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Comparative assessment of human observation in virtual and physical reality

By

Oumaima Larif

A Thesis
Submitted to the Faculty of
Mississippi State University
in Partial Fulfillment of the Requirements
for the Degree of Master of Science
in Aerospace Engineering
in the Department of Aerospace Engineering

Mississippi State, Mississippi

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2019

Comparative assessment of human observation in virtual and physical reality

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Virtual Reality (VR) is a computer-generated simulation of an environment that can be interacted with a seemingly real or physical way by a person using special electronic equipment. VR techniques have the potential to reduce design cycle times and reduce or eliminate physical prototyping costs if the human performance in VR is truly comparable to physical reality. In this research, human oversight of an assembly process in virtual reality (VR) and physical reality is compared for the ability to detect deviations (errors) in parts. This is relevant to verifying the use of VR to assess the vulnerability of cyber-physical systems with human observation.

DEDICATION

This work is dedicated to my family and friends, who have been a source of consolation, support, and encouragement during my life. I would like to express my profound gratitude to my parents, Said Larif and Samira Hamama, and my sister Rihab Larif, who always support, sacrifice, and love me unconditionally. I dedicate this work to my best friends Kaoula, Yousra, and Amina, whose support and words of encouragement helped me greatly to keep moving forward. Also, I want to thank Safae El Amrani for her help and support. I give thanks to Sayali for being a good work partner.

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I want to thank the faculty members and the academic staff from both the International University of Rabat and the Bagley College of Engineering for their valuable partnership, which presents a successful experience for the students. Also, I would like to thank the dean's office for giving me the opportunity to be here.

Lastly and most importantly I thank God for every single blessing. Thank you, Allah.

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CHAPTER I

INTRODUCTION

1.1 Background

What is virtual reality? This question can be answered by defining these two words, ‘virtual’ and ‘reality’ [25]. In general, virtual reality means near and reality can be defined as what we experience in real life as human beings. Thus ‘virtual reality’ basically means ‘near reality’. Technically, virtual reality illustrates a three dimensional and computer-generated environment where a human being becomes part of the environment and capable to interface with it [4].

The virtual reality world started in the 1590s when Morton Heilig wrote of an “Experience Theatre” such that all the senses that a human being has could be encompassed in an effective manner [3]. In 1962, he built a prototype of his idea called the Sensorama. From 1970 to 1990 the virtual reality devices were mainly implemented for medical, flight simulation, automobile industry design, and military training purposes [4]. Virtual reality is now used to ensure that people are capable of executing their job or learning a subject, also it is used to reduce training cost by eliminating the need for establishing a series of prototypes. Furthermore, virtual reality helps to create scenarios that they can be hard or expensive to create in real life, and it enables more flexibility to make changes in all different stages of development. Moreover, virtual reality provides a safe and controlled area (environment) especially in the fields that include potentially dangerous maneuvers performed by highly trained professionals such as pilot,

firefighter, and others. Thus, virtual reality replaces this with one model, which can be modified and used anytime from different locations. Likewise, virtual reality helps to save time, money, and eliminate risks. It is also an innovative and enjoyable method of working or learning. VR users are immersed in a virtual world, free to fly planes or perform surgery at no risk, also they can build big modules like smart buildings, car, and engines...

Cyber-Physical System (CPS) is a system or a mechanism that can control and monitor physical machines by computer-based algorithms. In other words, CPS consists of two considerable and dominant components: a cyber system and a physical process [1]. Commonly, the cyber system is controlling and monitoring the physical process since the cyber system is a networked system of small devices with computing, communication, and sensing capabilities. For instance, remote robot control, the distance operations or activities can be done economically and rapidly [5]. CPSs have strong interactions with the physical environments, which is the difference between CPSs and traditional Information Technology (IT). CPSs are cyber systems and the interaction between the physical and cyber systems. Thus, they are vulnerable to cyber-attacks [2].

A challenge in the advancement and evolution of embedded and cyber-physical systems is the large contrasts in the standard practices between the different engineering disciplines involved: programming and mechanical designing. There is no common "language" that applies to all the included disciplines in CPS. Nowadays, in a marketplace where quick advancement and development is thought to be fundamental, engineers from all disciplines should proactively investigate system structures cooperatively, assigning obligations to programming and physical components, and analyze trade-offs between them. Recent advances demonstrate that coupling

disciplines by utilizing co-simulation enables collaboration without implementing new standards or a common language [15].

A cyber-physical production can be designed and developed based on the 5Cs architecture (Connection, Conversion, Cyber, Cognition, and Configuration) [16]. The foundation of the 5C architecture is the smart connection level where devices are designed and programmed to self-connect and self-sense for their behavior. These devices or sensors are used to collect a variety of data like, voltage, current, and temperature. The second level is the Data-to-Information or the Conversion level; the data from the previous level helps to evaluate and consider component machine health and measure the features of critical and potential problems with self-sense capabilities. Cyber level is considered as the central information hub, in which all information from the machines are gathered to provide better understanding of individual machines. This level is based on a “Time Machine” methodology, that stores the information and data in an efficient way and records any change set or similarities of machine behavior [16]. In the cognition level, the content and the background of the potential issues can be easily determined and presented to users due to the existence of individual machine status and comparative information of similar machines [30]. And the last level is the configuration level, where the machine became self-optimized for disturbance, self-configured for resilience, and self-adjusted for variation, making the risk level low [3].

Recent progress in computer-generated reality, or virtual reality (VR), has led to exciting innovation with consumers, organizations, and businesses alike understanding and realizing VR's potential for changing and upgrading experiences.

1.2 Literature review

1.2.1 Cyber-physical security analysis for the manufacturing process

A cyber-physical system is a structure or a mechanism that is controlled, observed, and monitored by computer algorithms. Cyber-physical systems or CPSs are systems that link the physical world with the virtual world through sensors, software systems, and communications technology. The main operator for the development and evolution of CPS is the reduction of cost and time, and visualization provides more flexibility at a lower cost in all different stages of development. CPSs have been used in areas like transportation, smartphones, robotic surgery, aviation, and others [5].

Furthermore, cyber security systems had an important impact in industrial automation by controlling and monitoring the real-world physical infrastructure; the CPS were the main technological basis to facilitate the realization of large-scale complex systems such as smart buildings, transportation, healthcare, and manufacturing [7]. Regarding the transportation domain, CPS played an important role in Car-to-Car communications, or Vehicle-to-vehicle (V2V) system. This role was demonstrated in safety where vehicles show their position, speed, and direction over a wireless network to allow them to predict possible collisions and trigger speed limit reminders and accident warnings [8]. Also, it shared information on traffic and updates the map. CPSs played a role in industrial infrastructure to combine communication and information technologies to control distributed physical processes and systems [7]. Cyber-Physical systems had important advantages in manufacturing, design, modeling, and simulation. Thus, it is important to develop the cyber security tools; otherwise, a cyber-attack could modify the process parameters and it could also disturb the product or the system design that leads to disturbances in a product's launch and ruined equipment [9]. A case study was performed to

show the feasibility of cyber-attack on a straightforward assembly manufacturing system and to comprehend the analytic capacities of engineers who do not anticipate cyber-attacks. In this experiment, engineers were challenged to design and manufacture a tensile test specimen [8]. A tensile test specimen was chosen because of its ease of design, machining, and quantifiable performance. CPSs are also used in digital manufacturing with the aim of creating highly customizable products with higher quality and lower costs. In other words, CPSs are used to improve manufacturing productivity and cost efficiency. To determine the risks or any circumstances that may cause harm to an IT system for a manufacturing system, the first step is to identify the components, resources, and information of the system. Stuxnet is an example of innovation in industrial cyber-physical system security first uncovered in 2010 [9]. Stuxnet was designed to target systems that are configured to monitor and control industrial processes [31].

This computer was targeting industrial systems in critical high-security infrastructure, supervisory control and data acquisition systems and programmable controllers. These controllers allowed the automation of electromechanical processes such as those used to control machinery on factory assembly lines. Stuxnet made small change to the processes and data that were difficult for human operators to detect, and successfully persisted on targeted systems to significantly delay and degrade data over a long period of time. Stuxnet's design is not domain specific, and with a few adjustments and modifications it could be considered as a platform for attacking other systems such as in the automobile domain or power plant domain. Stuxnet is considered as a wakeup call and an increased awareness of security.

The improvement of cyber-physical methods was important to reduce the rate of uncertainty in design which brought a number of problems such as the need to provide effective communication between members or representatives of the design teams, prototyping and testing

in the information environment [1]. The concepts for cyber-physical system design should be proposed at the end of the conceptual design phase due to the lack of tools to handle the complexity of the CPS design in the early design phases [8]. Recent research focusing on CPS has been conducted using the virtual reality technology; such as the Oculus VR [29] is one way to involve in the virtual environment.

1.2.2 Virtual reality assembly process evaluation

Assembly evaluation is an important segment of the product configuration process in which insights regarding how parts of another product will be assembled are formalized. Virtual Reality technology can possibly support the joining of common human movements into the computer-aided assembly planning condition. This will enable assessments or evaluations of an assembler's capacity to control, manipulate, and assemble parts and result in diminished cost and time for product design. Assembly process planning is a basic advance in product improvement. It is critical to building up a legitimate assembly plan early in the structure or design stage. A healthy assembly plan considers operator safety, shortens the assembly time, and lowers cost. The best-designed assembly process can enhance product quality and efficiency; also reduce the product's time to market [15].

Assembly operations are a key segment of modern production frameworks. Designing, planning, and conducting assembly operations represent a critical and important part of the cost of an item or a product. Virtual reality facilitates assembly configuration, arrangement, and prototyping. Still, there are certain issues (for example, information interpretation, coordination of different equipment and programming frameworks like hardware and software systems) confronted while applying this popular technology to the assembly domain [11]. The virtual reality technologies give a richer arrangement of user experience. This virtual reality technology

is dependent on a Computer-Aided Design (CAD) model [8]. Based on CAD's methods the potential problems can be determined before launching a real factory and without using physical mockups, which helps to make the design cycle shorter and it helps in improving the product quality. For example, Boeing laboratories [13] use virtual reality technologies to visualize the computer-aided design (CAD) data. The size and location of display have been described by the VR framework, and it automatically calculates the correct perspective without the need to recompile the application. In this laboratory, the mouse, keyboard, and gamepad are used for moving around the virtual environment. This application consists of three layers of a virtual reality framework. The first layer manages the hardware input devices, the second layer is a physical or dynamic layer that processes the used input for navigation and collision detection in the virtual world, and the third layer is the scene graph that processes 3D models and data calculated by the second layer in order to output the graphic representation of the world. The main objectives of using CAD methods are the evaluation of the assembly process in the early stage and generation of practical assembly operation sequences [12]. Also, it helps in minimizing the number of workstations and maximizes the workload smoothness. Virtual Reality provides an approach to assemble virtual samples of physical models through simulating a realistic environment, which helps in reducing or eliminating the physical prototype, to shorten the product development cycle and avoids exposing humans to danger [14]. VR guarantees that the final product satisfies customer requirements and product constraints.

1.3 Objective and challenges

The research in this thesis is focused on investigating the feasibility of using VR technology to determine whether a human being is capable of visualizing and detecting part alteration. The ability to detect part alteration is related to detection of vulnerability of the CPS

with human observation inside the system. Furthermore, the aim of this research is to assess to what degree VR can be utilized to survey the CPS vulnerability by the assistance of human being participation, and how closely VR evaluations can match the real-world experiments.

The challenge faced in this research is to make the virtual environment and animation near or similar to the real one.

1.4 Thesis organization

This thesis is structured as follows. Starting with CHAPTER I that contains three main parts: the first part is the background that gave the definition and history of virtual reality. The second part is the literature review about the cyber-physical security analysis for manufacturing process and virtual reality-based assembly process evaluation and introducing virtual reality technique in cyber-physical analysis to consider the human perception in detection process changes. And the last part is the objectives of this research and challenges and. CHAPTER II is the proposed methodology that includes an overview and describes the experimental setup, procedure, data analysis, and results discussion of both, preliminary and assembly experiments. Finally, conclusions are discussed in CHAPTER III.

CHAPTER II

METHODOLOGY

2.1 Overview

This chapter describes the two experiments conducted in this research. The intent of this study is to investigate whether a human being can recognize part alteration and introduce virtual reality technique in cyber-physical analysis to consider the human perception in detection process change. As well as determining how closely VR evaluations can match the real-world experiments.

The safety of the participants is more important, that is why participants who were having some medical issues should not participate in these experiments. These experiments were established in the real world as well as in the virtual world. All criteria, environment measurements, object position, and applied materials were the same in both real and virtual environments. Choosing the software capable of producing a virtual environment closely matching the real environment was important. After considering several potential choices, CATIA V5 R20, MAYA 2018, and UNITY3D were chosen as software needed to achieve the goals of this thesis. To imitate the real-world experiment specification in the VR environment, a solid model is constructed in CATIA that is then imported to MAYA to create an animation and finally transferred it to Unity to apply the materials to the model, adjust the light settings and the OVR which is the participant perspective for VR.

Two experiments were conducted, referred to as the preliminary experiment and the assembly experiment. The preliminary experiment consisted of benchmark and variable male parts, oval table, black background, and a shield. In the preliminary experiment, the participant visualized a sequence of one pair of male parts, benchmark and variable. Benchmark refers to the nominal male part (10 mm boss height) and the variable parts' dimensions varied as shown in Figure 2.1. This experiment consisted of a 50% benchmark/benchmark and the other 50% represent benchmark/variable. The preliminary experiment results provided information on the accuracy of the participants' results to help understand if a human being is able to detect the dimensional change between the benchmark part and the variable ones.

The assembly experiment consisted of a rectangular table, female part, background, a benchmark male part as a reference, and variable male parts. In this experiment participants observed an assembly process of male and female parts and identified any error of the male parts. It was designed to provide information on the smallest change that a human eye could detect and to answer the question of whether participants were able to detect the error, in terms of dimensions, of the male parts during an assembly process.

In these two experiments, the participants saw two types of male parts: a benchmark that always remained the same and four versions of variable parts. The change was only on the cylinder, or boss, height and there were four changes: 5% (C), 10% (D), 20% (E), and 30% (F) of benchmark boss height added. Each change was referred to as a trial and each trial consisted of three rounds. One round included twelve displays. The first round always started with trial D, then E, then F and at last C; and the following two rounds were randomized. Before conducting the experiments, the experimenter told the participants that in the first sequences the pairs are the same.

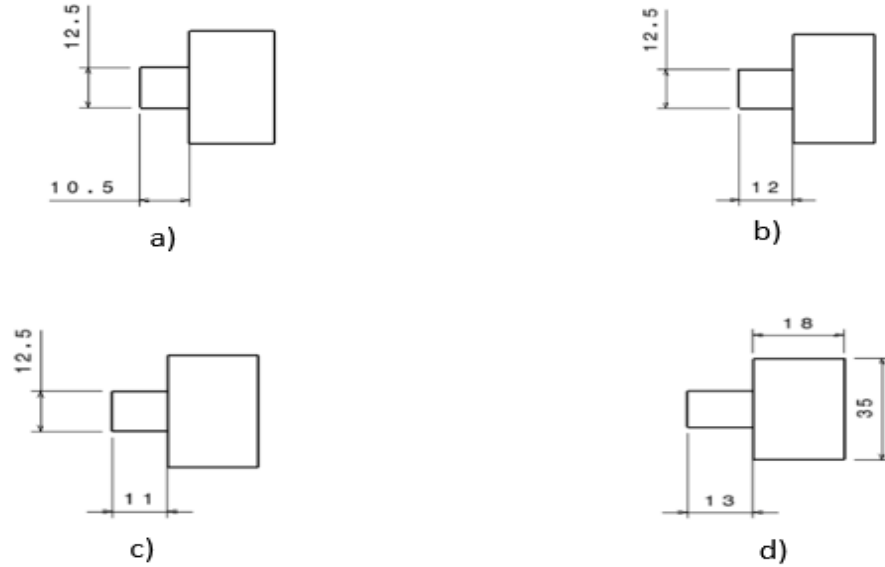


Figure 2.1 The four variable male parts: a) Trial C 5% change, b) Trial D 10% change, c) Trial E 20% change, d) Trial F 30% change

2.2 Preliminary experiment

The general procedure of the method to compare the physical and virtual reality-based results is as follow; in the beginning, the student arrived then began completing the registration form and signed the consent form to start the background survey, these actions may take up to 6 minutes. After that, the participant needed to familiarize himself with the VR device and environment with playing with VR for 5 to 6 minutes. Then, the participant began vulnerability experiments and assessments based on virtual reality for 15 to 20 minutes. Last but not least, the participant was ready to complete the VR motivation survey and the VR efficacy survey, and it took between 15 and 20 minutes.

This section illustrates the capability of a human being to detect a change in dimension. The equipment needed for this experiment were, an oval table, male parts, divider for pair test block, background board, shield that would appear and disappear. Therefore, as shown in Figures

3.1 and 3.2, the environment was built in CATIA V5 R20 [17] then imported to MAYA 2018 [18] to create the animation.

This experiment was based on four trials where each one would be repeated three rounds. As shown in the following Figures, the part in the right-hand side depicted the variable part while the one in the left-hand side referred to the benchmark part.

