Pi; 3) Passive omni-directional wheels to support the weight and to assist structural balancing for M-Block; 4) Armor, composed of medium-density fiberboard and polyethylene material, to protect the structure from crush with the surrounding objects/walls in the physical environment and to create solid surface for whole-body interaction for users such as sitting, laying, standing, etc. The detailed view of M-Block is shown in the Figure 3.2 and Figure 3.3. Bill of Material (BOM) is also included in the Table 3.1.

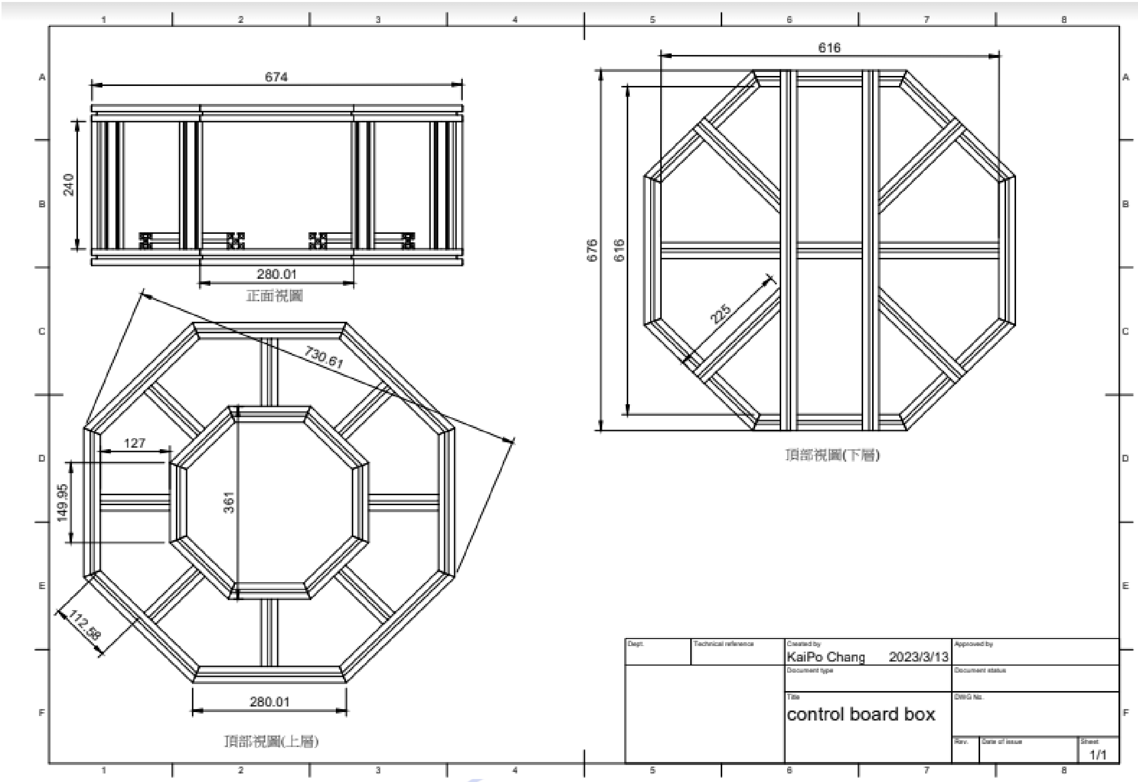


Figure 3.1 The blueprint of the aluminum extrusion for Robotic base.

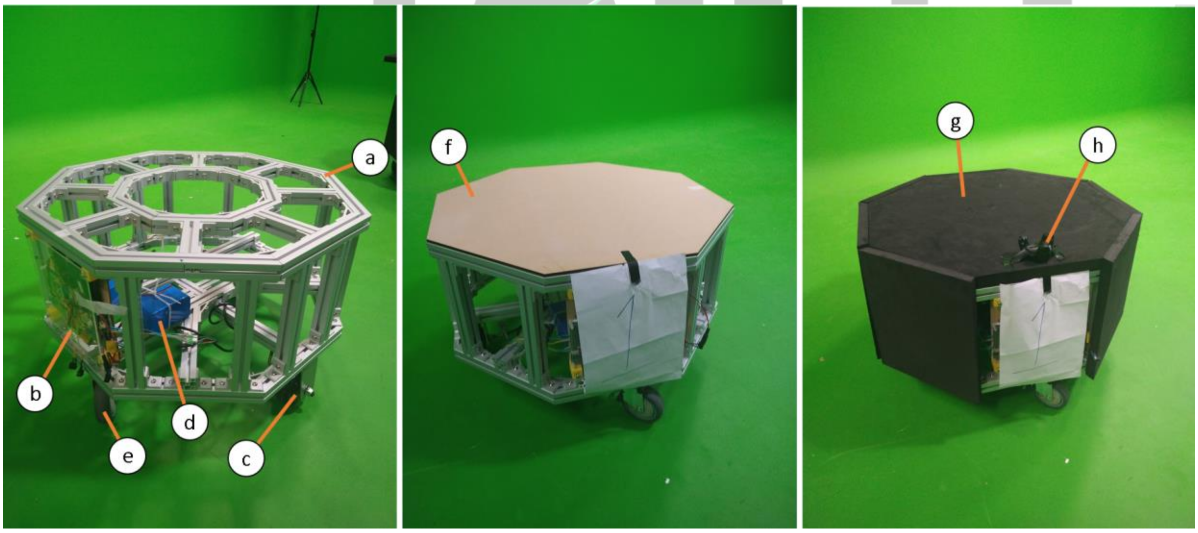


Figure 3.2 The components of the “M-Block”:

a) Aluminum extrusion, b) Controlling system box, c) Brushless hub motor, d) Lithium-ion battery pack, e) Passive omni-directional wheel, f) Medium-density fiberboard, g) Armor, h) Vive Tracker

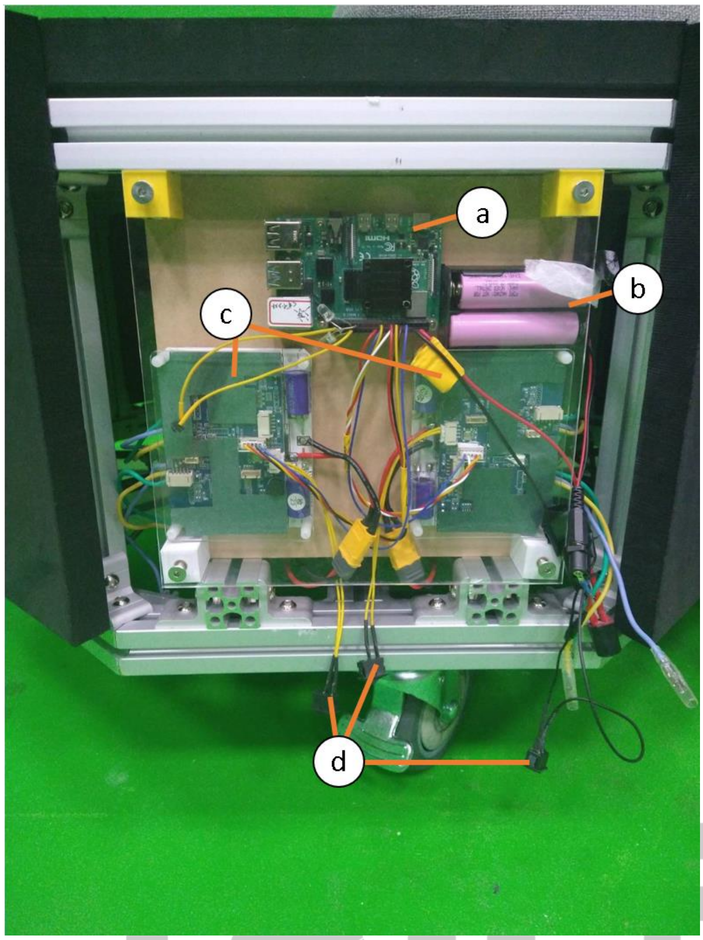


Figure 3.3 Close-up of controlling system box: a) Raspberry Pi, b) Lithium-ion battery with battery holder, c) Motor driver board, d) 2P Switches

Table 3.1 BOM of the M-Block.

Level	Name	Quantity	Description and Purpose
	M-Block	1	The completed device
1	Aluminum extrusion	1	• Octagonal shape for assembling and scalability • Strong structure to support weight-bearing
2	Controlling system	1	For mobility of the device
2.1	Raspberry Pi	1	The small board computer
2.2	Motor driver	2	For controlling the hub motors

	board		
2.3	Brushless hub motor	2	24V
2.4	Lithium-ion battery pack	2	For powering the hub motor
2.5	Lithium-ion battery	2	For powering the Raspberry Pi
2.6	Battery holder	1	For holding the Lithium-ion battery (2.5)
2.7	2P Switch	3	For controlling the electric circuit of hub motors and Raspberry Pi
3	Passive omni-directional wheels	2	For supporting the weight and balancing the structure of M-Block
4	Armor	1	• For protecting the device from crush • For creating solid surface for whole-body interaction by users
4.1	Medium-density fiberboard		For better support of weight, especially to fill up the hole in the center part of the aluminum extrusion
4.2	Polyethylene Plate	1	To be cut in octagonal shape fitting the top of aluminum extrusion
4.3	Polyethylene Block	7	Wrapping each side of the aluminum extrusion (except the side with the controlling system installed)
5	Vive tracker	1	For tracking the position of M-Block in the virtual environment

3.2.2 Software

This work would present potential applications for users in the SR setting, which is mainly developed using Unity and VIVE XR Elite, accompanied the usage of VIVE trackers.

3.2.2.1 Motor Controller Interface

The hub motors are coded to spin based on the combined value of "xValue" and "zValue"; If xValue is positive, both hub motors spin to drive M-Block forward, while negative xValue is the reversed case and to drive M-Block backward; If zValue is positive, hub motors spin in opposite direction in each other to rotate M-Block in the closewise direction, while negative zValue rotates M-Block in the anti-clockwise direction. The summary of the cases is shown in the following Table 3.2.

Table 3.2 Summary table for M-Block movement with different values.

Value	Case	Left motor	Right motor	M-Block movement	Input
xValue	Positive (+x)	Forward	Forward	Going forward	Up
	Negative (-x)	(Backward)	(Backward)	Going backward	Down
zValue	Positive (+z)	(Backward)	Forward	Rotate closewise	Right
	Negative (-z)	Forward	(Backward)	Rotate anti-clockwise	Left

The motor driver boards are connected to RaspberryPi which has built-in Wi-Fi capabilities and can be connected to other systems under the same network, thus enabling the motor control remotely from these systems. For example, we have tested using Android tablet and Windows OS to wrap the xValue and zValue into JSON package and send the package to the RaspberryPi with websocket plugin to control the motor. In this study, we developed a Unity application to control the hub motors on multiple M-Blocks by assigning different keyset to each M-Block for changing the value independently (Figure 3.4).

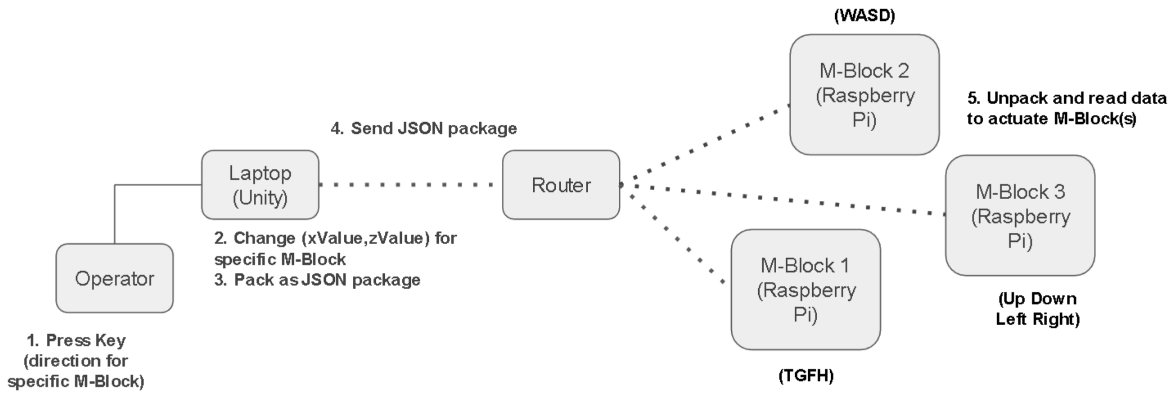


Figure 3.4 The operation process of the controller interface.

3.2.2.2 Object Recognition and Tracking

Before the development of the application, we need to work out the principle of how SR could be work by using MovableBlocks. One key issue is the integration of the physical and virtual environment. We need an approach to detect the position and rotation of M-Block in the physical environment, so to form the visual representation in the virtual environment to synchronize M-Block existence in both physical and virtual environment. Eventually we pick VIVE tracker because the tracking is quite stable from the previous experience in our VR projects, though adopting VIVE tracker means lighthouse setup is required for tracker capturing.

Regarding the positioning of the VIVE tracker on M-Block, we considered two choices: 1) On the surface of controlling system box (side of M-Block), or 2) On the surface of Amour (top of M-Block). There are two main considerations of the choice. The first one is the tracking stability, Choice 1 might have risk of lost tracking if the structure M-Block block the invisible light from the lighthouse to the tracker due to the rotation, while Choice 2 have much lower risk of tracker being blocked by M-Block structure. The second consideration is interruption to users' interaction, Choice 1 can minimize the interruption to users' whole-body interaction as the controlling system box is not the area designed for users' interaction; Choice 2 will more or less affect the users' experience as the top surface of Amour is designed for users' interaction, it is very likely that the users accidentally touch or hit the tracker which would interrupt their interactions.

After the consideration, we eventually picked Choice 2 because we believe the tracking stability is the first priority for SR experience; If M-Block cannot be constantly tracked and represented in the virtual environment, such discrepancy between virtual and real environment could severely impact the users' experience. But we also attempted to minimize the possible interruption to users' interaction by placing the tracker near the corner of the back of M-Block (Figure 3.5), which is also close to the controlling system box, and to remind users about the existence of the tracker and the controlling system box before using M-Block.

Figure 3.5 Vive tracker attached on the back of M-Block.

3.2.2.3 Choice of VR Headset

Considering the larger extend of movement of M-Block when user is sitting on it, wireless VR Headset would be appropriate choice for our work to prevent the cable knotted with fierce movement and hitting the cable may also adversely affect users' experience. VIVE XR Elite from HTC was chosen because it is one of the most advanced inside-out headsets with high quality imaging in pass-through mode. Adapting recent VR headset might be also helpful to learn from the latest VR technology and transferring them into better user experience when developing the SR applications in this work.

3.2.2.4 Application 1: “Dynamic Furniture”

One potential application “Dynamic Furniture” is proposed to use multiple M-Blocks to form different furnitures in the virtual environment in user’s home, and to allow user to interact with different furniture using the whole-body. Based on the number of modular base combined, three different virtual furniture is formed accordingly for user to interact with as the following:

Table 3.3 The virtual furniture available in “Dynamic Furniture”.

Furniture	Required number of M-Block	Purpose
1. Chair	1	Default setting for user’s initial interaction of sitting on the chair
2. Bed	2	Allow user to sit or even lay on it with whole-body
3. L-shape Sofa	3	1. Allow user to do more fierce interaction on the M-Blocks such as curling up and crossing the leg on them. 2. Leave the possibility for multi-user interaction such as sitting together with others

The formation of different furniture is based on the distance between devices: with one modular device only, it will form “chair” in the VE that allows user to sit on it; with two modular devices combined together, it will form “bed” in the VE that allows user to lay on it (Figure 3.6); with three modular devices combined together, it will form “sofa” in the VE that allows user to lean on or curl up on it or inviting friend to sit together (Figure 3.7).

