VIRTUAL REALITY ENABLED DESIGN REVIEWS USING HEAD MOUNTED DISPLAYS

by

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This research investigates the use of virtual reality technology to improve the interaction between design engineers and their virtual prototypes during the product development process. For this, two experiments were issued to elaborate on how the factors of point-of-view and assembly rotation affect the users three-dimensional understanding of their virtual prototype. Then, the best practices found from these experiments were incorporated into an open web platform for viewing virtual prototypes with smartphones in virtual reality. The virtual reality technology used in this work focused on the incorporation of head mounted displays to achieve a virtual experience at a lower cost than traditional CAVE systems and while being efficient with available space. The results show point of view freedom of the user inside the virtual environment significantly improves their ability to identify errors inside a virtual prototype when compared to having their point-of-view fixed.

Resumen de Tesis Presentado a Escuela Graduada de la Universidad de Puerto Rico como requisito parcial de los Requerimientos para el grado de Maestria en Ciencias

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por

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Consejero: José E. Lugo Ortiz

Departamento: Ingeniería Mecánica

Esta investigación explora el uso de la tecnología de realidad virtual con el propósito de mejorar la interacción entre ingenieros de diseño y sus prototipos virtuales durante el proceso de desarrollo del producto. Para esta meta, dos experimentos fueron diseñados para investigar como los factores de punto de vista y rotación de ensamblaje afecta la comprensión tridimensional de su prototipo virtual. Seguidamente, las mejores prácticas descubiertas en estos experimentos fueron incorporados en una página web abierta con el propósito de ver prototipos virtuales en realidad virtual usando celulares modernos. La tecnología de realidad virtual usada en este trabajo se enfoco en la incorporación de equipo de realidad virtual de pantalla montada en la cabeza de participantes dando asi la oportunidad de experimentar realidad virtual a un bajo costo comparado con sistemas tradicionales como el CAVE, a la misma vez usando poco espacio. Los resultados demuestran que la libertad en el punto de vista adentro de un ambiente virtual mejora significativamente la habilidad de los usuarios a encontrar errores en prototipos virtuales comparado a cuando no se tiene la libertad de punto de vista.

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List of Abbreviations

2D - Two Dimensional

3D - Three Dimensional

CAD - Computer Aided Design

VR - Virtual Reality

CAVE - Cave Automatic Virtual Environment

HMD - Head Mounted Display

POV - Point of View

1 CHAPTER 1 INTRODUCTION

1.1 Motivation

The contributions an engineer can make to society are a product of their ingenuity and the tools at their disposal. Virtual tools have proven to be a boon to the productivity of the engineering practice due to their ability to store and manipulate data with ease. One of the first collaborations between engineer and machine was performed at MIT, when Steven Anson Coons developed SketchPad, a precursor to contemporary Computer Aided Design (CAD). This allowed engineers to create the first virtual prototypes which aided in the communication and modification of designs amongst their peers. This in return, improved the development phase of new products through the use of studying virtual prototypes to implement incremental improvements earlier in the process [2]. With advancements in virtual technology, these virtual prototypes have become highly realistic and the interface of between humans and computers has improved providing the ability to perform intuitive design studies to identify errors. The **goal** of this research is to account how an increase in immersion through virtual reality (VR) via head mounted displays (HMDs) affects the quality of design reviews of virtual prototypes.

There are two components which affect the realism of a virtual prototype: fidelity and user interaction. These directly affect how well the user can mentally comprehend the three-dimensional (3D) nature of the object. The fidelity and interaction with the virtual prototype are directly affected via the equipment used in their rendering and for controlling the virtual environment. Currently, virtual prototypes are rendered via a two-dimensional (2D) computer monitor display which does not provide the user with the same visual data as if they were to view the same object as a physical prototype. Previous research has shown the medium in which a virtual prototype is shown has an effect on the users spatial comprehension of the intended design [3]. The research showed that 2D renderings did not provide the same amount of design data as the 3D data although users were able to read the information faster [3].

1.2 Contributions and Organization

This research is a result of over 2 years in development of a VR environment designed to identify the ideal factors for VR design reviews and validated with over 120 unique human trials. The contribution of this work is to show that VR HMDs can provide engineers with a cost effective alternative to perform high quality design reviews with the purpose of identifying errors in virtual prototypes. The The incorporation of this technology in the product development process has the potential to reduce cost and duration of design iterations before arriving at a finalized product. Two research articles [4, 5] and one developed tool were contributed as a result of this work and can be found at http://academic.uprm.edu/jose.lugo2/. The first article explores the effects of varying levels of immersion between the user and the design review environment on their ability to identify errors within an abstract virtual prototype. The second paper elaborates further on the effects described in the first paper through a refined realistic virtual prototype in addition to exploring the effects of different peripheral controllers and subjects previous experience on their ability to identify errors in virtual mechanical assemblies. The design review assemblies used resemble realistic but simple assemblies such as a gearbox or rack and pinion, thus the results may or may not be applicable to exceedingly complex assemblies such as a complete automobile or airplane. Additionally, the results of the study are dependent upon the hardware configuration as the human computer interaction and results may vary if different setups are used. Finally the open source design review web platform design incorporates the lessons learned in the previous two studies to provide an open platform to perform design reviews on STL models. All studies involving human participants received approval from the Institutional Review Board for the Protection of Human Subjects (Comite para la Proteccion de los Seres Humanos en la Investigacion CPSHI, in spanish) at the University of Puerto Rico Mayagüez (Protocol num. 20160106).

This document is organized as follows: Chapter 2 provides a literature review on the product design process, design visualization, VR, virtual prototypes, and human spatial cognition. Chapter 3 presents the study of point-of-view and assembly rotation factors on the ability of the user to identify errors in abstract virtual prototypes. Chapter 4 presents the study of point-of-view and assembly rotation factors on the ability of users to identify errors in realistic virtual mechanical assemblies in addition to studying the effect on users previous experience with a variety of peripheral controllers on their ability to interact with the virtual design review environment. Chapter 5 describes the open source platform designed for performing low cost design review on STL 3D models. Chapter 6 discusses the ramifications of this body of research on industry and discusses opportunities for further research.

2 CHAPTER 2 LITERATURE REVIEW

2.1 Product Design Process

The product design process can be summarized in six segments: planning, concept design, system-level design, detail design, testing and refinement, and production as seen in Fig **??** [6]. The planning phase consists of business analysis into the intended market and production viability. Afterwards, during concept design, the intended products functional and technical requirements are specified. Additionally, during this phase design engineers begin to take advantage of CAD by creating virtual prototypes to store and easily modify design data. These virtual prototypes will continue be used for the lifetime of the products development, facilitating rapid design iterations via design reviews. In the third phase, system design, subdivision teams are formed to provide solutions of a specific portion of the final product. After system design comes detail design where teams study manufacturing technologies viable for the product. In the next phase, testing and refinement, virtual or physical tests are conducted to verify the proposed design complies with requirements. Since virtual prototypes are more cost effective and faster to produce than conventional physical prototypes, it is beneficial to perform testing and design reviews in a virtual environment. Additionally, in the testing and refinement phase, it is highly likely engineers will use test data to suggest design changes in an effort to improve product performance. This results in refinement and design iterations of creating new prototypes to test. Once the performance of the product is satisfactory and satisfies all proposed requirements, it enters the final phase, production, where manufacturing and quality control takes place. Previous research has shown identifying errors and performing design reviews earlier in the design process, leads to a stronger overall design and less errors in future stages of development [7].

Earlier design reviews results in lower development cost and a shorter design schedule [1, 8], see Fig. 1. Additionally, the more realistic a virtual prototype the more errors can be found, increasing the quality of design review exercises [9]. However, high quality physical prototypes are costly and prohibit their consistent use in design reviews early in the design process. The use of VR has demonstrated success in the past for automotive design [1, 10], assembly planning [11, 12], and ergonomics [13]. This provides an opportunity for highly realistic virtual prototypes to be used early and consistently in the process due to their lower cost and time to produce.

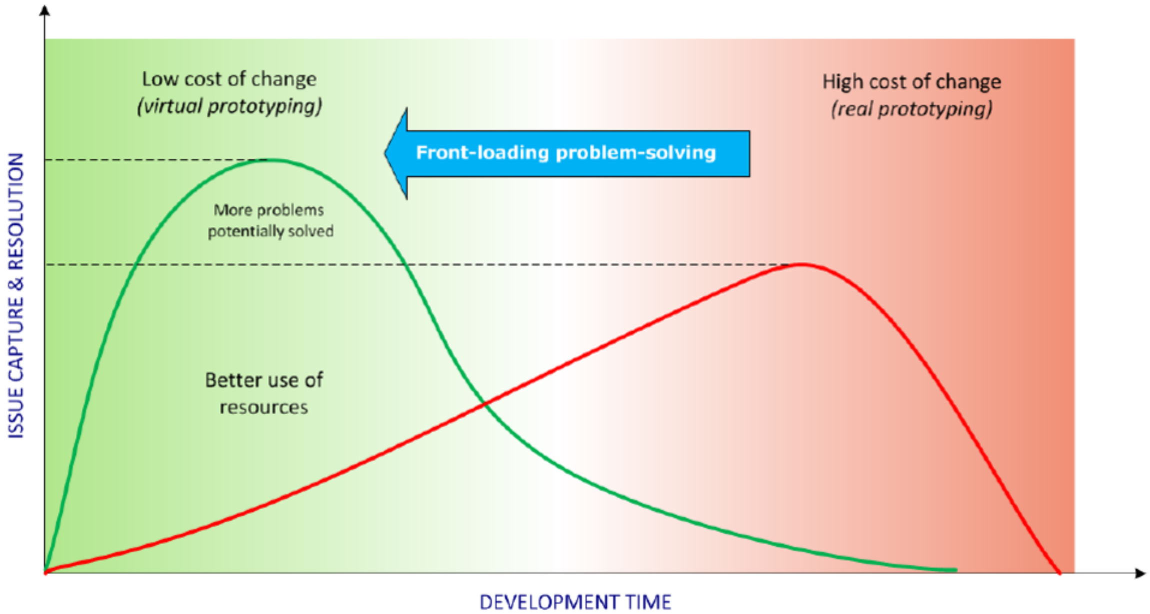


Figure 1: Benefit of Early Design Reviews [1]

2.2 Design Visualization

Due to the variety of virtual environments available during the development process it is important to understand when is each type of prototype best utilized. Research has shown the medium in which a prototype is presented for review has a significant effect on how the participant understands the design intentions [3, 14]. It was shown 2D representations, such as a sketch or engineering drawing, are understood faster than 3D representations but are not as accurate. Representations shown in 3D provide more information to the participant resulting in a more accurate mental picture of the design intent [15]. Increasing the the realism of the virtual prototype being reviewed allows the user to have a more accurate mental representation of the virtual prototype, increasing the quality of a potential design analysis [16, 17, 18]. The medium of design visualization is a result of computer hardware and software technologies and thus will improve with the advent of virtual rendering innovation.

2.3 Virtual Reality

Previously, VR has been a concept difficult to define as many innovators experimented with providing participants with additional sensory information other than 2D representations of a computer monitor and sound. Virtual reality is achieved by displaying 3D images with perceivable depth and by visually engaging the majority of a user's field of view [19]. The effect of producing this extra sensory experience is the increased realism and immersion for the viewer. Immersion is the sense of being in a different environment, and is achieved by substituting real world sensory information with simulated sensory information of a virtual environment [20]. Thus VR is an experience which provides the user with a human computer interface with greater immersion than 3D prototypes represented through a 2D medium such as representing 3D virtual prototypes via a 2D computer monitor. Advances in this space have largely come because of advances in small smartphone displays and large commercial adoption such as with Oculus Rift in 2012 with their HMDs providing a cost effective VR alternative [21].

Head mounted displays achieve VR by placing a smart phone sized high resolution screen inches from the eyes of the viewer. This method allows a small screen to encompass the majority of the user's vision. By using modified Fresnel lenses, a unique image containing depth information is provided to each of the user's eyes [22]. Improvement in display hardware technology has increased the screen resolution and improves the reproduction fidelity of the virtual prototype in HMDs [23]. Additionally, HMDs incorporate infrared head tracking which combined with the computer creates a 360° virtual environment by allowing the user to view their surroundings in the VR via natural head movement, increasing the user's sense of presence, the feeling of "being" in a space [24]. Head tracking is achieved using an infrared camera for positional tracking in conjunction with a gyroscope and accelerometer for directional tracking.