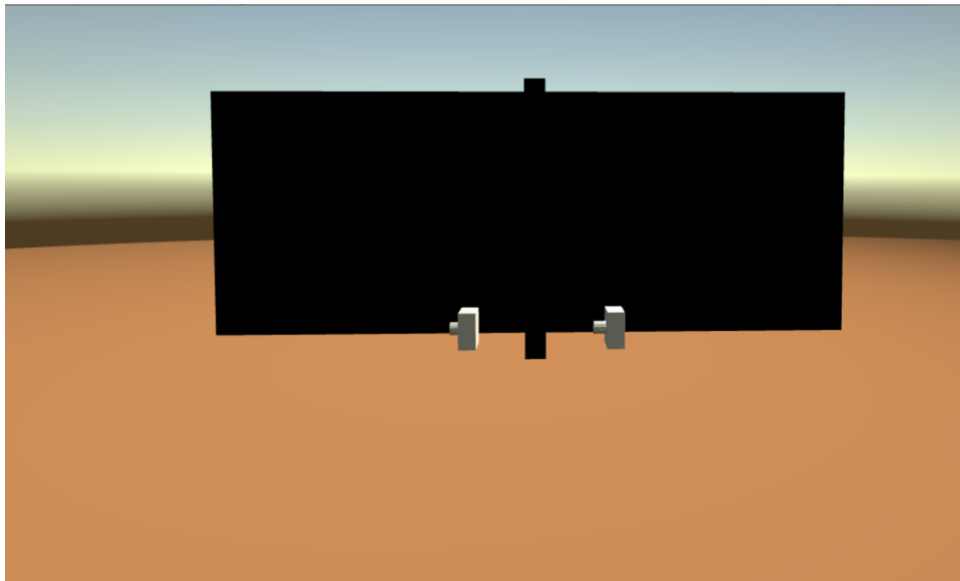


Figure 2.2 A view from UNITY of two male blocks. The nominal block A in the left-hand side and the block F in the right-hand side

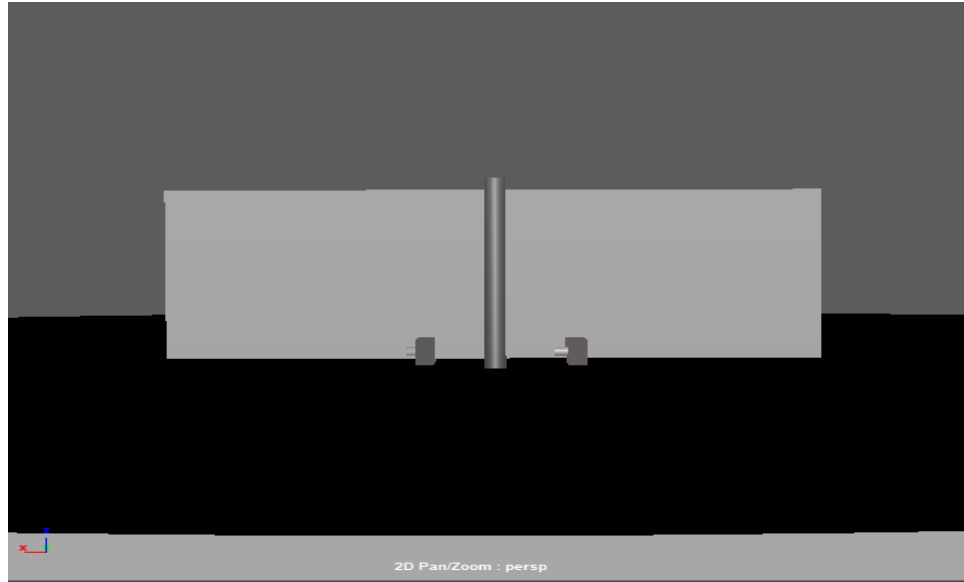


Figure 2.3 A view from MAYA of the two male blocks. The nominal block A in the left-hand side and the block F in the right-hand side

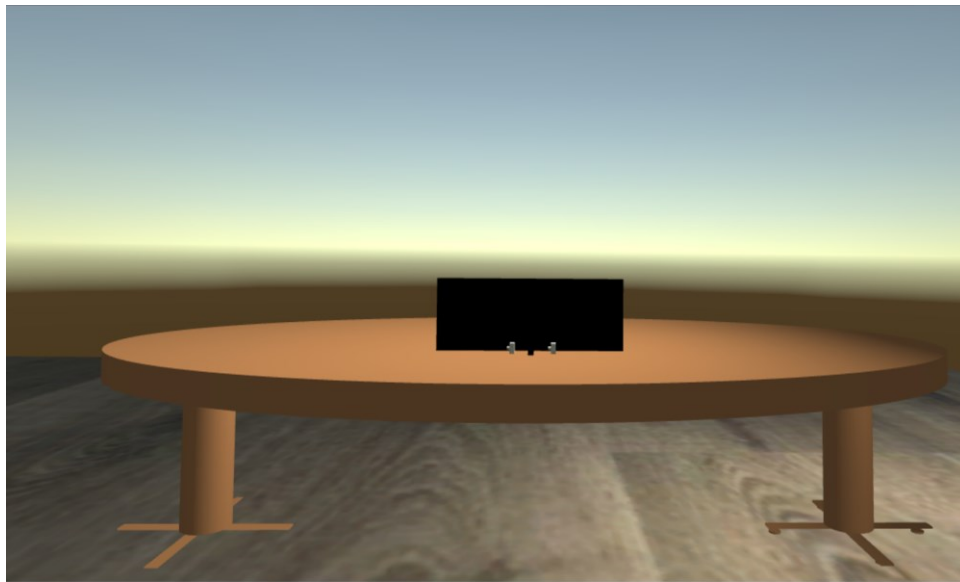


Figure 2.4 A front view from UNITY of the environment

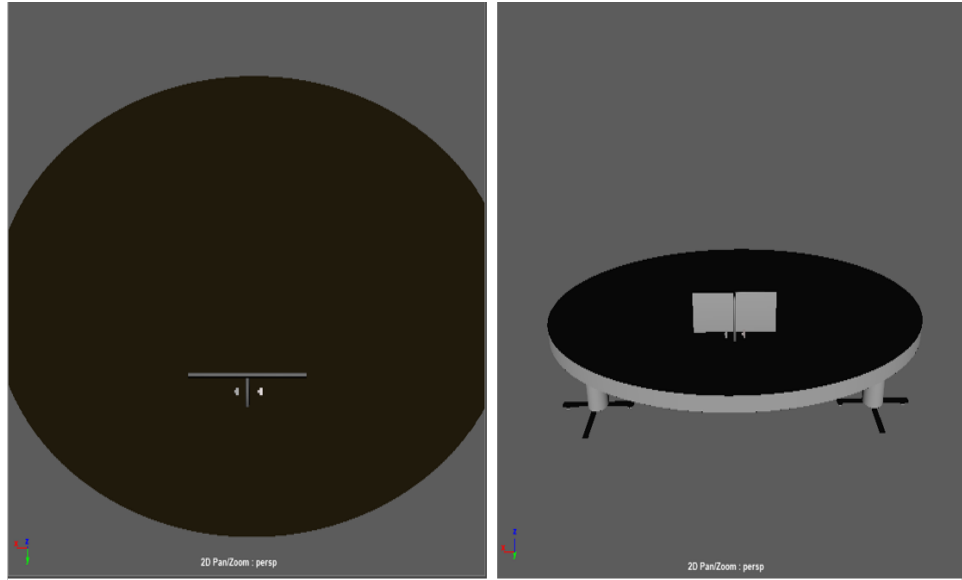


Figure 2.5 A front and top view from MAYA of the environment

As mentioned before, these experiments were set up in a virtual world and the real world. As shown in Figures 3.4 and 3.5, the dimensions and positions of each component of the real environment were the same as in the virtual environment.

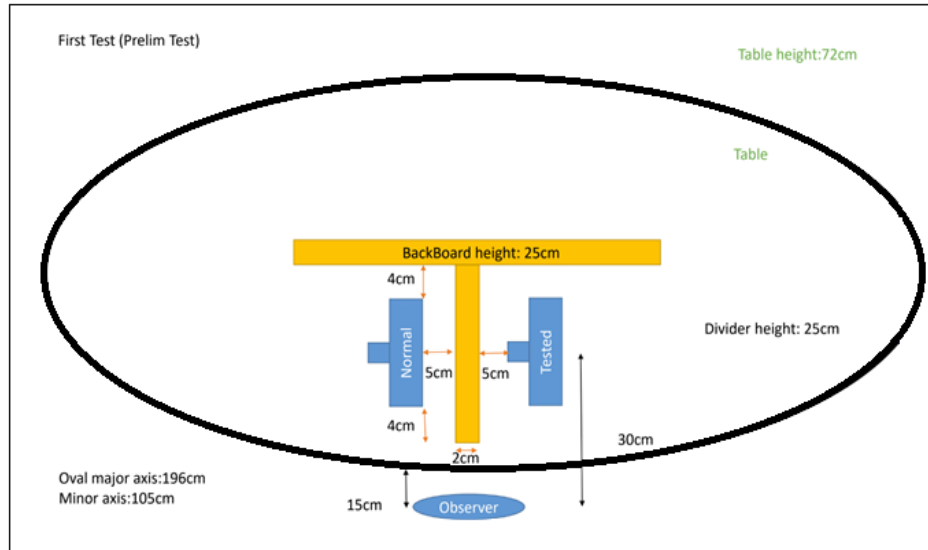


Figure 2.6 Dimensions of the environment: table, background, and shield with position of each component

2.2.2 Experiment setup

The environment established in this experiment was similar or identical to the real-world environment. Therefore, the first step was to build and design the environment which consisted of an oval table, a backboard, shield, separator, and male blocks in CATIA V5 R20 respecting all dimensions and positions shown in Figure 3.5. Then, the second step was to import the CATIA model to MAYA 2018, in which the animation was created. In this animation, the participant could visualize the two parts via the OVR player controller which is a folder of the Oculus Unity integration that consists of C# scripts [19]. OVRCameraRig replaces the Unity camera that helped to see the scene with the Rift. Thus, the OVRCameraRig was adjusted to be 15cm away from the table which means that the observer was 15 cm from the table edge. The distance between each block and the backboard was 4 cm. The distance between the human subject and the middle of the block was 30cm. This experiment consisted of four trials each one had three

rounds. And each trial included twelve pairs to show to the participant with one pair displayed at a time. The male parts varied in the height range of 0.5mm – 1mm – 2mm – 3mm, (block C, block D, block E, and block F).

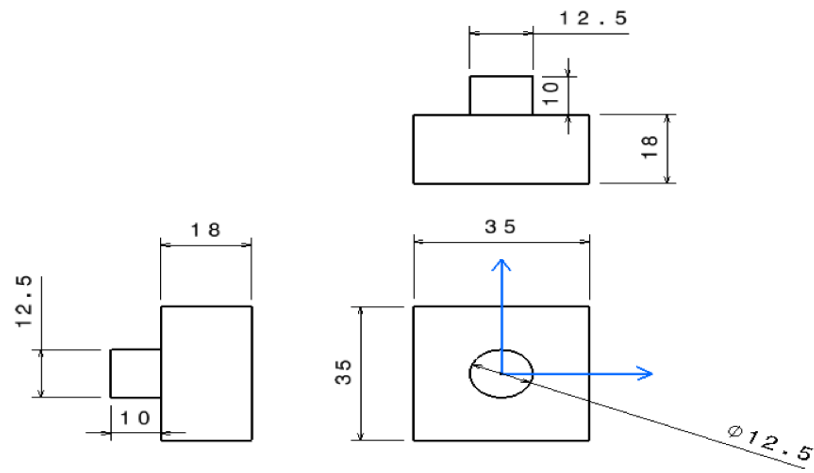


Figure 2.7 2D male part

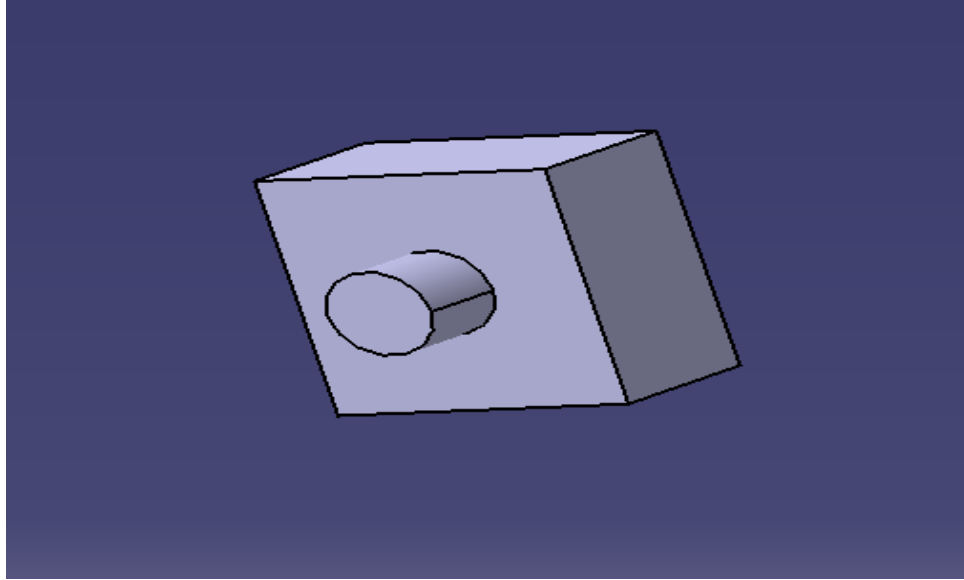


Figure 2.8 3D male part

Each trial consisted of 50% of benchmark/benchmark parts and the other 50% of the benchmark/variable part, the pairs were randomized within each trial. In a sitting position and a fixed chair position, the experiment should start with a warm-up that contained similar male parts so that the subject got familiar with the VR headset and the environment. The participants should be informed that color or texture differences were not considered as a defect, and only the dimensional feature change counted. By considering the participant's safety, they were asked to complete one round and then they would have a one-minute break or rest, then proceed with the following round.

The participants were asked during the break if they felt dizzy or uncomfortable, and asked to inform the experimenter if they felt uncomfortable or dizzy while taking the experiment.

The observer was allowed to visualize the two blocks for two seconds and then a shield would be on for five seconds, during these five seconds the participant should answer either with

Yes, if the blocks were not the same and there was a change in terms of dimensions, or with NO if the blocks were the same and there was no dimensional change. In the same time the experimenter should write down the answers in a data collection sheet, and the participant was informed that the two first pairs were the same (Block A) for all trials, and they were allowed to observe only one pair of test blocks at a time, the remaining pairs for the trial would be kept hidden or invisible, as shown in table 2.1.

Table 2.1 Data collection sheet

| | Trial 1 | | | Trial 2 | | | Trial 3 | | | Trial 4 | | |
|---|---------|-----|-----|---------|-----|-----|---------|-----|-----|---------|-----|-----|
| | R 1 | R 2 | R 3 | R 1 | R 2 | R 3 | R 1 | R 2 | R 3 | R 1 | R 2 | R 3 |
| 1 | No | No | No | No | No | No | No | No | No | No | No | No |
| 2 | No | No | No | No | No | No | No | No | No | No | No | No |
| 3 | | | | | | | | | | | | |
| 4 | | | | | | | | | | | | |
| 5 | | | | | | | | | | | | |
| 6 | | | | | | | | | | | | |
| 7 | | | | | | | | | | | | |
| 8 | | | | | | | | | | | | |

Table 2.1 (continued)

| | Trial 1 | | | Trial 2 | | | Trial 3 | | | Trial 4 | | |
|----|---------|-----|-----|---------|-----|-----|---------|-----|-----|---------|-----|-----|
| | R 1 | R 2 | R 3 | R 1 | R 2 | R 3 | R 1 | R 2 | R 3 | R 1 | R 2 | R 3 |
| 9 | | | | | | | | | | | | |
| 10 | | | | | | | | | | | | |
| 11 | | | | | | | | | | | | |
| 12 | | | | | | | | | | | | |

For all participants, the first round the sequence of trials should be the same as follow: D E F C. However, in the two other rounds the sequence of trials was randomized as shown in the following tables:

Table 2.2 The randomness of trials

| | Scene 1 | Scene 2 | Scene 3 | Scene 4 |
|---------|--------------|---------|---------|---------|
| Round 1 | D | E | F | C |
| Round 2 | Random order | | | |
| Round 3 | Random order | | | |

Table 2.3 The randomized sequence of the four trials

| Participant number | Round 1 | Round 2 | Round 3 |
|--------------------|---------|---------|---------|
| 1 | DEFC | ECDF | CDEF |
| 2 | DEFC | CDFE | FEDC |
| 3 | DEFC | FDEC | CEDF |
| 4 | DEFC | DFEC | EDFC |
| 5 | DEFC | FDCE | EDCF |
| 6 | DEFC | CFDE | CFED |
| 7 | DEFC | CEFD | DCEF |
| 8 | DEFC | DCFE | DECF |
| 9 | DEFC | DFCE | ECFD |
| 10 | DEFC | EFCD | EFDC |
| 11 | DEFC | FCDE | FCED |
| 12 | DEFC | FECD | DCFE |

The experimenter should have already created the sequence or the animation (visible/invisible) of the pairs in MAYA 2018. After that, it would be imported to UNITY to

apply materials on the environmental components and to set up the position of the OVR player controller and to fix and adjust the lights.

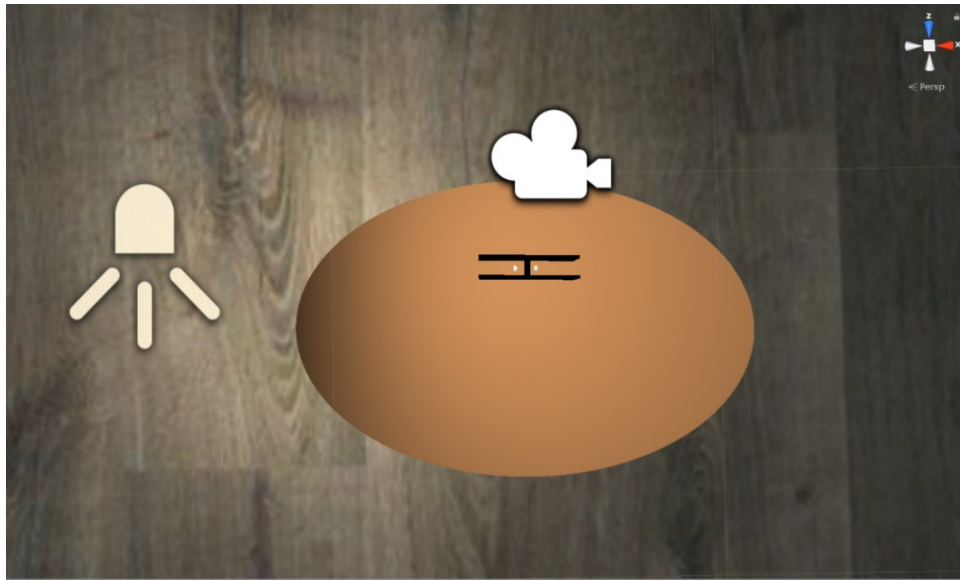


Figure 2.9 A UNITY scene view shows the OVR and light positions

Table 2.4 Original animation sequence of the male blocks

| | Trial 1 (10.5) C | | | Trial 2 (11) D | | | Trial 3 (12) E | | | Trial 4 (13) F | | |
|----|------------------|-----|-----|----------------|-----|-----|----------------|-----|-----|----------------|-----|-----|
| 1 | No | No | No | No | No | No | No | No | No | No | No | No |
| 2 | No | No | No | No | No | No | No | No | No | No | No | No |
| 3 | Yes | Yes | Yes | Yes | Yes | No | Yes | Yes | No | No | Yes | Yes |
| 4 | No | Yes | Yes | No | Yes | Yes | Yes | Yes | No | Yes | No | Yes |
| 5 | Yes | No | Yes | Yes | Yes | Yes | Yes | No | No | No | Yes | No |
| 6 | Yes | No | No | No | No | Yes | Yes | No | Yes | Yes | Yes | No |
| 7 | Yes | No | No | Yes | Yes | No | Yes | Yes | Yes | No | No | No |
| 8 | Yes | Yes | No | No | No | No | Yes | Yes | No | Yes | No | Yes |
| 9 | No | Yes | Yes | Yes | No | Yes | No | No | Yes | No | Yes | Yes |
| 10 | No | Yes | Yes | Yes | No | No | No | No | Yes | Yes | Yes | Yes |

Table 2.4 (continued)

| | Trial 1 (10.5) C | | | Trial 2 (11) D | | | Trial 3 (12) E | | | Trial 4 (13) F | | |
|----|------------------|-----|-----|----------------|-----|-----|----------------|-----|-----|----------------|-----|-----|
| 11 | No | Yes | No | No | Yes | Yes | No | Yes | Yes | Yes | No | Yes |
| 12 | Yes | No | Yes | Yes | Yes | Yes | No | Yes | Yes | Yes | Yes | No |

2.2.3 Experimental procedure

To start the experiment, the experimenter should have already checked the VR devices and calibrated the sensors so that everything is correct and under control. Then all participants should read and sign the Mississippi State University Informed Consent Form for Participation in Research so that they would have an idea about the experiment and also to sign that they are accepting and agree to take it. To make sure that the participant understood the experimenter explains the procedure of the experiment and asked if they had any questions. The same process was applied in a real-world experiment. The only difference was in the real-world experiment there was an operator who was picking the parts, showing them to the participant, and then hide them. Also, there was another operator who was taking the participant's answers.

2.3 Assembly experiment

Correspondingly the preliminary experiment, the assembly experiment established to be identical to the real-world environment. Therefore, the module measurements and dimensions were respected to be the same as in the physical environment, as shown in Figure 2.10.

This experiment designed to provide information on the smallest change that a human eye is capable to detect the deviation of the male part during an assembly process.