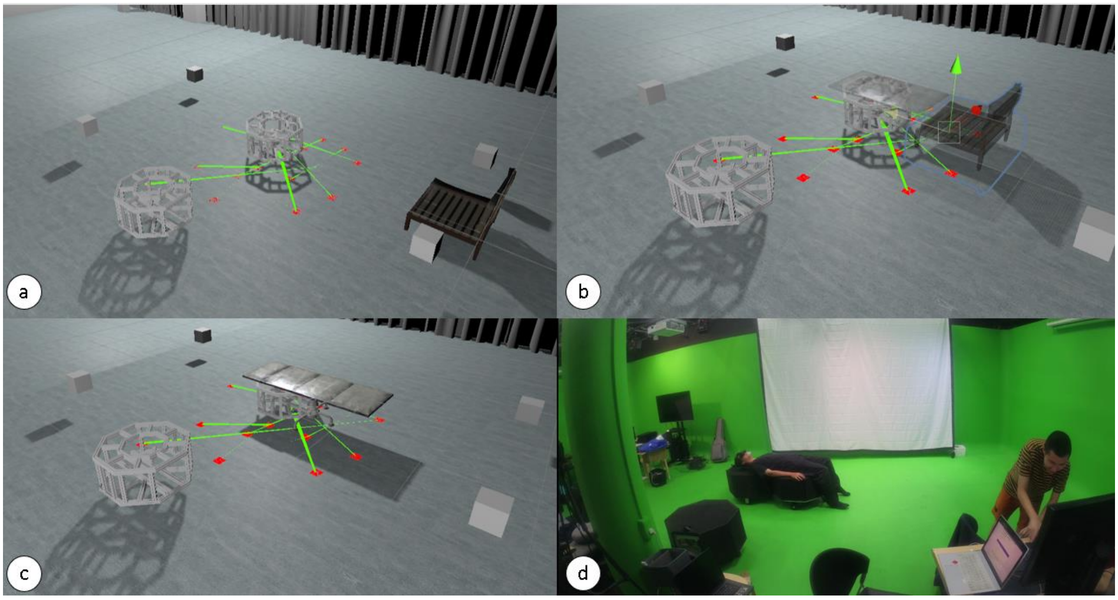


Figure 3.6 Formation of bed and interaction:

a) One device approach another device; b) The formation of bed begins when two devices are close enough; c) The model of the bed is formed; d) User is laying on the bed

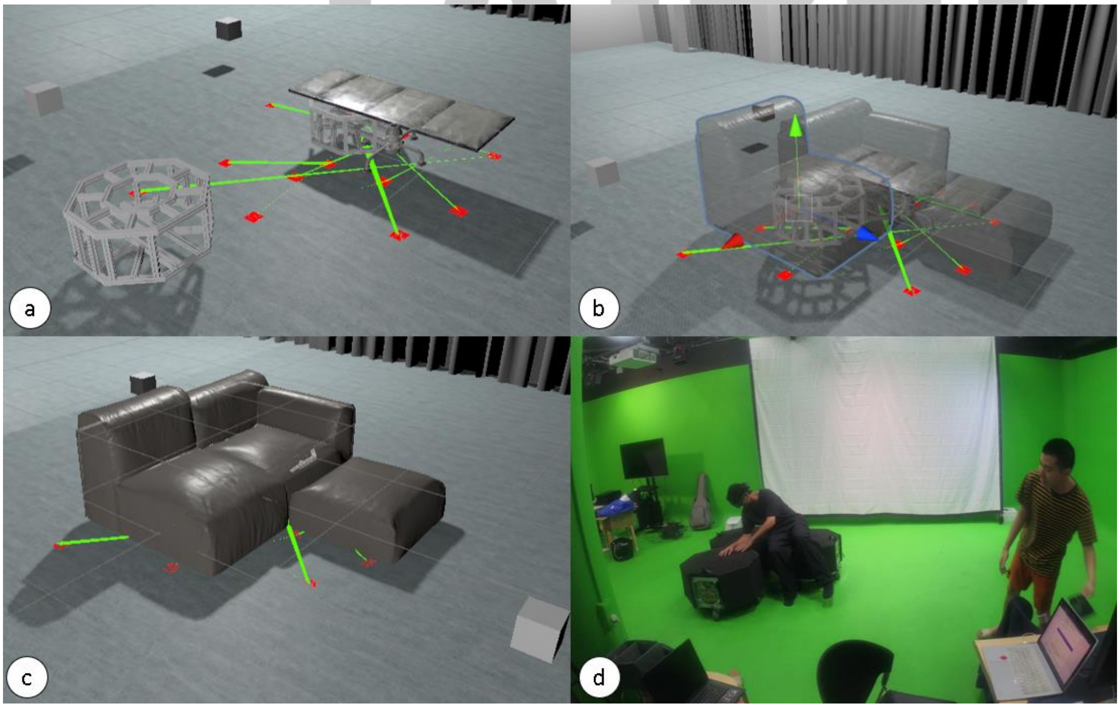


Figure 3.7 Formation of sofa and interaction:

a) Third device approach; b) Formation of sofa begin when devices are close enough; c) The model of sofa is formed; d) User is leaning on it

3.2.2.5 Applications 2: "Forest Tour"

Another potential application we proposed is "Forest Tour", which allows user to ride on M-Block (minecart in the VE) to navigate around the virtual forest surrounding with natural environment and animals. The current design of navigation distance between the physical environment and virtual environment is 1:1 scale, which means the distance moving in the physical environment will be equivalent to the distance moving in the virtual environment. In this application, users simply need to be seated on the M-Block and it initiates motion enabling users to move around, enjoying the natural scenery.

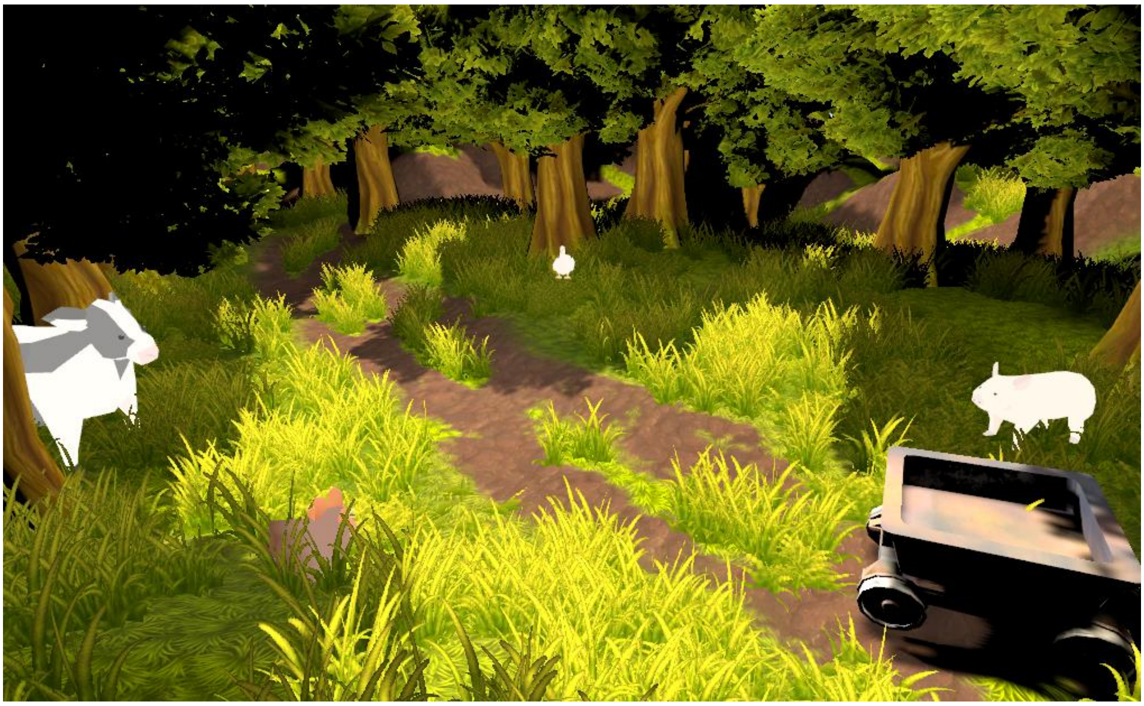


Figure 3.8 The scenario of virtual environment in Forest Tour –

"User seated in the minecart, embarking on a thrilling encounter with forest animals"

Chapter 4 Research Design

We conduct two technical evaluations to understand the ability of M-Block in terms of mobility and coordinating ability, and to do the appropriate adjustment for the M-Block before the user study for testing usability.

4.1 Technical Evaluation 1 – Single-robot Mobility

Before the evaluating the whole multi-robot system, it is critical that we should understand the ability of the M-Block as a single module first. One of the important factors is the mobility, especially when it is moving with weight. It is also important to understand the motor power value so it can be set appropriately for the future user study. So, our first technical evaluation would be testing of the robot mobility with weighting to inform us the utility of M-Block in the future design of the whole MovableBlocks system.

We conducted two mobility test sessions; a.) straight-line running test, and b) rotation test. For both test sessions, there are two dependent factors which are 1.) weight loading and 2) power of motor.

There are 6 cases in weight loading including 0kg (no weight-loading), 10 kg, 20 kg, 30 kg, 40 kg, and 50kg. The maximum weight loading is set to 50kg because with the net weight of M-Block(25.8kg) and the summation would be close to the weight-loading capacity of a hub motor stated in the specification which is 75kg. Four test cases of motor power is 20%, 30%, 40% and 50% respectively: The power below 20% cannot initiate any motion of M-Block which might be due to its net weight; The power above 50% with no weight-loading dash too fast which could be prone to crush and cause danger in the test sessions.

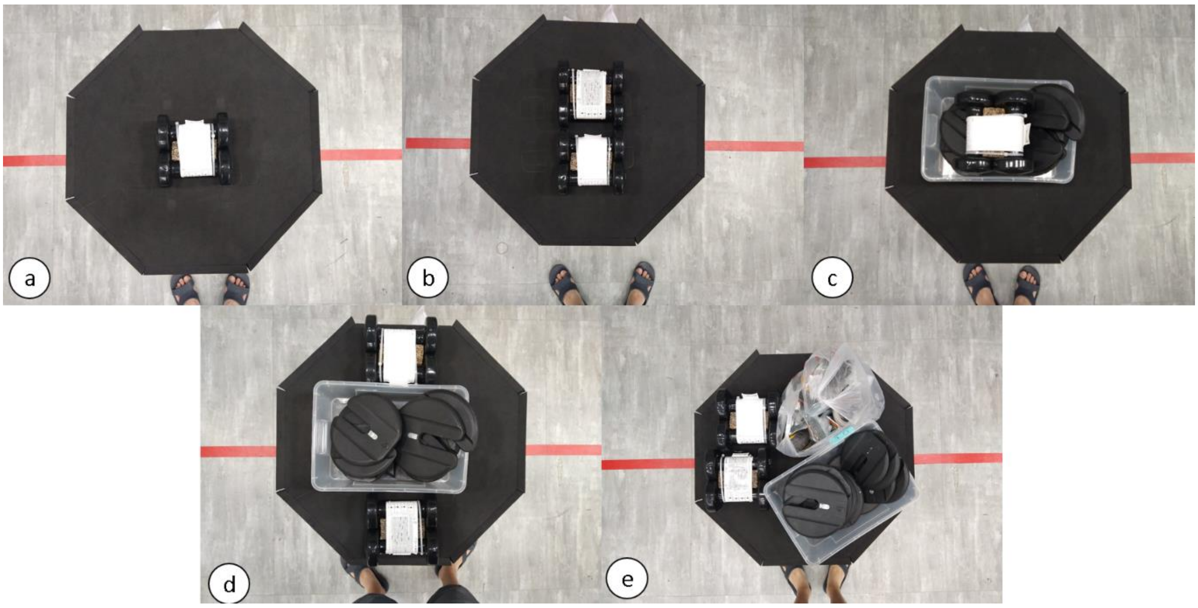


Figure 4.1 The setup of the weight loading in the test sessions:

a) 10kg: two 5kg dumbbell,

b) 20kg: four 5kg dumbbell,

c) 30kg: two 5kg dumbbell + 20kg of weight plate,

d) 40kg: four 5kg dumbbell + 20kg of weight plate,

e) 50kg: four 5kg dumbbell + 20kg of weight plate + 10kg of collected items from our lab

4.1.1 Straight-line Running Test

In the straight-line running test, we would like to test the mobility of M-Block with different combination of power and weight loading, which is helpful for us for the design in next step to set the appropriate power with according weight loading, to ensure the mobility of the M-Block can be kept steady with different weight loading to provide consistent experience.

The testing venue is set in one of the largest classrooms in our institution: Guanghua Building 4th floor, Room 400. It can ensure the longer distance for straight-line running test which fits the need of allowing our M-Block can be used in large-room scale. The test length is 12.2 meter long which is not the full length of the venue to ensure some buffer length for deceleration of the M-Block after passing the finish line. The detail setup is shown in the Figure 4.2.

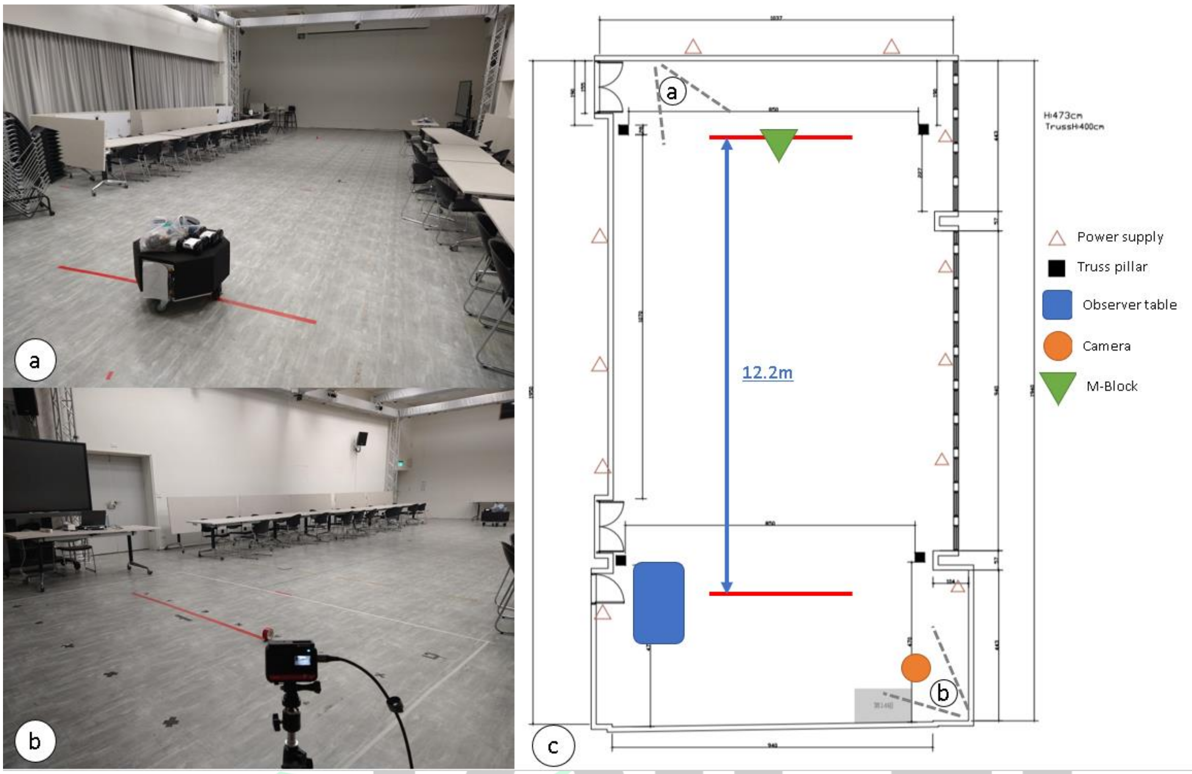


Figure 4.2 The setup of testing venue: a) Shooting from the front entrance, b) Shooting from another side, c) Floor plan of the testing environment

As mentioned in the previous sub-session, there would be 6(weight) x 4 (power) = 24 combinations in each test session. In this running test, 10 trials would be conducted for each combination, in each trial the amount of time is recorded and eventually average time is calculated for each combination. Based on the average speed recorded, we also attempt to calculate the depreciation rate of speed by weight and power to understand how each factor affects the speed. From the result, it is reported that the depreciation rate of power is higher than that of weights, particularly when looking the result for the column with 30% and 20% power, the speed remains around 60% and 40% respectively given the same weight loading. It means the adjustment of power is more critical factor for speed in our setting. The summary of results is shown in the following figure.