While HMDs have been used in the past mostly by large private companies or research organizations, Oculus Rift is one of the first HMDs marketed commercially and spurred small and large developers to experiment with the platform, leading HMDs to become synonymous with VR unlike other VR systems such as a Cave Automatic Virtual Environemt (CAVE). The CAVE consists of a room sized space where specialized projectors would render stereoscopic images on at least three walls around a participant, creating an immersive space [25]. The participant would use special glasses which would render the stereoscopic image into a 3D image with depth, providing a virtual prototype with significantly more visual information than if it were rendered on a computer monitor. However, this system proved expensive and required significant space to operate preventing widespread integration of this technology in the product development process. This results in limited available setups for engineers to perform design reviews on highly realistic virtual prototypes as their use needs to be justified [26]. This provides an opportunity for HMDs to be incorporated due to their lower cost and use of space. The low cost allows organizations to invest in more units which can alleviate the availability barrier to incorporate widespread VR design reviews and training (see Fig. 2).

Head mounted displays provide an immersive VR experience by placing a smartphone sized display around two inches from the eyes of the viewer. This allows a small screen to encompass most of the users line of sight. This increases immersion by restricting the amount of outside stimulus the viewer can see. The HMD

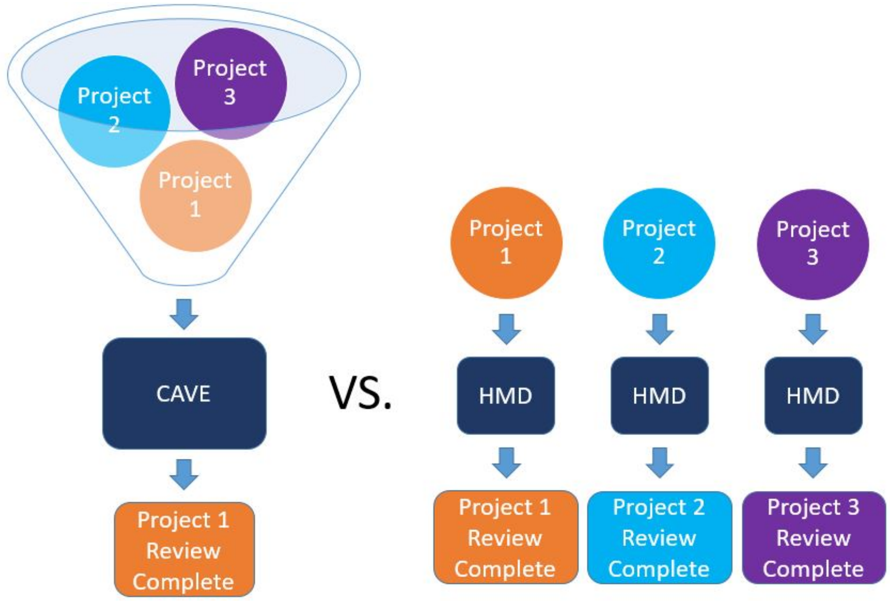


Figure 2: CAVE Use versus Proposed HMD Use in Industry

incorporates modified lenses which transform the 2D screen representation into a stereoscopic image with depth, providing realistic viewing angles for a virtual prototype. Additionally, the HMDs incorporate head tracking which provides directional tracking using a gyroscope and accelerometer allowing the equipment to know in which direction the user is facing. With the use of an infrared tracker the equipment can measure where the users eyes are in 3D space. The combination of these two functionalities allows the user to navigate a virtual environment intuitively by using natural head movement providing an increase in immersion.

2.4 Human Spatial Cognition

At the intersection of virtual prototypes and human computer interfaces lies how the human participant understands the 3D nature of the proposed object. This touches upon human spatial cognition, which is how the viewer comprehends the 3D aspects of the design intent. This concept includes the ability for the participant to visualize themselves inside a virtual environment such as in VR. Virtual reality has been successfully used for previous experiments with human spatial cognition, due to the ability to have detailed control over stimuli in the virtual environment while blocking real world stimuli [27]. Additionally, past research has used VR to examine a participants spatial cognition ability and has shown users with high spatial cognition capacity are more adept at using graphical user interfaces [28].

3 CHAPTER 3 VIRTUAL REALITY ENABLED DESIGN REVIEWS TO IDENTIFY ERRORS IN ABSTRACT VIRTUAL PROTOTYPES

3.1 Introduction

A virtual prototype is more quickly created and less costly than a physical prototype, which can result in a faster and more cost effective product development schedule. The decrease in time generating a prototype allows engineers to perform more design reviews earlier in the design process. Previous research has shown that when errors are encountered earlier in the design process, the total cost and time of development are reduced [1, 8]. Furthermore, it is beneficial to increase the realism of prototypes used in design reviews for improved design communication [9]. When compared to 2D representation, 3D is more effective for reviewing assembly designs due to the availability of more visual information available to the user [15]. This work presents designs in multiple environments (2D, 3D, and VR) with varying degrees of interaction (Point of view (POV) movement and assembly rotation) for design reviews. The **goal** of this work is to evaluate the differences in the ability of engineers to identify errors in virtual prototypes during a design review when modifying the degrees of interaction with the prototype and review environment.

The immersion a viewer experiences is heavily influenced by the human computer interface being used. The interface can be separated into two categories: input devices and output devices. Input devices are what the participants use to manipulate the virtual environment. Output devices are used to render the virtual environment to the viewer. To account for the differences of each participant to interpret 3D object their spatial ability was measured via the spatial cognition survey [29]. This survey consisted of showing the participant a pair cubes with only three sides visible each with unique letters and orientations and are asked "*Could the cubes be the same or are they different?*" see Fig 3 a and b shows spatial cognition cubes which are different and cubes which could be identical, respectively.

This forced the participant to mentally rotate each cube to determine if they could be identical or not. Thus if a participants design review score shows as an outlier, their spatial cognition ability at the time of the experiment can be verified. The design review score in experiment 1 is a measure of if the participant could correctly identify an error in the virtual assembly or ascertain if the virtual assembly did not have an error. In experiment 1 the answer format is a Likert scale from 1 to 5. Answering 1 means the participant is confident the assembly does have an error and answering 5 means the participant is confident the assembly does have an error. This allows the investigator to capture confidence of the participant of their design

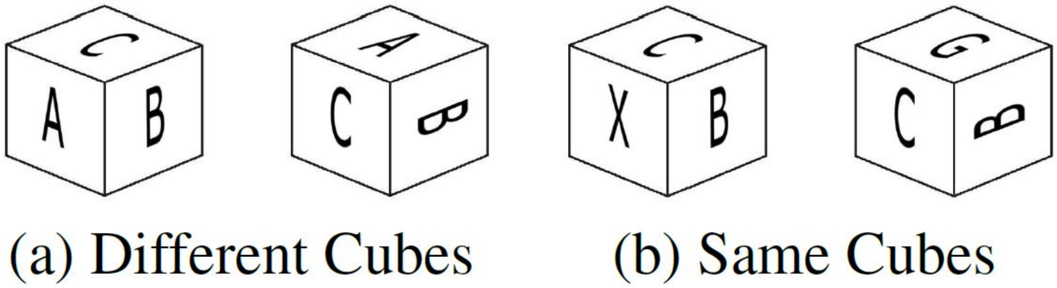


Figure 3: Example of Human Spatial Cognition Test Cubes

review decision.

A benefit of using recent commercially available HMDs is the ease of use across a variety of software due to their origins in the video game and entertainment industry. This allows several different peripheral controllers to be used such as a gamepad controller which may be more intuitive than the traditional keyboard and mouse interface. Additionally, software used to create video game environments have evolved to become significantly versatile in the virtual environment it can create while incorporating support for HMDs. The experiment purpose is to test the ability of participants to identify errors in abstract assemblies across four different environments with different levels of immersion. The varying levels of immersion are manipulated through the human computer interface used during those design reviews. The two factors used to differentiate immersion were POV and assembly rotation. To differentiate POV, two output devices were used, for a fixed POV the participant used a computer monitor to view the virtual prototype. This is a fixed POV because the participant is not able to change their viewpoint of the virtual environment or virtual prototype. For a free POV interaction the participant used an HMD. With the head tracking and positional the HMD provides, the participant is able to change their viewpoint to explore within the virtual environment. Additionally, within each POV environment, fixed or free, assembly rotation can be made fixed or free to add additional interaction between the human and the virtual prototype. A fixed assembly rotation virtual prototype is defined as the participant cannot change the orientation or position of the object. A free assembly rotation virtual prototype allows the participant to change the orientation or position if they wish to do so. Thus, the lowest immersion design review environment was created as a fixed POV and fixed assembly rotation scenario achieved by presenting the participant with static 2D images of the virtual prototype through a computer monitor. The highest immersion scenario consisted of the presenting the virtual prototype via an HMD and allowing the participant to rotate the object using a gamepad controller.

The virtual prototype in this experiment is an assembly of various differently shaped components when placed together form a cube. The goal of each design reviews is to determine whether all components form a perfect cube without gaps. A total of eight different cube assemblies were created, four forming a perfect cube and four with gaps. The assemblies were created combining multiple interactions between lines and curves account for the variety of shapes encountered in real world virtual prototypes.

3.2 Experiment Methodology

The experiment consisted of three parts: the spatial cognitive survey, design reviews, and experiential survey. Upon entering the experiment space the participant is given a brief introduction on the tasks needed to complete the experiment and the design intent of the virtual prototypes being used. Next the participant will be given their participant number and sign the consent form. Afterwards, the participant will complete the spatial cognition survey. Then, the participant will complete eight design reviews in four different environments in either low to high immersion order or vice versa, see Fig. 4.

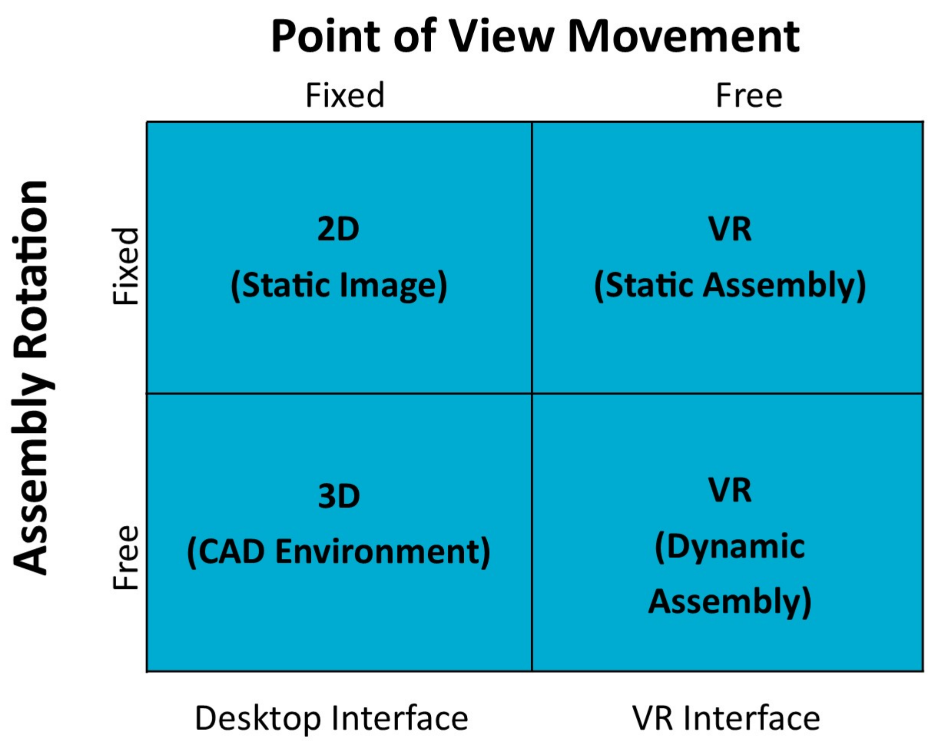


Figure 4: Experiment 1 Factors and Design Review Environments

The order in which the participant completes the design reviews depends on their participant number being odd or even. Once the participant has completed each design review they will complete the experiential survey via computer and complete the experiment.

3.2.1 Participants

The format of the experiments were submitted and approval by the IRB board prior to soliciting participation (Protocol num. 20160106). A total of 43 subjects participated in the experiment (23 males; 20 females). The participants' age range was from 21 to 30 years old, with a mean of 23 years old. As a prerequisite for eligibility, participants needed to have normal or corrected to normal vision, and have taken a CAD course. Of the 43 participants, 16 subjects used CAD for projects and 8 subjects used CAD professionally. Additionally, 31 participants reported no prior experience with VR. Subjects volunteered their participation, no compensation was offered to complete the survey. Of the surveys completed, three were rejected due to participant experiencing some dizziness and those trials were restarted using new participants.

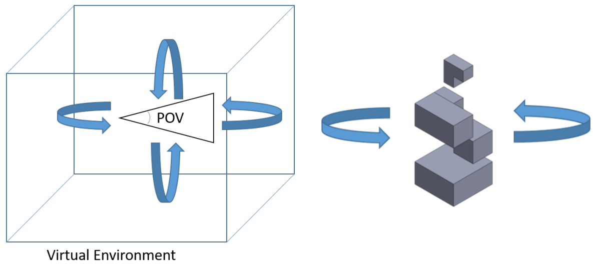
3.2.2 Spatial Cognition Survey

Each person has a different spatial cognition ability, to investigate this ability at the time of the experiment the spatial cognition survey was used [30]. This survey collects data on the participants' comprehension of 3D space [29]. The test will show isometric views of two cubes and subjects are asked to determine if the two cubes could be the same taking into account the orientation of unique letters on each face. The participants can answer the question by clicking one of two radio buttons which read "same" or "different". This is completed twelve times, with varying letters and orientations.