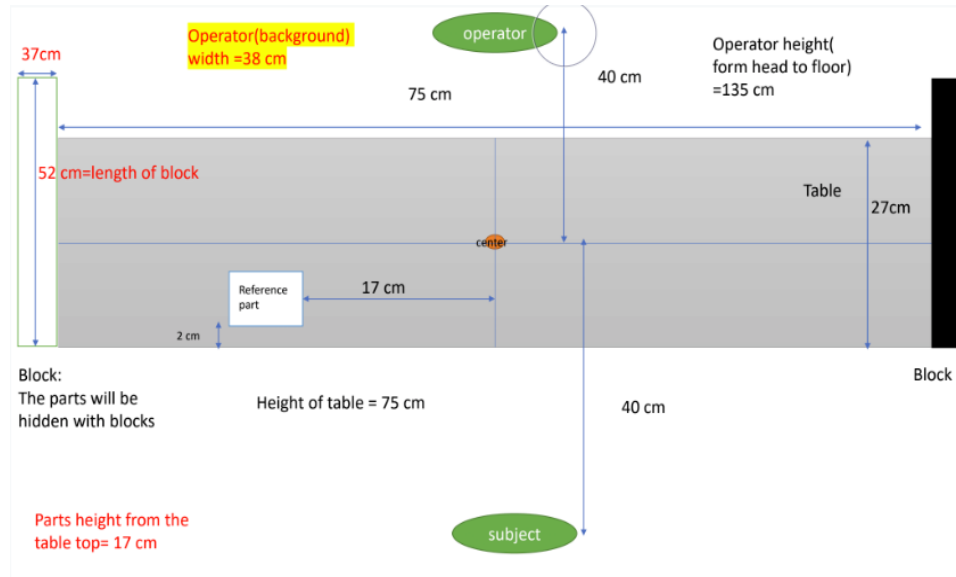


Figure 2.10 Assembly experiment setup

After building the model in CATIA V5 R20, the following step was creating the animation in MAYA, without forgetting not to rescale the module so that it would always remain the same and converting time unit in the real world, which is seconds, to FPS (Frame Per Second) time unit in MAYA. Using the Time slider helps to specify the animation start and end times. Also, as shown in Figure 3.10, time slider helps to change the time unit form fps to seconds.

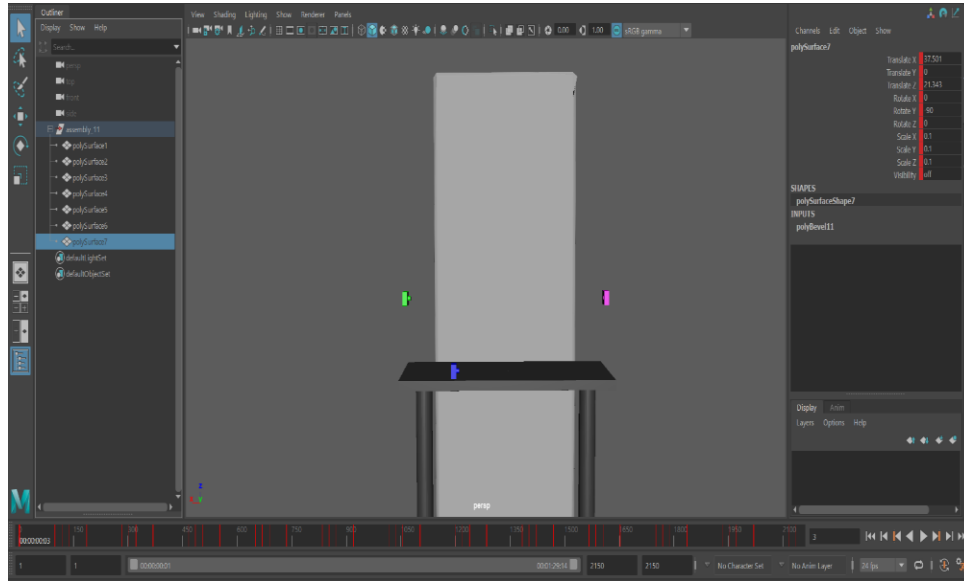


Figure 2.11 The environment in MAYA with the time slider

Consequently, it was important to calculate the average timing, as shown in table 2.5, for each motion of all the assemblies made in a real-world experiment.

Table 2.5 Average timing for each motion of six assemblies

| | Motion 1 | Motion 2 | Motion 3 |
|------------|----------|----------|----------|
| Assembly 1 | 2.46 | 0.48 | 1.34 |
| Assembly 2 | 3 | 1 | 1.23 |
| Assembly 3 | 3.89 | 0.38 | 1.4 |
| Assembly 4 | 3.53 | 0.4 | 1.39 |
| Assembly 5 | 4 | 0.36 | 1.33 |
| Assembly 6 | 4.2 | 0.32 | 1.1 |
| Average | 3.513 | 0.49 | 1.298 |

To reach the goal of having a similar virtual experiment to the real one, the timing should be considered as well. Thus, according to MAYA setup, two seconds were equivalent to 48 fps. Hence, the following table is showing the average timing used in MAYA.

Table 2.6 Average timing for each motion of six assemblies in fps

| | Motion 1 | Motion 2 | Motion 3 |
|-------------------|----------|----------|----------|
| Average (seconds) | 3.513 | 0.49 | 1.298 |
| Average (fps) | 84.31 | 11.76 | 31.15 |

2.3.2 Assembly experiment setup

This section represents and describes the second experiment performed in this study. This experiment was about comparing the ability of human detection of the part modification or alteration. To get this experiment done there were two major steps. The first step was to create the environment in CATIA V5 R20, as shown in Figure 2.12, which consisted of a rectangular table, female part in the left-hand side of the operator, male part (C, D, E, F) in the right-hand of the operator, and a male part (type C) as a reference in front of the subject. Then, imported the module to MAYA to create the animation.

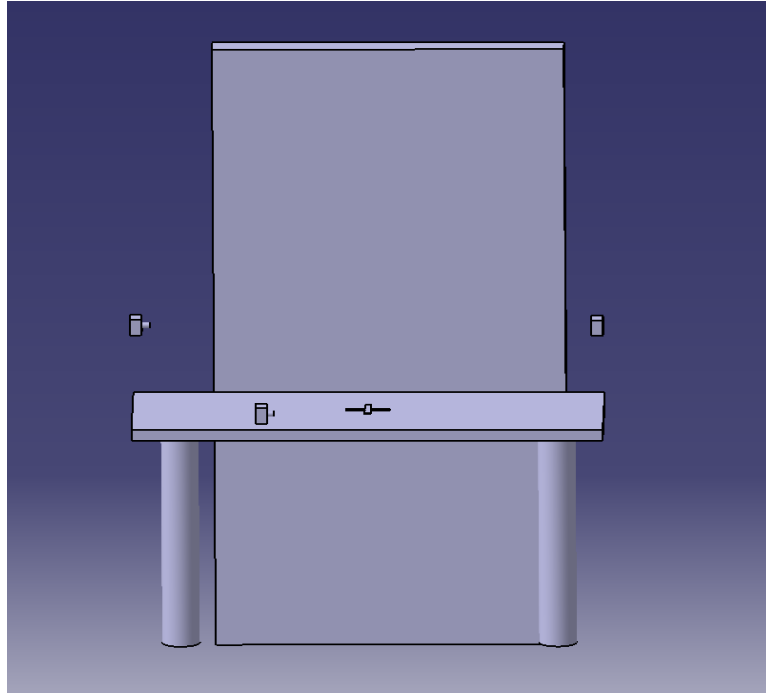


Figure 2.12 Assembly experiment environment build in CATIA V5 R20

The second step was performed with the human subject sitting at an office seat with the male parts were shown to him/her based on a sequence in his/her left-hand side and the female part in the opposite side. The female block, as shown in Figure 2.13 and Figure 2.14, had a 10mm deep, 12.5mm diameter blind hole, and the male block had a 10mm tall 12.5mm boss. both blocks are 35mm x 35mm x 18mm.

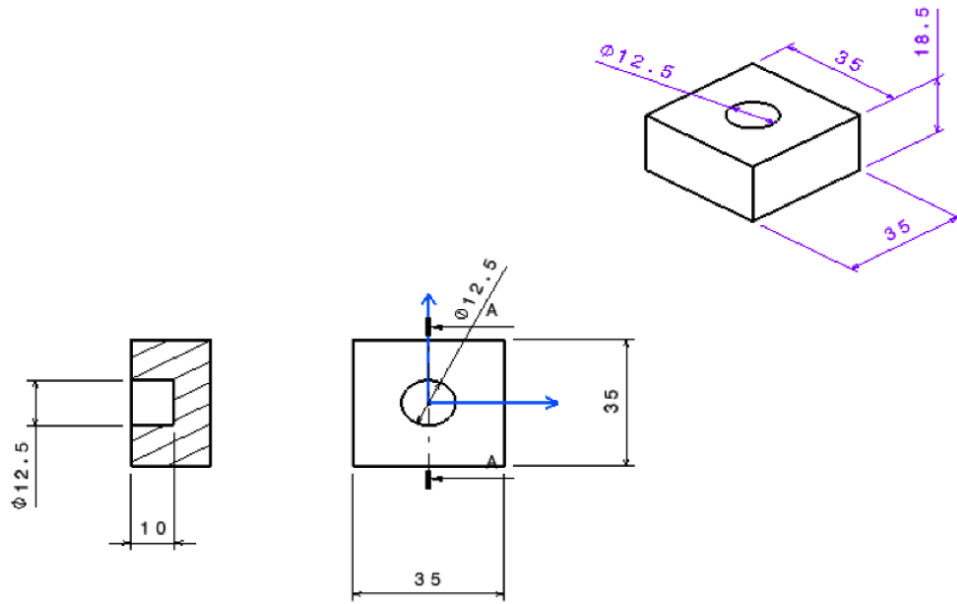


Figure 2.13 Female part in 2D

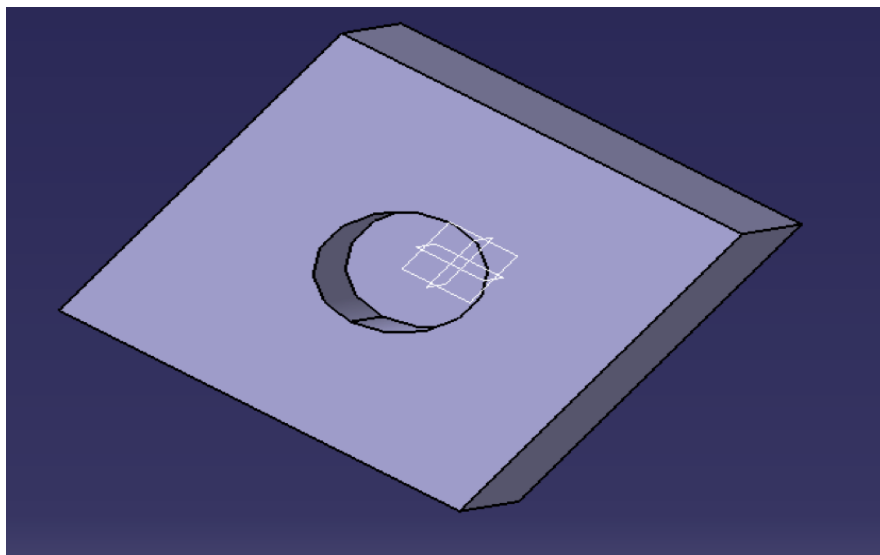


Figure 2.14 Female part in 3D

To begin the experiment, the experimenter should pull a female and a male part. Then, the assembly process considered once the two parts have been shown to the participant. The

assembly comprised inserting the male part into the female part and acquired the most ideal arrangement. Meanwhile, this experiment performed the same physical scenario in the first step but with using virtual reality technology. In the beginning, the whole environment, which includes a rectangular table, male parts, and female part should be built or designed using CATIA V5 R20 then imported it to MAYA 2018 to create the animation of inserting or connecting the male part with the female part.

As long as the goal of this study was to compare between the real world and virtual reality results, this module had been created based on a real environment, in terms of components dimensions positions and timing.

Before the experiment started, the participant should read and sign the Mississippi State University Informed consent for participation in research and the operator should inform the participant that he/she can withdraw from the experiment anytime when feel dizzy or uncomfortable due to the VR headset. Then, the operator should explain to the participant that in this experiment were three rounds, each round had four trials and each trial the participant observed the assembly process of a male and a female part for twelve time and in each trial the first two pairs were always the same as the reference male part. Thus, the participant is required to make a judgment on whether he/she could see a difference or not, and they should not assume any percentage of different parts in each trial. However, if the human subject could not see a dimensional difference, his/her answer should always be “No”. An example of what the participants would see in the VR environment is illustrated in Figure 2.15 below.

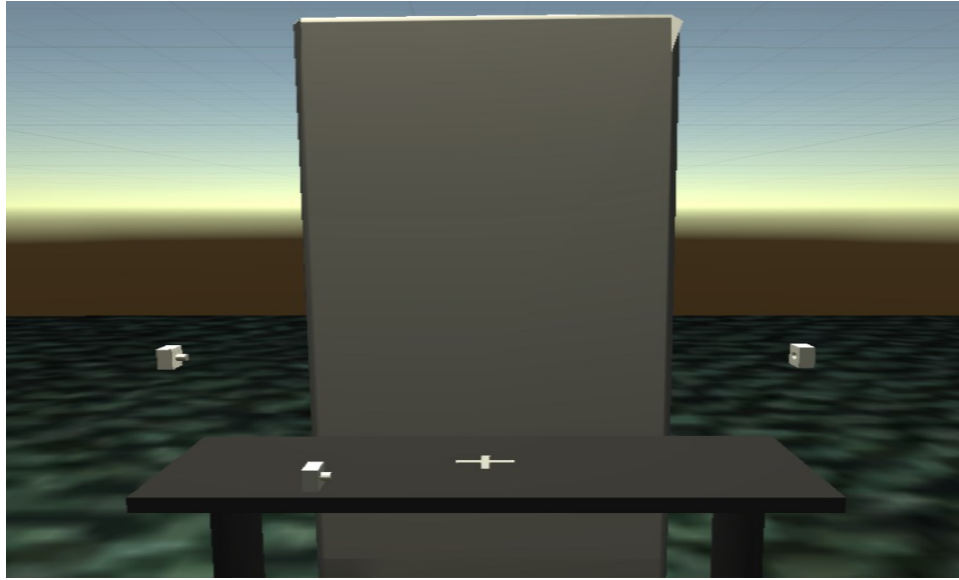


Figure 2.15 The virtual environment in UNITY

Between two assemblies there were two seconds that the participant can use to let the experiment facilitator know if he/she could see a difference between the male part and the reference part. Moreover, the operator should inform the participant that only dimensional differences were regarded as differences. Therefore, the participant should not pay attention to materials, colors, position, or any environmental factors. After completing one round participant had a one-minute break and after completing all the three rounds, participants should take a survey to know how he/she felt after taking the experiment.

Similarly, to the preliminary experiment, the first round should be the same for all participants as follow D E F C. Then, the two other rounds the sequence of the trial was randomized as shown previously in tables 2.2 and 2.3.

2.3.3 Assembly experiment procedure

After building the environment CATIA V5 R20, the final module was imported to MAYA where the animation was created. The animation was divided into three steps. The first step was when the participant was able to see that a male block (in his/her right-hand side) and a female block (in his/her left-hand side) were moving. The second step was when the two blocks were getting closer to each other until they had connected or linked. And finally, the third step was when the two blocks were joined, and then the two parts disappeared. Figure 2.16 shows a picture taken from a video clip recorded from the real-world environment that included six assemblies. Using this video enabled to convert all motions done by the operator in real-world environment to VR environment. As shown in table 2.5, there were three steps for each pair and according to the video taken from the real-world experiment; there were six pairs (six male blocks and six female blocks).

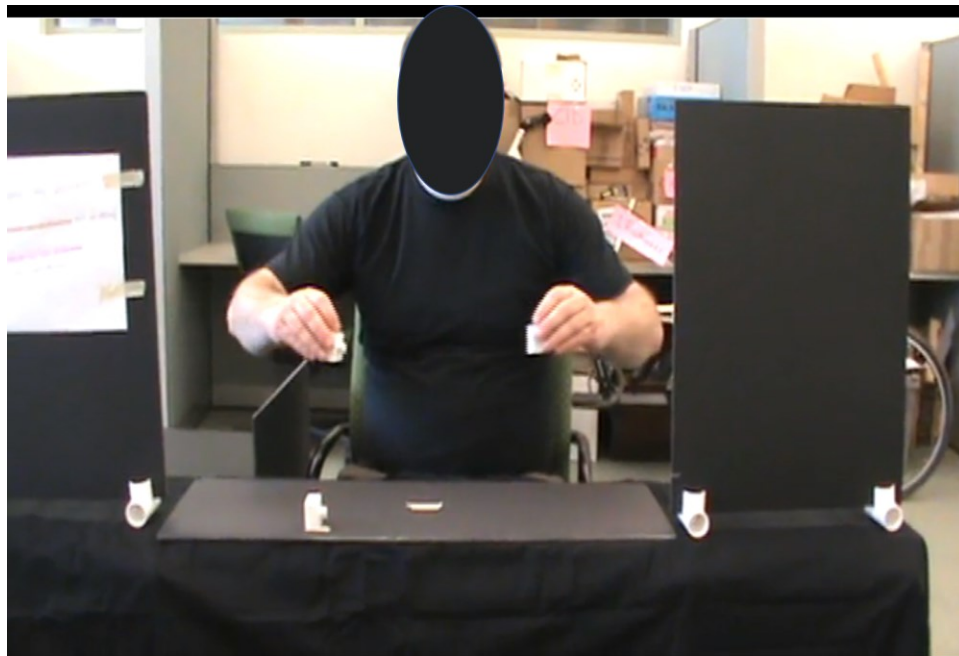


Figure 2.16 Real world environment

2.4 Data analysis

After collecting data from participants for both experiments, in physical and virtual environments, the results were coded and compared with the true sequence of the pairs to calculate accuracy for each participant. The accuracy was evaluated to facilitate calculating the average of the three rounds for all four trials and help to filter the final results using the T-test method to remove the illogical or insignificant results. Then moving to the last step which was modeling the data using a linear regression method.

In the preprocessing stage, a T-test is a statistical tool that helped in the elimination of insignificant results. The reasons behind insignificant results can be the lack of motivation, misunderstanding, VR equipment connection or the weak interaction between the participant and the VR headset. After the elimination of the insignificant results, the second step was the data modeling, where the strength of the relationship between the results was identified by using the linear regression approach. In this step three parameters were extracted: the slope, the intercept, and the change point. The slope represented the slope of the line connecting the change point with the intercept. The intercept was simply the intersection point of the line with the correct answers' axis. And finally, the change point was the first value of length change where the highest ranking was achieved. The final step in analyzing the data represented a comparison between preliminary results for both the real world and VR, assembly in the real world and VR and preliminary with assembly experiments results. This process repeated for all participants as described in the following flow chart.

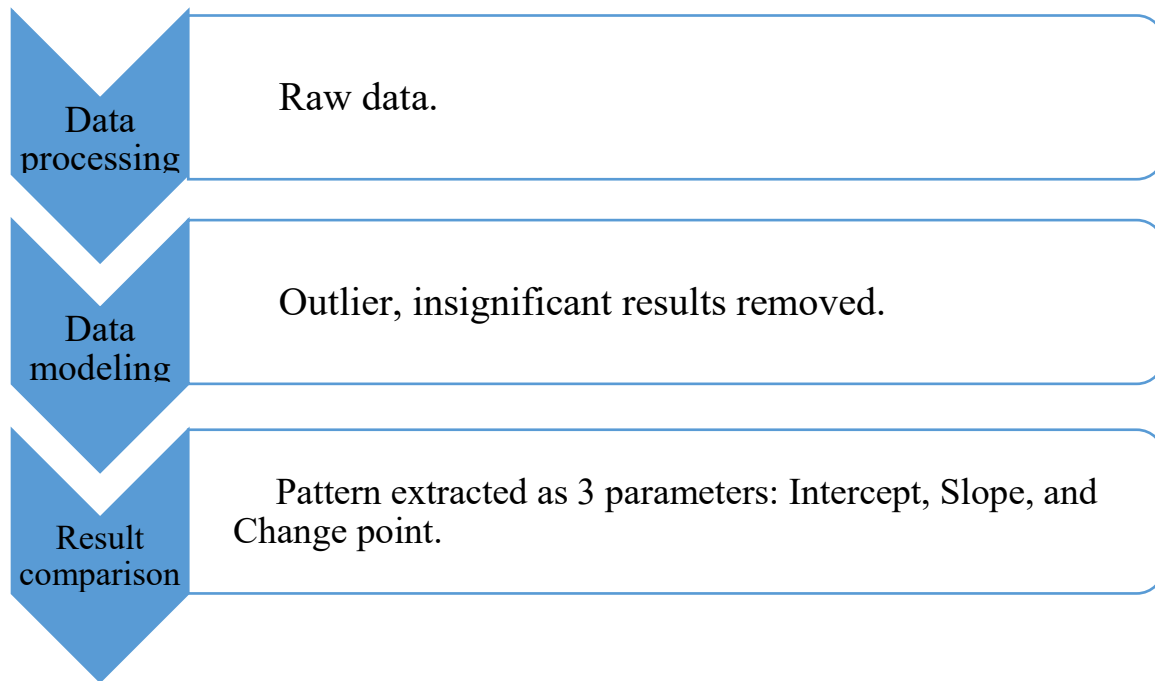


Figure 2.17 Data analysis process chart

2.4.2 Data processing

T-test used in this research to enable removing the subject's results that have $\mu_C = \mu_F$, where μ_C was the hypothesis of trial C and μ_F was the hypothesis of trial F. In other words, if there was no significant change between results when displaying the smallest change and results when displaying the largest change, the results of that participant should be removed and it should not be taken into consideration.