Technical Test 1 Result (straight-line running)		Power 50%	40%	30%	20%
0kg	Straight (m/s)	1.76	1.43	1.10	0.68
10kg	Straight (m/s)	1.52	1.28	0.94	0.62
20kg	Straight (m/s)	1.49	1.28	0.93	0.61
30kg	Straight (m/s)	1.46	1.24	0.89	0.56
40kg	Straight (m/s)	1.40	1.15	0.84	0.51
50kg	Straight (m/s)	1.27	1.15	0.83	0.46

a

Technical Test 1 Result (straight-line running): Overall Depreciation		Power 50%	40%	30%	20%
0kg	Straight (m/s)	100%	82%	63%	39%
10kg	Straight (m/s)	87%	73%	53%	35%
20kg	Straight (m/s)	85%	73%	53%	35%
30kg	Straight (m/s)	83%	71%	51%	32%
40kg	Straight (m/s)	80%	66%	48%	29%
50kg	Straight (m/s)	73%	65%	47%	26%

b

Technical Test 1 Result (straight-line running): Weight		Power 50%	40%	30%	20%
0kg	Straight (m/s)	100%	100%	100%	100%
10kg	Straight (m/s)	87%	89%	85%	92%
20kg	Straight (m/s)	85%	89%	84%	89%
30kg	Straight (m/s)	83%	87%	80%	83%
40kg	Straight (m/s)	80%	80%	76%	75%
50kg	Straight (m/s)	73%	80%	75%	67%

c

Technical Test 1 Result (straight-line running): Power		Power 50%	40%	30%	20%
0kg	Straight (m/s)	100%	82%	63%	39%
10kg	Straight (m/s)	100%	84%	62%	41%
20kg	Straight (m/s)	100%	86%	62%	41%
30kg	Straight (m/s)	100%	85%	61%	38%
40kg	Straight (m/s)	100%	83%	60%	36%
50kg	Straight (m/s)	100%	90%	65%	36%

d

Figure 4.3 The summary of result for straight-line running test: a) The average speed for each combination, b) The depreciation rate of speed (Overall), c) The depreciation rate of speed (Weight), d) The depreciation rate of speed (Power)

4.1.2 Rotation Test

In the rotation test, we would like to test the rotation ability of M-Block with the same combination of power and weight loading as in the straight-line running test. It is also helpful to determine the appropriate power with different weight loading in the future system.

Similar to the straight-line running test, 20 combinations of power and weight loading are used for the rotation test. Beside the previous 20 combinations, we also take into the consideration of the rotation direction of anti-clockwise and clockwise. So literally there are 40 combinations. For each combination, 5 trials would be conducted and each trial the M-Block need to do five full rotations. The finished time is recorded for each trial and the average time is calculated based on the collected data. The depreciation rate of speed is also calculated and analyzed similar to the straight-line running test. The summary of the result is shown in the Figure 4.4.

Regarding the result, it is worth to take note that 20% power is not sufficient to enable the rotation of the M-Block. It might be the larger force is required for rotation than for moving forward.

Technical Test 1 Result (revolution)		Power 50%	40%	30%	20%
0kg	Spin-L (revolution/s)	0.58	0.48	0.34	N/A
	Spin-R (revolution/s)	0.61	0.47	0.32	N/A
10kg	Spin-L (revolution/s)	0.55	0.45	0.32	N/A
	Spin-R (revolution/s)	0.58	0.44	0.30	N/A
20kg	Spin-L (revolution/s)	0.52	0.43	0.31	N/A
	Spin-R (revolution/s)	0.54	0.45	0.29	N/A
30kg	Spin-L (revolution/s)	0.51	0.41	0.29	N/A
	Spin-R (revolution/s)	0.52	0.41	0.29	N/A
40kg	Spin-L (revolution/s)	0.48	0.39	0.27	N/A
	Spin-R (revolution/s)	0.45	0.37	0.27	N/A
50kg	Spin-L (revolution/s)	0.42	0.35	0.24	N/A
	Spin-R (revolution/s)	0.43	0.37	0.25	N/A

a

Technical Test 1 Result (revolution) - average (overall dep)		Power 50%	40%	30%	20%
0kg	Spin-avg (revolution/s)	100%	81%	69%	N/A
10kg	Spin-avg (revolution/s)	96%	75%	65%	N/A
20kg	Spin-avg (revolution/s)	90%	74%	63%	N/A
30kg	Spin-avg (revolution/s)	87%	69%	61%	N/A
40kg	Spin-avg (revolution/s)	79%	64%	57%	N/A
50kg	Spin-avg (revolution/s)	72%	61%	51%	N/A

c

Technical Test 1 Result (revolution) - average (weight dep)		Power 50%	40%	30%	20%
0kg	Spin-avg (revolution/s)	100%	100%	100%	N/A
10kg	Spin-avg (revolution/s)	96%	93%	94%	N/A
20kg	Spin-avg (revolution/s)	90%	92%	91%	N/A
30kg	Spin-avg (revolution/s)	87%	86%	88%	N/A
40kg	Spin-avg (revolution/s)	79%	80%	82%	N/A
50kg	Spin-avg (revolution/s)	72%	76%	74%	N/A

d

Technical Test 1 Result (revolution) - average		Power 50%	40%	30%	20%
0kg	Spin-avg (revolution/s)	0.59	0.48	0.33	N/A
10kg	Spin-avg (revolution/s)	0.57	0.44	0.31	N/A
20kg	Spin-avg (revolution/s)	0.53	0.44	0.30	N/A
30kg	Spin-avg (revolution/s)	0.51	0.41	0.29	N/A
40kg	Spin-avg (revolution/s)	0.46	0.38	0.27	N/A
50kg	Spin-avg (revolution/s)	0.43	0.36	0.24	N/A

b

Technical Test 1 Result (revolution) - average (power dep)		Power 50%	40%	30%	20%
0kg	Spin-avg (revolution/s)	100%	81%	56%	N/A
10kg	Spin-avg (revolution/s)	100%	78%	55%	N/A
20kg	Spin-avg (revolution/s)	100%	83%	56%	N/A
30kg	Spin-avg (revolution/s)	100%	80%	57%	N/A
40kg	Spin-avg (revolution/s)	100%	82%	58%	N/A
50kg	Spin-avg (revolution/s)	100%	85%	57%	N/A

e

Figure 4.4 The summary of result for rotation test: a) The average speed for each combination, b) The average speed for each combination (combined clockwise and anti-clockwise), c) The depreciation rate of speed (Overall), d) The depreciation rate of speed (Weight), e) The depreciation rate of speed (Power)

By combing the result of two tests, it gives us the overall picture of the motor power adjustment regarding the loading weight on the M-Block to produce certain amount of speed in the future operations such as targeted movement and multi-robot coordination, which should be at least 50% of power. And the data from the above also help to provide the appropriately good estimation of the signal input to the motor power for automated movement via Unity for next technical evaluation.

4.2 Technical Evaluation 2 – Automated Targeted Movement Performance

Upon the completion of technical evaluation 1, we gained understanding how the speed is affected by both motor power and weight to create the Unity program for enabling the M-Block's automated movement. Unity is used for creating virtual environment and to connect with the physical environment by using sensors such as VIVE trackers, which are attached to the M-Block. Thus, the position and rotation of the M-Block can be tracked and display in the virtual environment.

4.2.1 Algorithm for Automated Movement

In this phase, we attempted to design and write simple algorithm to allow automated movement by the M-Block to specific target position and ending facing angle.

The logical step is listed out as the following with 3 phases:

Phase 1 - Rotation

Step 1: To determine the rotation angle required by the M-Block to face the direction of the target, and calculate the time required for rotation.

Step 2: The signal required will be sent to the Raspberry Pi for the calculated time to control the hub motor spinning.

Step 3: After the time, the system will check angle of the M-Block towards the direction of the target (based on the updated rotation of the M-Block)

Step 3A: If the angle is less than specific degree, go to Phase 2

Step 3B: Else repeat Step 1 and 2.

Phase 2 – Going forward

Step 1: To determine the forward distance required by calculating the distance between the M-Block and the target location, and calculate the time required for going forward.

Step 2: The signal required will be sent to the Raspberry Pi for the calculated time to control the hub motor spinning. Step 3: After the time, the system will check the distance of the M-Block with the target location (based on the updated location of the M-Block) Step 3A: If the distance is less than specific amount, go to Phase 3 Step 3B: Else repeat Step 1 and 2.
<u>Phase 3 – Adjusting facing angle</u> Step 1: To determine the rotation angle required by the M-Block to face the facing direction of the target, and calculate the time required for rotation. Step 2: The signal required will be sent to the Raspberry Pi for the calculated time to control the hub motor spinning. Step 3: After the time, the system will check the forward-facing angle of the M-Block and the target (based on the updated rotation of the M-Block) Step 3A: If the angle is less than specific degree, the operation is done. Step 3B: Else repeat Step 1 and 2.

4.2.2 Evaluation Methodology

As in this technical evaluation we attempted to test the performance of automated movement of the M-Block with different paths to test its adaptability under different settings. In each trial, 16 target points are generated in the venue and are randomly connected to from a path sequence. The M-Block will then travel from point 1 to point 16 one by one. For each point arrival, the performance data will be collected, including "number of steps", "time used", "angle deviation from target", "distance deviation from target" to measure the efficiency and accuracy of the automated movement. In total 6 trials were taken in this technical evaluation. The results are as the following figures:

Target	Step used	Position deviation	Angle deviation
1	20	0.4834421	2.63158
2	6	0.6474584	25.09842
3	14	0.3078819	2.261486
4	12	0.5042576	20.8285
5	6	0.2144008	8.985025
6	23	0.347331	18.98271
7	12	0.7310789	15.34128
8	6	0.5013761	9.811574
9	4	0.6264004	3.349657
10	5	0.5921944	15.8977
11	1	0.09902775	3.062029
12	16	0.4960752	2.023907
13	2	0.5153087	24.43563
14	6	0.3383562	18.53214
15	7	0.1578366	9.738961
16	27	0.3529988	13.28244
Total Distance		**22.81412**	

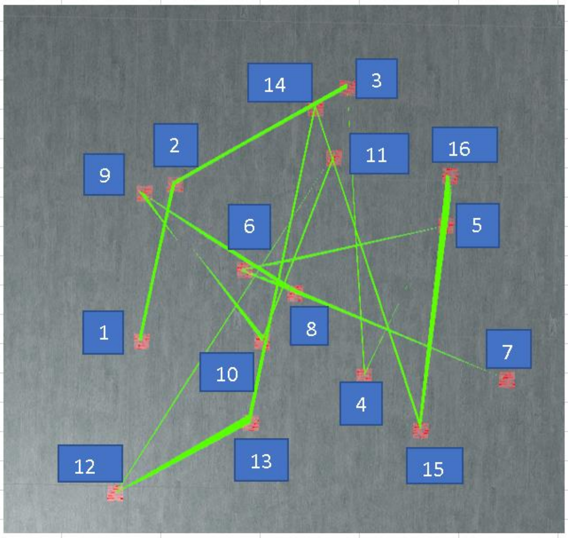


Figure 4.5 Automated Target Movement Result – Trial 1

Target	Step used	Position deviation	Angle deviation
1	11	0.5430663	8.307068
2	7	0.5957134	7.72535
3	8	0.4269016	3.042403
4	15	0.6116742	1.700769
5	42	0.7141324	24.59717
6	37	0.3065878	23.84703
7	23	0.535449	4.447393
8	6	0.7366876	20.09342
9	11	0.6252883	19.53159
10	5	0.4567446	7.478163
11	10	0.6814124	25.3758
12	7	0.3587932	0.3911712
13	8	0.5729629	8.074627
14	7	0.4261955	2.72787
15	6	0.2912486	25.22488
16	5	0.5818117	10.5704
total distance		**23.13896**	

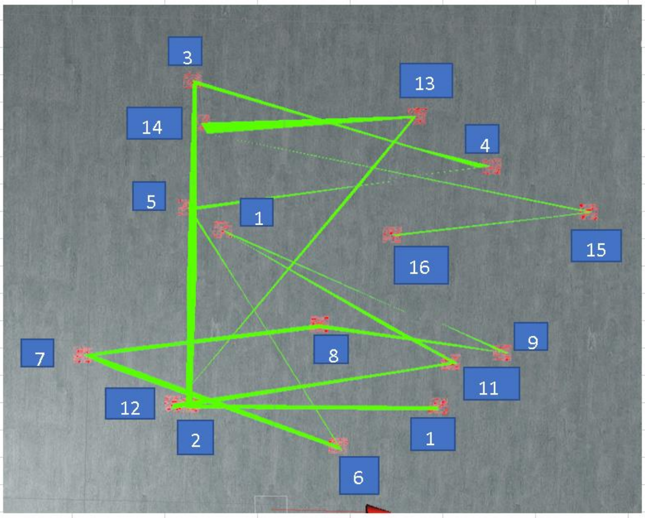


Figure 4.6 Automated Target Movement Result – Trial 2

Target	Step used	Position deviation	Angle deviation
1	4	0.6144933	20.50941
2	5	0.5173609	11.59551
3	12	0.5645669	10.11499
4	6	0.3208313	21.20287
5	4	0.07641323	14.56118
6	25	0.6360254	27.13781
7	13	0.3583151	13.1815
8	9	0.4757923	15.25299
9	6	0.6062959	26.13205
10	7	0.5064836	9.804436
11	12	0.444173	17.73286
12	11	0.09627917	15.80242
13	10	0.3456651	26.18893
14	4	0.1690094	19.42658
15	11	0.4309437	4.578126
16	1	0.4022825	8.199296
total distance		**25.13164**	

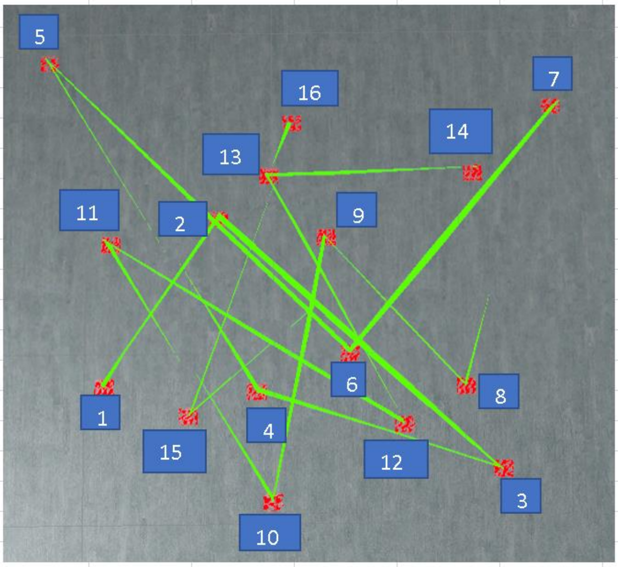


Figure 4.7 Automated Target Movement Result – Trial 3

Target	Step used	Position deviation	Angle deviation
1	7	0.4370643	17.65689
2	15	0.5436261	11.15856
3	7	0.543412	14.23343
4	8	0.2110912	13.63161
5	2	0.5692593	20.07469
6	8	0.3984321	16.89976
7	3	0.5192108	23.89604
8	3	0.3422563	22.29994
9	8	0.3732636	7.990702
10	2	0.5898145	9.92244
11	9	0.1502434	14.01308
12	7	0.4495534	1.672925
13	11	0.4316564	2.908047
14	8	0.3250756	5.313785
15	7	0.08990806	25.26018
16	10	0.5434705	5.777129
total distance		**24.18894**	