3.2.3 Design Review

The purpose of this part of the experiment is to measure the participants' ability to identify errors in CAD assembly models in four environments with different levels of interaction. To vary environment interaction we use two factors: user POV movement, and assembly rotation. User POV movement is the user's change in viewpoint inside the environment and assembly rotation is the movement that the assembly can have inside the environment (see Fig. 5a and 5b, respectively). Through restricting and/or allowing each functionality, four environments are created: static image (2D), CAD environment (3D), VR static assembly (3D), and VR dynamic assembly (3D) as can be seen in Fig. 4.

In order to use different assembly models in each environment, eight assemblies where developed for the design review portion of the experiment (see Fig. 6). Individual components were developed in CAD with the purpose of being assembled into a cube. The cube models vary in number of components, component



(a) POV Movement (b) Assembly Rotation

Figure 5: Experiment 1 Factors of Human Interaction with Virtual Environment

variations and number of curves. The first model is the simplest with four components, no curves and no additional variations. The second and third model also consist of four components, however these components have material removed and/or added, created variations. The fourth and fifth model have a larger number of components. Additionally, the individual components of the fourth and fifth models vary more from the rectangular shape of the previous assembly models. The remaining three models incorporate curved components. Half of the assembly models were developed with intentional gaps, which the subjects need to identify. The model is presented in an exploded view which will remain static to allow the participants to view how the components collapse together. The participants were asked the question “Will the object form a perfect cube?” and answer using a Likert scale from 1 to 5. Each assembly in the study has a correct answer of 1 or 5, 1 meaning the assembly will not form a perfect cube and 5 meaning the assembly will form a perfect cube. The design review score is calculated by subtracting the difference between the participant’s answer and the correct answer from the maximum score of 5. For example, if the participant answers 5, on an assembly which has a correct score of 5, the difference between the participant answer and correct answer is 0. As a result the participant scored a maximum score of 5 for that design review. Each one of the participants performed assembly reviews on all eight models, two in each of the four environments. To mitigate order bias, eight different assembly review testing orders were created. This allows each model to be reviewed in the four different environments. Additionally, the subjects will alternate which environment they begin with, low to high immersion testing order or vice versa.

The 2D rendering environments were created by embedding a static image of the assembly (see Fig. 7). The interface setup consists of a 24-inch computer monitor with 1920 $\times$ 1080 pixel resolution and a keyboard/mouse as an input method. Participants were instructed to respond to the proposed question using Likert scale radio buttons.

The 3D rendering environments were created using an online survey tool and embedding a plug-in which allows participants to drag, rotate, and zoom in on the object as well as select different preset views of the

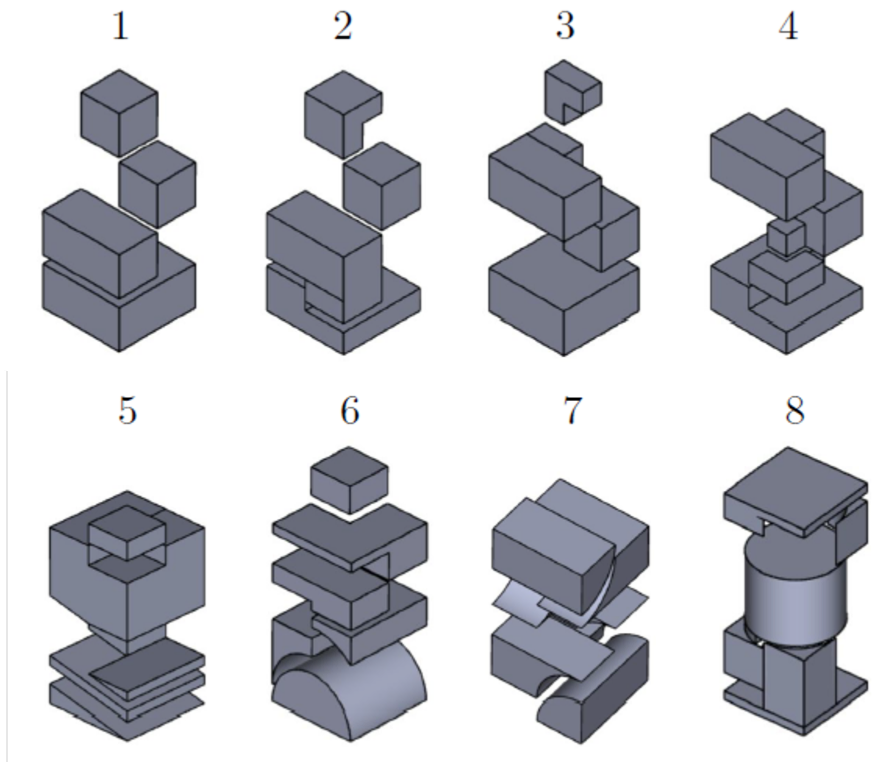


Figure 6: Experiment 1 Abstract Assemblies for Design Review

object, including an isometric view (see Fig. 8). The interface setup consisted of a 24-inch computer monitor with 1920 $\times$ 1080 pixel resolution and a keyboard/mouse as an input method. Participants were instructed to respond to the proposed question using Likert scale radio buttons.

The VR rendering environments were created using a video game engine. This environment is composed of a room with a table in the center and prompts on the surrounding walls (see Fig. 9). Assemblies will appear before the participants in the center of the table. The game engine allows the environment to allow or restrict assembly rotation. If rotation is permitted, participants can rotate the assembly using the right stick of gamepad controller. The proposed question is constantly displayed on the wall directly facing the subject and they were instructed to respond using the buttons on the gamepad controller.

3.2.4 Experiential Survey

The Experiential Survey uses a Likert scale to collect personal data on the participants. This includes participants' profiles and their experience inside the virtual environment. The participants were asked on their preference of environment, whether CAD or VR platform for performing design reviews. Additionally,

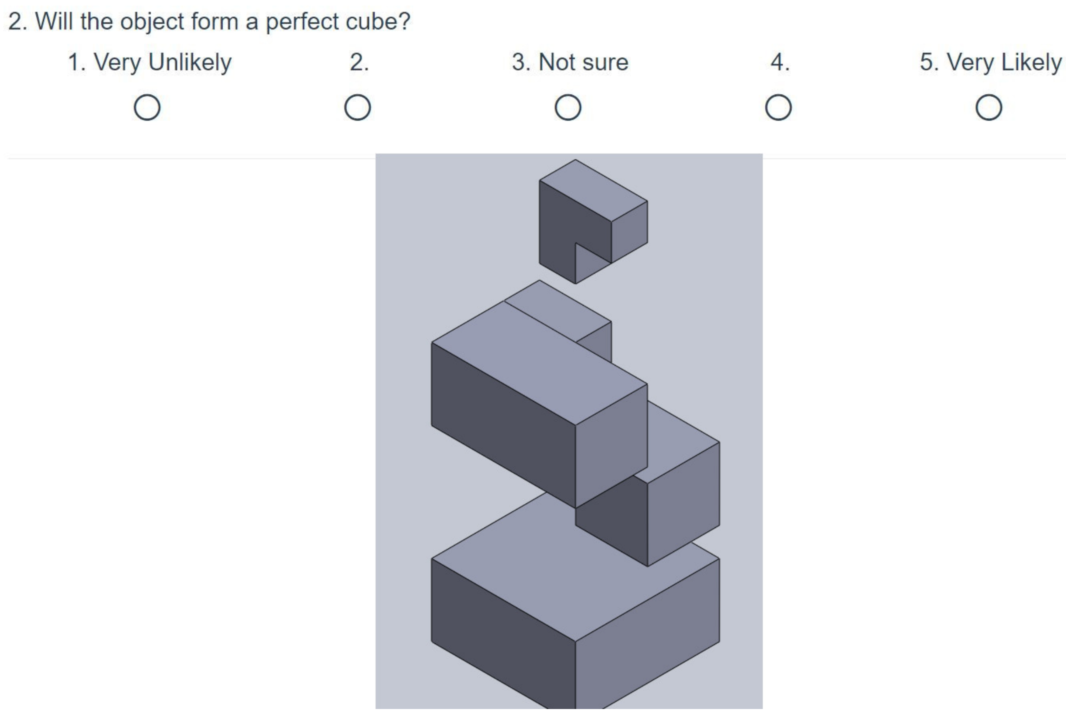


Figure 7: Experiment 1 2D Design Review Environment (Static Image)

participants were asked if they experienced delay, dizziness, or distraction.

3.3 Experiment 1 Hypothesis

The general hypothesis is: subjects will spend more time reviewing assembly models if they have more interaction such as free POV movement and free assembly rotation. Additionally, with this added range of interaction subjects will be able to analyze more information and increase their design review score. With that in mind, the following are investigated:

- **Hypothesis 1a:** The aggregated assembly review time with free POV movement will be statistically higher than the aggregated assembly review time with a fixed POV.
- **Hypothesis 1b:** The aggregated assembly review time with free assembly rotation will be statistically higher than the aggregated assembly review time with a fixed assembly rotation.
- **Hypothesis 1c:** The aggregated design review score with free POV movement will be statistically higher than the aggregated design review score with a fixed POV.
- **Hypothesis 1d:** The aggregated design review score with free assembly rotation will be statistically

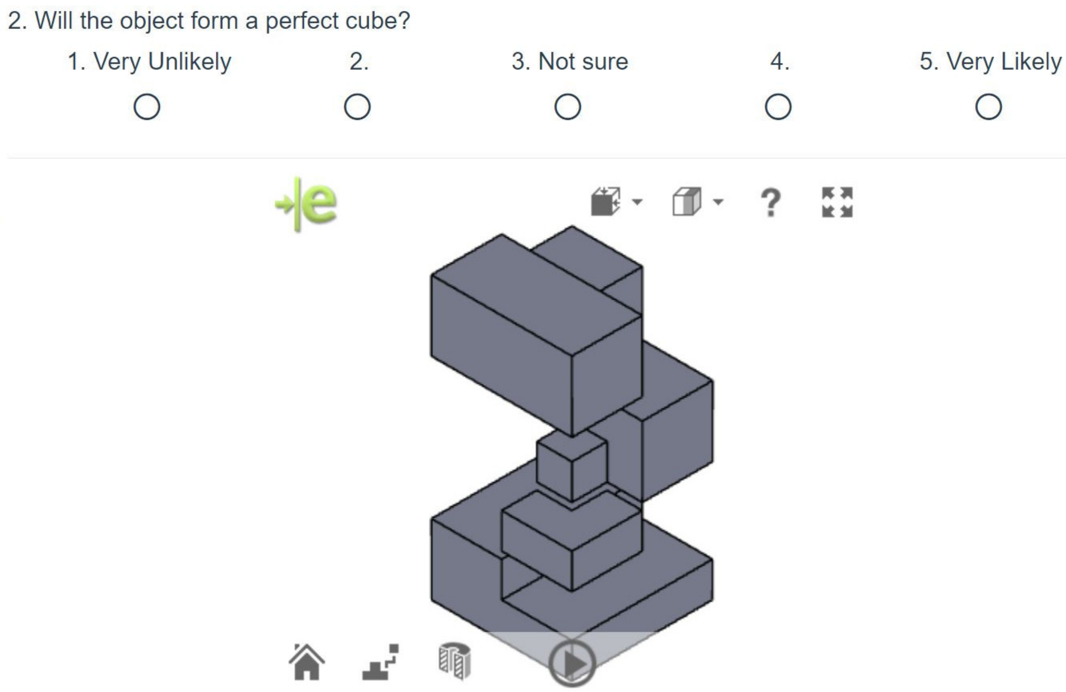


Figure 8: Experiment 1 3D Design Review Environment (CAD Environment)

Figure 9: Experiment 1 VR Design Review Environment

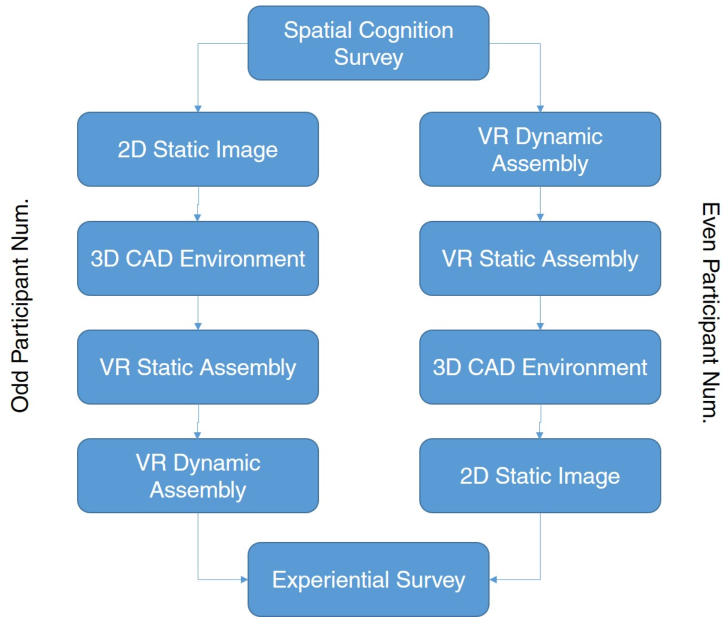


Figure 10: Experiment 1 Procedure

higher than the aggregated design review score with a fixed assembly rotation.