T-test is a sort of inferential statistic used to decide or determine whether there is a significant distinction between the means of two groups, which might be connected in specific features [20]. It is for the most part utilized when the informational indexes or the data sets, similar to the informational index recorded as result from flipping a coin multiple times, would pursue an ordinary distribution and may have obscure fluctuations [21]. A t-test is utilized as a

hypothesis-testing instrument, which permits the testing of an assumption material to a population [22]. A t-test took the t-statistic, the t-distribution values, and the degrees of freedom to decide the probability between two arrangements of information [22]. To lead a test with at least three factors, one must utilize analysis of variance. When the assumption of a normal distribution exists, then the probability of a particular outcome can be identified. This method helps to evaluate if there was a sign of accuracy results for each participant or not. The aim behind using this method was to find the best fifteen participants that had reasonable and significant results. After collecting the data, the statistic test should be calculated using the following formula [22]:

$$t = (\bar{x} - \mu) / (s / \sqrt{n}) \quad (2.1)$$

Where:

\bar{x} : the sample mean

μ : the hypothesized mean

s : the sample standard deviation

n : the sample size

In this research, \bar{x} was the mean of the difference between the correct answers of trial C and the correct answers of trial F for each participant. μ equaled to 0. s was the standard deviation of differences between correct answers of trials C and F. Since there were three rounds n or the number of pairs equal to 3. The following two examples, both represent results of two different participants who participated in the preliminary experiment VR environment. The first example shows results with little variation. However, the second example shows a significant difference between the results of trials C and F.

Example 1:

| Total of correct answers of trial C in the 3 rounds | Total of correct answers of trial F in the 3 rounds | The difference of correct answers of trial C and correct answers of trial F |
|---|---|---|
| 4 | 6 | 2 |
| 4 | 5 | 1 |
| 4 | 4 | 0 |

Example 2:

| Total of correct answers of trial C in the 3 rounds | Total of correct answers of trial F in the 3 rounds | The difference of correct answers of trial C and correct answers of trial F |
|---|---|---|
| 4 | 9 | 5 |
| 6 | 10 | 4 |
| 6 | 10 | 4 |

These two examples explain how the process of elimination is done. The numbers illustrated in the tables stand for how many correct answers the participants got in three rounds of two different trials. In example 1, it is noticeable that the correct answers of trials C and F were close. However, in example 2 it is notable that there was a difference between the correct

answers of the two trials. This finding has been supported by the P-value or the probability value, shown in the following table, which was part of the hypothesis test. The hypothesis test was used to evaluate the validity of the null hypothesis, which is sort of an initial assumption. The null hypothesis in these two examples was no significant difference between the correct answers of trial C and trial F.

| | Participant of example 1 | Participant of example 2 |
|-----------|--------------------------|--------------------------|
| n | 3 | 3 |
| \bar{x} | 1 | 4.333 |
| s | 1 | 0.577 |
| t | 1.732 | 13 |
| p | 0.225 | 0.005 |

This part shows the parameters needed to conduct a t-test calculated for each participant. Also, it showed how the decision was made about the quality of the results (if the results were significant or not) based on the P-value. Comparing the results of these two participants, the P-value corresponded to the first participant, equal to 0.225, which was greater than 0.05. In the other hand, the P-value corresponds to the second participant, 0.005, which was less than 0.05. Thus, the first participant's results were not significant and the results of the second participants were significant. Therefore, the first participant's results had to be removed.

Calculating a t-test requires three key information or data values [21]. They incorporate the distinction between the mean qualities from every data set (called the mean difference), the standard deviation of each group, and the quantity or number of data values of each group.

P-value or probability value is a number, usually between 0 and 1, helps to determine the significance of the results. In general, a small p-value (less or equal 0.05) illustrates that the evidence against the null hypothesis μ is strong enough, which means that the null hypothesis is rejected and the alternative hypothesis is accepted as shown in Figure 2.17 [26].

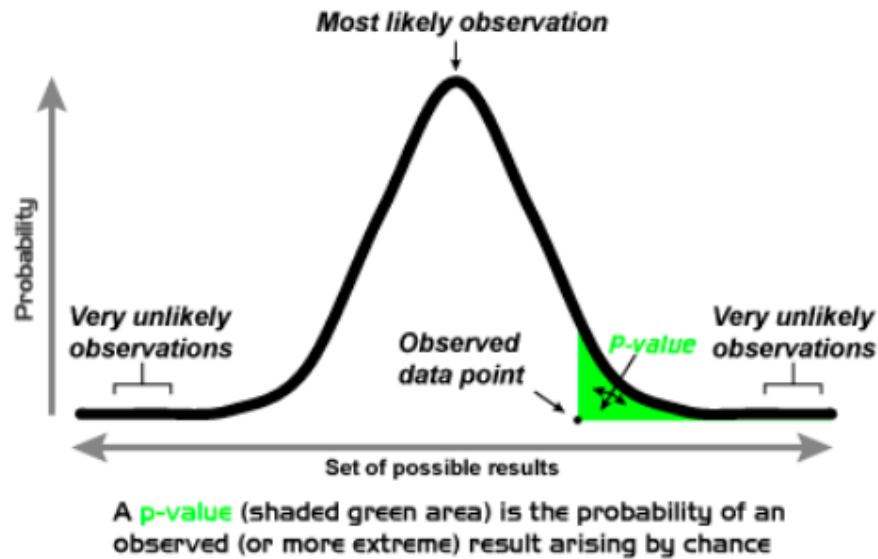


Figure 2.18 P-value graph

As shown in the following tables, a summary of P-values calculated using t-test method for the preliminary and assembly experiments results for all participants:

Table 2.7 Summary of P-values calculated using the t-test method for the preliminary experiment results

| Participants number | P_ Value |
|---------------------|----------|
| 1 | 0.225 |
| 2 | 0.052 |
| 3 | 0.795 |
| 4 | 0.121 |
| 5 | 0.463 |
| 6 | - |
| 7 | 0.578 |
| 8 | 0.035 |
| 9 | 0.005 |
| 10 | 0.072 |
| 11 | 0.207 |
| 12 | - |
| 13 | 0.019 |
| 14 | 0.019 |

Table 2.7 (continued)

| Participants number | P_Value |
|---------------------|---------|
| 15 | 0.074 |
| 16 | 0.005 |
| 17 | 0.008 |
| 1 | 0.005 |
| 19 | 0.022 |
| 20 | 0.015 |
| 21 | 0.019 |
| 22 | 0.037 |
| 23 | 0.02 |

Table 2.8 Summary of P-values calculated using the t-test method for assembly experiment results

| Participant number | P_Value |
|--------------------|---------|
| 1 | 0.37 |
| 2 | 0.013 |
| 3 | 0.029 |
| 4 | 0.015 |
| 5 | 0.057 |
| 6 | 0.019 |
| 7 | 0.015 |
| 8 | 0.015 |
| 9 | 0.018 |
| 10 | 0.031 |
| 11 | 0.069 |
| 12 | 0.063 |
| 13 | 0.031 |
| 14 | 0.004 |

Table 2.8 (continued)

| Participant number | P_Value |
|--------------------|---------|
| 15 | 0.022 |
| 16 | 0.003 |

According to the t-test results, subjects: 1, 3, 4, 5, 6, 7, 11, and 12 participated in the preliminary experiment and subject number 1 who participated in the assembly experiment, should be removed due to their high P-value.

2.4.3 Data modeling

The following step is describing the relationship between the preliminary (physical and virtual environment) and the assembly (physical and virtual environment) experiments results. Regression is used to model the data to give an idea about the strength of the relationship between a series of changing variables and one dependent variable [27]. Linear regression method is used since this study has only one independent variable, which is the rate of deviation from the original length, and one dependent variable that represents the number of correct answers. The general equation form of the linear regression is:

$$Y = a + bX \quad (2.2)$$

Where:

Y: Number of correct answers.

X: Deviation from correct length.

a: the intercept.

b: the slope.

The aim behind using linear regression method in this study is to extract the pattern as three parameters, which are as following that help to know the behavior of the results along with the change ratio and the correct answers:

- **Intercept:** refers to the point where the curve intersects or crosses the y-axis, which in this case represents the correct answers.
- **Slope:** indicates the curve's direction on an x-y axis and determines the behavior of the curve, whether it is positive or negative.
- **Change point:** shows in which point or change ratio the participants were able to achieve 100% accuracy or 10 correct answers.

After the elimination of the insignificant results, only the significant ones are left. The next step is identifying the strength of the relationship between the results using the linear regression approach. The following Figures, 2.18, 2.19, and 2.20, represent a piecewise linear regression of correct answers for the three rounds of a subject who participated in the preliminary experiment, including the change point, linear regression, and leveled pieces or zero slope. the purpose behind using piecewise linear regression is to know where participants were able to get 10 correct answers (which is the 100% accuracy) and to study the behavior of the curve without including the points in which the change point occurred by giving the intercept and the slope, this part referred in the plots as AB. Because after the change point occurred the result's plot remains constant, which is the part BC or the zero-slope part.

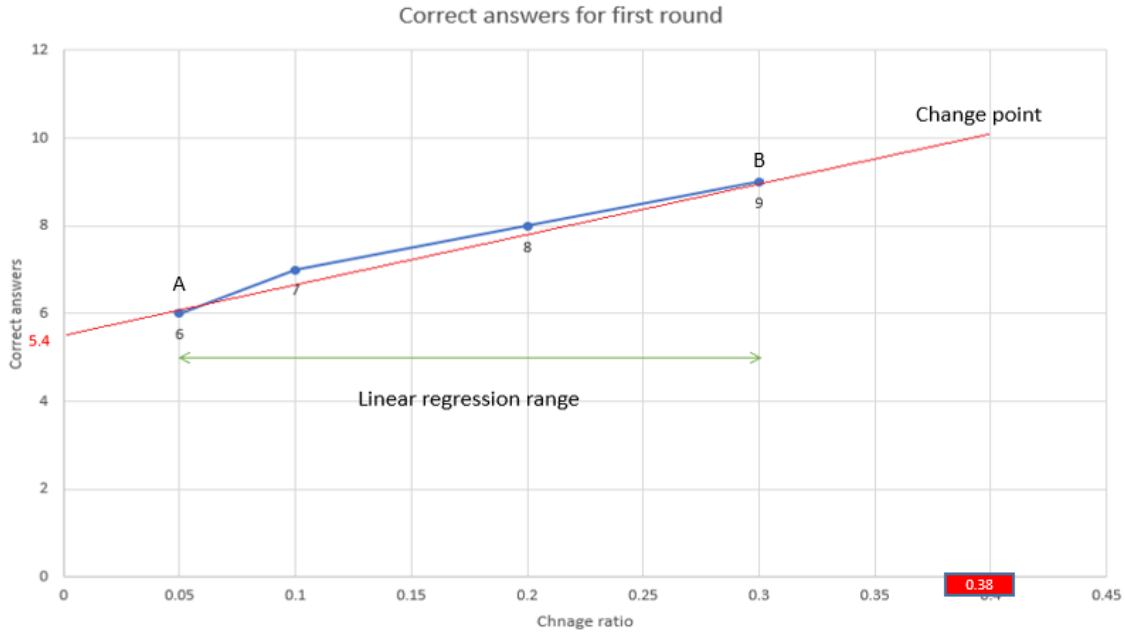


Figure 2.19 Piecewise linear regression of correct answers for the first round of the preliminary experiment

This graph shows that the participant was not able to get 10 correct answers in the first round in all four trials (0.05, 0.1, 0.2, and 0.3 ratio change from the original length). This implies that the change point will occur beyond 0.3 ratio change. Therefore, all four points, from A to B, should be included in the linear regression. The slope, in this case, is positive, equal to 16.94, which means that whenever the change ratio increases the correct answers will increase as well. The intercept equal to 5.4, it indicates the intersection of the curve and the y-axis will be in 5.4. And the change point will occur in the 0.38 change ratio.

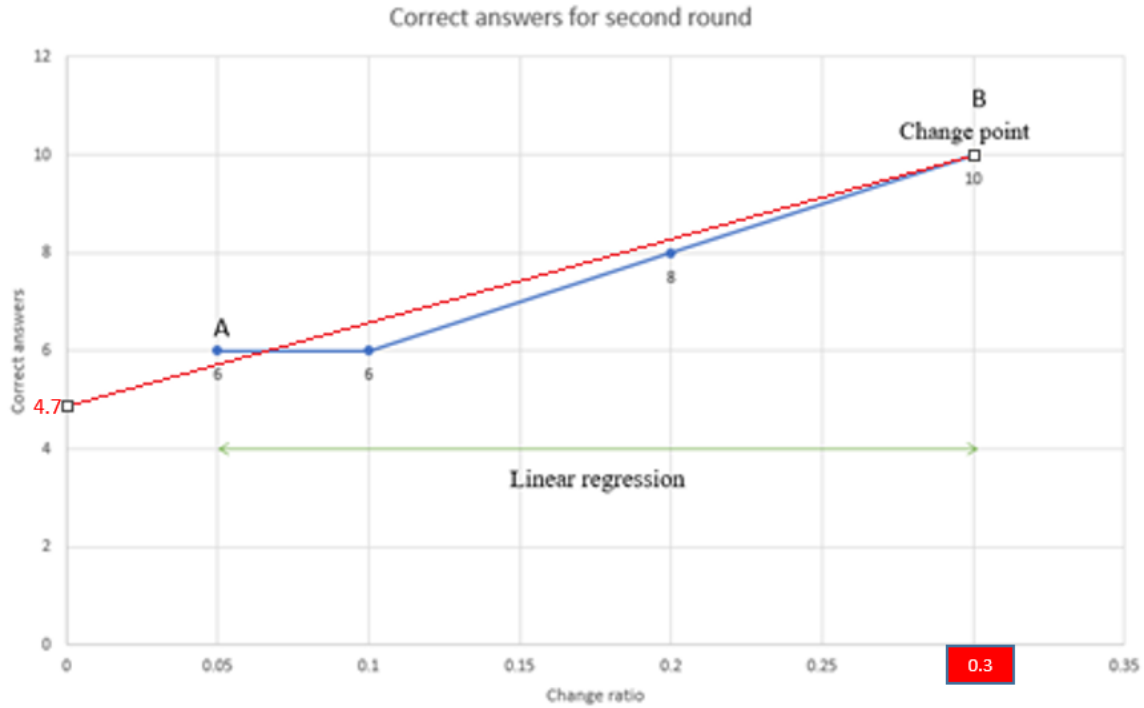


Figure 2.20 Piecewise linear regression of correct answers for the second round of the preliminary experiment

This Figure shows that the participant could achieve the 100% accuracy and got 10 correct answers in the 0.3 ratio change trial, which means that the change point is 0.3. However, all four points from A to B should be included in the linear regression since the change point occurred in the last point of the graph. Therefore, the intercept and the slope are equal to 4.74 and 16.94.

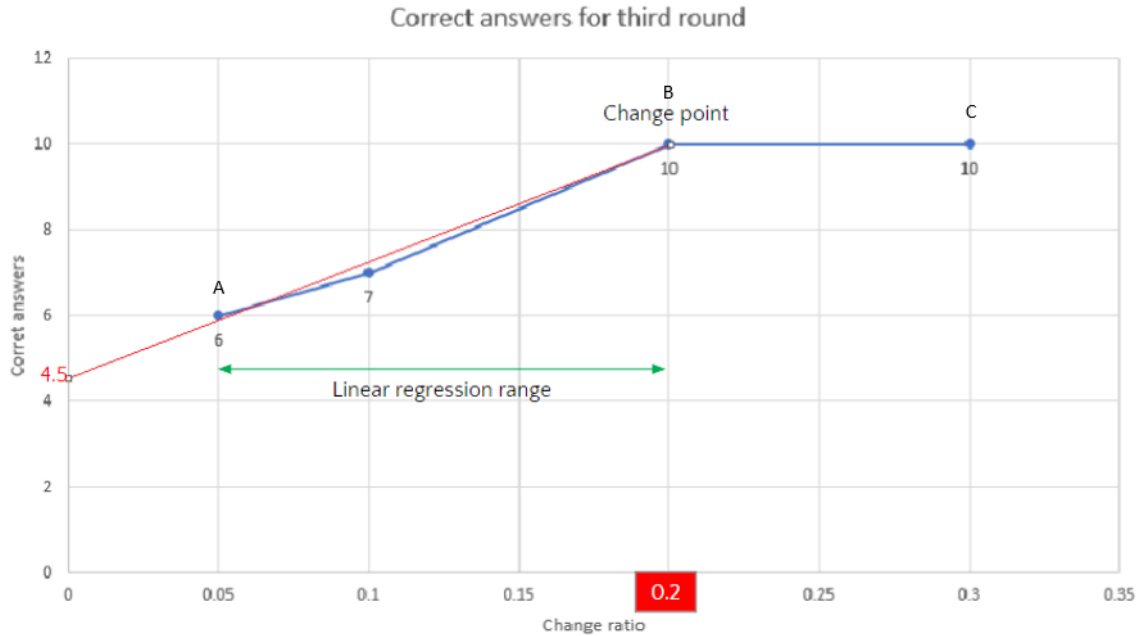


Figure 2.21 Piecewise linear regression of correct answers for the third round of the preliminary experiment

This graph shows one participant's answers in the third round of fall trials. In the last round, the participant could get 10 correct answers in the third trial (0.2 change ratio). Thus, the linear regression will include just the first 3 points (from A to B) and from B to C is the leveled piece or the zero-slope part of the graph. The slope and the intercept are equal to 27.14 and 4.5.

The following table shows the change point of assembly and preliminary experiments in both real world and VR environments of three rounds for all participants; this table helps to know if participants were capable or not to get 10 correct answers by knowing where the change point occurs in all experiments for all participants. As shown in table 2.9, the majority of subjects participated in both experiments were not able to get 10 correct answers in the first round. Concerning the preliminary experiment, subjects who participated in the VR and real-

world environments were not able to get the 10 correct answers in the first round. However, in the second two rounds of the VR and real-world environment experiment could achieve 100% accuracy and the change point mainly occurred in 0.2 and 0.3 change ratio. Regarding the assembly experiment, half of the subjects participated in the VR environment of the experiment could not get 10 correct answers but the rest were able to reach 10 correct answers and the change point was detected in 0.3 change ratio. In the two last rounds, the change point was occurring in 0.1, 0.2, and 0.3 (the first, second, and third change ratio). For the real-world environment, there were just 9 subjects participated in the experiment, four of them were not able to get 10 correct answers in the first round, which implies that the change point will occur after 0.3 which is in this study the largest change ratio.