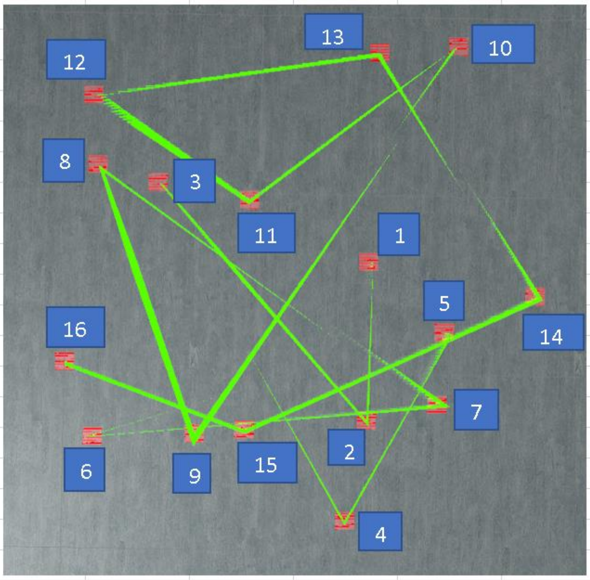


Figure 4.8 Automated Target Movement Result – Trial 4

Target	Step used	Position deviation	Angle deviation
1	0	0.5646327	2.228707
2	5	0.4959472	16.21655
3	5	0.5462459	25.7775
4	17	0.3026045	25.18747
5	11	0.5813927	5.809575
6	13	0.3148376	17.30988
7	6	0.4827852	21.08029
8	2	0.4576969	21.05255
9	8	0.5280793	11.96953
10	12	0.4835074	2.111832
11	9	0.2053272	23.30272
12	7	0.3635987	18.55681
13	9	0.4431578	24.24873
14	7	0.3972085	11.82365
15	6	0.3409595	2.467914
16	14	0.1580587	27.54348
total distance		**23.07195**	

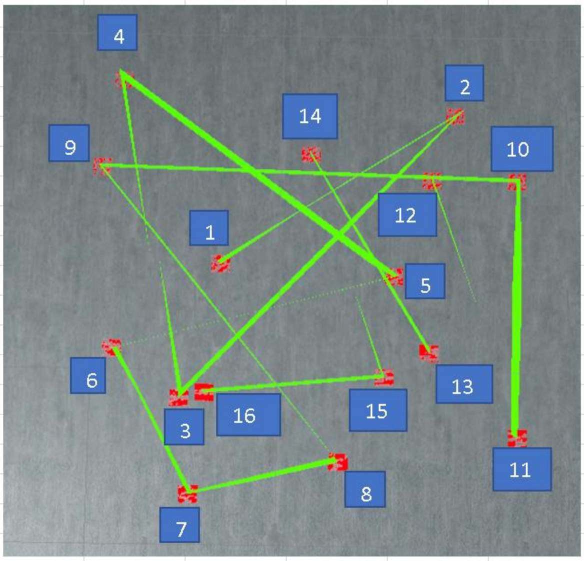


Figure 4.9 Automated Target Movement Result – Trial 5

Target	Step used	Position deviation	Angle deviation
1	4	0.345813	11.23333
2	3	0.517491	19.65713
3	6	0.6753277	25.03845
4	6	0.5732875	2.115073
5	6	0.7768239	4.742187
6	6	0.6975955	18.77795
7	5	0.3875639	13.2391
8	6	0.3938777	9.629066
9	11	0.4345846	25.34035
10	9	0.6580019	4.513579
11	8	0.4686238	21.08475
12	9	0.6439438	6.301452
13	2	0.5150999	3.229497
14	6	0.4911191	6.312736
15	4	0.2797051	17.99216
16	6	0.1011727	18.56162
total distance		**25.63502**	

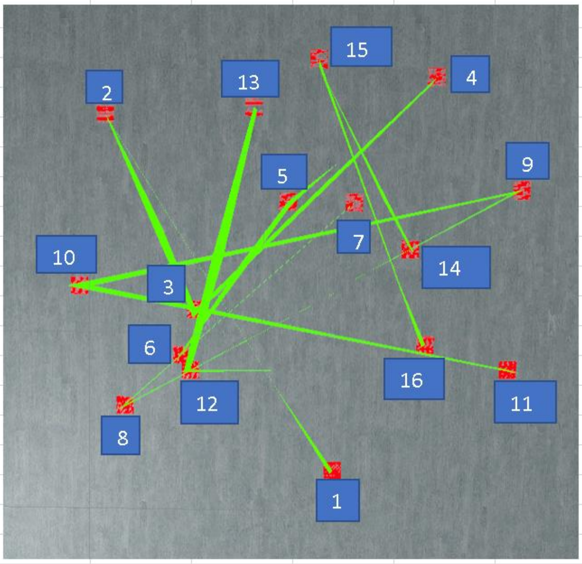


Figure 4.10 Automated Target Movement Result – Trial 6

The overall performance was generally satisfactory in terms of operation efficiency; in most case the movement towards target can be completed in 10 steps or less. The deviation in position and angle are also acceptable.

However, one issue is found during the evaluation that the straight-line movement can be easily altered in Phase 2 after the rotation movement because of the friction created from passive omni-directional wheel at the start of straight-line movement. It could make the M-

Block slip from the correct direction when making straight-line movement, so it took more steps back to the Phase 1 for angle adjustment before going forward.

Another limitation is that the deviation of angle and position from the M-Block in each step is unstable, which hinders the M-Block from the fine and accurate movement that is required by the “Dynamic Furniture”.

With the above considerations and limitation, manual operation of the M-Block will be adopted for the user study. It also helps to ensure the safety of participants in the SR experience by the skilled operator who gained lots of techniques with many trials in the previous technical evaluation.

4.3 User Study – “Presence” for SR Applications

The user study session is conducted to evaluate and understand users’ experience of using MovableBlocks in SR. Each participant experienced two applications, Dynamic Furniture (Application 1) and Forest Tour (Application 2).

4.3.1 Demographics

Twenty-four participants (12 males and 12 females) between the ages of 20 and 31 (SD = 2.86) took part in the user study. The weight of all participant is ranged from 39.1kg to 90kg (SD = 11.50), with it of the 12 males is ranged from 49.6kg to 90kg (SD = 10.80), and of the 12 females is ranged from 39.1kg to 79.3kg (SD = 10.66). 23 participants had had experience with VR technologies, and 1 participant had no experience with VR technologies.

4.3.2 Experiment Design

The objective of the experiment is to understand the participants’ feeling for “Presence” when using the SR Application with the aid of MovableBlocks. In our experiment the two SR applications (Dynamic Furniture and Forest Tour) mentioned in previous session are used to collect the relevant data from the participants about the feeling of Presence and overall evaluation of using MovableBlocks in the virtual environment. Igroup Presence Questionnaire (IPQ) is used in our study to measure the sense of presence experienced in a virtual environment [48], which consists of 14 question items that can be classified into 4 sub-scales of measurements including General Presence (PRES), Spatial Presence (SP), Involvement (INV), Experienced Realism (REAL).

Table 4.1 List of IPQ items.

#	Loading on…	Question	Anchors
1	PRES	In the computer generated world I had a sense of "being there"	not at all--very much
2	SP	Somehow I felt that the virtual world surrounded me.	fully disagree--fully agree
3	SP	I felt like I was just perceiving pictures.	fully disagree--fully agree
4	SP	I did not feel present in the virtual space.	did not feel--felt present
5	SP	I had a sense of acting in the virtual space, rather than operating something from outside.	did not feel--felt present
6	SP	I felt present in the virtual space.	fully disagree--fully agree
7	INV	How aware were you of the real world surrounding while navigating in the virtual world? (i.e. sounds,	extremely aware-moderately aware-not aware at all

		room temperature, other people, etc.)?	
8	INV	I was not aware of my real environment.	fully disagree--fully agree
9	INV	I still paid attention to the real environment.	fully disagree--fully agree
10	INV	I was completely captivated by the virtual world.	fully disagree--fully agree
11	REAL	How real did the virtual world seem to you?	completely real--not real at all
12	REAL	How much did your experience in the virtual environment seem consistent with your real world experience?	not consistent-moderately consistent-very consistent
13	REAL	How real did the virtual world seem to you?	about as real as an imagined world--indistinguishable from the real world
14	REAL	The virtual world seemed more realistic than the real world.	fully disagree--fully agree

Source: www.igroup.org – project consortium (http://igroup.org/pq/ipq/download.php)

The objective of the experiment is to understand the participants' feeling for "Presence" when using the SR Application with the aid of MovableBlocks. In our experiment the two SR applications (Dynamic Furniture and Forest Tour) mentioned in previous session are used to collect the relevant data from the participants about the feeling of Presence and overall evaluation of using MovableBlocks in the virtual environment. Igroup Presence Questionnaire (IPQ) is used in our study to measure the sense of presence experienced in a virtual environment [48], which consists of 14 question items that can be classified into 4 sub-scales of measurements including General Presence (PRES), Spatial Presence (SP), Involvement (INV), Experienced Realism (REAL).

Apart from IPQ, few questions to evaluate the general experience in 5-point Likert scale of using MovableBlock are also included as the following:

1. How safe do you feel when interacting with the device? (***Safety***)

   (1=Not safe at all, 5=Very Safe)
2. How do you feel about the movement speed of the device? (***Speed appropriateness***)

   (1=Too slow, 5=Too fast)
3. Do you feel comfortable by interacting with the device? (***Comfortability***)

   (1=Not comfortable at all, 5=Very comfortable)

There are few open-end questions asking for the possible interactions that user would like to perform with the M-Block and any concern or issued would like to address to facilitate the investigation of our work from qualitative perspective:

1. What other kinds of interaction that you would like to try on the device? (which was not able to do so in this experiment)
2. Do you have any concern/worry when using this device?
3. Other comments

4.3.3 Procedures

Upon the arrival of participants, there will be a brief introduction of the experiment and a short introduction of the MovableBlocks and two application scenarios that the user is going to experience to give them the expectation of what will happening in the experiment and how they can interact with the M-Blocks. After the briefing, participant is required use the body scale to measure the body weight for record with the purpose of analysis and also for setting up the appropriate power of motor. Then the participant is asked to sit on the MovableBlocks and wear the VR HMD to start the experience. There will be total two experience of applications:

In Application 1 – Dynamic Furniture, participant is asked to sit on the M-Block for 30 seconds to feel and look around the environment. After 30 seconds, the M-Block is activated to getting closer to another M-Block to form “virtual bed” for participant to lay down on it for 1 minute. After 1 minute, the third M-Block will come to form L-shape sofa that participant can explore more interaction with it for another 1 minute. The application 1 is ended after the interaction with the sofa.

In application 2 – Forest Tour, participant is asked to sit on the M-Block, and the M-Block will bring the participants to move around in the virtual environment. The experiment will last for 2.5 minutes, which the first 30 second is for the participant to feel and look around the environment, then the M-Block will keep moving for the 2 minutes to bring users navigate around the virtual environment.

Upon the completion of each application, participant is asked to fill in the IPQ, and the general questions to evaluate MovableBlocks are asked to gain the comprehensive understanding of participants’ opinion towards the M-Blocks.

The counter-balancing technique of application order is adopted in the experimental design to remove confounding variables and to control the order effects; Half of the participants were firstly exposed to Application 1 and then Application 2 (Group A); while another half of the participants were firstly exposed to Application 2 and then Application 1 (Group B). The group is assigned upon participant arrival and will be assigned based on the number of current participants and sex in each group (Figure 4.11).

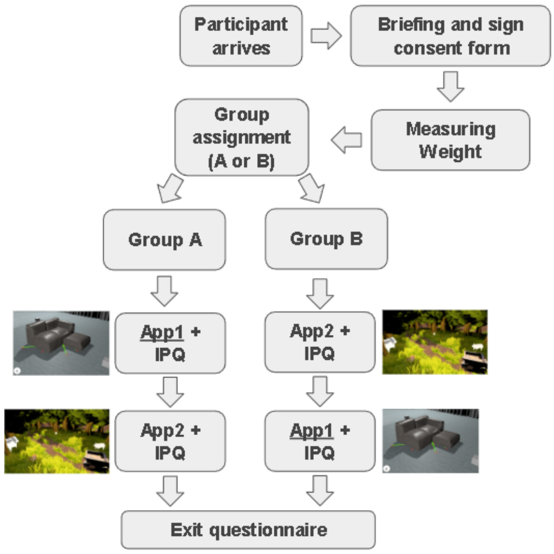


Figure 4.11 The procedure of user study.

The venue of the experiment is set in the room with boundary area of around 2.5m x 4.5m. The detailed floor plans for each application are included in the following figures.

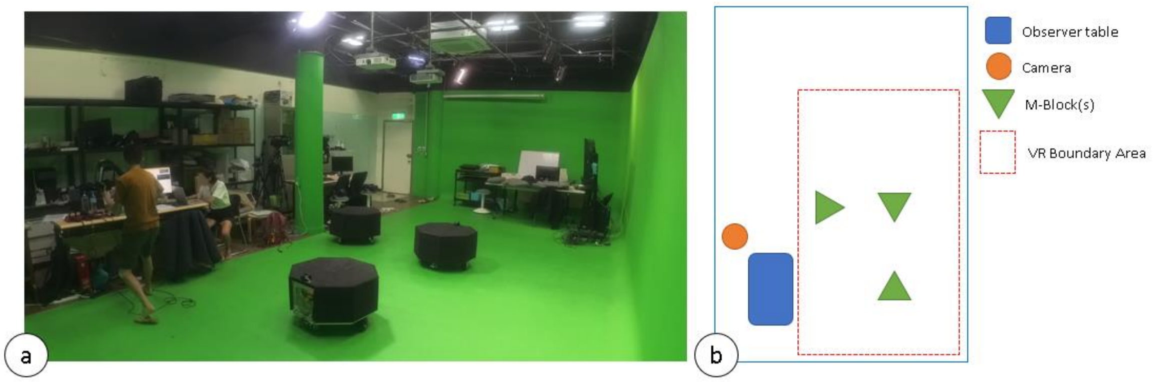


Figure 4.12 Setup of the Application 1 – Dynamic Furniture.

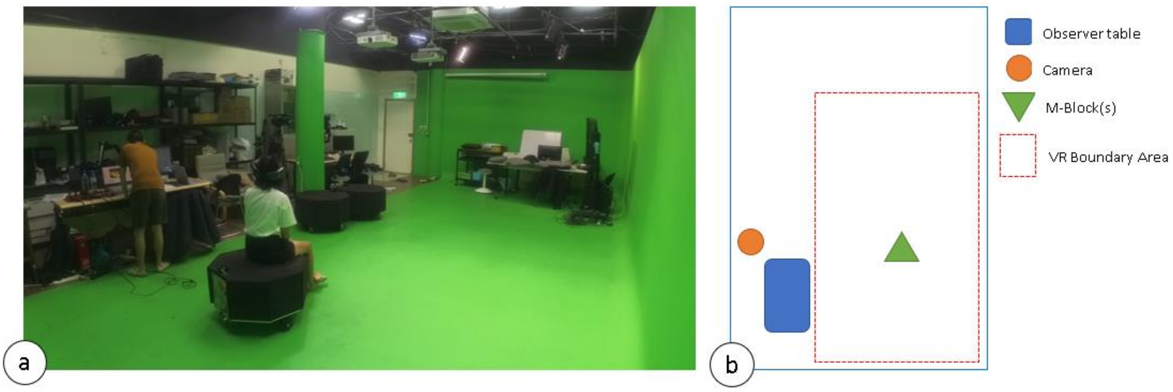


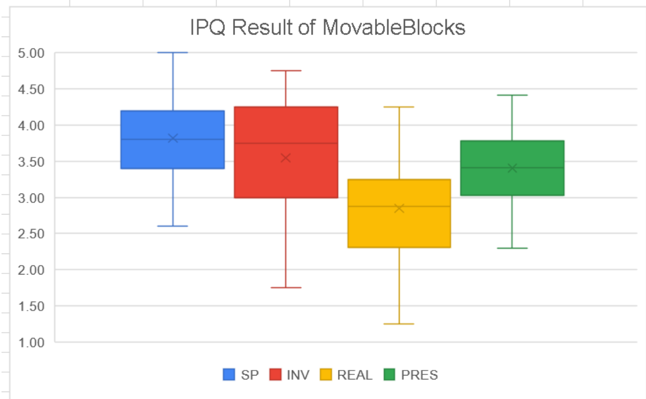
Figure 4.13 Setup of the Application 2 – Forest Tour.

4.3.4 Result and Analysis

In this session, we would investigate the result and conduct some statistical analysis to gain insights about the participants' sense of "Presence" towards the SR applications with the aid of the MovableBlocks, and to discuss the possible factors that might affect their sense of presence.