3.4 Results

In total, 43 subjects completed the experiment. The average duration of the whole experiment was approximately 15 minutes. For each environment-model combination the design review score and completion time was recorded. Table 1 presents the recorded information. Each participant reviewed independently two assemblies per environment (see Table 2).

3.5 Data Analysis

The assembly review time data is a continuous variable, thus a repeated measures ANOVA was used to analyze the data. The review time data was submitted to a 2 (POV: fixed and free) $\times$ 2 (Assembly Rotation: all fixed and free to rotate) $\times$ 2 (Order: VR first and non-VR first) $\times$ 8 (Assembly model: eight different models found in Fig. 6) repeated measures ANOVA (see Table 7). This is a statistical test that determines whether or not the means of review time are equal. Significant results are as follows.

There are three main effects: POV, assembly rotation, and assembly model. The aggregated assembly review time for the fixed POV ($M = 35.70$, $SD = 19.80$) is statistically shorter than the aggregated assembly review time for the free POV ($M = 44.38$, $SD = 28.49$), ($F = 9.93$, $p < 0.002$). This confirms **hypothesis**

Table 1: Experiment 1 Raw Data

Participant # (Spatial Score)	2D (sec)	3D (sec)	VR (sec)	VR+ (sec)	Participant # (Spatial Score)	2D (sec)	3D (sec)	VR (sec)	VR+ (sec)
1 (11)	4 (22) 4 (13)	4 (45) 0 (37)	4 (N/A) 4 (23)	4 (14) 4 (21)	23 (10)	4 (25) 1 (13)	4 (25) 4 (27)	4 (N/A) 2 (25)	3 (24) 4 (24)
2 (12)	4 (25) 4 (14)	4 (45) 4 (84)	0 (29) 4 (37)	0 (N/A) 4 (21)	24 (8)	2 (37) 0 (16)	4 (48) 0 (60)	4 (60) 3 (64)	1 (N/A) 0 (50)
3 (7)	4 (17) 2 (15)	4 (31) 4 (69)	4 (N/A) 0 (52)	4 (15) 4 (74)	25 (8)	4 (49) 4 (19)	1 (68) 3 (49)	4 (N/A) 1 (51)	4 (35) 1 (49)
4 (8)	0 (N/A) 1 (21)	0 (46) 1 (34)	4 (28) 4 (25)	3 (N/A) 1 (37)	26 (10)	4 (10) 4 (8)	4 (47) 2 (80)	4 (34) 1 (39)	0 (N/A) 1 (64)
5 (10)	0 (N/A) 4 (32)	4 (31) 4 (37)	4 (N/A) 4 (17)	0 (40) 0 (33)	27 (6)	3 (9) 3 (38)	3 (77) 3 (64)	3 (N/A) 2 (61)	3 (59) 2 (106)
6 (7)	1 (19) 0 (16)	4 (25) 0 (29)	3 (41) 0 (30)	4 (N/A) 0 (63)	28 (8)	0 (N/A) 4 (36)	0 (35) 4 (26)	3 (46) 0 (28)	4 (N/A) 4 (60)
7 (11)	2 (21) 0 (13)	4 (18) 3 (39)	3 (N/A) 4 (21)	4 (46) 1 (23)	29 (7)	0 (N/A) 1 (26)	3 (79) 3 (81)	3 (N/A) 3 (9)	1 (45) 2 (40)
8 (12)	4 (45) 3 (26)	0 (21) 0 (10)	0 (15) 3 (98)	0 (N/A) 1 (66)	30 (11)	4 (46) 4 (71)	4 (76) 4 (71)	4 (64) 0 (64)	4 (N/A) 0 (83)
9 (11)	3 (42) 1 (18)	4 (62) 4 (42)	4 (N/A) 4 (57)	4 (18) 4 (32)	31 (11)	1 (76) 3 (65)	4 (39) 4 (42)	4 (N/A) 4 (27)	4 (47) 4 (58)
10 (10)	3 (59) 2 (73)	3 (64) 3 (58)	1 (53) 1 (120)	4 (N/A) 1 (23)	32 (10)	3 (43) 0 (20)	4 (24) 0 (40)	0 (49) 3 (71)	0 (N/A) 0 (40)
11 (11)	4 (11) 3 (27)	3 (41) 3 (17)	4 (N/A) 2 (42)	1 (15) 1 (47)	33 (9)	0 (23) 4 (29)	0 (20) 3 (49)	0 (N/A) 3 (148)	4 (12) 4 (20)
12 (9)	0 (N/A) 3 (18)	3 (48) 0 (47)	4 (8) 3 (55)	4 (N/A) 4 (31)	34 (11)	4 (38) 3 (56)	4 (42) 4 (55)	0 (90) 3 (71)	0 (N/A) 0 (114)
13 (11)	2 (N/A) 4 (19)	0 (33) 0 (23)	3 (N/A) 0 (22)	1 (53) 4 (67)	35 (12)	4 (10) 4 (11)	4 (53) 4 (46)	4 (N/A) 0 (92)	4 (53) 4 (187)
14 (11)	4 (26) 4 (24)	4 (38) 0 (43)	4 (51) 0 (48)	4 (N/A) 0 (52)	36 (11)	3 (N/A) 3 (27)	4 (61) 3 (65)	4 (22) 4 (19)	3 (N/A) 3 (60)
15 (8)	1 (35) 0 (6)	1 (12) 0 (17)	4 (54) 1 (49)	4 (54) 1 (49)	37 (12)	0 (N/A) 0 (14)	4 (25) 4 (51)	4 (N/A) 4 (25)	4 (54) 3 (40)
16 (10)	1 (39) 4 (16)	3 (26) 4 (39)	0 (72) 4 (91)	0 (N/A) 0 (28)	38 (10)	4 (23) 4 (18)	0 (25) 4 (55)	4 (19) 0 (23)	4 (N/A) 0 (10)
17 (9)	2 (19) 2 (15)	4 (74) 3 (49)	3 (N/A) 4 (24)	4 (68) 4 (38)	39 (9)	1 (10) 0 (15)	3 (39) 1 (19)	2 (N/A) 1 (6)	3 (20) 0 (25)
18 (12)	3 (23) 4 (18)	4 (26) 4 (19)	0 (29) 3 (32)	0 (N/A) 1 (23)	40 12)	2 (42) 1 (39)	4 (27) 4 (53)	2 (88) 1 (33)	4 (N/A) 1 (34)
19 (9)	4 (12) 3 (23)	3 (60) 2 (89)	3 (N/A) 1 (63)	4 (68) 3 (50)	41 (12)	3 (20) 2 (12)	3 (64) 3 (76)	3 (N/A) 3 (44)	3 (33) 4 (86)
20	0 (N/A) 3 (27)	3 (58) 0 (23)	4 (9) 0 (14)	4 (N/A) 4 (27)	42 (10)	4 (14) 4 (10)	0 (41) 4 (40)	0 (20) 4 (10)	4 (N/A) 1 (25)
21 (8)	2 (N/A) 3 (16)	4 (17) 0 (20)	3 (N/A) 1 (17)	0 (92) 1 (31)	43 (10)	4 (20) 4 (20)	3 (27) 4 (36)	1 (N/A) 3 (12)	4 (21) 4 (13)
22 (8)	4 (35) 0 (46)	0 (35) 3 (72)	4 (50) 0 (27)	4 (N/A) 0 (46)					

1a: that subjects spent significantly more time in VR based assembly reviews than the non-VR assembly reviews.

The aggregated assembly review time for the fixed assembly rotation (M = 34.17, SD = 23.97) is statistically shorter than the aggregated assembly review time for the free assembly rotation (M = 44.60, SD = 23.79), (F = 16.72, $p < 0.001$). This confirms **hypothesis 1b**: that subjects spend more time in assembly review when the assembly is able to rotate on at least one axis.

The assembly model was shown to have a significant effect on review time (F = 2.89, $p < 0.006$). Table 4 displays the means and standard deviations of the review time for each assembly model. This shows the aggregated review time for models varied according to the number of components, component variations and curves. The simplest model, model 1 (M = 30.51, SD = 18.41), was the lowest among all assembly models

Table 2: Experiment 1 Abstract Assemblies Reviewed per Participant

Participant #	2D	3D	VR	VR+	Participant #	2D	3D	VR	VR+
1	7 , 8	4 , 6	3 , 5	1 , 2	23	4 , 6	3 , 5	1 , 2	7 , 8
2	1 , 2	3 , 5	4 , 6	7 , 8	24	7 , 8	1 , 2	3 , 5	4 , 6
3	1 , 2	7 , 8	4 , 6	3 , 5	25	7 , 8	4 , 6	3 , 5	1 , 2
4	3 , 5	4 , 6	7 , 8	1 , 2	26	1 , 2	3 , 5	4 , 6	7 , 8
5	3 , 5	1 , 2	7 , 8	4 , 6	27	1 , 2	7 , 8	4 , 6	3 , 5
6	4 , 6	7 , 8	1 , 2	3 , 5	28	3 , 5	4 , 6	7 , 8	1 , 2
7	4 , 6	3 , 5	1 , 2	7 , 8	29	3 , 5	1 , 2	7 , 8	4 , 6
8	7 , 8	1 , 2	3 , 5	4 , 6	30	4 , 6	7 , 8	1 , 2	3 , 5
9	7 , 8	4 , 6	3 , 5	1 , 2	31	4 , 6	3 , 5	1 , 2	7 , 8
10	1 , 2	3 , 5	4 , 6	7 , 8	32	7 , 8	1 , 2	3 , 5	4 , 6
11	1 , 2	7 , 8	4 , 6	3 , 5	33	7 , 8	4 , 6	3 , 5	1 , 2
12	3 , 5	4 , 6	7 , 8	1 , 2	34	1 , 2	3 , 5	4 , 6	7 , 8
13	3 , 5	1 , 2	7 , 8	4 , 6	35	1 , 2	7 , 8	4 , 6	3 , 5
14	4 , 6	7 , 8	1 , 2	3 , 5	36	3 , 5	4 , 6	7 , 8	1 , 2
15	4 , 6	3 , 5	1 , 2	7 , 8	37	3 , 5	1 , 2	7 , 8	4 , 6
16	7 , 8	1 , 2	3 , 5	4 , 6	38	4 , 6	7 , 8	1 , 2	3 , 5
17	7 , 8	4 , 6	3 , 5	1 , 2	39	4 , 6	3 , 5	1 , 2	7 , 8
18	1 , 2	3 , 5	4 , 6	7 , 8	40	7 , 8	1 , 2	3 , 5	4 , 6
19	1 , 2	7 , 8	4 , 6	3 , 5	41	7 , 8	4 , 6	3 , 5	1 , 2
20	3 , 5	4 , 6	7 , 8	1 , 2	42	1 , 2	3 , 5	4 , 6	7 , 8
21	3 , 5	1 , 2	7 , 8	4 , 6	43	1 , 2	7 , 8	4 , 6	3 , 5
22	4 , 6	7 , 8	1 , 2	3 , 5					

reviewed.

There are two interaction effects: POV × assembly rotation (AR), and POV × assembly model. The aggregated assembly review time statistically increases as both POV and AR increase in immersion ($F = 7.42$, $p < 0.007$). The aggregated assembly review time was shown to be significantly affected by the interaction of POV and assembly model ($F = 3.21$, $p < 0.003$) (see Fig.11). Assembly review time of models 1 through 6 increased with free POV. However, models 7 and 8 decreased review times with free POV. Model 5 had the highest difference in review time between free and fixed POV.

Through ANOVA analysis, the participants' spatial cognition survey score showed no correlation to the participants' average assembly review duration ($F = 1.56$, $p < 0.158$). Through Kruskal-Wallis H-Test analysis, the participants' spatial cognition survey score showed no correlation to the participants' average design review score ($H = 11.08$, $p < 0.086$).