Table 2.9 Change point for preliminary and assembly experiments of real-world and VR environments in three rounds for all participants

| Participant number | Change point for preliminary VR experiment | Change point for preliminary real-world experiment | Change point for assembly VR experiment | Change point for assembly real-world experiment |
|--------------------|--|--|---|---|
| Participant 1 | 0.3 | 0.3 | 0.38 | 0.37 |
| | 0.2 | 0.59 | 0.1 | 0.41 |
| | 0.3 | 1.39 | 0.3 | 0.2 |
| Participant 2 | 0.408 | 0.1 | -0.97 | 0.3 |
| | 0.3 | 0.2 | 0.3 | 0.2 |
| | 0.3 | 0.2 | 0.2 | 0.2 |
| Participant 3 | 0.31 | 0.43 | 0.39 | 0.3 |
| | 0.3 | 0.3 | 0.2 | 0.2 |
| | 0.2 | 0.2 | 0.2 | 0.3 |
| Participant 4 | 1.22 | 0.55 | 0.72 | 0.46 |
| | 0.44 | 0.32 | 0.2 | 0.2 |
| | 0.3 | 0.34 | 0.1 | 0.2 |

Table 2.9 (continued)

| Participant number | Change point for preliminary VR experiment | Change point for preliminary real-world experiment | Change point for assembly VR experiment | Change point for assembly real-world experiment |
|--------------------|--|--|---|---|
| Participant 5 | 0.42 | 0.3 | 0.3 | 0.39 |
| | 0.3 | 0.2 | 0.3 | 0.2 |
| | 0.3 | 0.46 | 0.2 | -3.23 |
| Participant 6 | 0.3 | 0.2 | 0.3 | 0.3 |
| | 0.1 | 0.3 | 0.3 | 0.2 |
| | 0.2 | 0.2 | 0.2 | 0.2 |
| Participant 7 | 0.47 | 0.2 | 0.3 | 0.2 |
| | 0.3 | 0.2 | 0.2 | 0.3 |
| | 0.1 | 0.2 | 0.2 | 0.3 |
| Participant 8 | 0.33 | 0.45 | 10 | 0.2 |
| | 0.3 | 0.6 | 0.2 | 0.2 |
| | 0.2 | 0.37 | 0.1 | 0.1 |

Table 2.9 (continued)

| Participant number | Change point for preliminary VR experiment | Change point for preliminary real-world experiment | Change point for assembly VR experiment | Change point for assembly real-world experiment |
|--------------------|--|--|---|---|
| Participant 9 | 0.39 | 0.35 | 0.3 | 10 |
| | 0.3 | 0.4 | 0.2 | 0.2 |
| | 0.2 | 0.37 | 0.1 | 0.3 |
| Participant 10 | 0.31 | 0.3 | 0.3 | - |
| | 0.3 | 0.3 | 0.2 | - |
| | 0.2 | 0.2 | 0.2 | - |
| Participant 11 | 0.33 | 0.3 | 0.58 | - |
| | 0.3 | 0.36 | 0.2 | - |
| | 0.2 | 0.3 | 0.2 | - |
| Participant 12 | 0.3 | 0.3 | 0.3 | - |
| | 0.3 | 0.2 | 0.1 | - |
| | 0.2 | 0.2 | 0.1 | - |

Table 2.9 (continued)

| Participant number | Change point for preliminary VR experiment | Change point for preliminary real-world experiment | Change point for assembly VR experiment | Change point for assembly real-world experiment |
|--------------------|--|--|---|---|
| Participant 13 | 0.63 | 0.35 | 0.41 | - |
| | 0.2 | 0.43 | 0.31 | - |
| | 0.3 | 0.41 | 0.3 | - |
| Participant 14 | 0.9 | 0.49 | 0.32 | - |
| | 0.63 | 0.44 | 0.1 | - |
| | 0.2 | 0.3 | 0.1 | - |
| Participant 15 | 0.3 | 0.3 | 0.2 | - |
| | 0.46 | 0.2 | 0.2 | - |
| | 0.35 | 0.2 | 0.2 | - |

Table 2.10 The average location of the change point of the three rounds for each participant in assembly and preliminary experiments

| Participant number | Change point for preliminary VR experiment | Change point for preliminary real-world experiment | Change point for assembly VR experiment | Change point for assembly real-world experiment |
|--------------------|--|--|---|---|
| Participant 1 | 0.26 | 0.76 | 0.26 | 0.33 |
| Participant 2 | 0.33 | 0.16 | -0.15 | 0.23 |
| Participant 3 | 0.27 | 0.31 | 0.26 | 0.26 |
| Participant 4 | 0.65 | 0.41 | 0.34 | 0.28 |
| Participant 5 | 0.34 | 0.32 | 0.26 | -0.87 |
| Participant 6 | 0.2 | 0.23 | 0.26 | 0.23 |
| Participant 7 | 0.29 | 0.2 | 0.23 | 0.26 |
| Participant 8 | 0.27 | 0.47 | 3.43 | 0.16 |
| Participant 9 | 0.29 | 0.37 | 0.2 | 3.5 |
| Participant 10 | 0.27 | 0.26 | 0.23 | - |
| Participant 11 | 0.27 | 0.32 | 0.32 | - |
| Participant 12 | 0.26 | 0.23 | 0.16 | - |

Table 2.10 (continued)

| Participant number | Change point for preliminary VR experiment | Change point for preliminary real-world experiment | Change point for assembly VR experiment | Change point for assembly real-world experiment |
|--------------------|--|--|---|---|
| Participant 13 | 0.37 | 0.4 | 0.34 | - |
| Participant 14 | 0.57 | 0.41 | 0.17 | - |
| Participant 15 | 0.37 | 0.23 | 0.2 | - |

The following table represents the total average of all participants' results of the real world and VR environments for preliminary and assembly experiments. As shown in table 2.11 in the average, participants could have 10 correct answers after 0.3 which is the largest change ratio. Comparing between VR and real-world environments of the preliminary experiment, positions where the change points occur are approximately the same and close to 0.3. But the comparison between VR and real-world environments of the assembly experiment shows that the location of the change point of the VR experiment occurred before the real-world environment change point. This means that the participants who performed the VR assembly experiment were able to get a higher percentage of accuracy than subjects who participated in real-world assembly.

Table 2.11 Average of all participants' results

| | Change point for preliminary VR experiment | Change point for preliminary real-world experiment | Change point for assembly VR experiment | Change point for assembly real-world experiment |
|---------|--|---|---|--|
| Average | 0.33 | 0.34 | 0.43 | 0.48 |

2.4.4 Results comparison

After eliminating the bad or non-significant results using the t-test method, final results should be summarized in terms of slope, intercept, and change point for each participant and gather the line fit plot of all 3 rounds. Concerning the preliminary experiment, as shown in the appendix Figures 4.1-4.15, the VR environment results for the first two rounds are in a linear relationship with the predicted Y values or the correct answers since the predicted Y values and the Y values are approximately the same, but the third round is a little bit not linear in the first and second trials (0.05 and 0.1 change ratio) because the deviation of the predicted and the original Y values is noticeable. Regarding the assembly experiments, the VR environment results for round 2 are not linear compared to the predicted Y values, but for the first and third rounds are linear as demonstrated in Figures 4.1 to 4.30.

The comparison of the preliminary results in both environments shows that the change point occurs in a position close to 0.3 which means that the participants were able to detect the alteration in the largest change. For the assembly experiment, the change point associated with VR occurred before the real-world change point.

P-value is calculated to compare between the results of the two experiment in both environments as shown in the following table.

Table 2.12 P-value results

| | Change point for preliminary experiment VR vs. Real-World | Change point assembly experiment VR vs. Real-World | Change point for preliminary vs. assembly |
|---------|---|--|---|
| P-value | 0.014 | 0.028 | 0.9 |

The P-value was determined for the three comparisons in the change point. In the preliminary experiment it is notable that there is a change since the P-value is less than 0.05 (0.014), same remark for the assembly experiment. On the other hand, there is no difference between the preliminary and the assembly results.

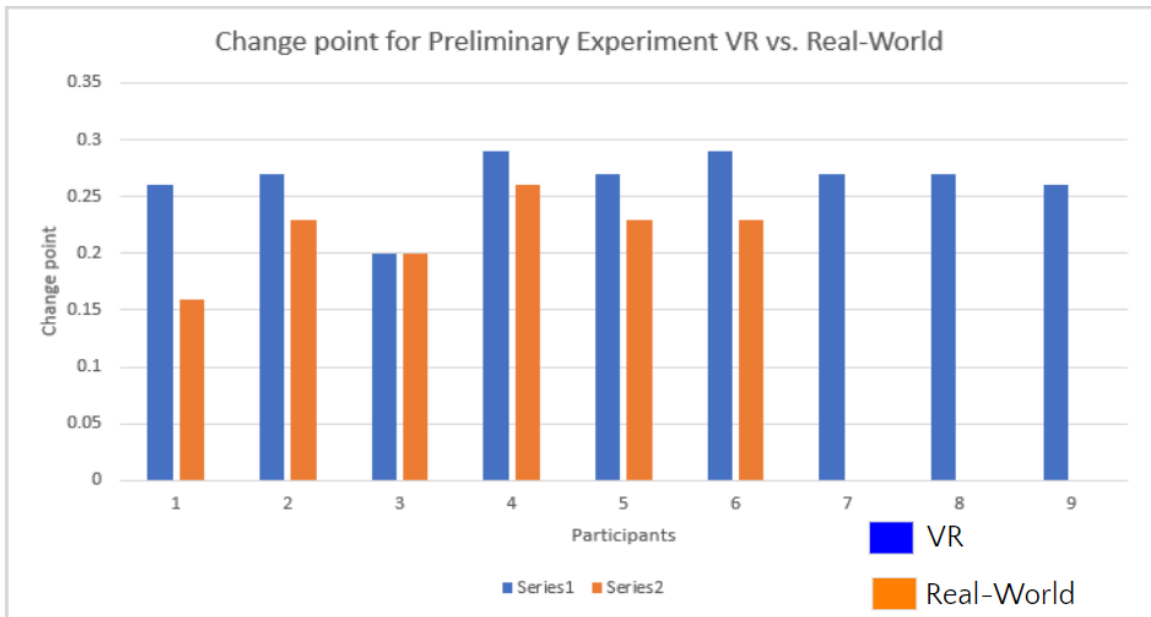


Figure 2.22 Change point for preliminary experiment, VR vs. Real-World

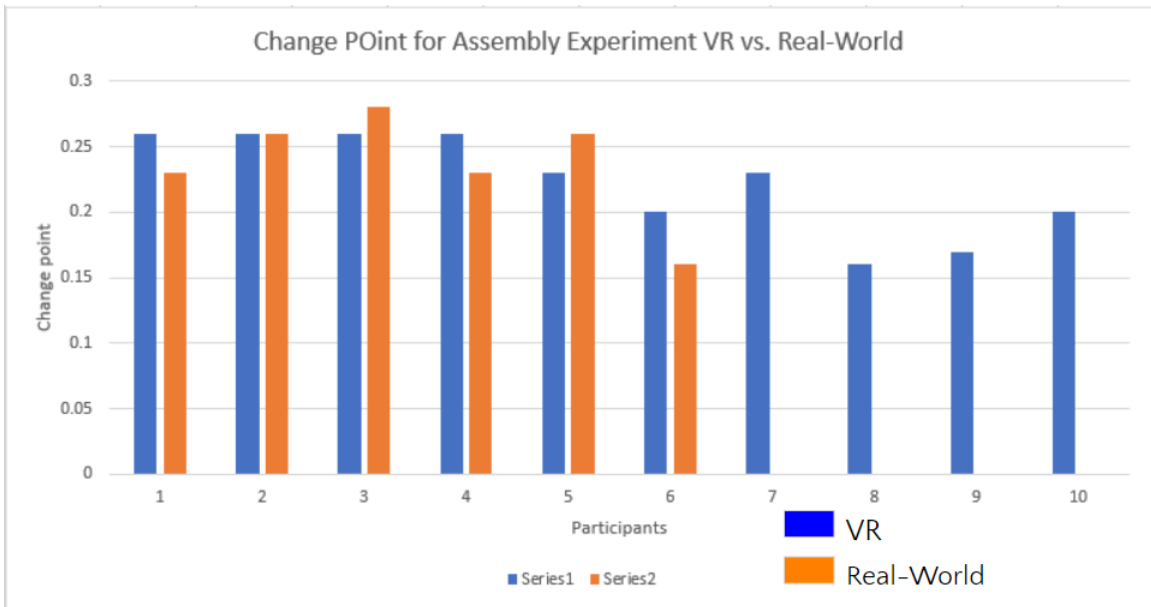


Figure 2.23 Change point for assembly experiment VR vs. Real-World

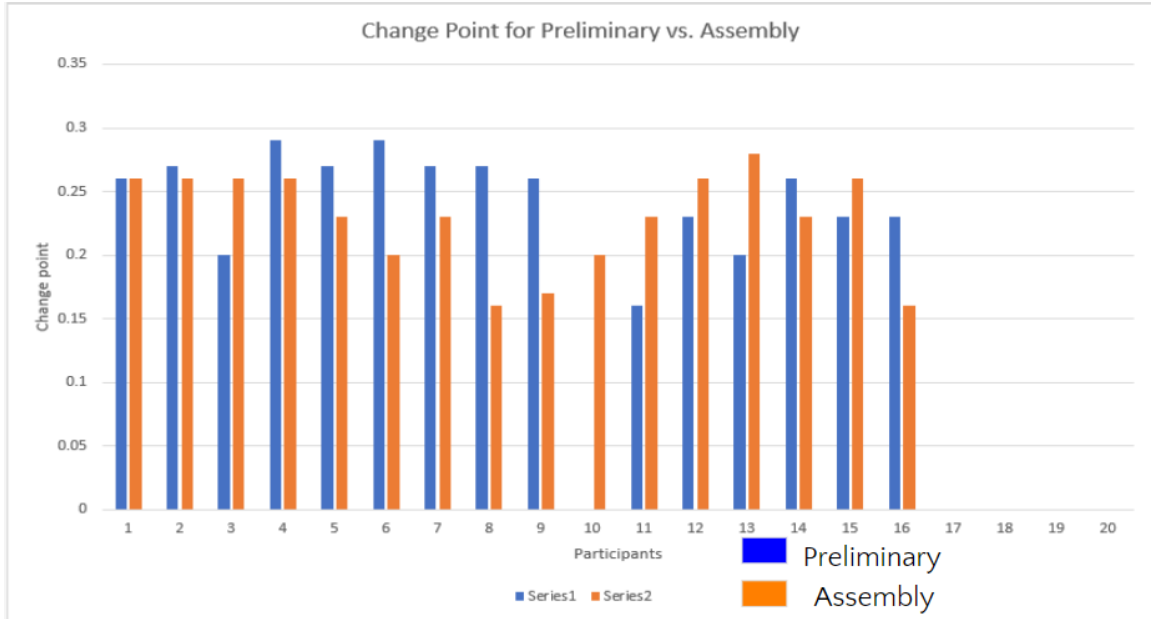


Figure 2.24 Change point for preliminary experiment Vs. assembly experiment results

The chart in Figure 21 represents the change point of the preliminary experiment in VR and real-World environments. It is noticeable that there is only one case where the VR and the Real-World results are the same versus 8 cases, which means that there is a difference between the two environments' results, and this supports the P-value results. Similarly, for the assembly experiment. However, the last chart illustrated in Figure 23, that represent the comparison of the change point of the preliminary and the assembly experiments in both environments. This comparison shows that the mean of the two results are somehow equal.

Choosing the right method to compare between the results is important. Therefore, the Multivariate Analysis of Variance or MANOVA is the best method to analyze this research results. ANOVA [23] or Analysis of Variance is a selection of a mathematical set of statistical assumptions regarding the data generating process, and their associated variation among and

between groups. ANOVA used to compare more than three group means for statistical significance [23]. MANOVA considered as an extension of ANOVA, where MANOVA is the same as ANOVA but with more than one dependent variable involved. This method is mainly used in experimental studies where more than one factor affects the dependent variable [24]. MANOVA helps to create new dependent variables. These artificial or new dependent variables are a linear combination of original dependent variables. Therefore, when the relationship between the dependent variables deviates from linearity, the performance of this analysis will be compromised.

Using MATLAB [28], all results of assembly and preliminary experiments of virtual and real-world environments are uploaded to generate the intercept, slope, and change point graphs, and also to calculate the P-value for each case as shown in table 2.13. The aim behind calculating the P-value is to use it as an alternative to providing the lower level of significance at which the null hypothesis μ would be rejected. As said before, when the P-value is less than 0.05 means that the results are significant.

Table 2.13 P-value calculated for the three cases

| | Static experiment VR vs. Real- World | Assembly experiment VR vs. Real-World | Assembly experiment vs. Static experiment |
|---------|--------------------------------------|---------------------------------------|---|
| P-value | 0.0027 | 0.0658 | 0.0065 |

As shown in table 2.13, the comparison between the real world and VR environments of the preliminary experiment is significant because the resultant P-value equal to 0.0027, which is less than 0.05. However, the real world and VR environments of the assembly experiment

comparison results are not significant since their p-value is larger than 0.05. The results of the third case, which is comparing static and assembly experiments, are also significant.

In the first case, MATLAB code helps gather or combine the real world and the VR results of the preliminary experiment and compare the intercept, slope, and the change point of each participant.

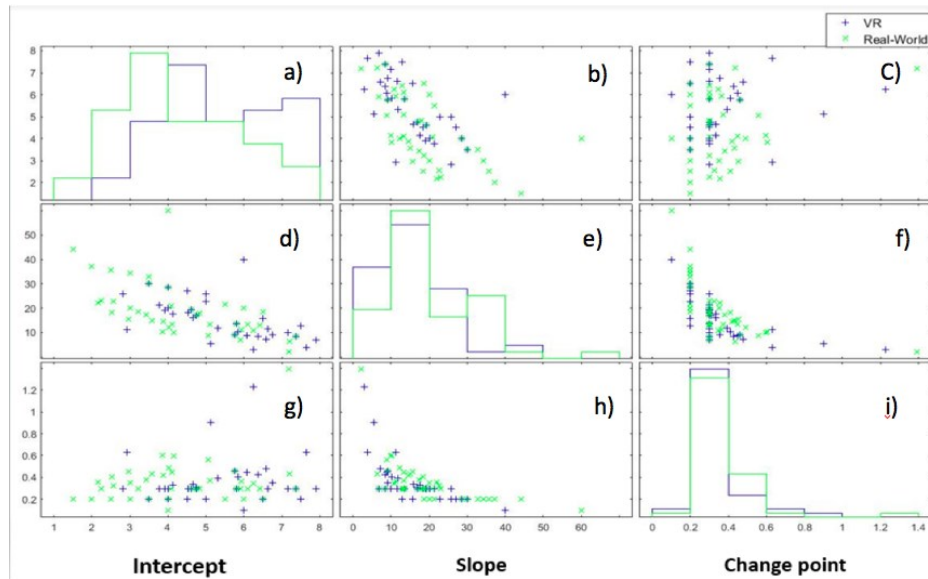


Figure 2.25 Comparison between VR and real-world environment of preliminary experiment: a) line plot of the intercept, b) scatter plot of slope vs. intercept, c) scatter plot of change point vs. intercept, d) scatter plot of intercept vs. slope, e) line plot of slope, f) scatter plot of change point vs. slope, g) scatter plot of intercept vs. change point, h) scatter plot of slope vs. change point, i) line plot of change point.

As can be seen in Figure 2.24 graph a) the intercept values start increasing proportionally until it reaches the maximum values, which are 8 for the real-world environment and 7.5 for the VR environment, then both graphs start decreasing. In graphs b) and d), the comparison of the intercept with the slope is negatively weak correlated. Which means that there is a significant

difference between the VR and real-world results. From graph e) the real-world and VR results show that the slope reaches the highest values, 50 for VR results and 60 for real-world results. However, it starts decreasing to reach 5 for the real-world and 0 for VR. The change point illustrated in graph i) in both real-world and VR results are approximately the same, 1.2 and 1.4 respectively, which means that the majority of the attendees who participated in both environments of the preliminary experiment were capable to detect the dimension change or the alteration in the second and third trials (20% and 30% of change from the original length). From the comparison between the change point and the intercept illustrated in graphs c) and g), it shows that the VR and real-world results are widely distributed and there is no correlation.