4.3.4.1 General Interpretation of the IPQ Result

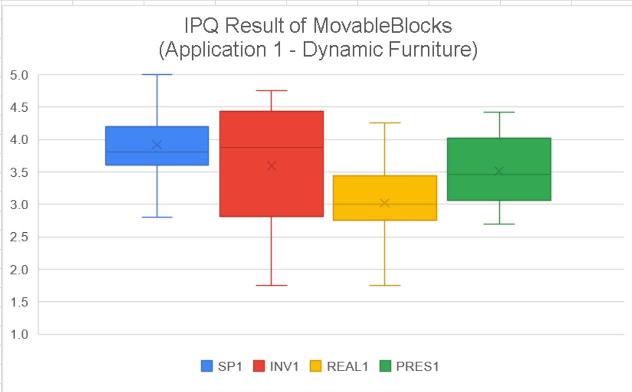
With the complete set of IPQ for each application from 24 participants, there are 48 sample data for IPQ, each contains 14 items and can be divided into 4 sub-scale: 1) Spatial Presence (SP), 2) Involvement (INV), 3) Realism (REAL), and 4) Overall Sense of Presence (PRES). The first 3 sub-scale is calculated by taking the average of the relevant items belong to their sub-scale while PRES is calculated based on the average of other 3 sub-scales. The descriptive statistics and boxplot of aggregate IPQ result and separate IPQ result of both applications is shown in the figures in next page.



Descriptive Statistics

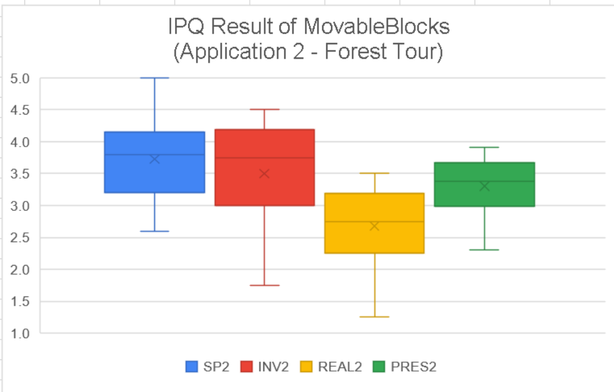
	SP	INV	REAL	PRES
Mean	3.82083	3.54688	2.84896	3.40556
Standard Error	0.08192	0.1211	0.09199	0.0697
Median	3.8	3.75	2.875	3.40833
Mode	3.8	4.5	2.75	4.01667
Standard Deviation	0.56755	0.83897	0.63736	0.48287
Sample Variance	0.32211	0.70387	0.40622	0.23316
Kurtosis	-0.12057	-0.65539	-0.01268	-0.60199
Skewness	0.16387	-0.63153	-0.13497	-0.12247
Range	2.4	3	3	2.11667
Maximum	5	4.75	4.25	4.41667
Minimum	2.6	1.75	1.25	2.3
Sum	183.4	170.25	136.75	163.467
Count	48	48	48	48
Geometric Mean	3.77917	3.43354	2.77272	3.371
Harmonic Mean	3.73697	3.30307	2.68771	3.33541
AAD	0.43264	0.70573	0.49479	0.39306
MAD	0.4	0.625	0.375	0.36667
IQR	0.8	1.25	0.8125	0.72917

Figure 4.14 IPQ Result of MovableBlocks (Overall).



Descriptive Statistics	SP1	INV1	REAL1	PRES1
Mean	3.91667	3.59375	3.02083	3.51042
Standard Error	0.10489	0.18171	0.12938	0.10556
Median	3.8	3.875	3	3.46667
Mode	3.6	4.5	2.75	4.01667
Standard Deviation	0.51387	0.8902	0.63381	0.51712
Sample Variance	0.26406	0.79246	0.40172	0.26741
Kurtosis	0.33238	-0.77207	-0.22113	-1.2961
Skewness	0.3734	-0.6454	0.09031	-0.02096
Range	2.2	3	2.5	1.71667
Maximum	5	4.75	4.25	4.41667
Minimum	2.8	1.75	1.75	2.7
Sum	94	86.25	72.5	84.25
Count	24	24	24	24
Geometric Mean	3.88465	3.47031	2.95476	3.47337
Harmonic Mean	3.85272	3.32883	2.88582	3.43608
AAD	0.39306	0.75781	0.48438	0.44792
MAD	0.2	0.625	0.25	0.49167
IQR	0.6	1.375	0.5625	0.94167

Figure 4.15 IPQ Result of MovableBlocks (Application 1 – Dynamic Furniture).



Descriptive Statistics	SP2	INV2	REAL2	PRES2
Mean	3.725	3.5	2.67708	3.30069
Standard Error	0.125	0.16347	0.12361	0.08806
Median	3.8	3.75	2.75	3.38333
Mode	3.2	3.75	3	3.43333
Standard Deviation	0.61237	0.80081	0.60559	0.43139
Sample Variance	0.375	0.6413	0.36673	0.1861
Kurtosis	-0.32891	-0.34808	-0.34004	-0.19594
Skewness	0.20959	-0.70999	-0.5283	-0.67841
Range	2.4	2.75	2.25	1.61667
Maximum	5	4.5	3.5	3.91667
Minimum	2.6	1.75	1.25	2.3
Sum	89.4	84	64.25	79.2167
Count	24	24	24	24
Geometric Mean	3.67656	3.39716	2.60189	3.27165
Harmonic Mean	3.62796	3.2777	2.51505	3.24047
AAD	0.4875	0.64583	0.50174	0.34363
MAD	0.4	0.5	0.5	0.3
IQR	0.85	1.0625	0.8125	0.65

Figure 4.16 IPQ Result of MovableBlocks (Application 2 – Forest Tour).

In order to evaluate the IPQ result from our work is “good” or not, we adopt the benchmark comparison from [49] who interprets the database of IPQ from near 2000 responses to suggest the scale of Presence scores for VR experiences based on the IPQ result. It would help to evaluate our work more objectively by comparing the result with other previous works. The Table 4.2 shows the qualitative grading description from their research based on IPQ sub-scale scores.

Table 4.2 Qualitative grading description according to IPQ sub-scale score (convert to 5-point scale) [49].

Presence	Spatial Presence	Involvement	Experienced Realism	Grade	Adjective	Acceptability
≥ 3.94	≥ 4.5	≥ 4.25	≥ 4.00	A	Excellent	Acceptable
≥ 3.71	≥ 4.17	≥ 4.00	≥ 3.50	B	Very Good	
≥ 3.57	≥ 4.00	≥ 3.67	≥ 3.25	C	Satisfactory	
≥ 3.43	≥ 3.83	≥ 3.50	≥ 3.00	D	Marginal	Marginally acceptable
≥ 3.31	≥ 3.67	≥ 3.25	≥ 2.75	E	Unsatisfactory	
< 3.31	< 3.67	< 3.25	< 2.75	F	Unacceptable	Not Acceptable

The tables in the next page shows the result of comparison between the mean score in each sub-scale of our MovableBlocks and the grading description above.

Table 4.3 The evaluation result of MovableBlocks (Overall) based on Melo's qualitative grading description.

Evaluation of MovableBlocks (Overall)				
Sub-scales	Mean score	Grade	Adjective	Acceptability
Presence	3.41	E	Unsatisfactory	Marginally acceptable
Spatial Presence	3.82	E	Unsatisfactory	Marginally acceptable
Involvement	3.55	D	Marginal	Marginally acceptable
Experienced Realism	2.85	E	Unsatisfactory	Marginally acceptable

Table 4.4 The evaluation result of MovableBlocks (Application 1 – Dynamic Furniture) based on Melo's qualitative grading description.

Evaluation of MovableBlocks (Application 1 – Dynamic Furniture)				
Sub-scales	Mean score	Grade	Adjective	Acceptability
Presence	3.51	D	Marginal	Marginally acceptable
Spatial Presence	3.92	D	Marginal	Marginally acceptable
Involvement	3.59	D	Marginal	Marginally acceptable
Experienced Realism	3.02	D	Marginal	Marginally acceptable

Table 4.5 The evaluation result of MovableBlocks (Application 2 – Forest Tour) based on Melo's qualitative grading description.

Evaluation of MovableBlocks (Application 2 – Forest Tour)				
Sub-scales	Mean score	Grade	Adjective	Acceptability
Presence	3.30	F	Unacceptable	Not Acceptable
Spatial Presence	3.73	E	Unsatisfactory	Marginally acceptable
Involvement	3.5	D	Marginal	Marginally acceptable
Experienced Realism	2.68	F	Unacceptable	Not Acceptable

The overall result shows that the overall sense of presence is unsatisfactory from the SR experiences in the user study, with only marginal performance in Involvement, which indicates there are large room of improvement. When the result of Application 1 and Application 2 are separately investigated, Application 1 is generally rated higher in most sub-scales than Application 2, though marginally acceptable according to the Melo's grading. Application 2 was rated poorly in many sub-scales, particularly Realism and Presence are unacceptable, while Spatial presence is unsatisfactory. It may indicate that the application design of Application 2 is worse than Application 1 in terms of offering Presence feeling to the users and requires investigation and modification for improvement.

As in this experiment, several demographic factors are collected from participants such as age, sex, weight, which might be investigated to check if these are influencing factors towards the Presence of SR experience. Besides, each participant tried two different applications in the user study and we expect that the different application design might also greatly influence users' sense of presence. It will be worthy to conduct further statistical analysis by comparing the means of different groups such as T-test and Analysis of Variance (ANOVA). Before conducting further statistical analysis, Shapiro-Wilk Test and d'Agostino-Pearson Test are conducted on the whole set of data to check its normality, which the result could impact the available statistical tools in the next steps. The Figure 4.17 in the following shows that the null hypothesis of the population is normally distributed for most of the sub-scales rating are not rejected, except Involvement in the Shapiro-Wilk Test.

Shapiro-Wilk Test				
	SP	*INV*	*REAL*	*PRES*
W-stat	0.97031	0.92008	0.97853	0.98699
p-value	0.26041	0.00299	0.51913	0.86708
alpha	0.05	0.05	0.05	0.05
normal	yes	no	yes	yes
d'Agostino-Pearson				
DA-stat	0.25052	4.68798	0.21008	1.15847
p-value	0.88227	0.09594	0.90029	0.56033
alpha	0.05	0.05	0.05	0.05
normal	yes	yes	yes	yes

Figure 4.17 The result of normality test with Shapiro-Wilk Test and d'Agostino-Pearson Test on the whole dataset.

4.3.4.2 Comparison of IPQ Result between Applications

For each participant they have been exposed to Application 1 – Dynamic Furniture and Application 2 – Forest Tour in the SR experience with MovableBlocks. As the both applications are designed with different purposes and interaction techniques which is expected that the design of different application could impact the feeling of Presence of participants.

To investigate the overall IPQ Result between applications, Two-way Repeated Measures ANOVA is adopted to study if there is statistically interaction effect between the four IPQ sub-scales and the 2 SR application that the participant experienced. From the computation, there is no statistically significant difference found. However, the factor A (Application) shows p-value of 0.069 which is close to the significance threshold of 0.05. The detailed result is shown in the following Figure 4.18.

Two-way Repeated Measures Anova						
ANOVA				Alpha	0.05	
	SS	*df*	*MS*	*F*	*P value*	*P Eta-sq*
Factor A	2.111204	1	2.111204	3.644281	0.068817	0.136775
Error	13.32435	23	0.57932			
Factor B	24.10691	3	8.035637	22.56443	2.73E-10	0.49522
Error	24.57226	69	0.35612			
A x B	0.380868	3	0.126956	0.923563	0.434143	0.038605
Error	9.484965	69	0.137463			
Subject	28.39852	23	1.234718			
Total	102.3791	191	0.536016			

Figure 4.18 The result of Two-way Repeated Measure ANOVA on the whole dataset.

As from the above statistical analysis, it might indicate that the Application 1 and Application 2 leads to significant difference in the feeling of Presence. We took the next step to do the Two-paired Sample T-test for each sub-scale to investigate if there is any significant difference to each of the sub-scale in IPQ so to understand which sub-scale that either of the application differently to inform the future design of relevant SR experience.

For each sub-scale, Shapiro-Wilk Test and d'Agostino-Pearson Test are conducted to test the normality. If the null hypothesis of normal distribution is not rejected, further statistical analysis can be undertaken. As mentioned in the session 4.3.3, counterbalancing technique was adopted and so two-paired Sample T-test would conduct for the all the data in Group A and Group B together to check if mean change of each sub-scale score is significantly different within the group (which significance threshold was set at 0.05). And the mean score for each sub-scale of Application 1 and Application 2 between Group A and Group B could be also compared for more insights. The computation results of Shapiro-Wilk Test and d'Agostino-Pearson Test, plus Two-paired Sample T-test for each sub-scale are shown on the following pages:

Shapiro-Wilk Test	SP(Spatial Presence)	
	App1	*App2*
W-stat	0.947096	0.968441
p-value	0.234207	0.62865
alpha	0.05	0.05
normal	yes	yes
d'Agostino-Pearson		
DA-stat	1.042905	0.258882
p-value	0.593658	0.878586
alpha	0.05	0.05
normal	yes	yes

Shapiro-Wilk Test	INV(Involvement)	
	App1	*App2*
W-stat	0.95027	0.941631
p-value	0.274612	0.177348
alpha	0.05	0.05
normal	yes	yes
d'Agostino-Pearson		
DA-stat	1.29904	1.129797
p-value	0.522296	0.568418
alpha	0.05	0.05
normal	yes	yes

Shapiro-Wilk Test	REAL(Realism)	
	App1	*App2*
W-stat	0.958263	0.973284
p-value	0.404526	0.747941
alpha	0.05	0.05
normal	yes	yes
d'Agostino-Pearson		
DA-stat	1.059623	1.269293
p-value	0.588716	0.530123
alpha	0.05	0.05
normal	yes	yes

Shapiro-Wilk Test	PRES(Overall Sense of Presence)	
	App1	*App2*
W-stat	0.964346	0.941242
p-value	0.531695	0.173852
alpha	0.05	0.05
normal	yes	yes
d'Agostino-Pearson		
DA-stat	0.869705	2.593491
p-value	0.64736	0.27342
alpha	0.05	0.05
normal	yes	yes

Figure 4.19 The result of normality test with Shapiro-Wilk Test and d'Agostino-Pearson Test.

T Test: Two Paired Samples			SP(Spatial Presence)					
SUMMARY			Alpha	0.05		Hyp Mean	0	
Groups	*Count*	*Mean*	*Std Dev*	*Std Err*	*t*	*df*	*Cohen d*	*Effect r*
App1	24	3.916667	0.513866					
App2	24	3.725	0.612372					
Difference	24	0.191667	0.655357	0.133774	1.432763	23	0.292461	0.28625
T TEST								
	p-value	*t-crit*	*lower*	*upper*	*sig*			
One Tail	0.082689	1.713872			no			
Two Tail	0.165379	2.068658	-0.08507	0.4684	no			

T Test: Two Paired Samples			INV(Involvement)					
SUMMARY			Alpha	0.05		Hyp Mean	0	
Groups	*Count*	*Mean*	*Std Dev*	*Std Err*	*t*	*df*	*Cohen d*	*Effect r*
App1	24	3.716667	0.609823					
App2	24	3.475	0.658886					
Difference	24	0.241667	0.731833	0.149385	1.617746	23	0.330221	0.319628
T TEST								
	p-value	*t-crit*	*lower*	*upper*	*sig*			
One Tail	0.059676	1.713872			no			
Two Tail	0.119351	2.068658	-0.06736	0.550693	no			

T Test: Two Paired Samples			REAL(Realism)					
SUMMARY			Alpha	0.05		Hyp Mean	0	
Groups	*Count*	*Mean*	*Std Dev*	*Std Err*	*t*	*df*	*Cohen d*	*Effect r*
App1	24	3.566667	0.694492					
App2	24	3.5	0.610061					
Difference	24	0.066667	0.726317	0.148259	0.449664	23	0.091787	0.093352
T TEST								
	p-value	*t-crit*	*lower*	*upper*	*sig*			
One Tail	0.32858092	1.713872			no			
Two Tail	0.65716184	2.068658	-0.24003	0.373363	no			

T Test: Two Paired Samples			PRES(Overall Sense of Presence)					
SUMMARY			Alpha	0.05		Hyp Mean	0	
Groups	*Count*	*Mean*	*Std Dev*	*Std Err*	*t*	*df*	*Cohen d*	*Effect r*
App1	24	3.683333	0.726915					
App2	24	3.541667	0.67109					
Difference	24	0.141667	0.701499	0.143193	0.98934092	23	0.201948	0.202038
T TEST								
	p-value	*t-crit*	*lower*	*upper*	*sig*			
One Tail	0.166395	1.713872			no			
Two Tail	0.332791	2.068658	-0.15455	0.437884	no			

Figure 4.20 The result of Two-paired Samples T-test for each sub-scale

For all sub-scale they pass the normality test and can be proceeded for Two-paired Samples T-test. The result shows that there is no statistically significant difference shown in all sub-scale, though the sub-scale of SP and INV shows their p-value close to the threshold (with p-value of 0.0827 and 0.0597 respectively). With the statistical analysis above, based on the current data collected there is not statistical evidence showing that the difference between Application 1 and Application 2 in this user study pose the significant impact to the difference between any of the sub-scale of feeling of Presence in IPQ.