The design review score is captured using a Likert scale, making the data non-parametric. Therefore the Kruskal-Wallis test is used to analyze the data. The design review score data was submitted to a Kruskal-Wallis H-test against POV, assembly rotation, testing order, and assembly model (see Table 5). This statistical test allows us to determine whether or not the means of the design review scores are equal

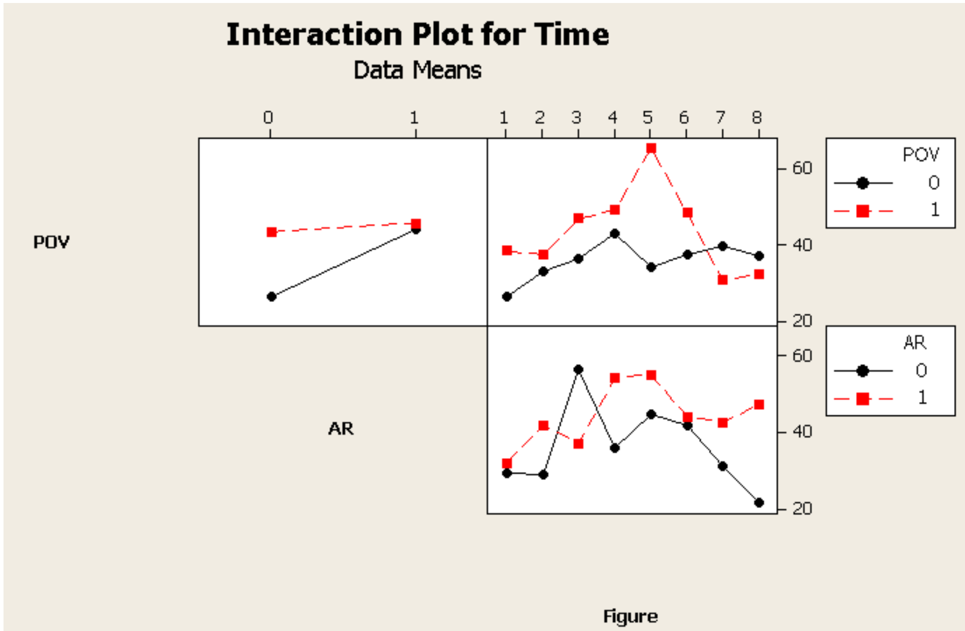


Figure 11: Experiment 1 Design Review Time Interactions Plot (0 = Fixed, 1 = Free)

against four factors: POV, assembly rotation, testing order, and assembly model. Significant results are as follows. The mean and standard deviation of the design review score for each level are: 2D ($M = 2.477$, $SD = 1.547$), 3D ($M = 2.674$, $SD = 1.605$), VR ($M = 2.465$, $SD = 1.714$), VR+ ($M = 2.360$, $SD = 1.714$).

There are two main effects: testing order and assembly model. The aggregated design review score for the high to low immersion testing order ($M = 2.71$, $SD = 1.45$) is statistically higher than the aggregated design review score for the low to high immersion testing order ($M = 2.26$, $SD = 1.74$), ($H = 4.50$, $p < 0.034$). This shows participants correctly reviewed more assembly models when beginning the reviews with the highest immersion.

The aggregated design review score for model 1 ($M = 3.53$, $SD = 0.91$) was statistically higher than the average design review score for all models ($M = 2.49$, $SD = 1.61$), ($Z = 4.29$,$p < 0.001$). This shows participants scored higher than average on the least complex model. Additionally, the aggregated design review score for model 6 ($M = 1.77$, $SD = 1.55$) was statistically lower than the average. This shows the participants scored lower on models with higher amount of components, component variations, and curves.

The aggregated design review score for free POV movement was shown to not be statistically different than the aggregated design review score for fixed POV movement ($H = 3.15$, $p < 0.551$). This does not confirm **hypothesis 1c** because subjects had similar assembly review scores in the VR and non-VR interface.

The aggregated design review score for free assembly rotation movement was shown to not be statistically

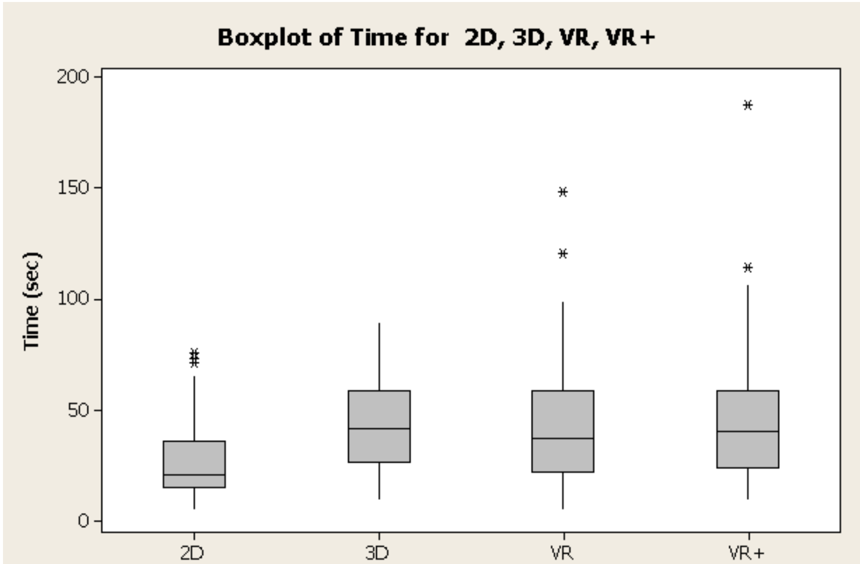


Figure 12: Experiment 1 Design Review Time Boxplot

different than the aggregated design review score for fixed assembly rotation ($H = 0.35$, $p < .530$). This does not confirm **hypothesis 1d** because subjects had similar assembly review scores with or without the ability to rotate the assembly.

The experiential survey data showed subjects preferred the VR interface over the CAD interface (see Fig. 13). Of the 43 subjects only 8.3% preferred specifically CAD and 43.8% preferred specifically VR. This demonstrates a clear preference for the VR environment as a platform for assembly reviews. Additionally, participants described the VR environment as not dizzying, without delay, and not distracting.

The results of the human spatial cognition survey can be seen in Table 6. No correlation between spatial cognition score and design review score or duration was found.

3.6 Discussion

The previous section results show there is enough evidence to confirm **hypotheses 1a and 1b** of free POV movement and free assembly rotation increasing the aggregated assembly review time. Increasing the available range of motion for subjects gives them more possibilities with which to analyze the assembly model, also leading to a more realistic interaction. Due to the novel test experience, participants actively explored the possible ranges of motion, either by changing their POV or rotating the model. This exploration increased the time taken to review the assembly model, as expected. This is clear in the aggregated review time between 2D and 3D CAD representations, where subjects reviewing models in the 2D environment took

Table 3: Experiment 1 Repeated Measures ANOVA Analysis for Design Review Time

Source	DF	Seq SS	Adj SS	Adj MS	F	P
POV	1	5424.5	3078.6	3078.6	6.26	0.013
AR	1	8359.0	3437.0	3437.0	6.99	0.009
Order	1	1345.2	488.9	488.9	0.99	0.320
Model	7	10070.4	9942.1	1420.3	2.89	0.006
POV*AR	1	3322.7	3648.5	3648.5	7.42	0.007
POV*Order	1	61.0	358.9	358.9	0.73	0.394
POV*Model	7	11027.2	11054.4	1579.2	3.21	0.003
AR*Order	1	956.7	1348.0	1348.0	2.74	0.099
AR*Model	7	5379.4	4046.8	578.1	1.18	0.317
Order*Model	7	2155.9	2155.9	308.0	0.63	0.734
Error	257	126346.1	126346.1	491.6		
Total	291	174447.9				

S = 22.1725 R-Sq = 27.57%

Table 4: Experiment 1 Statistics by Assembly Model

Model #	Mean Time [sec]	St. Dev. [sec.]	Mean Design Review Score [0-4]
1	30.51	18.41	3.53
2	35.07	19.87	2.51
3	41.43	20.84	2.47
4	44.90	20.79	2.02
5	50.00	36.16	2.56
6	42.87	23.34	1.77
7	36.70	16.40	2.84
8	34.68	23.23	2.26

less time than in the 3D CAD environment (see Fig.12). With 2D, there is no available user interaction with the model, thus there is no manner of gathering more information resulting in a short assembly review time. In the 3D environment, participants were able to rotate the model to gather more information; this rotation increases the time needed to complete the review and offers more information. Interestingly, from Fig.12 there is not much difference between the aggregated assembly review time between 3D and VR environments, regardless of the previous experience of participants being focused on CAD. This shows subjects were able to gather information through the VR interface and make a decision on the review in the same time subjects were able to make a decision in the 3D environment.

For **hypotheses 1c and 1d** the results where opposite than expected. The data did not supported those hypotheses. For the subjects in this experiment, an increase in interaction with the assembly did not result in an increase in the design review score. This can be due to multiple factors, such as figure and

Table 5: Experiment 1 Kruskal-Wallis H Test Analysis on Design Review Score

POV	N	Median	Ave Rank	Z
Fixed	172	3	175.5	0.57
Free	172	3	169.5	-0.57
Overall	344		172.5	
H=3.15	DF=1	P=0.551	(adjusted for ties)	
AR	N	Median	Ave Rank	Z
Fixed	172	3	169.3	-0.60
Free	172	3	175.7	0.60
Overall	344		172.5	
H=0.35	DF=1	P=0.530	(adjusted for ties)	
Order	N	Median	Ave Rank	Z
Non-VR	168	3	161.4	-2.02
VR	176	3	183.1	2.02
Overall	344		172.5	
H=4.50	DF=1	P=0.034	(adjusted for ties)	
Model	N	Median	Ave Rank	Z
1	43	4	233.4	4.29
2	43	3	175.9	0.24
3	43	3	173.2	0.05
4	43	1	149.3	-1.63
5	43	3	172.7	0.01
6	43	1	127.4	-3.18
7	43	3	187.5	1.06
8	43	3	160.5	-0.84
Overall	344		172.5	
H=31.90	DF=7	P=0.001	(adjusted for ties)	

Table 6: Experiment 1 Human Spatial Cognition Survey Results

Spatial Cognition Score	6	7	8	9	10	11	12
Avg. Score	2.75	2.25	1.96	2.48	2.45	2.86	2.64
Avg. Time	59	39	40	38	34	42	42
Participants per SCS	1	3	7	5	10	10	7

ground contrast in the VR environments, abstract assembly models (i.e. it does not represent a real world assembly of a machine), and simplicity of the assembly models.

After encountering these results, a usability study was conducted on the VR environment to examine any environmental effects on the participants' ability to conduct the review. It was found there is low contrast between the assembly model and the environment background. This was slightly mitigated by the lighting and shadows present on the model at the time of review but there is the possibility this could have affected the subjects ability to review the model. Additionally, the models were created using abstract design intended to form a cube. This is not a real world situation which could have affected the participants' effort to be fully engaged in the experiment. The vast difference in previous experience in CAD and VR may have led the subjects to become distracted by the novelty of the VR experience. The increase in immersion by

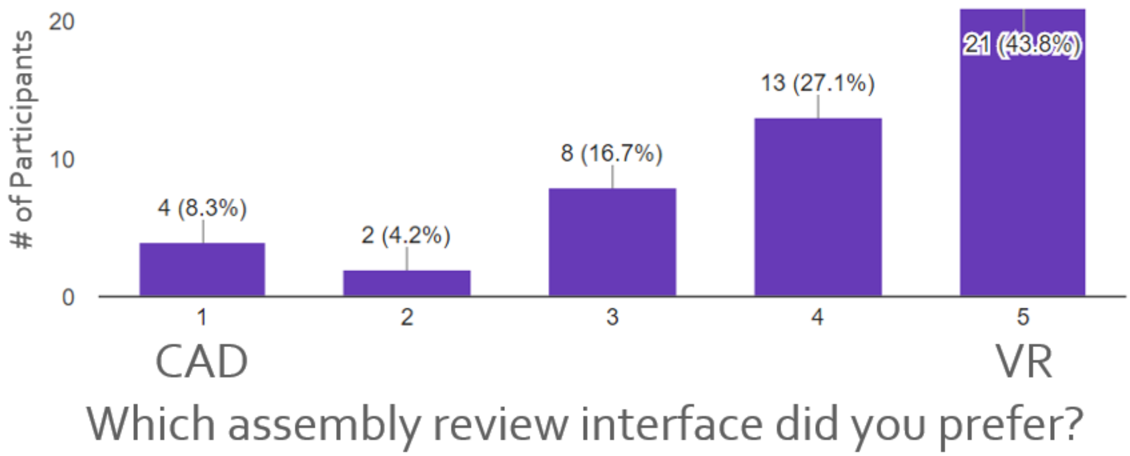


Figure 13: Experiment 1 Participant Design Review Environment Preference

VR is a step forward in terms of traditional human computer interfaces but it is not yet widely used.