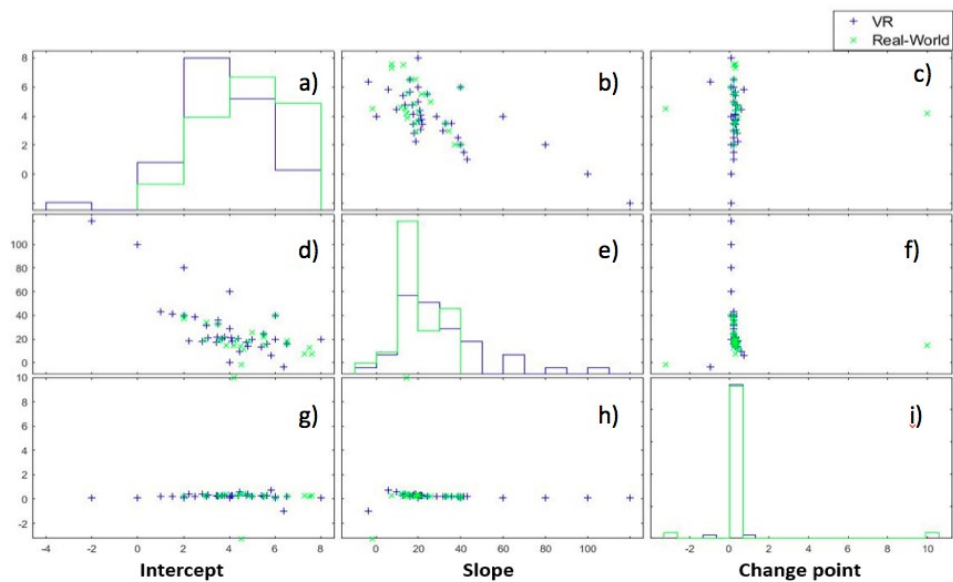


Figure 2.26 Comparison between VR and real-world environment of assembly experiment; a) line plot of the intercept, b) scatter plot of slope vs. intercept, c) scatter plot of change point vs. intercept, d) scatter plot of intercept vs. slope, e) line plot of slope, f) scatter plot of change point vs. slope, g) scatter plot of intercept vs. change point, h) scatter plot of slope vs. change point, i) line plot of change point.

According to the intercept graph a), it is noticeable that the results of the VR environment experiment start from negative values. However, the values corresponding to the real-world environment are all positive. The VR environment experiment results reach a higher value of intercept, which is 8, than the real-World environment experiment results, that reach 7 as the maximum value for the intercept. From the comparison between the slope and the intercept shown in graph b, it can be noticed that when the intercept increases the slope decreases. This reflects the existence of a weak negative correlation. The same remark is applied to graph d). For both graphs c) and g), it is illustrated that there is no correlation. This implies that no prediction can be anticipated among the variables. From graph e) the slop, the real-world and the VR environments experiments results reached the highest values, which are 120 and 50 respectively, at the same time. The change point in graph i) shows that VR and Real-World environments experiment results reached the same maximum change point at the same time.

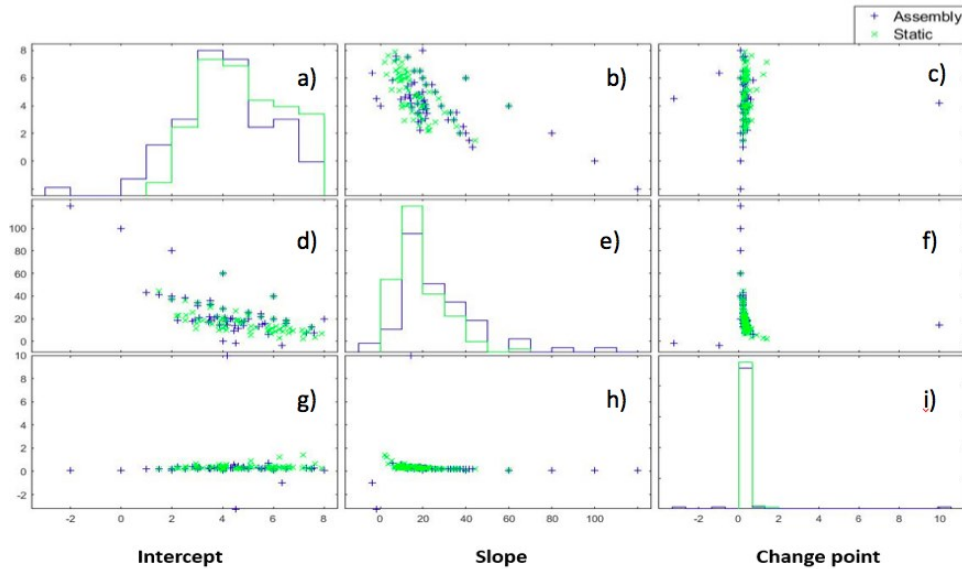


Figure 2.27 Comparison between preliminary and assembly experiments: a) line plot of the intercept, b) scatter plot of slope vs. intercept, c) scatter plot of change point vs. intercept, d) scatter plot of intercept vs. slope, e) line plot of slope, f) scatter plot of change point vs. slope, g) scatter plot of intercept vs. change point, h) scatter plot of slope vs. change point, i) line plot of change point

Graph a) shows an increase in the assembly experiment intercept values starting from -2 to reach the maximum value of 8 and then start decreasing to 0. However, the static experiment results plot shows that the intercept values increase positively to reach 7 as the maximum value then starts decrease to a minimum value of -2. For the slope, static experiment results reach the highest value of 120, and the assembly experiment results reach 98. In graphs b) and d) the slope is compared to the intercept and vice versa. From these graphs, a strong negative correlation is recognized. This means that the assembly and the preliminary results are close and if the intercept increases the slope decreases. Then in graph e), the slope values start decreasing for both experiments to reach 0. Graph i) shows that the changing point was not reachable for all trials in the assembly experiment since it starts from the negative value of -3 and then reaches the

maximum value that is 8 to decrease again to -3 as a change point. This means that there were some cases in which the participants could not give 100% correct answers. In graphs c) and g), it is remarkable that there is no correlation between the change point and the slope. However, the assembly and static experiments results are somehow similar. The same observation can be noted for graphs f) and h).

CHAPTER III

CONCLUSION

Virtual reality (VR) is a simulation technique, which provides a virtual environment to evaluate various design scenarios with minimized cost and time.

The objective of this research was to study the effectiveness and the capability of the VR-based models to determine the ability of a human being to detect the part alteration and modification in terms of dimensions. Also, to compare the real-world environment experiments and the VR environment experiments results.

This study consisted of two major parts. The first part was about the preliminary or static experiment, in which the ability of a human being to detect the difference between the two parts was examined. While the second part was about the assembly experiment, where the capability of a human being to recognizing the wrong and good parts with different rates of change during an assembly process was evaluated. Both parts were conducted in real-world and VR environments.

The preliminary or static experiment conducted showed that the Real-World environment results were better than the obtained ones from VR. Participants were able to detect the parts alterations or the error in real-world environments more than in VR environment, due to the ease of interaction with the environment. Also, it was due to the lack of motivation and the participants felt the monotony.

For the assembly experiment results of VR and real-world environments, a difference had been detected. Participant's reactions were accurate in the VR environment experiment more than in the Real-World. Participants were excited to try and discover new technology.

After studying the assembly and the preliminary results in VR and real-world environments, it turned out that approximately there was no difference between the two experiments results.

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APPENDIX A

LINE FIT PLOT OF THE PRELIMINARY AND ASSEMBLY EXPERIMENTS OF VIRTUAL
ENVIRONMENT FOR 15 PARTICIPANTS

The static experiment results in the VR environment show that approximately all participants were giving wrong answers in the first round and especially the first and second trials, where the change percentage is small (5% and 10%). However, in the other two rounds, they were giving the right answers for all trials. As shown in the following Figures, the line fit plot for preliminary and assembly experiments of three rounds for all participants. Where Y represents the number of correct answers given by the participant, X stands for the change percentage, and the predicted Y is the closest values to the real Y values to fit them in a line plot.

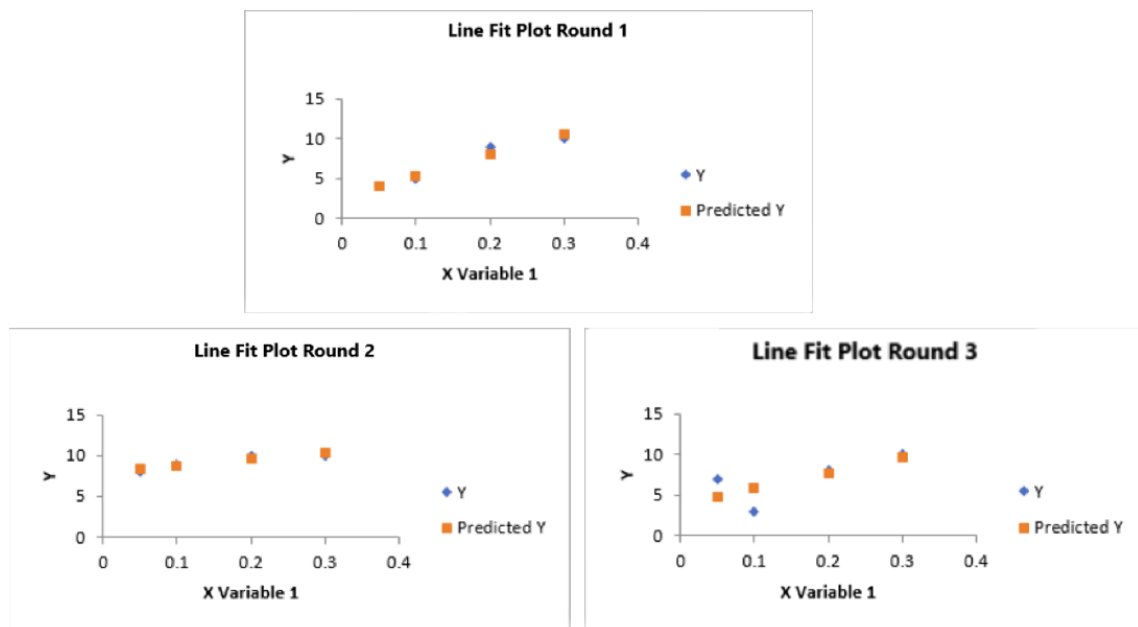


Figure A.1 Line fit plot of virtual environment for preliminary experiment 1st participant

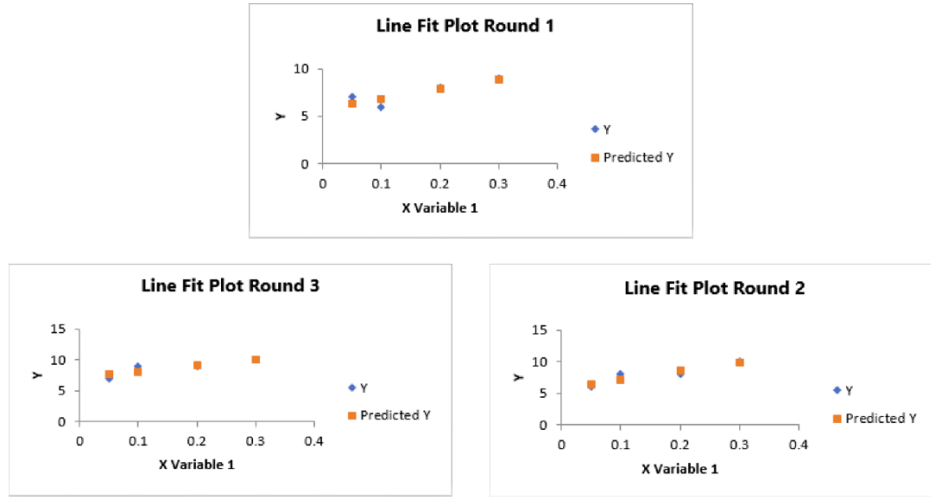


Figure A.2 Line fit plot of virtual environment for preliminary experiment 2nd participant

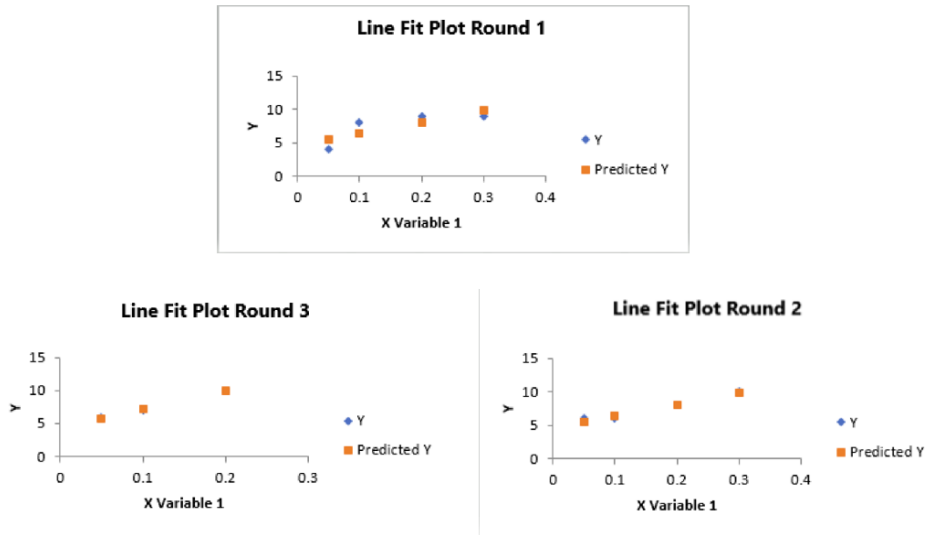


Figure A.3 Line fit plot of virtual environment for preliminary experiment 3rd participant

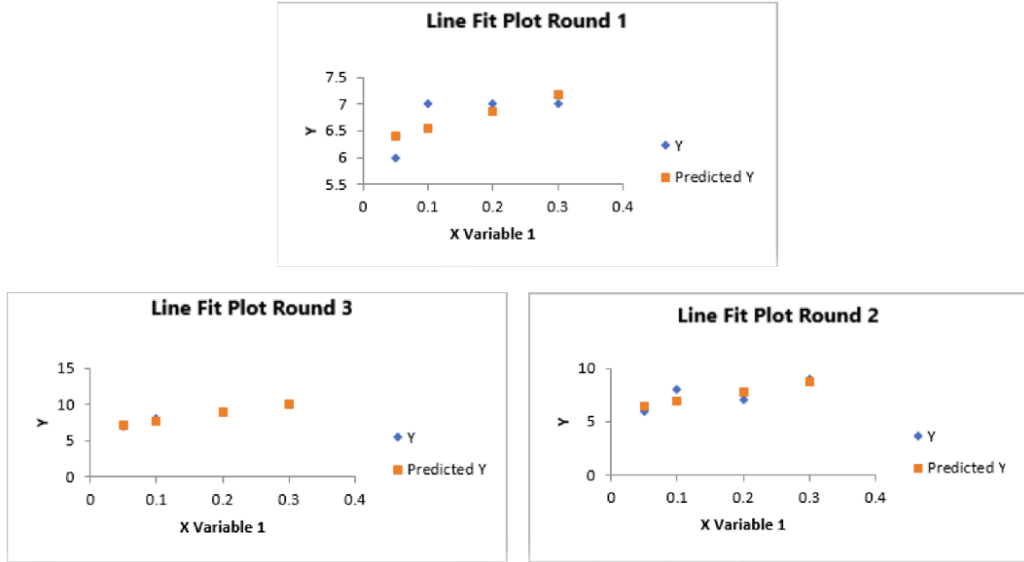


Figure A.4 Line fit plot of virtual environment for preliminary experiment 4th participant

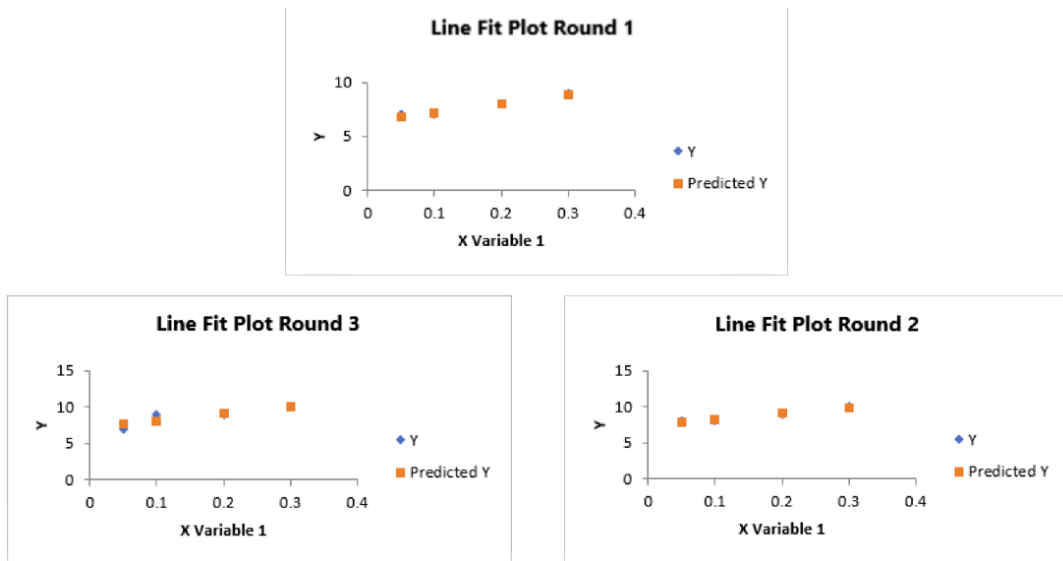


Figure A.5 Line fit plot of virtual environment for preliminary experiment 5th participant

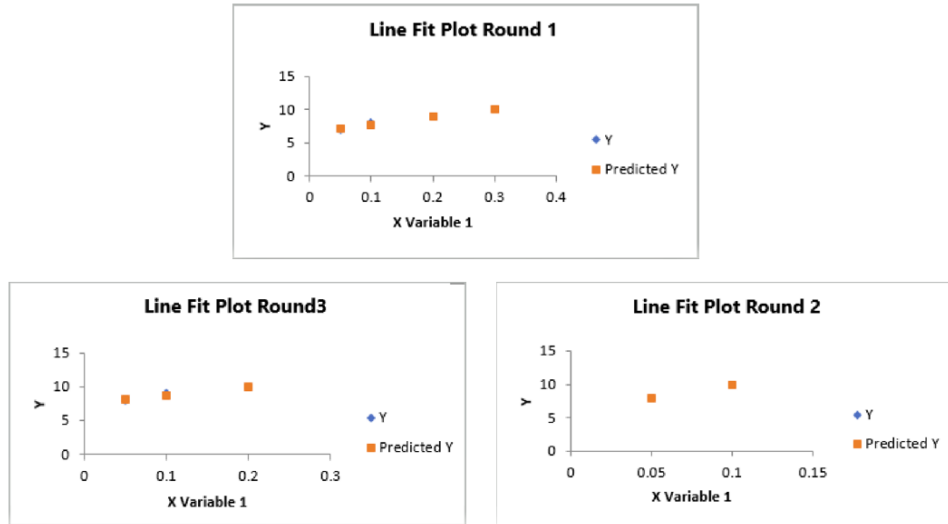


Figure A.6 Line fit plot of virtual environment for preliminary experiment 6th participant