However, by looking at the difference of mean score for each sub-scale within Group A and Group B in “Before and After” setting, all sub-scale mean scores are improved in Group B, which participants are exposed to Application 2 first than Application 1. While in Group A there are less enhanced in REAL and PRES, and even with decrement in SP and INV. It may imply that there is ordering effect of feeling of Presence, which is enhanced by exposing participants to Application 2 first then Application 1.

Table 4.6 The mean score difference for each sub-scale in “Before” and “After” case of Group A

Group A			
Sub-scale	Before (App1)	After (App2)	Difference
SP	3.833	3.7	(0.133)
INV	3.53	3.42	(0.11)
REAL	3.30	3.47	0.17
PRES	3.45	3.47	0.02

Table 4.7 The mean score difference for each sub-scale in “Before” and “After” case of Group B

Group B			
Sub-scale	Before (App2)	After (App1)	Difference
SP	3.75	4.00	0.25
INV	3.53	3.90	0.37
REAL	3.53	3.83	0.30
PRES	3.62	3.92	0.30

In order to validate this phenomena, Two-paired sample T-test can be used for checking the data from each group as the following:

In Group A, there is no significant difference found from each of the sub-scale and the detailed result is shown in the following figure:

Shapiro-Wilk Test

	SP1	SP2
W-stat	0.835008	0.946607
p-value	0.024089	0.588035
alpha	0.05	0.05
normal	no	yes

d'Agostino-Pearson

DA-stat	3.360406	0.468825
p-value	0.186336	0.791035
alpha	0.05	0.05
normal	yes	yes

Wilcoxon Signed-Rank Test for Paired Samples — SP

	SP1	SP2
median	3.6	3.6
count	12	
# unequal	11	
T+	25.5	
T-	40.5	
T	25.5	

	one tail	two tail
mean	33	
std dev	11.18034	ties
z-score	0.626099	yates
effect r	0.127802	
p-norm	0.265625	0.53125
p-exact	0.259766	0.519531
p-simul	N/A	N/A

Shapiro-Wilk Test

	INV1	INV2
W-stat	0.942287	0.894511
p-value	0.528263	0.13474
alpha	0.05	0.05
normal	yes	yes

d'Agostino-Pearson

DA-stat	1.85205	1.803207
p-value	0.396125	0.405918
alpha	0.05	0.05
normal	yes	yes

T Test: Two Paired Samples — INV

SUMMARY — Alpha 0.05 — Hyp Mean 0

Groups	Count	Mean	Std Dev	Std Err	t	df	Cohen d	Effect r
INV1	12	3.270833	1.025018					
INV2	12	3.416667	0.967267					
Difference	12	-0.14583	0.985453	0.284476	-0.51264	11	0.147986	0.152753

T TEST

	p-value	t-crit	lower	upper	sig
One Tail	0.30917	1.795885			no
Two Tail	0.618341	2.200985	-0.77196	0.480294	no

Shapiro-Wilk Test

	REAL1	REAL2
W-stat	0.875015	0.986245
p-value	0.075686	0.997915
alpha	0.05	0.05
normal	yes	yes

d'Agostino-Pearson

DA-stat	4.117358	0.266416
p-value	0.127622	0.875283
alpha	0.05	0.05
normal	yes	yes

T Test: Two Paired Samples — REAL

SUMMARY — Alpha 0.05 — Hyp Mean 0

Groups	Count	Mean	Std Dev	Std Err	t	df	Cohen d	Effect r
REAL1	12	2.6875	0.414578					
REAL2	12	2.479167	0.634772					
Difference	12	0.208333	0.620056	0.178995	1.163907	11	0.335991	0.331133

T TEST

	p-value	t-crit	lower	upper	sig
One Tail	0.134543	1.795885			no
Two Tail	0.269086	2.200985	-0.18563	0.602298	no

Shapiro-Wilk Test

	PRES1	PRES2
W-stat	0.935074	0.943418
p-value	0.437006	0.54358
alpha	0.05	0.05
normal	yes	yes

d'Agostino-Pearson

DA-stat	1.058983	1.704014
p-value	0.588904	0.426558
alpha	0.05	0.05
normal	yes	yes

T Test: Two Paired Samples — PRES

SUMMARY — Alpha 0.05 — Hyp Mean 0

Groups	Count	Mean	Std Dev	Std Err	t	df	Cohen d	Effect r
PRES1	12	3.263889	0.455096					
PRES2	12	3.198611	0.541904					
Difference	12	0.065278	0.588332	0.169837	0.384356	11	0.110954	0.115117

T TEST

	p-value	t-crit	lower	upper	sig
One Tail	0.354021	1.795885			no
Two Tail	0.708041	2.200985	-0.30853	0.439086	no

Figure 4.21 The result of Two-paired Samples T-test for each sub-scale (Group A)

In Group B, there is significant difference found in the sub-scale REAL (p-value=0.0283) and PRES (p-value=0.0113), indicating that the sequence setting of Group B (Application 2 than Application 1) might lead to significant different effect on these two scales. The detailed result is shown in the following figure:

Shapiro-Wilk Test

	SP1	SP2
W-stat	0.920312	0.952947
p-value	0.288508	0.680385
alpha	0.05	0.05
normal	yes	yes

d'Agostino-Pearson

DA-stat	1.827569	0.159093
p-value	0.401004	0.923535
alpha	0.05	0.05
normal	yes	yes

T Test: Two Paired Samples SP

SUMMARY			Alpha	0.05		Hyp Mean	0	
Groups	Count	Mean	Std Dev	Std Err	t	df	Cohen d	Effect r
SP1	12	4	0.55922					
SP2	12	3.75	0.553501					
Difference	12	0.25	0.748939	0.2162	1.156337	11	0.333806	0.329213

T TEST

	p-value	t-crit	lower	upper	sig
One Tail	0.13602	1.795885			no
Two Tail	0.27204	2.200985	-0.22585	0.725853	no

Shapiro-Wilk Test

	INV1	INV2
W-stat	0.841208	0.966606
p-value	0.028641	0.872214
alpha	0.05	0.05
normal	no	yes

d'Agostino-Pearson

DA-stat	6.158247	0.594894
p-value	0.046	0.742712
alpha	0.05	0.05
normal	no	yes

Wilcoxon Signed-Rank Test for Paired Samples INV

	INV1	INV2
median	4	3.625
count	12	
# unequal	11	
T+	17	
T-	49	
T	17	

	one tail	two tail
mean	33	
std dev	11.12991	ties
z-score	1.392643	yates
effect r	0.284272	
p-norm	0.081864	0.163728
p-exact	0.087402	0.174805
p-simul	N/A	N/A

Shapiro-Wilk Test

	REAL1	REAL2
W-stat	0.954056	0.871811
p-value	0.696813	0.068901
alpha	0.05	0.05
normal	yes	yes

d'Agostino-Pearson

DA-stat	1.081507	1.55856
p-value	0.582309	0.458736
alpha	0.05	0.05
normal	yes	yes

T Test: Two Paired Samples REAL

SUMMARY			Alpha	0.05		Hyp Mean	0	
Groups	Count	Mean	Std Dev	Std Err	t	df	Cohen d	Effect r
REAL1	12	3.354167	0.652428					
REAL2	12	2.875	0.527645					
Difference	12	0.479167	0.779411	0.224996	2.129663	11	0.614781	0.540317

T TEST

	p-value	t-crit	lower	upper	sig
One Tail	0.028306	1.795885			yes
Two Tail	0.056613	2.200985	-0.01605	0.974381	no

Shapiro-Wilk Test

	PRES1	PRES2
W-stat	0.922335	0.946892
p-value	0.305848	0.59208
alpha	0.05	0.05
normal	yes	yes

d'Agostino-Pearson

DA-stat	1.328927	0.625951
p-value	0.51455	0.731268
alpha	0.05	0.05
normal	yes	yes

T Test: Two Paired Samples PRES

SUMMARY			Alpha	0.05		Hyp Mean	0	
Groups	Count	Mean	Std Dev	Std Err	t	df	Cohen d	Effect r
PRES1	12	3.756944	0.46842					
PRES2	12	3.402778	0.269664					
Difference	12	0.354167	0.462597	0.13354	2.652133	11	0.765605	0.624527

T TEST

	p-value	t-crit	lower	upper	sig
One Tail	0.01125	1.795885			yes
Two Tail	0.022501	2.200985	0.060246	0.648087	yes

Figure 4.22 The result of Two-paired Samples T-test for each sub-scale (Group B)

4.3.4.3 Comparison of IPQ Result between Participants' Weight

Weight-bearing is one of the important design considerations for MovableBlocks to offer ability for supporting users' body to explore the virtual environment with the aid of movable M-Blocks. As the participants have the direct contact and interaction with the M-Block, it could be possible that the participants' weight lead to the difference feeling of Presence.

To do the statistical analysis, we ranked the weight of 24 participants and evenly divided them into 3 weight groups (Light, Medium, Heavy) as to create categorical independent variable, combine with the rating of each sub-scale from IPQ to compute Mixed Two-way Repeated Measures ANOVA for comparing the data between the three weight groups and each IPQ sub-scale to see if there is a significant effect of weight on the rating of each sub-scale from IPQ. After the grouping, the range of weight for each group is as the following Table:

Table 4.8 The range of each weight group

Weight group	Range
Light	39.1 – 58.0kg
Medium	58.3 – 65.7kg
Heavy	65.9 – 90.0kg

For each weight group, there will have 8 participants with 4 IPQ sub-scales for each of the 2 Applications, and Mixed two-way Repeated Measures ANOVA will be used to understand the compute the mean of each of the IPQ sub-scales and the according weight group. Brown-Forsythe Test is also done to test the assumption of equal variance among different weight groups in ANOVA.

With the statistical analysis, there are two statistical significances found;

First, in the sub-scale of INV (Involvement), the statical significant difference is shown in "Within Subjects – Interaction" (P-value = 0.325), indicating that the significant difference exists between the sub-scale of INV by different applications (averaging all weight groups) and also significant difference between the average rating of INV by different applications and weight group.

Another statistical significance is shown in the sub-scale of REAL (Realism) in “Within Subjects – Columns” (P-value = 0.030), indicating that the participant from specific weight group have statical significant difference of in Realism rating towards different applications.

In the sub-scale of PRES, it shows the p-value that is close to the significance threshold in “Within Subjects – Columns” (p-value = 0.067), which indicates the possibility of the specific weight group of participants have significant different feeling of presence towards the different applications. The detailed result is shown in the following figures:

COUNT	balanced		
	SP1	SP2	
Light	8	8	16
Medium	8	8	16
Heavy	8	8	16
	24	24	48

MEAN			
	SP1	SP2	
Light	3.8	3.675	3.7375
Medium	4	3.8	3.9
Heavy	3.95	3.7	3.825
	3.916667	3.725	3.820833

VARIANCE			
	SP1	SP2	
Light	0.205714	0.605	0.3825
Medium	0.377143	0.32	0.336
Heavy	0.26	0.297143	0.276667
	0.264058	0.375	0.32211

GG epsilon	1
HF epsilon	1

Mixed Two-way Repeated Measures Anova — SP

ANOVA				Alpha	0.05	
	SS	*df*	*MS*	*F*	*P value*	*P Eta-sq*
Between Subjects	9.759167	23				
- Rows	0.211667	2	0.105833	0.232783	0.794342	0.021689
- Error	9.5475	21	0.454643			
Within Subjects	5.38	24				
- Columns	0.440833	1	0.440833	1.886398	0.184095	0.082424
- Interaction	0.031667	2	0.015833	0.067753	0.934694	0.006411
- Error	4.9075	21	0.23369			
Total	15.13917	47	0.32211			

Greenhouse and Geisser				Alpha	0.05	
Sources	*SS*	*df*	*MS*	*F*	*P value*	*P Eta-sq*
Columns	0.440833	1	0.440833	1.886398	0.184095	0.082424
Interaction	0.031667	2	0.015833	0.067753	0.934694	0.006411
Error	4.9075	21	0.23369			

Huyhn and Feldt				Alpha	0.05	
Sources	*SS*	*df*	*MS*	*F*	*P value*	*P Eta-sq*
Columns	0.440833	1	0.440833	1.886398	0.184095	0.082424
Interaction	0.031667	2	0.015833	0.067753	0.934694	0.006411
Error	4.9075	21	0.23369			

COUNT	balanced		
	INV1	INV2	
Light	8	8	16
Medium	8	8	16
Heavy	8	8	16
	24	24	48

MEAN			
	INV1	INV2	
Light	4.0625	3.53125	3.796875
Medium	3.1875	3.71875	3.453125
Heavy	3.53125	3.25	3.390625
	3.59375	3.5	3.546875

VARIANCE			
	INV1	INV2	
Light	0.388393	0.972098	0.710156
Medium	0.745536	0.52567	0.66849
Heavy	1.02567	0.482143	0.72474
	0.792459	0.641304	0.703873

GG epsilon	1
HF epsilon	1

Mixed Two-way Repeated Measures Anova — INV

ANOVA				Alpha	0.05	
	SS	*df*	*MS*	*F*	*P value*	*P Eta-sq*
Between Subjects	24.11328	23				
- Rows	1.53125	2	0.765625	0.711988	0.502135	0.063502
- Error	22.58203	21	1.075335			
Within Subjects	8.96875	24				
- Columns	0.105469	1	0.105469	0.346365	0.562455	0.016226
- Interaction	2.46875	2	1.234375	4.053757	0.032453	0.278537
- Error	6.394531	21	0.304501			
Total	33.08203	47	0.703873			

Greenhouse and Geisser				Alpha	0.05	
Sources	*SS*	*df*	*MS*	*F*	*P value*	*P Eta-sq*
Columns	0.105469	1	0.105469	0.346365	0.562455	0.016226
Interaction	2.46875	2	1.234375	4.053757	0.032453	0.278537
Error	6.394531	21	0.304501			

Huyhn and Feldt				Alpha	0.05	
Sources	*SS*	*df*	*MS*	*F*	*P value*	*P Eta-sq*
Columns	0.105469	1	0.105469	0.346365	0.562455	0.016226
Interaction	2.46875	2	1.234375	4.053757	0.032453	0.278537
Error	6.394531	21	0.304501			

Figure 4.23 The result of Mixed two-way Repeated Measured ANOVA for IPQ sub-scale (SP and INV) and different weight groups

Mixed Two-way Repeated Measures Anova — REAL

COUNT	balanced		
	REAL1	REAL2	
Light	8	8	16
Medium	8	8	16
Heavy	8	8	16
	24	24	48

MEAN			
	REAL1	REAL2	
Light	2.96875	2.46875	2.71875
Medium	2.9375	2.6875	2.8125
Heavy	3.15625	2.875	3.015625
	3.020833	2.677083	2.848958

VARIANCE			
	REAL1	REAL2	
Light	0.793527	0.507813	0.673958
Medium	0.120536	0.299107	0.2125
Heavy	0.373884	0.303571	0.33724
	0.401721	0.366735	0.406222

GG epsilo	1
HF epsilon	1

ANOVA (Alpha 0.05)