The limitations of the VR assembly review system can be explained by the lack of previous experience when using the setup. The data demonstrates there is no significant difference between the assembly review ability of trained CAD users and new VR users. Additionally, there is a strong preference for using VR as an assembly review platform as evidenced in Fig.13. This presents an opportunity for industry to incorporate VR assembly reviews without extensive training or sacrificing the quality of their assembly reviews. Naturally, the VR setup and environment interface can be improved, as evidenced by the usability study.

In the next iteration of this experiment the authors improved the assembly review environment for contrast between the assembly and its surroundings. Also, models will be based on real machines to increase complexity of the model and to have a concrete, instead of abstract, assembly model. With these changes, **hypotheses 1c and 1d** could be re-evaluated.

This work documented that designers preferred the VR system for design review over the traditional system. It was witnessed how subjects quickly learned to use the VR system. The implementation of when to use VR over CAD visualization is still unclear, however, the user preference of the tool, which is something important, already exists.

3.7 Summary

Virtual reality enabled designed reviews are as effective in finding errors in assemblies as traditional design reviews, however there is potential to increase its usefulness. The intuitiveness of the VR environment allows the participants to have a more natural engagement with the assembly models, lessening the need of previous experience required to successfully analyze virtual prototypes. Further research can be used to improve the VR environment and facilitate participants intuitive ability to review virtual prototypes. The comparable design review scores of participants in CAD and VR design reviews, coupled with the low cost of the VR HMD hardware used, presents an opportunity for industry to increase the amount of assembly reviews performed earlier in the process without sacrificing the quality of reviews or having to invest in extensive training.

4 CHAPTER 4 EFFECTS OF IMMERSION ON VIRTUAL REALITY PROTOTYPE DESIGN REVIEWS OF SIMPLE MECHANICAL ASSEMBLIES

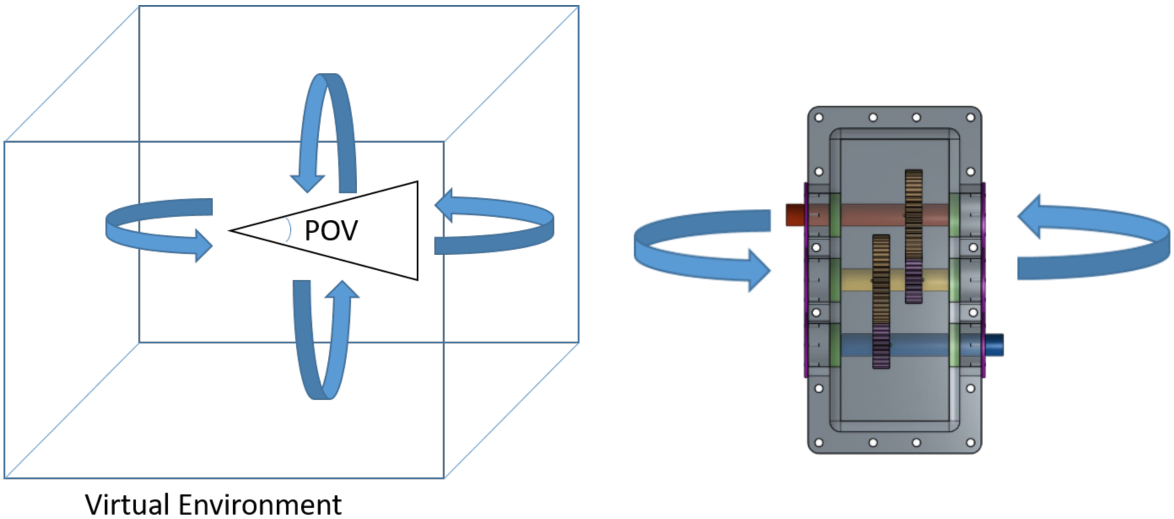
4.1 Introduction

This chapter details two experiments, a modified version of the first experiment detailed in chapter 3 with realistic mechanical assemblies and an experiment exploring the effects of using different commercially available input controllers on the ability of participant to identify errors in a complex mechanical assembly.

The manner in which a human interacts with a virtual environment is directly affected by the design of the controls at hand. The keyboard and mouse interface is still dominant after decades in part because the manner in which most of the virtual world also has not changed that being the 2D webpage modeled after a piece of paper representing 2D information. Additionally the only actions to be completed by the participant in such a webpage is to view, click, and input information which is the design intent of the keyboard and mouse. With the development of 3D worlds such as in video games other tasks became available such as navigation by lateral movement within the virtual environment.

With these new tasks came the development of alternative interfaces such as the gamepad which provide a greater level of intuitiveness and creative engagement with the virtual environment. Additionally with the development of virtual environment with the purpose of simulating real world situations such a driving a car or flying a plane came controllers with the design intent of mimicking real life controller mechanisms. These controllers vary greatly from the keyboard and mouse because of providing mechanisms such as joysticks to manipulate the axis of 3D space or 3D objects. However, the keyboard and mouse is still able to complete these tasks because the user is able to view the equipment. With the advent of VR, the viewer's sense of presence has gone from the real environment to virtual environment due to the complete engagement of their visual senses. At this point the keyboard interface proves difficult to use because the user is not able to see the equipment.

In the previous chapter, experiment 1 used abstract cube assemblies to assess the participants ability to find errors in virtual prototypes. However, since this was the first time participants have seen an assembly of this kind they were not familiar with the design intent and had difficulty assessing what consisted of an error in those specific assemblies. For this reason in this chapter, experiment 2 and 3 used virtual prototypes of a gearbox and rack and pinion assemblies due to the participants familiarity with these assemblies through their engineering education. This allows the participants to analyze the virtual prototype while understanding



(a) POV Movement (b) Assembly Rotation

Figure 14: Experiment 2 Factors of Human Interaction with Virtual Environment

its design intent. Additionally, the real world virtual prototypes contained more complex and realistic interactions between components compared to the abstract cube assemblies, leading to more realistic errors being created for analysis.

4.2 Experiment Methodology

4.2.1 Experiment 2: Design Review with Varying Immersion (Output Devices)

This portion of the experiment measures the participants' ability to identify different CAD assembly errors in four different environments with varying levels of interaction. To modify each environment interaction we use two factors: user POV movement, and assembly rotation. User POV movement enables the user to change their viewpoint inside the environment. Assembly rotation is the manner in which the participant can manipulate an object inside the environment (see Fig. 14a and 14b, respectively). By enabling and restricting each functionality, four environments are created: static image (2D), CAD environment (3D), VR Static assembly (VRS), and VR Dynamic assembly (VRD), see Fig. 15.

Sixteen gearbox assemblies with unique errors where developed for participant design reviews (see Fig. 16 for an example). Three different types of errors were purposely implemented in the assemblies: misalignment, collision, and ergonomic. A misalignment error is evident when a component is not in the correct position but is not interfering with another component, see Fig. 17. A collision error is seen when a component is out

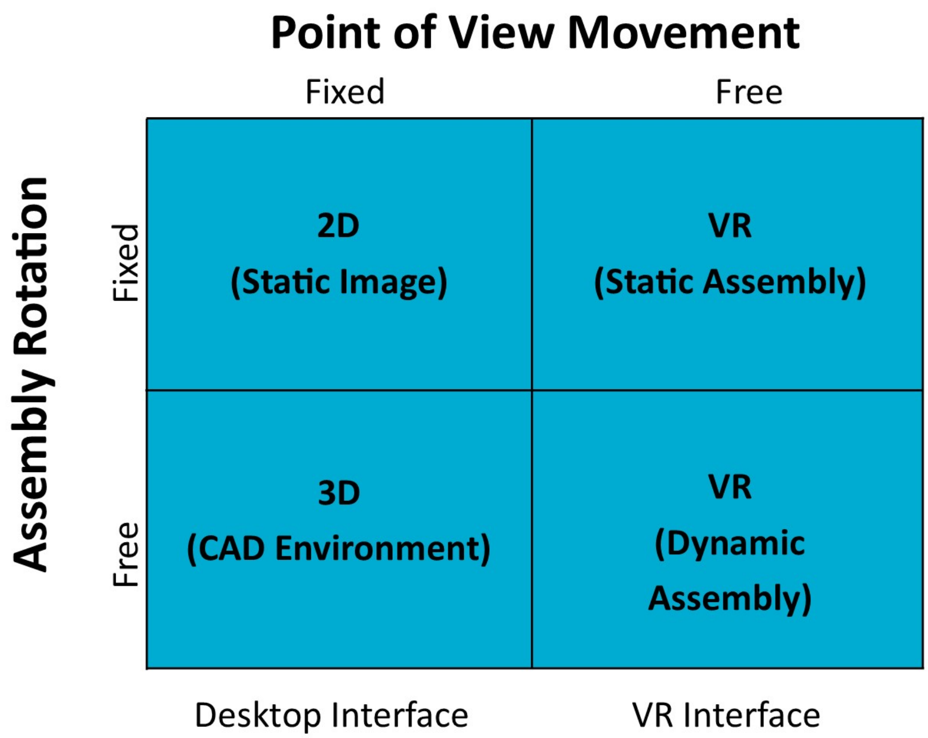


Figure 15: Experiment 2 Factors and Design Review Environments

of position and interfering with another component such that there is one volume inside another, see Fig. 18. An ergonomic error occurs when the position of components or subassembly interfere with the assembly or disassembly of the gearbox, see Fig. 19. Each error was created to be distinctively different from other error types to prevent confusion among the participants when performing the design review. In the design review the participants were asked two questions. First they are asked "*Are there CAD errors present?*" and afterwards are asked "*If there are CAD errors present where are they located? If no errors are present select none.*" Participants are able to select from a multiple choice list presented on the wall in the virtual environment. The answer list always includes the option to select "None" or "Other" to prevent participants using the answer list to find errors. Different to experiment 1, the design review score data in experiment 2 is binary, meaning each design review can be either correct or incorrect. If the participant succesfully identifies the type of error and location of the error if there is one, that design review will be deemed successful, providing a more realistic design review experience compared to using abstract assemblies. Each one of the participants performed assembly reviews on all sixteen assemblies, four in each of the four environments. To mitigate order bias, eight different assembly review testing orders were created. This allows each model to be reviewed in the four different environments. Additionally, the subjects will alternate which environment they begin with, low to high immersion testing order or vice versa.

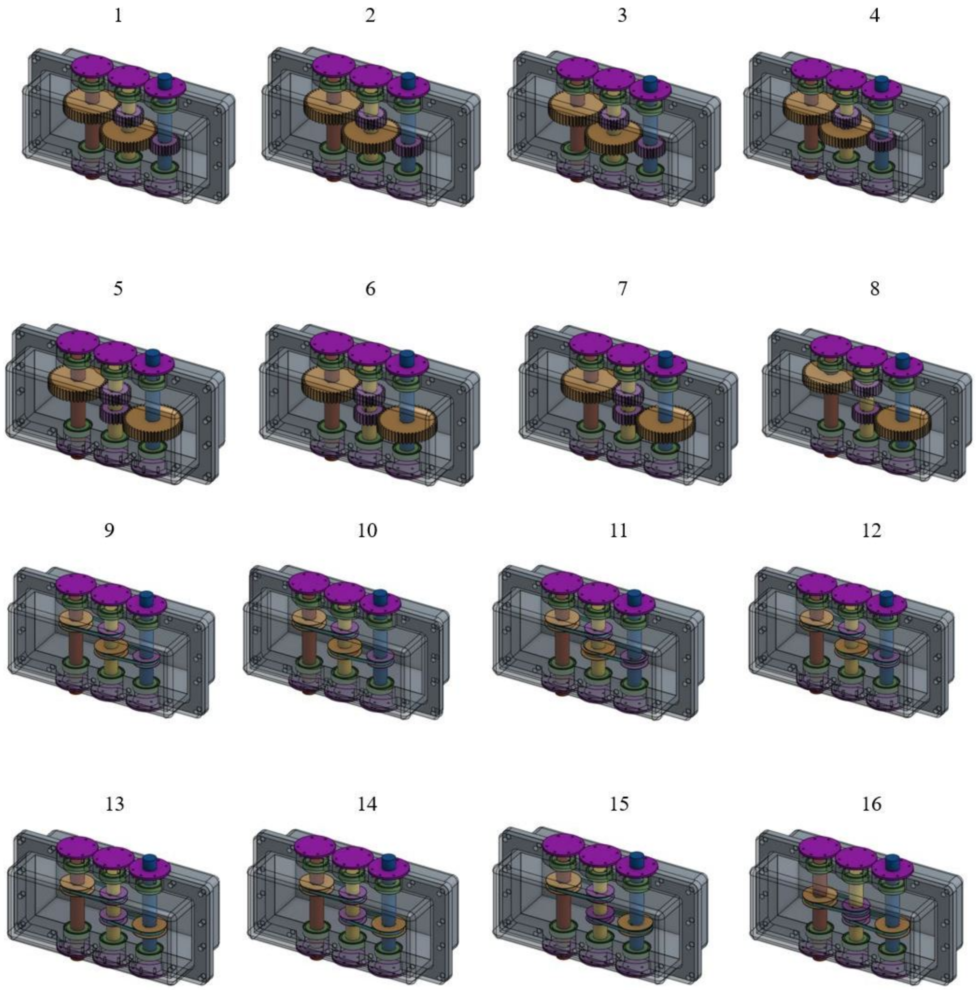


Figure 16: Experiment 2 Gearbox Assemblies for Design Review

The 2D design review environments used an online survey tool featuring both a top view and isometric view of the assembly (see Fig. 21). The environment uses a traditional computer setup hardware consists of a 24-inch computer monitor with 1920 × 1080 pixel resolution and a keyboard/mouse as the controller. Participants were asked to answer multiple choice questions to identify the nature and location of the errors.