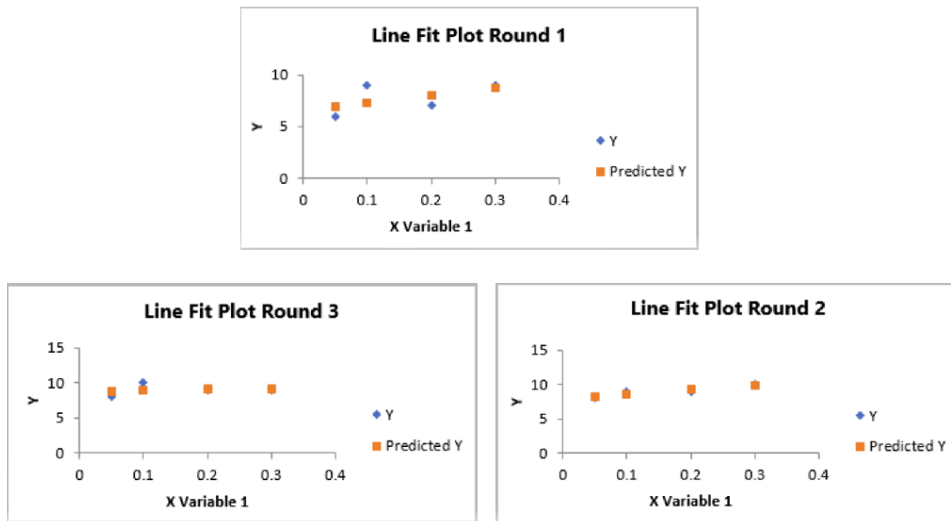


Figure A.7 Line fit plot of virtual environment for preliminary experiment 7th participant

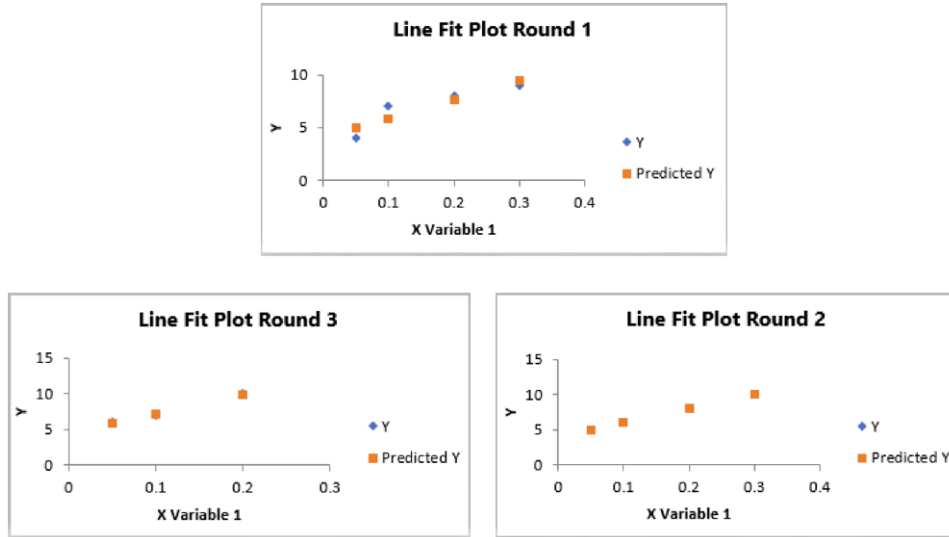


Figure A.8 Line fit plot of virtual environment for preliminary experiment 8th participant

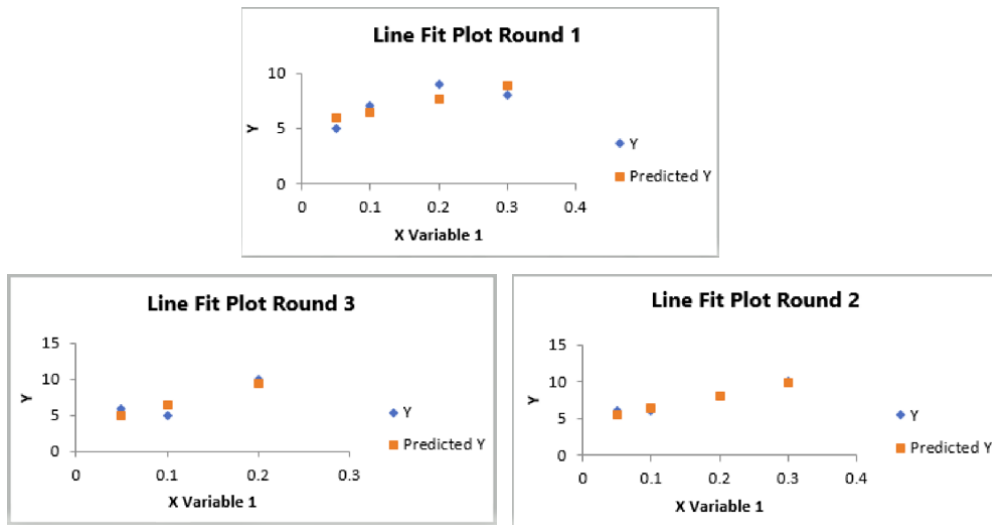


Figure A.9 Line fit plot of virtual environment for preliminary experiment 9th participant

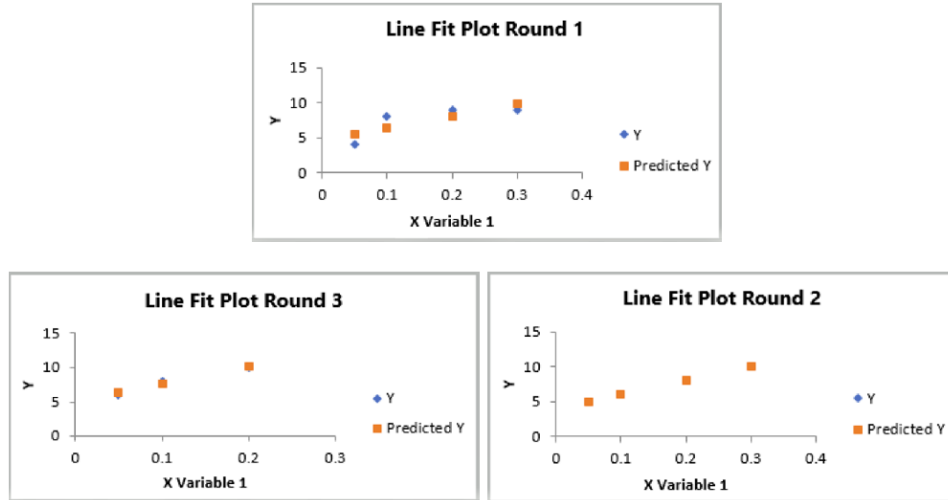


Figure A.10 Line fit plot of virtual environment for preliminary experiment 10th participant

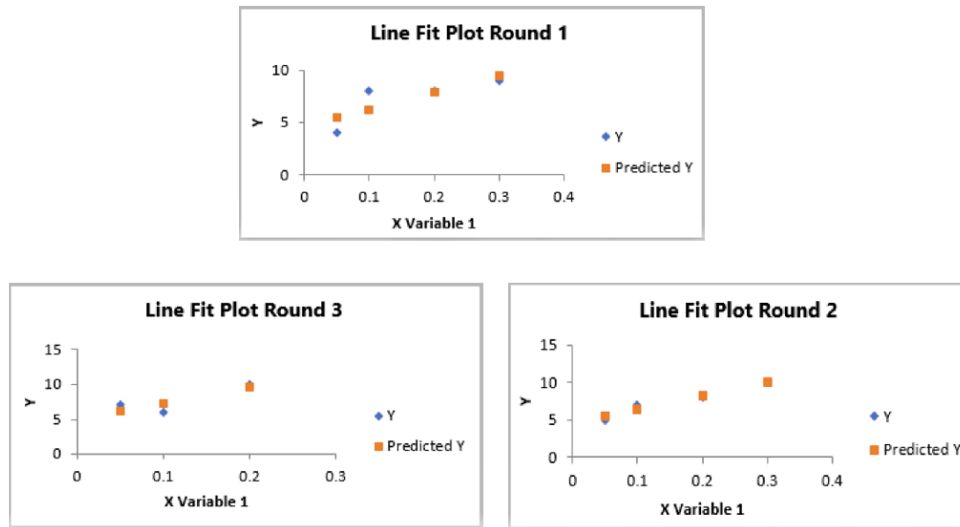


Figure A.11 Line fit plot of virtual environment for preliminary experiment 11th participant

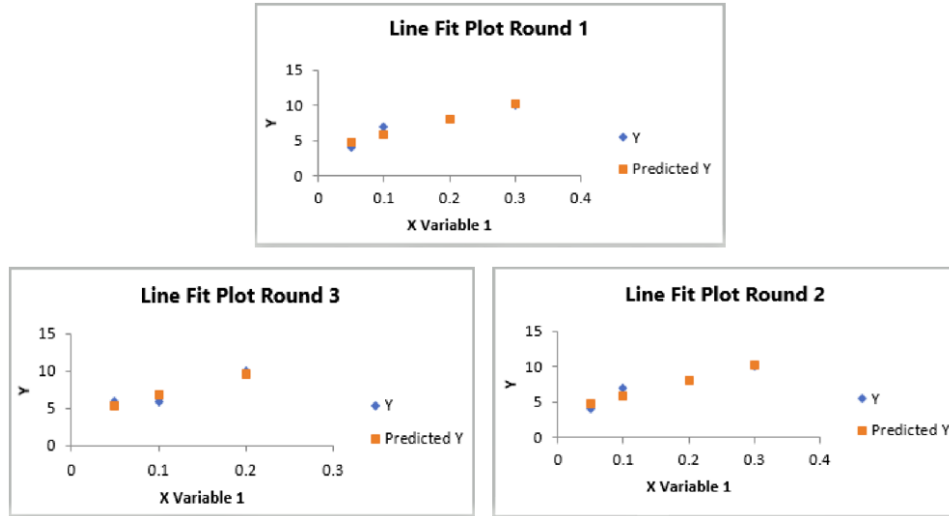


Figure A.12 Line fit plot of virtual environment for preliminary experiment 12th participant

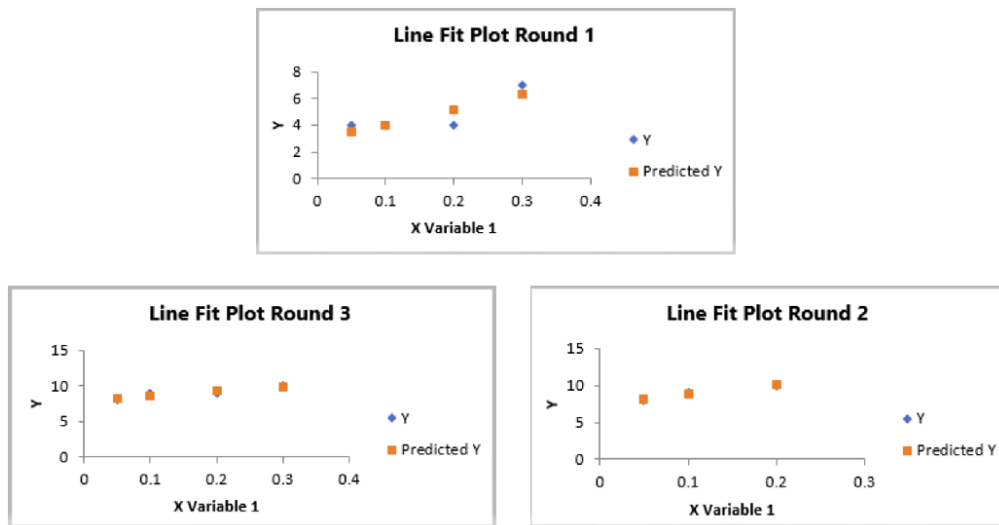


Figure A.13 Line fit plot of virtual environment for preliminary experiment 13th participant

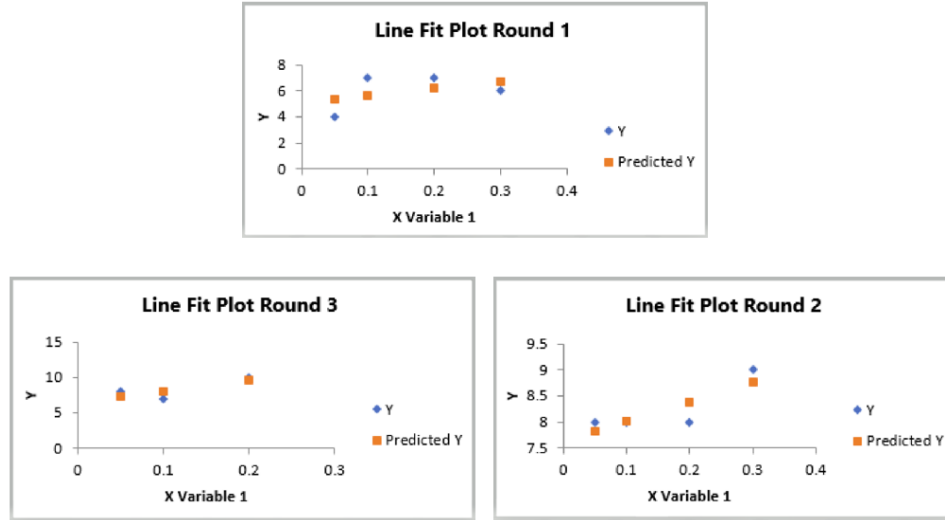


Figure A.14 Line fit plot of virtual environment for preliminary experiment 14th participant

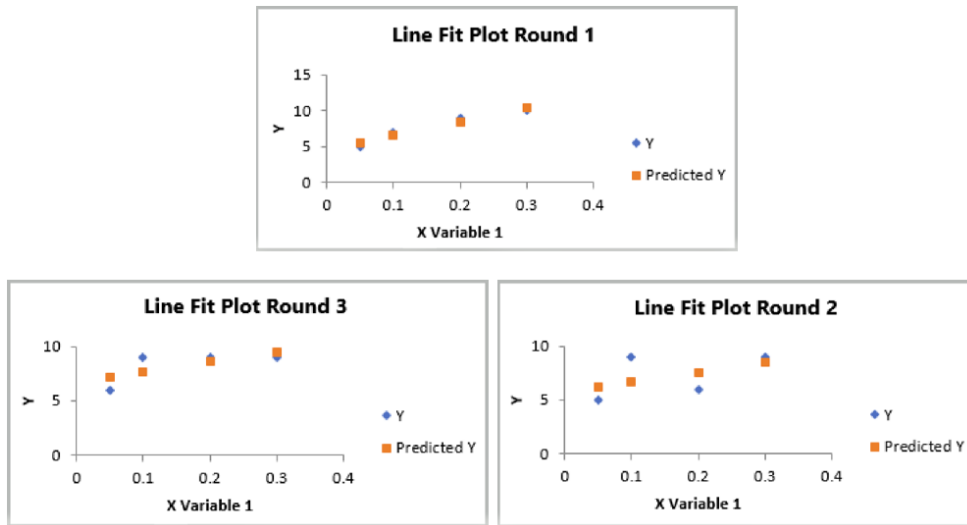


Figure A.15 Line fit plot of virtual environment for preliminary experiment 15th participant

Similarly, the assembly experiment results show that participants did not know the experiment scenario so they were confused in the first round in all trials. But they gave better feedback in second and the third rounds.

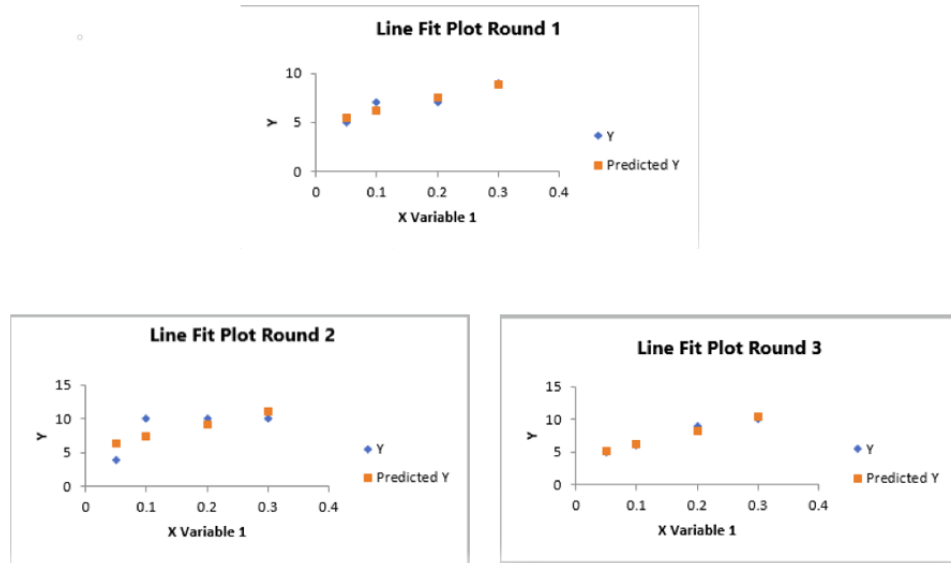


Figure A.16 Line fit plot of virtual environment for assembly experiment 1st participant

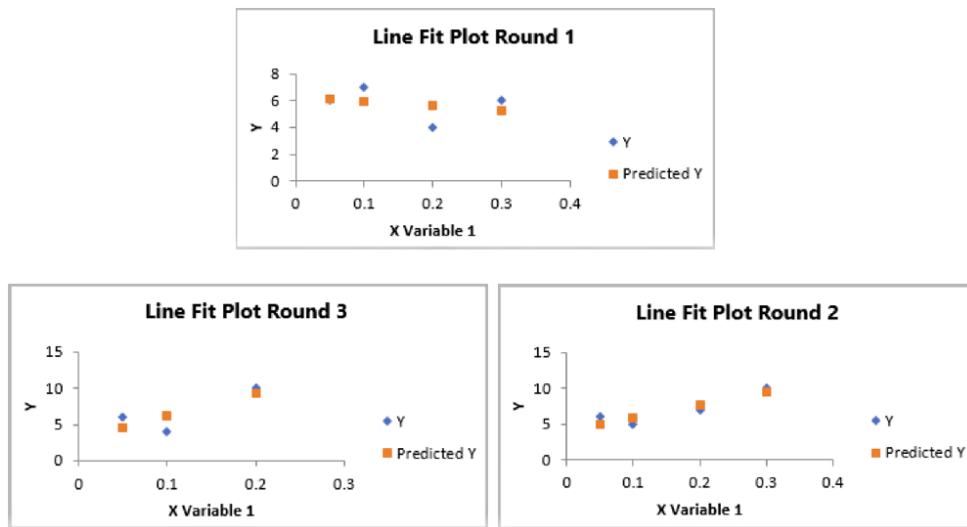


Figure A.17 Line fit plot of virtual environment for assembly experiment 2nd participant

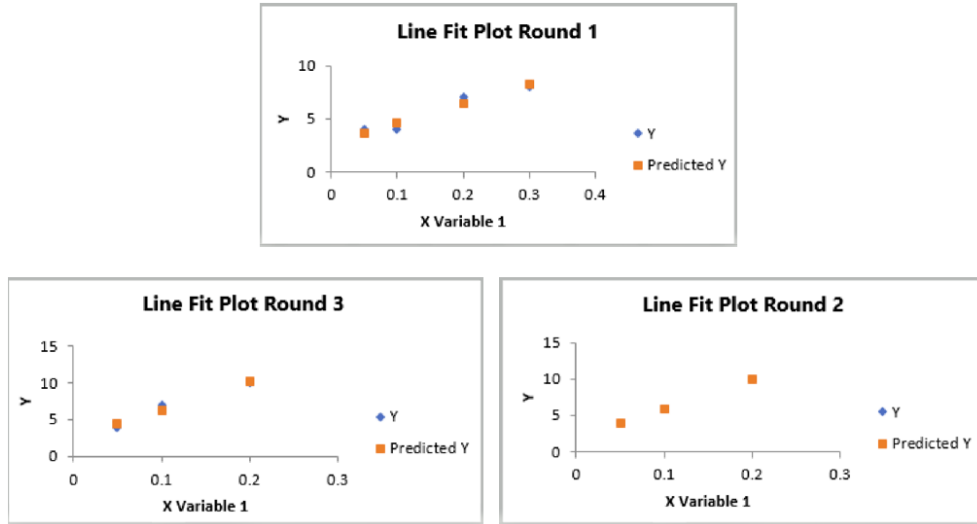


Figure A.18 Line fit plot of virtual environment for assembly experiment 3rd participant