	SS	df	MS	F	P value	P Eta-sq
Between Subjects	11.9987	23				
- Rows	0.736979	2	0.36849	0.687131	0.513974	0.061422
- Error	11.26172	21	0.536272			
Within Subjects	7.09375	24				
- Columns	1.417969	1	1.417969	5.387279	0.030428	0.204162
- Interaction	0.148438	2	0.074219	0.281979	0.757101	0.026153
- Error	5.527344	21	0.263207			
Total	19.09245	47	0.406222			

Greenhouse and Geisser (Alpha 0.05)

Sources	SS	df	MS	F	P value	P Eta-sq
Columns	1.417969	1	1.417969	5.387279	0.030428	0.204162
Interaction	0.148438	2	0.074219	0.281979	0.757101	0.026153
Error	5.527344	21	0.263207			

Huyhn and Feldt (Alpha 0.05)

Sources	SS	df	MS	F	P value	P Eta-sq
Columns	1.417969	1	1.417969	5.387279	0.030428	0.204162
Interaction	0.148438	2	0.074219	0.281979	0.757101	0.026153
Error	5.527344	21	0.263207			

Mixed Two-way Repeated Measures Anova — PRES

COUNT	balanced		
	PRES1	PRES2	
Light	8	8	16
Medium	8	8	16
Heavy	8	8	16
	24	24	48

MEAN			
	PRES1	PRES2	
Light	3.610417	3.225	3.417708
Medium	3.375	3.402083	3.388542
Heavy	3.545833	3.275	3.410417
	3.510417	3.300694	3.405556

VARIANCE			
	PRES1	PRES2	
Light	0.295947	0.298968	0.31724
Medium	0.220873	0.136622	0.167027
Heavy	0.327996	0.156825	0.24581
	0.267411	0.186099	0.23316

GG epsilo	1
HF epsilon	1

ANOVA (Alpha 0.05)

	SS	df	MS	F	P value	P Eta-sq
Between Subjects	7.09963	23				
- Rows	0.007373	2	0.003686	0.010915	0.98915	0.001038
- Error	7.092257	21	0.337727			
Within Subjects	3.858889	24				
- Columns	0.527801	1	0.527801	3.733977	0.066918	0.150966
- Interaction	0.36272	2	0.18136	1.283048	0.298045	0.108889
- Error	2.968368	21	0.141351			
Total	10.95852	47	0.23316			

Greenhouse and Geisser (Alpha 0.05)

Sources	SS	df	MS	F	P value	P Eta-sq
Columns	0.527801	1	0.527801	3.733977	0.066918	0.150966
Interaction	0.36272	2	0.18136	1.283048	0.298045	0.108889
Error	2.968368	21	0.141351			

Huyhn and Feldt (Alpha 0.05)

Sources	SS	df	MS	F	P value	P Eta-sq
Columns	0.527801	1	0.527801	3.733977	0.066918	0.150966
Interaction	0.36272	2	0.18136	1.283048	0.298045	0.108889
Error	2.968368	21	0.141351			

Figure 4.24 The result of Mixed two-way Repeated Measured ANOVA for IPQ sub-scale (REAL and PRES) and different weight groups

To follow up the above statistical analysis, Two-paired Sample T-test could be conducted for each weight group with all of the IPQ sub-scales to do within-subject investigation of each participant in same weight group, to investigate if the weight significantly affects the perception of presence for both applications.

In sub-scale of SP, statistic significant difference is found for the weight group “Heavy” with p-value of 0.006 (One-tailed) and 0.011 (Two-tailed), which indicates the participants categorized as heavy weight in this user study have significant difference feeling of Spatial

Presence towards different applications. The detailed result is shown in the following figure:

SP — Light

Shapiro-Wilk Test

	SP1	SP2
W-stat	0.814786	0.972495
p-value	0.041117	0.916836
alpha	0.05	0.05
normal	no	yes

d'Agostino-Pearson

	SP1	SP2
DA-stat	9.349731	0.274014
p-value	0.009327	0.871964
alpha	0.05	0.05
normal	no	yes

Wilcoxon Signed-Rank Test for Paired Samples

	SP1	SP2		
median	3.9	3.6		
count	8			
# unequal	7			
T+	11.5			
T-	16.5			
T	11.5			
	one tail	two tail		
mean	14			
std dev	5.905506	ties		
z-score	0.338667	yates	<1.96	not sig
effect r	0.084667			
p-norm	0.36743	0.734861		
p-exact	0.34375	0.6875		
p-simul	N/A	N/A		

SP — Medium

Shapiro-Wilk Test

	SP1	SP2
W-stat	0.74429	0.940859
p-value	0.007062	0.619548
alpha	0.05	0.05
normal	no	yes

d'Agostino-Pearson

	SP1	SP2
DA-stat	3.931133	0.948942
p-value	0.140077	0.622214
alpha	0.05	0.05
normal	yes	yes

Wilcoxon Signed-Rank Test for Paired Samples

	SP1	SP2		
median	3.6	3.9		
count	8			
# unequal	7			
T+	13			
T-	15			
T	13			
	one tail	two tail		
mean	14			
std dev	5.86302	ties		
z-score	0.08528	yates	<1.96	not sig
effect r	0.02132			
p-norm	0.466019	0.932039		
p-exact	0.46875	0.9375		
p-simul	N/A	N/A		

SP — Heavy

Shapiro-Wilk Test

	SP1	SP2
W-stat	0.882665	0.860054
p-value	0.19967	0.120224
alpha	0.05	0.05
normal	yes	yes

d'Agostino-Pearson

	SP1	SP2
DA-stat	4.564736	3.587838
p-value	0.102042	0.166307
alpha	0.05	0.05
normal	yes	yes

T Test: Two Paired Samples

SUMMARY — Alpha 0.05 — Hyp Mean 0

Groups	Count	Mean	Std Dev	Std Err	t	df	Cohen d	Effect r
SP1	8	3.95	0.509902					
SP2	8	3.7	0.545108					
Difference	8	0.25	0.20702	0.073193	3.41565	7	1.207615	0.790569

T TEST

	p-value	t-crit	lower	upper	sig
One Tail	0.005601	1.894579			yes
Two Tail	0.011201	2.364624	0.076927	0.423073	yes

Figure 4.25 The result of two-paired samples T-test and non-parametric equivalent for SP and different weight groups

In sub-scale of INV, statistic significant difference is found for the weight group "Light" with p-value of 0.025 (One-tailed) and 0.049 (Two-tailed), which indicates the participants categorized as light weight in this user study have significant difference feeling of Involvement towards different applications, while the weight group "Medium" shows p-value of 0.082 which is only close to the threshold. The detailed result is shown in the following figure:

Shapiro-Wilk Test

	INV1	INV2
W-stat	0.882567	0.897759
p-value	0.199239	0.275792
alpha	0.05	0.05
normal	yes	yes

d'Agostino-Pearson

DA-stat	5.940208	1.486867
p-value	0.051298	0.475479
alpha	0.05	0.05
normal	yes	yes

T Test: Two Paired Samples | INV | **Light**

SUMMARY | Alpha 0.05 | Hyp Mean [0

Groups	Count	Mean	Std Dev	Std Err	t	df	Cohen d	Effect r
INV1	8	4.0625	0.623212					
INV2	8	3.53125	0.98595					
Difference	8	0.53125	0.632985	0.223794	2.373836	7	0.839278	0.667823

T TEST

	p-value	t-crit	lower	upper	sig
One Tail	0.024664	1.894579			yes
Two Tail	0.049327	2.364624	0.002062	1.060438	yes

Shapiro-Wilk Test

	INV1	INV2
W-stat	0.882567	0.897759
p-value	0.199239	0.275792
alpha	0.05	0.05
normal	yes	yes

d'Agostino-Pearson

DA-stat	5.940208	1.486867
p-value	0.051298	0.475479
alpha	0.05	0.05
normal	yes	yes

T Test: Two Paired Samples | INV | **Medium**

SUMMARY | Alpha 0.05 | Hyp Mean [0

Groups	Count	Mean	Std Dev	Std Err	t	df	Cohen d	Effect r
INV1	8	3.1875	0.863444					
INV2	8	3.71875	0.725031					
Difference	8	-0.53125	0.967669	0.342123	-1.552805	7	0.549	0.506168

T TEST

	p-value	t-crit	lower	upper	sig
One Tail	0.082206	1.894579			no
Two Tail	0.164413	2.364624	-1.340242	0.277742	no

Shapiro-Wilk Test

	INV1	INV2
W-stat	0.891199	0.923108
p-value	0.240106	0.455585
alpha	0.05	0.05
normal	yes	yes

d'Agostino-Pearson

DA-stat	1.337296	0.745192
p-value	0.512401	0.688943
alpha	0.05	0.05
normal	yes	yes

T Test: Two Paired Samples | INV | **Heavy**

SUMMARY | Alpha 0.05 | Hyp Mean [0

Groups	Count	Mean	Std Dev	Std Err	t	df	Cohen d	Effect r
INV1	8	3.53125	1.012753					
INV2	8	3.25	0.694365					
Difference	8	0.28125	0.699968	0.247476	1.136473	7	0.401804	0.394676

T TEST

	p-value	t-crit	lower	upper	sig
One Tail	0.146582	1.894579			no
Two Tail	0.293163	2.364624	-0.303938	0.866438	no

Figure 4.26 Two-paired T-test for each weight group and INV

In sub-scale of REAL, statistic significant difference is not found for every weight group, though the weight group “Light” shows p-value of 0.083 which is close to the significance threshold. The detailed result is shown in the following figure:

REAL – Light

Shapiro-Wilk Test

	REAL1	REAL2
W-stat	0.933061	0.890525
p-value	0.544344	0.236674
alpha	0.05	0.05
normal	yes	yes

d'Agostino-Pearson

	REAL1	REAL2
DA-stat	0.561338	1.017189
p-value	0.755278	0.60134
alpha	0.05	0.05
normal	yes	yes

T Test: Two Paired Samples — REAL — Light

SUMMARY — Alpha 0.05 — Hyp Mean 0

Groups	Count	Mean	Std Dev	Std Err	t	df	Cohen d	Effect r
REAL1	8	2.96875	0.890801					
REAL2	8	2.46875	0.71261					
Difference	8	0.5	0.916125	0.323899	1.54369	7	0.545777	0.503953

T TEST

	p-value	t-crit	lower	upper	sig
One Tail	0.083287	1.894579			no
Two Tail	0.166574	2.364624	-0.2659	1.2659	no

REAL – Medium

Shapiro-Wilk Test

	REAL1	REAL2
W-stat	0.857843	0.942343
p-value	0.114264	0.634266
alpha	0.05	0.05
normal	yes	yes

d'Agostino-Pearson

	REAL1	REAL2
DA-stat	2.983484	0.528933
p-value	0.22498	0.767616
alpha	0.05	0.05
normal	yes	yes

T Test: Two Paired Samples — REAL — Medium

SUMMARY — Alpha 0.05 — Hyp Mean 0

Groups	Count	Mean	Std Dev	Std Err	t	df	Cohen d	Effect r
REAL1	8	2.9375	0.347183					
REAL2	8	2.6875	0.546907					
Difference	8	0.25	0.64087	0.226582	1.103355	7	0.390095	0.3849

T TEST

	p-value	t-crit	lower	upper	sig
One Tail	0.153177	1.894579			no
Two Tail	0.306354	2.364624	-0.28578	0.785781	no

REAL – Heavy

Shapiro-Wilk Test

	REAL1	REAL2
W-stat	0.918289	0.928485
p-value	0.416133	0.502386
alpha	0.05	0.05
normal	yes	yes

d'Agostino-Pearson

	REAL1	REAL2
DA-stat	0.796147	0.666619
p-value	0.671613	0.716548
alpha	0.05	0.05
normal	yes	yes

T Test: Two Paired Samples — REAL — Heavy

SUMMARY — Alpha 0.05 — Hyp Mean 0

Groups	Count	Mean	Std Dev	Std Err	t	df	Cohen d	Effect r
REAL1	8	3.15625	0.61146					
REAL2	8	2.875	0.550973					
Difference	8	0.28125	0.573795	0.202867	1.386374	7	0.490157	0.46414

T TEST

	p-value	t-crit	lower	upper	sig
One Tail	0.104091	1.894579			no
Two Tail	0.208183	2.364624	-0.19845	0.760955	no

Figure 4.27 Two-paired T-test for each weight group and REAL

In sub-scale of PRES, two statistic significant differences are found for weight group "Light" (p-value = 0.039) and "Heavy" (p-value = 0.035). The detailed result is shown in the following figure:

Shapiro-Wilk Test		
	Group 1	Group 2
W-stat	0.836138	0.909941
p-value	0.06873	0.353648
alpha	0.05	0.05
normal	yes	yes

d'Agostino-Pearson		
DA-stat	2.081931	1.171037
p-value	0.353114	0.556817
alpha	0.05	0.05
normal	yes	yes

T Test: Two Paired Samples — PRES — **Light**

SUMMARY		Alpha	0.05			Hyp Mean	0	
Groups	Count	Mean	Std Dev	Std Err	t	df	Cohen d	Effect r
PRES1	8	3.610417	0.54401					
PRES2	8	3.225	0.54678					
Difference	8	0.385417	0.528207	0.186749	2.063816	7	0.729669	0.615056

T TEST	p-value	t-crit	lower	upper	sig
One Tail	0.038962	1.894579			yes
Two Tail	0.077925	2.364624	-0.05618	0.827009	no

Shapiro-Wilk Test		
	Group 1	Group 2
W-stat	0.889891	0.912817
p-value	0.233482	0.37433
alpha	0.05	0.05
normal	yes	yes

d'Agostino-Pearson		
DA-stat	1.35355	1.302272
p-value	0.508253	0.521453
alpha	0.05	0.05
normal	yes	yes

T Test: Two Paired Samples — PRES — **Medium**

SUMMARY		Alpha	0.05			Hyp Mean	0	
Groups	Count	Mean	Std Dev	Std Err	t	df	Cohen d	Effect r
Group 1	8	3.375	0.469971					
Group 2	8	3.402083	0.369624					
Difference	8	-0.02708	0.664098	0.234794	-0.11535	7	0.040782	0.043557

T TEST	p-value	t-crit	lower	upper	sig
One Tail	0.455704	1.894579			no
Two Tail	0.911408	2.364624	-0.58228	0.528117	no

Shapiro-Wilk Test		
	Group 1	Group 2
W-stat	0.950386	0.906994
p-value	0.715127	0.333379
alpha	0.05	0.05
normal	yes	yes

d'Agostino-Pearson		
DA-stat	0.458958	2.095818
p-value	0.794948	0.35067
alpha	0.05	0.05
normal	yes	yes

T Test: Two Paired Samples — PRES — **Heavy**

SUMMARY		Alpha	0.05			Hyp Mean	0	
Groups	Count	Mean	Std Dev	Std Err	t	df	Cohen d	Effect r
PRES1	8	3.545833	0.572709					
PRES2	8	3.275	0.396012					
Difference	8	0.270833	0.357876	0.126528	2.140495	7	0.756779	0.628967

T TEST	p-value	t-crit	lower	upper	sig
One Tail	0.034792	1.894579			yes
Two Tail	0.069583	2.364624	-0.02836	0.570025	no

Figure 4.28 Two-paired T-test for each weight group and PRES

To wrap up the statistical analysis for comparing the IPQ result with different weight group, we provide the following summary table of p-score (or converted from z-score if T-test was not be able to be conducted due to violation of normality). The statistical result shows that there is high confidence level that weight is a factor that could significantly impact different IPQ sub-scale in our applications, particularly the PRES scale as statistical significance was shown in weight group of "Light" and "Heavy", which is important indicator that there is high confidence level that the overall sense of presence in our applications are affected by weight.

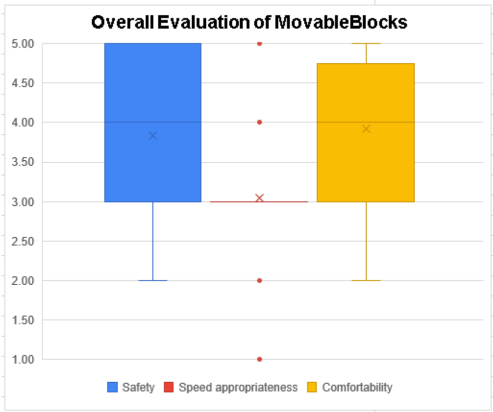
Statistical significance was shown in INV scale with the weight group of "Light". In SP scale, there is even highly significant statistical difference found in the weight group of "Heavy", which means that the difference of the spatial presence feeling in applications is very likely contributed by the heavier participant.