The 3D design review environment used an online survey tool and embedding a CAD window via an e-drawings plugin, where participants were able to interact with the model similarly to a traditional CAD environment. Participants are able to drag, rotate, zoom objects as well as use section views (see Fig. 22). The environment uses a traditional computer setup hardware consists of a 24-inch computer monitor with 1920 × 1080 pixel resolution and a keyboard/mouse as the controller. Participants were asked to answer

Figure 17: Experiment 2 Example of Misalignment Error between Gears

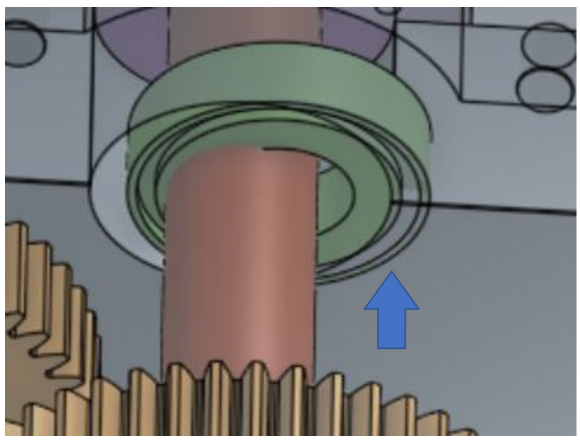


Figure 18: Experiment 2 Example of Collision Error between Bearing and Wall

multiple choice questions to identify the nature and location of the errors.

The VR design review environments where created using a video game engine due to its versatility and easy integration of alternative consumer controls such as the gamepad, joystick and keyboard. To view the environment the participants used a HMD as an output device and gamepad as the controller. Subjects were asked to answer multiple choice question that were constantly displayed on the walls along with simple instructions.

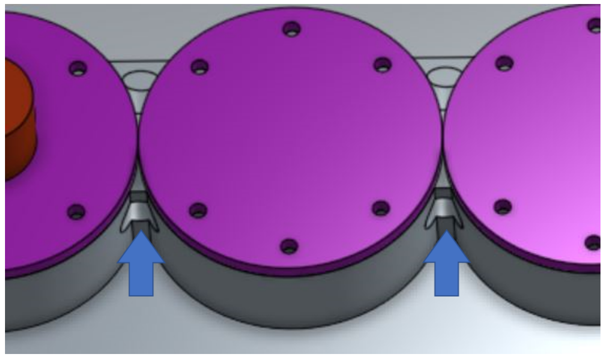


Figure 19: Experiment 2 Example of Ergonomic Error of Bolt-hole

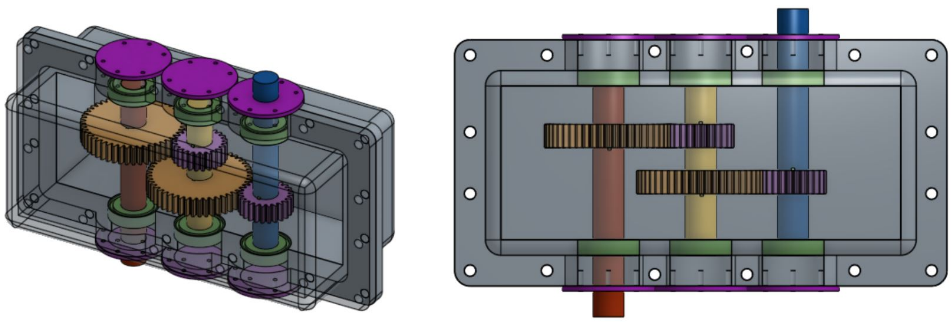


Figure 20: Experiment 2 Gearbox Assembly for Design Review

4.2.2 Experiment 3: VR Design Review with Different Controllers (Input Devices)

This task measures the participant's proficiency to locate errors in virtual prototypes when using different controllers to interact with the virtual environment. The three controllers used can be seen in Fig. 24 in which a) is the gamepad, b) is the joystick, and c) is the keyboard/mouse. The participant will complete three design reviews with each controller for a total of nine. All CAD assemblies were created for review based of a rack and pinion assembly, see Fig 25. Eight of the nine assemblies were created with an intentional error, while the remaining assembly is a control sample and does not have an error. The intended errors are collisions between two or more components, evident by one volume inside another. This assembly is presented to the participant floating in the center of the virtual environment, which is a small room with four walls. Participants will be able to rotate each assembly using the controller for better viewing angles. Inside this virtual environment the participant will answer the question which is posted on the wall "*Is there a CAD error present? If so where?*" Participants can select their answer by using the controller and cycling through the available answers. Different to experiment 1, the design review score data in experiment 2 is binary, meaning each design review can be either correct or incorrect. If the participant succesfully identifies the

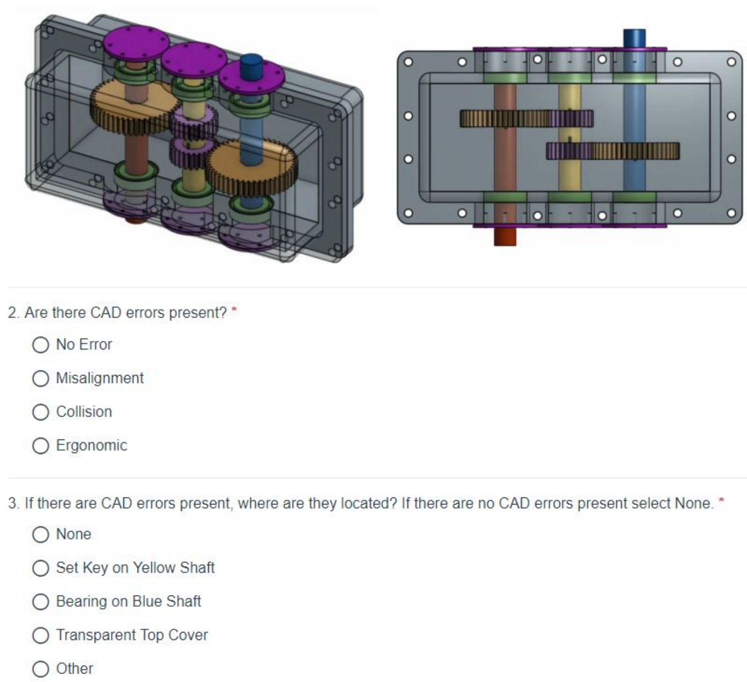


Figure 21: Experiment 2 2D Design Review Environment (Static Image)

type of error and location of the error if there is one, that design review will be deemed successful, providing a more realistic design review experience compared to using abstract assemblies. To mitigate order bias, six different controller testing orders and two different assembly testing orders were create for a total of twelve unique trials. Each participant will complete one trial according to their participant number.

The virtual environment was creating using video game software, Unreal Engine 4. For this phase there are two VR environments. First the participant begins in the introductory environment to familiarize themselves with the three controls and the rack and pinion assembly without errors. In this intro level, participants are able to practice maneuvering the environment, rotating the assembly, and answering the question prompt with each controller. Once, the participant is ready and is moved to the experiment environment, only one controller at a time will allow interaction with the level to ensure the participant uses the correct controller for each assembly being reviewed.

4.3 Participants

The format of the experiments were submitted and approval by the IRB board prior to soliciting participation (Protocol num. 20160106). Participants were required to have previously passed a CAD course and have normal or corrected to normal vision. Subjects voluntarily participated in the study and no compensation

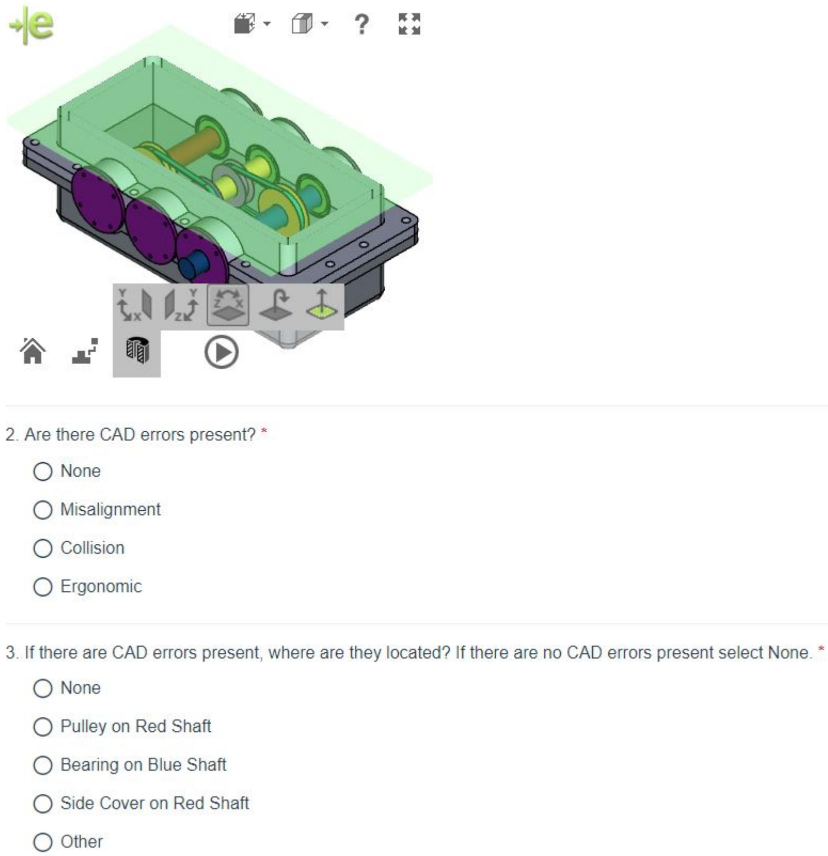


Figure 22: Experiment 2 3D Design Review Environment with Section View (CAD Environment)

was offered. The experiment data consists of design reviews performed by 40 participants (31 males; 9 females). The age range of participants was from 19 to 33 years old, with an average age of 24. Of the 40 participants, 24 stated to have used CAD personally or for student projects, 19 stated to have no prior VR experience and 10 which had between 1 and 2 hours of experience. Out of 40 design review trials, one participant was not able to participate in the study due to dizziness and another participant was used to complete that specific trial from the beginning.

4.4 Hypothesis

The general hypothesis for experiment 2 is: subjects will spend more time reviewing assembly models if they have more interaction such as free POV movement and free assembly rotation. Additionally, with this added range of interaction subjects will be able to analyze more information and increase their design review score. With that in mind, the following are investigated:

Figure 23: Experiment 2 VR Design Review Environment

- **Hypothesis 2a:** The aggregated design review time with free POV movement will be statistically higher than the aggregated design review time with a fixed POV.
- **Hypothesis 2b:** The aggregated design review time with free assembly rotation will be statistically higher than the aggregated design review time with a fixed assembly rotation.
- **Hypothesis 2c:** The aggregated design review score with free POV movement will be statistically higher than the aggregated design review score with a fixed POV.
- **Hypothesis 2d:** The aggregated design review score with free assembly rotation will be statistically higher than the aggregated design review score with a fixed assembly rotation.

The general hypothesis for experiment 3 is: subjects will spend less time reviewing models when using the gamepad or joystick controller than the keyboard and mouse specifically with subjects who have video game experience. Subjects without video game experience will spend more time using the keyboard and mouse due to its difficulty of use when in VR. With that in mind, the following are investigated:

- **Hypothesis 3a:** The aggregated design review time with gamepad and joystick controller will be statistically higher than the aggregated design review time with keyboard controller.
- **Hypothesis 3b:** The aggregated design review score with gamepad and joystick controller will be statistically higher than the aggregated design review score with the keyboard controller.

a b c

Figure 24: Experiment 3 Input Controllers used as Factors

In total, 40 subjects completed the experiment. Commonly, the whole experiment was approximately 65 minutes. For each environment-model combination the design review score and completion time was recorded.

4.4.1 Experiment 2

The assembly review time data is a continuous variable, thus a repeated measures ANOVA was used to analyze the data. The review time data was submitted to a 2 (POV: fixed and free) × 2 (Assembly Rotation: fixed and free) × 2 (Order: VR first and non-VR first) × 16 (Assembly model: sixteen different assemblies) repeated measures ANOVA (see Table 7). This is a statistical test that determines whether or not the means of review time are equal. Significant results are as follows.