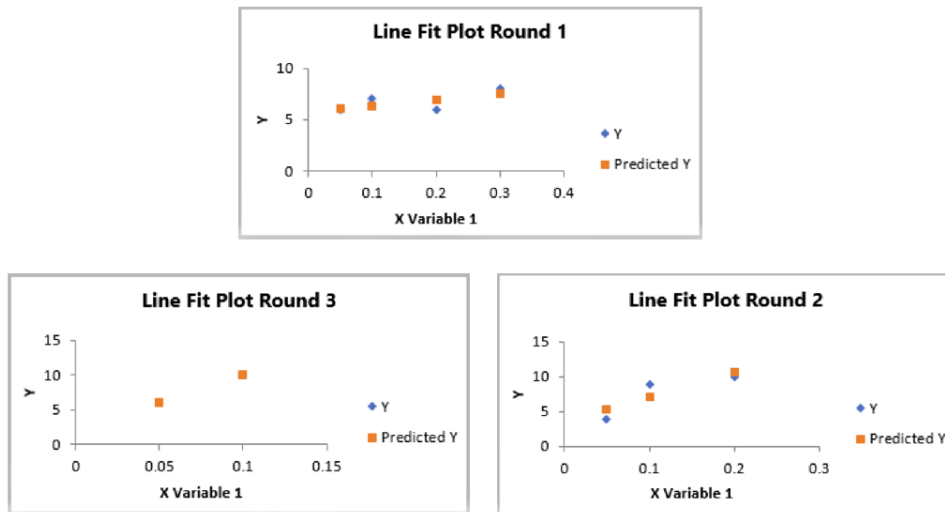


Figure A.19 Line fit plot of virtual environment for assembly experiment 4th participant

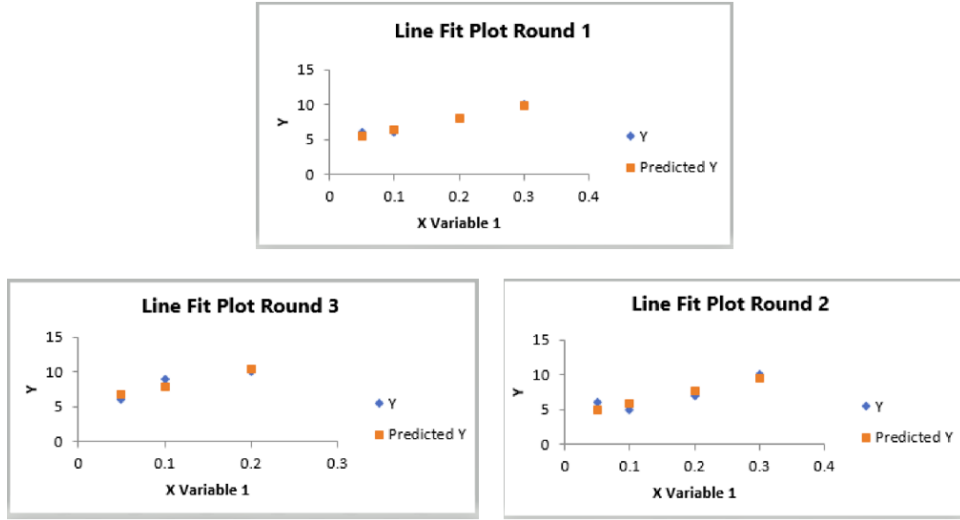


Figure A.20 Line fit plot of virtual environment for assembly experiment 5th participant

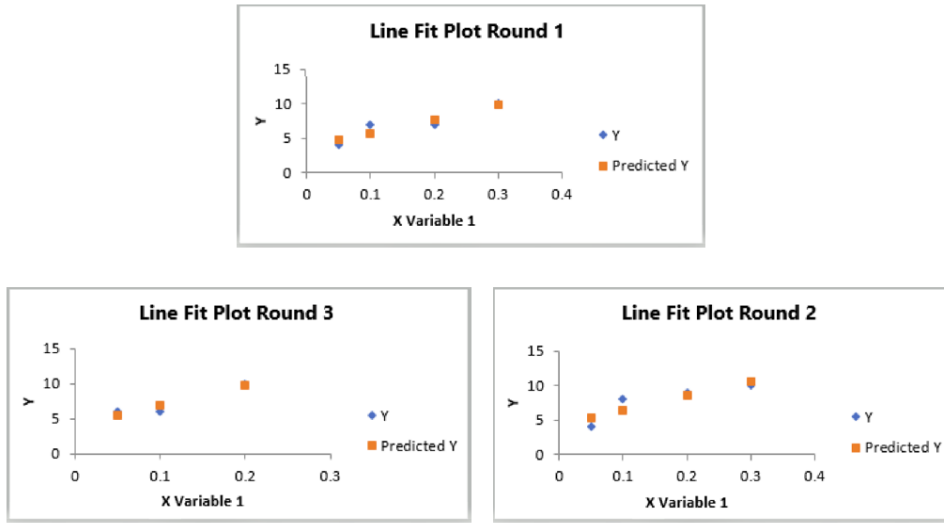


Figure A.21 Line fit plot of virtual environment for assembly experiment 6th participant

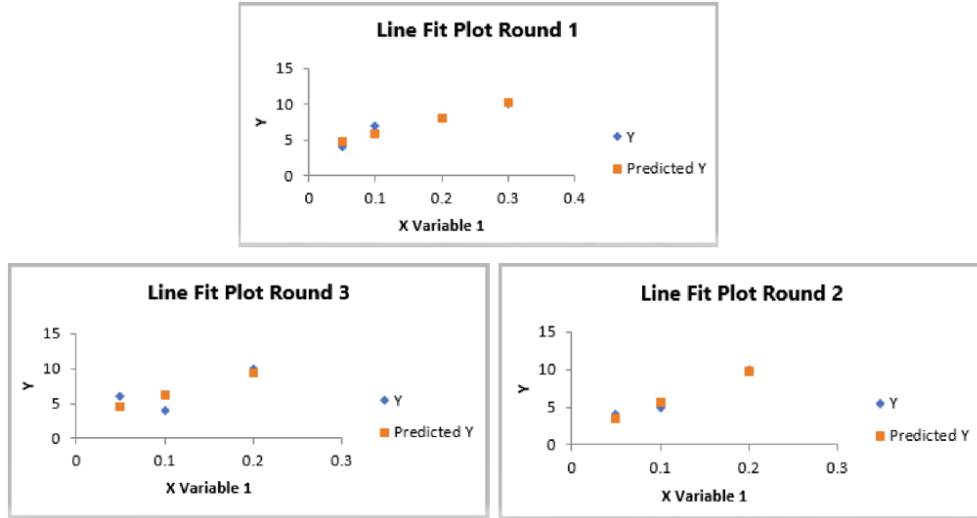


Figure A.22 Line fit plot of virtual environment for assembly experiment 7th participant

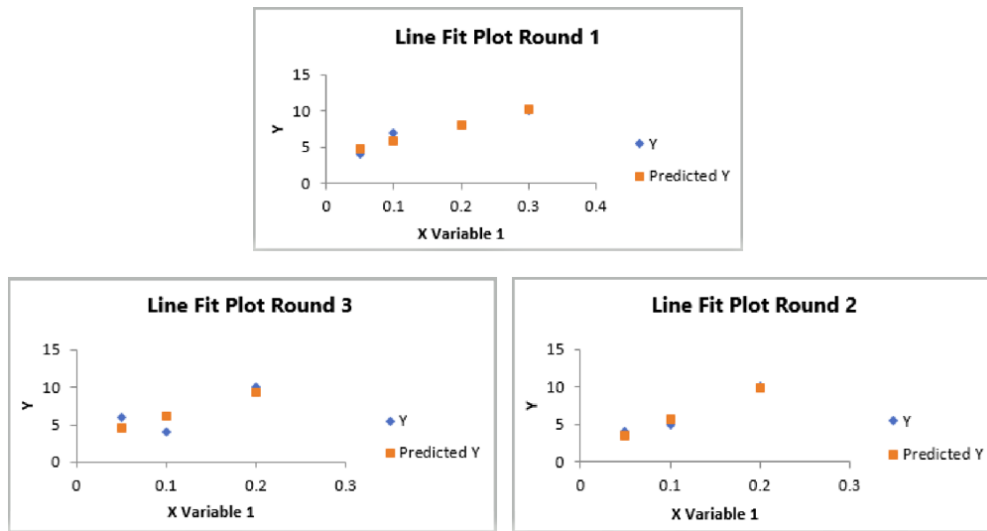


Figure A.23 Line fit plot of virtual environment for assembly experiment 8th participant

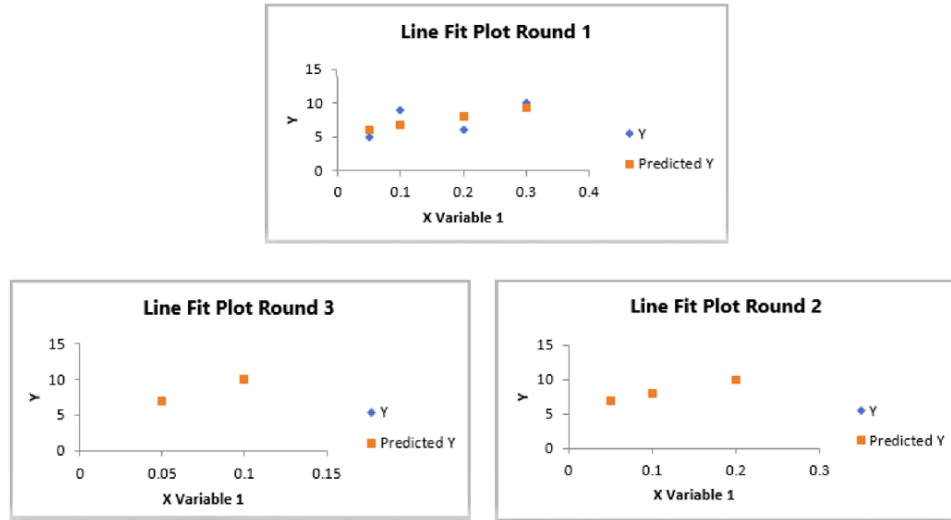


Figure A.24 Line fit plot of virtual environment for assembly experiment 9th participant

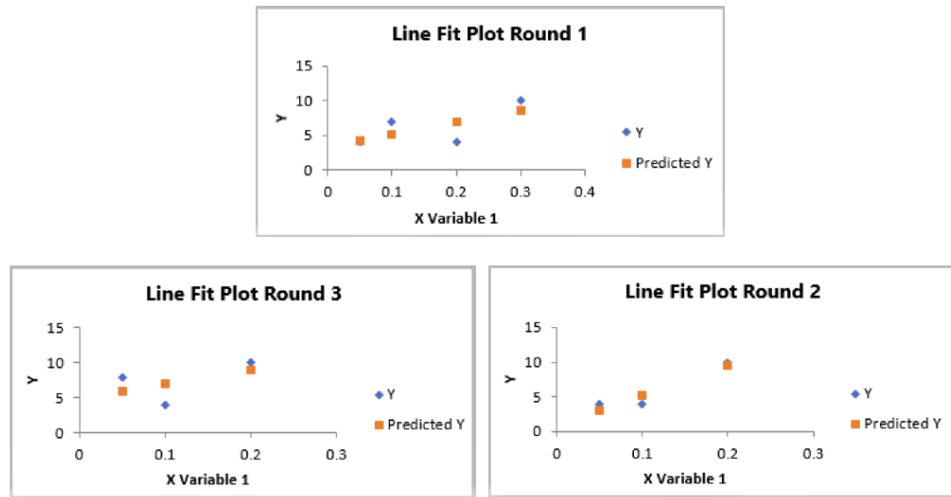


Figure A.25 Line fit plot of virtual environment for assembly experiment 10th participant

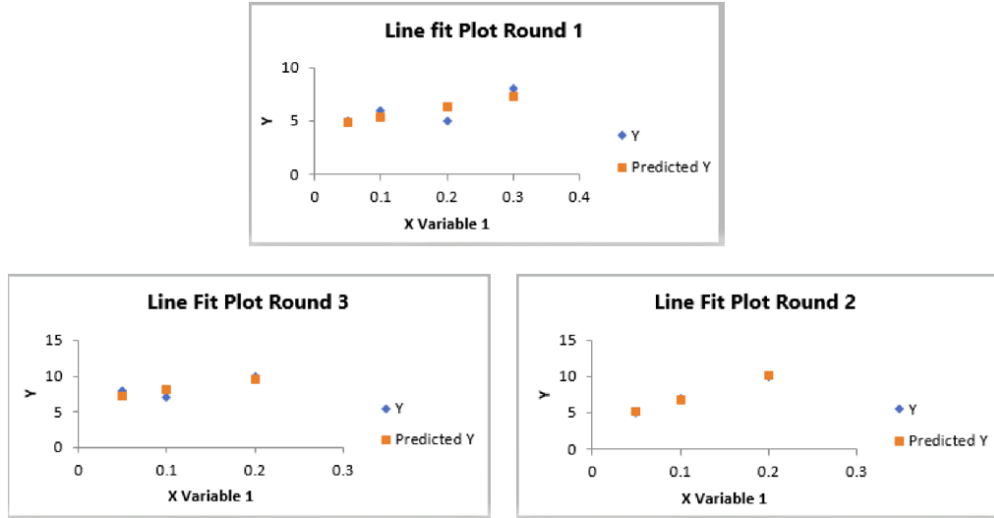


Figure A.26 Line fit plot of virtual environment for assembly experiment 11th participant

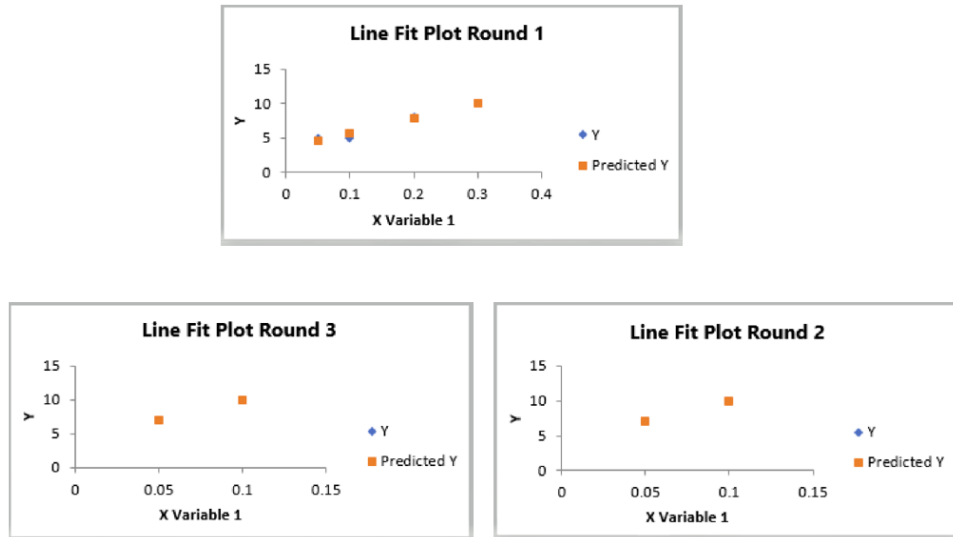


Figure A.27 Line fit plot of virtual environment for assembly experiment 12th participant

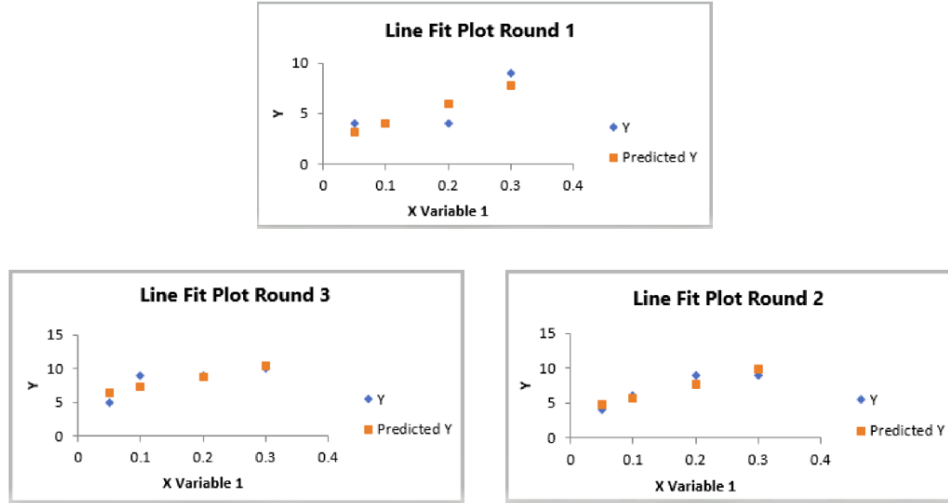


Figure A.28 Line fit plot of virtual environment for assembly experiment 13th participant

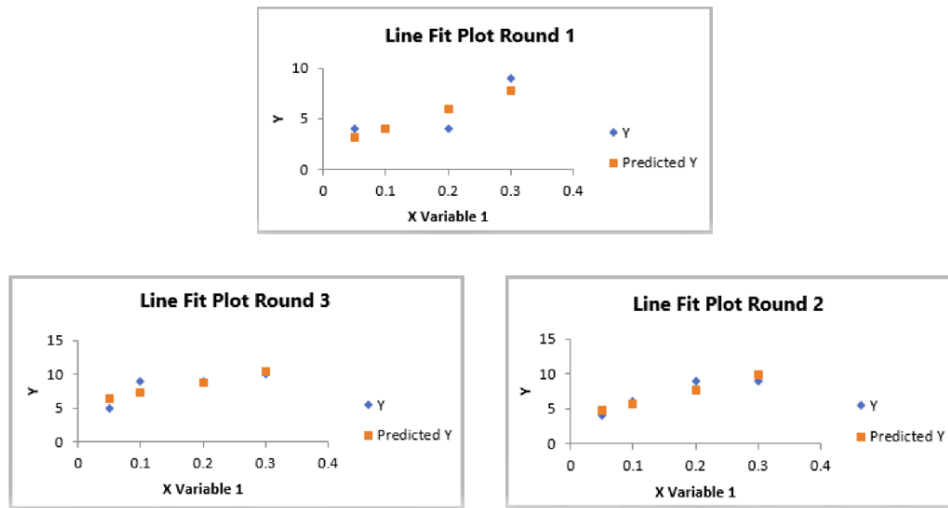


Figure A.29 Line fit plot of virtual environment for assembly experiment 14th participant

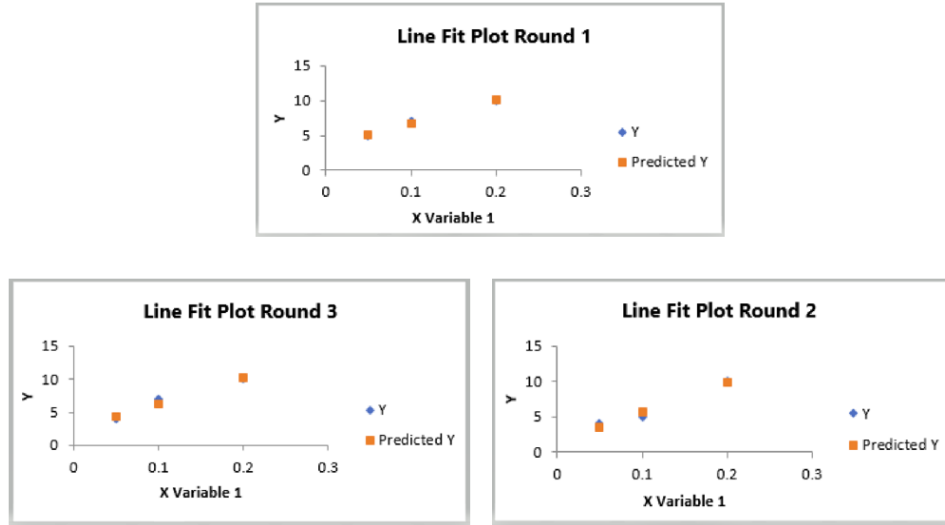


Figure A.30 Line fit plot of virtual environment for assembly experiment 15th participant