Table 4.9 The summary table for p-score between each IPQ sub-scale and weight group

Sub-scale\Weight group	**Light** (39.1 – 58.0kg)	**Medium** (58.3 – 65.7kg)	**Heavy** (65.9 – 90.0kg)
SP (Spatial Presence)	.3674 (z-score=.3387)	.4661 (z-score=.0852)	****.0056**
INV (Involvement)	***.0247**	**.0822**	.1466
REAL (Realism)	**.0833**	.1532	.1041
PRES (Overall Sense of Presence)	***.0390**	.4557	***.0348**

4.3.4.4 Overall Evaluation

Apart from filling in IPQ items for each application, we also asked participants to rate their overall experience of the SR experience with MovableBlocks in terms of safety, speed appropriateness and comfortability. The graphical representation of the result with the detailed descriptive statistics are shown in the below figure.



Descriptive Statistics

	Safety	Speed appropriateness	Comfortability
Mean	3.833333333	3.041666667	3.916666667
Standard Error	0.187147414	0.140897314	0.169362259
Median	4	3	4
Mode	3	3	4
Standard Deviation	0.916831342	0.690253052	0.829702234
Sample Variance	0.84057971	0.476449275	0.688405797
Kurtosis	-1.14863258	5.257875262	-0.337590387
Skewness	-0.013676654	-0.053582998	-0.334471754
Range	3	4	3
Maximum	5	5	5
Minimum	2	1	2
Sum	92	73	94
Count	24	24	24
Geometric Mean	3.723320908	2.948216184	3.823929651
Harmonic Mean	3.609022556	2.8125	3.720930233
AAD	0.777777778	0.322916667	0.618055556
MAD	1	0	1
IQR	2	0	1.25

Figure 4.29 Overall Evaluation of MovableBlocks in different aspects

It seems that in general the participants feel positive for all these aspects; Safety and comfortability have the mean rating of nearly 4 out of 5. For speed appropriateness, the rating "3" indicates that participants feel the speed is appropriate; "1" means too slow and "5" means too fast. So, the mean rating of nearly 3 in speed appropriateness indicates that most participant feel the moving speed of MovableBlock is appropriate in the SR experience.

Chapter 5 Result and Discussion

5.1 Feeling of Presence in SR Experience

In general interpretation of IPQ result, the MovableBlocks performs marginally in the qualitative grading description from [49] when compared to other previous works. It indicates that from the current applications as suggested in user study might not be a very good fit for participants to feel the "Presence" in SR experience or might be the SR applications we developed are not of good combination with MovableBlocks.

From the statistical analysis of previous chapter, there was no statistical significance found when comparing sub-scale of IPQ and the applications, though it seems there is order effect found when comparing the change of mean score of sub-scales in two groups with different sequence of exposure to applications, showing that the IPQ result is better when participants are firstly exposed to application 2 (Forest Tour) then application 1 (Dynamic Furniture).

There was is statistical significance found in some sub-scales of IPQ compared to factor of weight, specifically for the weight group of "Light" and "Heavy", that are likely to contribute the different perception of presence in our applications. In order to facilitate the discussion and investigation of how the IPQ score of applications be contributed by weight, we tried to list out the characteristics and features of both applications to check those which may be related to participants' weight, and these characteristics and features could be served as reference for the future design of relevant SR experience with the movable devices supporting the users' weight. The listing of the characteristics and features of our applications is as the following:

Table 5.1 Characteristics and features comparison between our proposed applications

Application 1 – Dynamic Furniture		Application 2 – Forest Tour
Various whole-body interaction on the M-Blocks (e.g., sitting, laying, touching, pushing)	Designed Interaction with the M-Block	Sitting on the M-Block only
Nearly none (focus on the virtual furniture)	Interaction with the virtual environment	Looking around (natural scenery and animal)
Less frequent (only move when transforming into other virtual furniture)	Movement frequency of the M-Block	More frequent (keep moving during the experience)
Three (3)	Number of M-Block(s) used	One (1)
Indoor (classroom)	Environment	Outdoor (natural environment)
• Can voluntarily walk around and interact with M-Block from different angle and position	Other features	• Natural ambient sound is included

From the above list, we expect that the designed interaction with the M-Block and the movement frequency of the M-Block between applications could be important reasons that relates to participant's weight that might lead to possibly significantly different IPQ rating in two applications.

In terms of designed interaction with the M-Block, there are more various of whole-body interaction available to the participants in "Dynamic Furniture" and they have more opportunities to exert force in various mean (different body part) and amount towards the M-Block; While "Forest Tour", participant only sit on the M-Block and have not many choices to interact with the M-Block. The various of whole-body interaction might lead to higher INV rating in "Dynamic Furniture" than in "Forest Tour. However, there are some participants reflect that they can feel feeling of slippery when performing whole-body interaction on multiple M-Blocks in "Dynamic Furniture", especially the participants who are categorized in the "Heavy" weight group; there are four participants addressed this issues, and two participants are from "Heavy" weight group.

Regarding the movement frequency of M-Block, "Dynamic Furniture" got very few movements compared to "Forest Tour". The M-Blocks move only when transformation of furniture is needed in "Dynamic Furniture" and the moving distance is quite short. The latter one is designed to keep moving during the whole experience. Combined with the qualitative feedback from some participants mentioned about the issue of "sound of motor sometimes drags one's attention back to the physical environment", the higher frequency of movement of M-Block means more often of sound emission from the motor. This issue is also closely related to the weight of participants as the power of motor is adjusted according to participants' weight before the experiment; the heavier the participant is, the stronger the motor power is and also means the louder the sound emitted from motor. Such effect might be elevated due to much longer time of M-Block movement in "Forest Tour" than "Dynamic Furniture", causing the significant difference in the IPQ result when compared both applications with different weight group. One participant from "Light" weight group mentioned about fear of the motor power bringing too much acceleration to the body and falling off from the M-Block. The potential issues from the motor power affecting the feeling of presence should be addressed in the future design, such as reducing the sound emission from the motor, and more appropriate adjustment of motor power according to users' weight.

Besides, we tried to categorize the qualitative data such as the opinion and feedback from participants into the relevant sub-scale in IPQ as reference for future work to improve the application of MovableBlocks in terms of different sub-scales of IPQ in the following Table 5.2.

Table 5.2 Categorized comments from participants regarding each sub-scale

Sub-scales	Comments from participants	Issues
Spatial Presence (SP)	Able to see users' own legs or body to have stronger perception inside the virtual, especially when sitting or lying on the M-Block (P3, P21, P23)	**Lacking sense of body**
	The sound from the motor drags the attention of participants back to the physical environment (P12, P16, P21)	**Motor sound**
	Touching the tracker during the experience causing feeling worried and concerned (P5, P7)	**Placement of tracker**
Involvement (INV)	Allowing users to have control of the movement over the M-Block (P1, P2, P10, P16, P17, P18)	**Control over M-Block**
	Allow to have more interaction with other virtual objects in the virtual environment (P3, P4, P9, P11, P17, P19)	**Interaction with VE**
Realism (REAL)	Able to offer more elements such as audio to enhance the immersiveness in environment (P6, P13)	**Ambient audio**
	Can have better matching between the physical objects and virtual objects, such as the back of chair and sofa (P5, P7, P10, P11, P24)	**Object matching**
	Able to provide stronger haptic feedback when interaction with the environment (P1, P8, P14, P22, P24)	**Stronger haptics**

5.2 Safety and Comfortability

Although in terms of safety and comfortability looks quite high from the statistical analysis in the previous session, there are various comment and concerns from the participants' reflection in the qualitative part of the questionnaire as the following Table 5.3.

Table 5.3 Categorized comments from participants regarding each aspect

Aspects	Comments from participants	Issue
Safety	The mismatch between the virtual object and real object may mislead the users for dangerous interaction, like leaning back on sofa (P1, P11, P16)	Object matching
	The connection between M-Blocks is not tight enough and can feel a bit slippery when interacting with whole-body (P4, P18, P24)	Slippery issue
	Cannot see own body and legs may lead to accidentally hit something or falling from the M-Block (P3, P14, P16)	Lacking sense of body
	Worrying about the sound from motor power and the movement may bring too much acceleration toward body or crush the wall (P12, P16, P17, P20, P21)	Motor sound + acceleration
Comfortability	Get dizzy easily during the movement (P9, P19)	Dizziness
	Soft materials can be used on the surface of M-Block to make it more comfortable to be seat (P11, P20)	Soft surface

There are many feedbacks from the participants regarding the safety, which are mostly related to the structure of the M-Block such as lacking protection mechanism or the motor power issue making participants feel worry.

Participants' concern regarding the connection and slippery issue when interacting with multiple M-Blocks worth discussions; when proposing the MovableBlocks, we concern about the mobility of the M-Block with human weight on it which is more force from vertically upward to the M-Block, but did not paid attention to the possible issue of slippery when the force is exerted from different horizontal or diagonal direction towards the M-Block. Follow-up work to improve the structure of the M-Block such as adding dynamic breaking or locking system during the interaction might be required to address this issue.

For other raised issues such as mismatching between the virtual object and real object, it could be solved from both hardware and software design. From hardware perspective, physical support structure can be added to the M-Block to allow user to interact with the M-Block with more different postures safely. From software side, the calibration between tracker and the position of virtual object in the virtual environment can be extensively done to ensure more accurate matching between virtual and physical objects.

When comparing two tables, there are few issues can be found in both table such as "object matching", "lacking sense of body" and "motor sound" which means these issues can affect in both sense of presence and, safety and comfortability that should be taken care of to improve the overall SR experience. The following Figure is the summary of the issue we found in these two sessions.

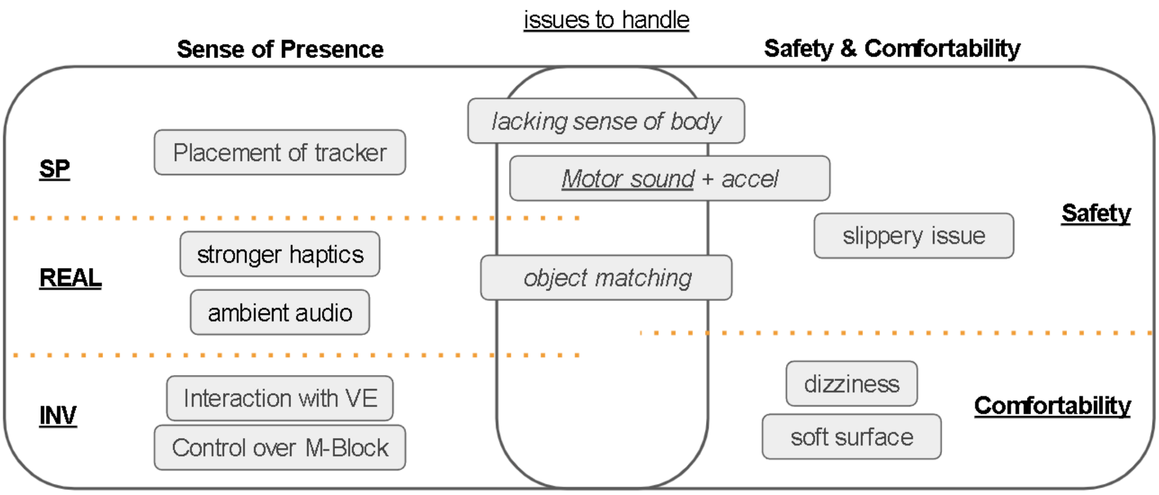


Figure 5.1 Summary for issues to handle from the qualitative finding in user study.

5.3 Possible Future Applications

Regarding the results from the user study, it seems the current proposed SR applications with MovableBlocks did not provide high feeling of Presence to users based on result of IPQ, which the reasons might be attributed to the design of application or the structural and mechanical design of the M-Block or even both. The issue addressed by the participants and their opinions from the previous sessions could be investigated to improve the work for better SR experience for users in the future.

Besides, some possible future interesting interaction and applications are suggested by the participants in the user study, such as "*able to stand on it or lying on own's stomach for interacting virtual objects on height or swimming and diving*" (P7), "*air cabin*" (P12), "*watching video when laying on sofa*" (P16), and "*applications in amusement park*" (P5). These could be served as good reference for the future applications of MovableBlocks.

Chapter 6 Limitations and Challenges

Due to the experiment design, there are several limitations of the result of each evaluation and user study. In user study, it was difficult to explain how our work affecting the SR experience of participants because there was no baseline comparison between the enabling and disabling certain functionality of the work among the same SR application. Besides, the design of the two SR applications could be modified to emphasize the functionality of our work for effective reflection of IPQ result and rating. For example, applications could be focused on investigating how “mobility” of the device would affect the SR experience when user is sitting on it, or investigating on how “interaction between multiple devices” affecting the SR experience, etc. It would be helpful to identify how each key factors affecting sense of presence of participants.

Besides, all of the technical evaluation and users’ study are conducted in our venue in lab setting and by invitation to participants who are mostly students from our department, which means that the result and samples could be biased by our sampling method and own environment setting, particularly ensuring the flat floor leveling for room-scale size venue is important, or to develop an algorithm to tackle the issue of uneven floor such as increasing the motor power dynamically when it is detected that the device keep staying at the fixed position.

Another challenge we found in this work is about the automated movement for multiple devices, which they are prone to crushing each other with the actual deviation in movement even though with careful path planning. The devices should have the ability to detect the real-time position of each other for preventing from crushing, which could be also considered in the future similar study. It can also ensure the safety of the participants when sitting on the device.

Chapter 7 Conclusion and Future Works

In this research we proposed MovableBlocks, an interactive solution with modular mobile blocks, and attempted to improve the SR experience with the aid of movable device that can support the human weight for whole-body interaction. This kind of experience lacks discussion previously with only the device can be either mobile or supporting heavy weight but not both, which we believe that such kind of device worth more discussion in SR context with the aim of providing immersive experience to users.

Upon the completion of structural and mechanical design of MovableBlocks, two technical evaluations were conducted to test the mobility of the M-Block with weight-loading and the efficiency of automated movement in the virtual environment. The M-Block can move smoothly with weight-loading though the automated movement took more steps than expected with discrepancy of movement when going forward after the rotation and it cannot perform very fine movement with certain amount deviation between actual and targeted position and facing angle.

We proposed two possible applications, "Dynamic Furniture" and "Forest Tour", for conducting the user study adopting the IPQ measurement to investigate how MovableBlocks affect the users' feeling of presence in the SR experience. The general result shows marginal performance compared to previous works indicating that there is large room of improvement for the future application. From the statistical analysis, some statistically significance found in the factors such as application design and the users' weight. We attempted to explain the significance by comparing the features and characteristics of applications, supplemented by the qualitative data of the overall opinion and feedback from the participants. Their feedback also helped us to gain insight from the qualitative perspective to uncover some hidden issues that we ignored in the previous design considerations such as the slippery issue. Some participants also proposed some interesting applications that we could work on to further improve the design for better SR experience in the future.

More different kind of applications with similar device can be explored such as assembled elevated runway or stage for larger space adoption with more variety of activities, multi-user interaction of sitting together on one or multiple movable devices for entertainment purpose like tug-of-war and virtual roller coaster which can deceive human perceptions by creating mismatch between virtual and physical environment for excitement.

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Appendix

Here is the reference list of the online resources used for developing the SR applications for MovableBlocks:

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Hospital bed- free 3D Asset | 3D Interior | Unity Asset Store. (2021, December 28). Retrieved from Unity Asset Store website: https://assetstore.unity.com/packages/3d/props/interior/hospital-bed-free-3d-asset-190310

Modular Sofa FREE | 3D Furniture | Unity Asset Store. (2023, June 24). Retrieved from Unity Asset Store website: https://assetstore.unity.com/packages/3d/props/furniture/modular-sofa-free-189368

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Download Free Forest Sound Effects | MixKit. (n.d.-b). Retrieved from https://mixkit.co/free-sound-effects/forest/

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