There are three main effects: POV, assembly rotation, and assembly model. The aggregated design review time for the fixed POV ($M = 89.30$, $SD = 64.49$) is statistically longer than the aggregated design review time for the free POV ($M = 78.70$, $SD = 42.70$), ($F = 7.84$, $p < 0.005$). This rejects **hypothesis 2a**: that subjects spent significantly more time in VR based design reviews than the non-VR design reviews reviews.

The aggregated design review time for the fixed assembly rotation ($M = 67.35$, $SD = 43.72$) is statistically shorter than the aggregated assembly review time for the free assembly rotation ($M = 100.66$, $SD = 59.77$), ($F = 77.46$, $p < 0.000$). This confirms **hypothesis 2b**: that subjects spend more time in assembly review when the assembly is able to rotate on at least one axis.

The assembly model had a significant effect on review time ($F = 4.03$, $p < 0.000$). Table 8 displays the means and standard deviations of review time by assembly model. The assemblies used in the experiment

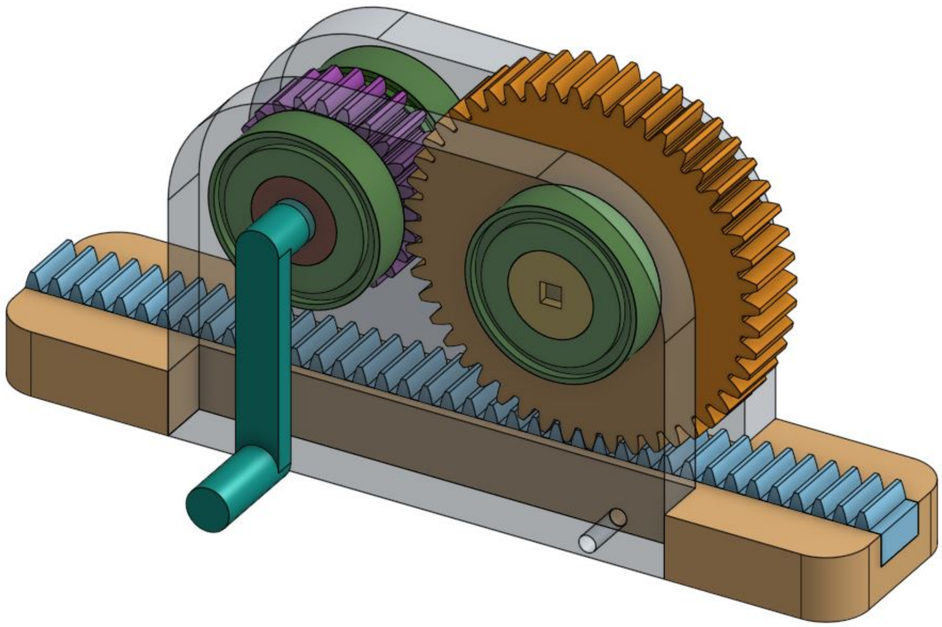


Figure 25: Experiment 3 Rack and Pinion Assembly for Design Review

had errors varying levels of difficulty.

There are four interaction effects: POV × assembly rotation, POV × assembly model, POV × order, and assembly rotation × order. The aggregated assembly review time statistically increases when the participant has free assembly rotation. ($F = 37.97$, $p < 0.000$). The aggregated assembly review time was shown to be significantly affected by the interaction of POV and the varying difficulty of errors present in assembly models ($F = 3.21$, $p < 0.003$). Participants performing design reviews with free assembly rotation and POV fixed levels show a significant increase in time compared to free assembly rotation POV free levels ($F = 10.81$, $p < 0.001$). Participants performing design review with POV fixed levels and free assembly rotation showed a significant increase in time compared to POV fixed levels with fixed assembly rotation (see Fig.26).

The design review score is captured using a multiple choice selection. The participant answer was scored 0 for incorrect and 1 for correct. Therefore the score data was submitted to a two-tailed z test against POV and assembly rotation. This statistical test allows us to determine whether or not the means of the design review scores are equal against the experiment factors: POV and assembly rotation. The mean and standard deviation of the design review score for each level are: 2D ($M = 0.44$, $SD = 0.50$), 3D ($M = 0.53$, $SD = 0.50$), VRS ($M = 0.70$, $SD = 0.49$), VRD ($M = 0.61$, $SD = 0.46$) as seen in Fig. 28. The significant results are as follows:

Table 7: Experiment 2 Design Review Time ANOVA Analysis

Source	DF	SS	MS	F	P
POV	1	17964	17964	7.84	0.005
Assem. Rot.	1	177500	177500	77.46	0.000
Assembly	15	138653	9244	4.03	0.000
Order	1	4991	4991	2.18	0.141
POV*Assem. Rot.	1	86995	86995	37.97	0.000
POV*Assembly	15	80001	5333	2.33	0.003
POV* Order	1	24759	24759	10.81	0.001
Assem. Rot.*Assembly	15	27217	1814	0.79	0.687
Assem. Rot.*Order	1	37631	37631	16.42	0.000
Assembly*Order	15	23752	1583	0.69	0.795
Error	573	1312952	2291		
Total	639	1932414			

S = 47.86 R-Sq = 32.06%

Assembly No.	1	2	3	4	5	6	7	8
Mean Time (sec)	92.3	79.5	63.3	92.7	91.2	107.0	102.3	92.8
Assembly No.	9	10	11	12	13	14	15	16
Mean Time (sec)	94.9	64.3	53.3	82.6	87.3	95.0	77.5	68.1

Table 8: Experiment 2 Average Design Review Duration per Assembly Model

The aggregated design review score for the fixed POV (M = 0.48, SD = 0.50) is statistically less than the aggregated design review score for the free POV (M = 0.65, SD = 0.47), (z = 4.23, $p < 0.000$). This confirms **hypothesis 2c**: that subjects succesfully identified more errors in VR based design reviews than the non-VR design reviews. The design review score was similar with and without assembly rotation. Thus, there is not enough evidence to support **hypothesis 2d**.

The results of the human spatial cognition survey can be seen in Table 9. No correlation between spatial cognition score and design review score or duration was found.

Table 9: Experiment 2 Human Spatial Cognition Survey Results

Spatial Cognition Score	4	6	8	9	10	11	12
Avg. Score	0.75	0.59	0.31	0.53	0.5	0.61	0.6
Avg. Time	92	76	57	76	87	83	92
Participants per SCS	1	2	1	6	7	13	10

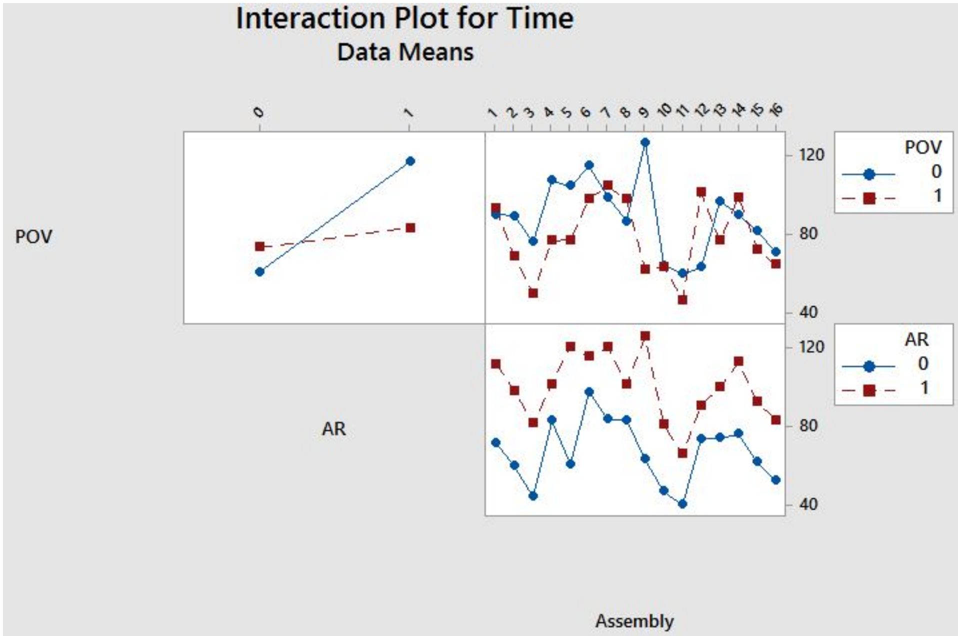


Figure 26: Experiment 2 Design Review Time Factor Interaction Plot (0 = fixed, 1 = free)

4.4.2 Experiment 3

Regarding experiment 3, design reviews with different controllers, the time data was subjected to a 3 (Controller: gamepad, joystick, keyboard) × 2 (Order: Order 1 and Order 2) × 9 (Assembly model: nine different assemblies) repeated measures ANOVA. This test determines if there is significant difference between the means of the design review times. The significant results are as follows:

The aggregated design review time for participants beginning the experiment with Order 1 ($M = 70.97$, $SD = 55.25$) is statistically higher than the aggregated assembly review time for participants beginning the experiment with Order 2 ($M = 57.17$, $SD = 32.24$), ($F = 9.25$, $p < 0.003$). This shows that participants who started with the most difficult design reviews first, Order 1, took longer overall to complete their design reviews. Note that Order 2 is Order 1 reversed.

The assembly model was shown to have a significant difference on the design review time regardless of controller used ($F = 9.10$, $p < 0.003$). This shows assemblies with increasing difficulty of CAD error required more design review time than assemblies with simpler errors. There was no significant difference in design review time between gamepad, joystick, and keyboard controllers. Thus, we cannot confirm **hypothesis 3a**.

The design review score is captured using a multiple choice selection. Therefore the two-tailed z test is used to analyze the data. The design review score data was submitted to a two-tailed z test against

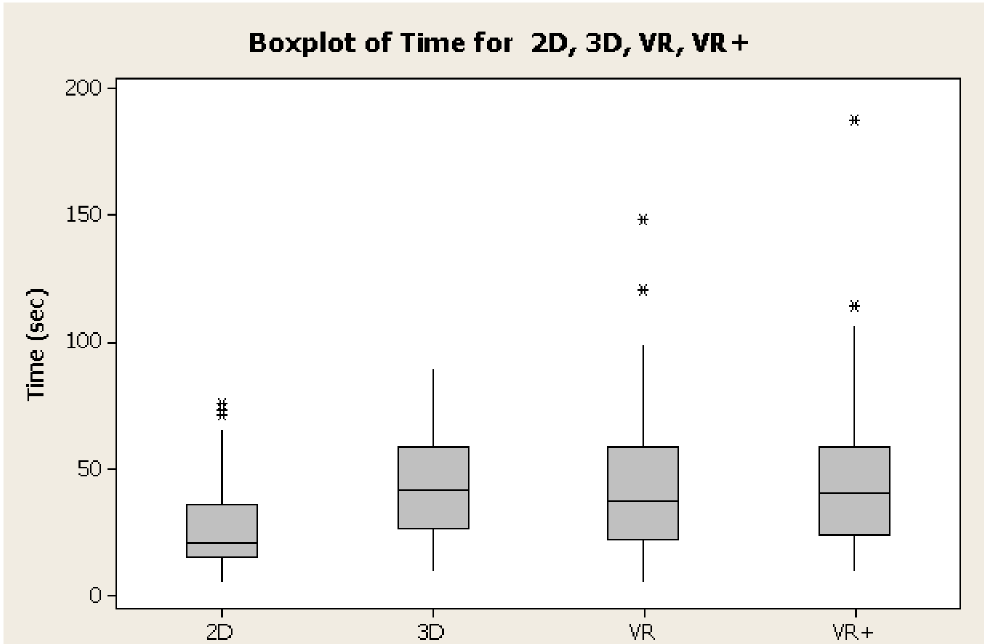


Figure 27: Experiment 2 Design Review Time BoxPlot

the controller method used. This statistical test allows us to determine whether or not the means of the design review scores are equal against the experiment controller factor: gamepad, joystick, and keyboard. Significant results are as follows:

The aggregated design review score was found to be significantly higher when participants used the gamepad controller ($M = 0.7$, $SD = 0.46$) when compared to the keyboard ($M = 0.61$, $SD = 0.49$), ($z = 2.44$, $p < 0.007$). There was no significant difference found comparing design review scores using the joystick controller against design reviews using the gamepad or keyboard controllers. This shows that **hypothesis 3b** was partially confirmed, the gamepad controller design review score was significantly higher

Table 10: Experiment 3 Design Review Time ANOVA Analysis

Source	DF	SS	MS	F	P
Controller	2	989	494.6	0.27	0.764
Order	1	16963	16963.3	9.25	0.003
Assembly	8	133537	16692.1	9.10	0.000
Error	348	638233	183 4.0		
Lack of Fit	42	125671	2992.2	1.79	0.003
Pure Error	306	512562	1675.0		
Total	359	789745			
S = 42.83		R-Sq =	19.18%		

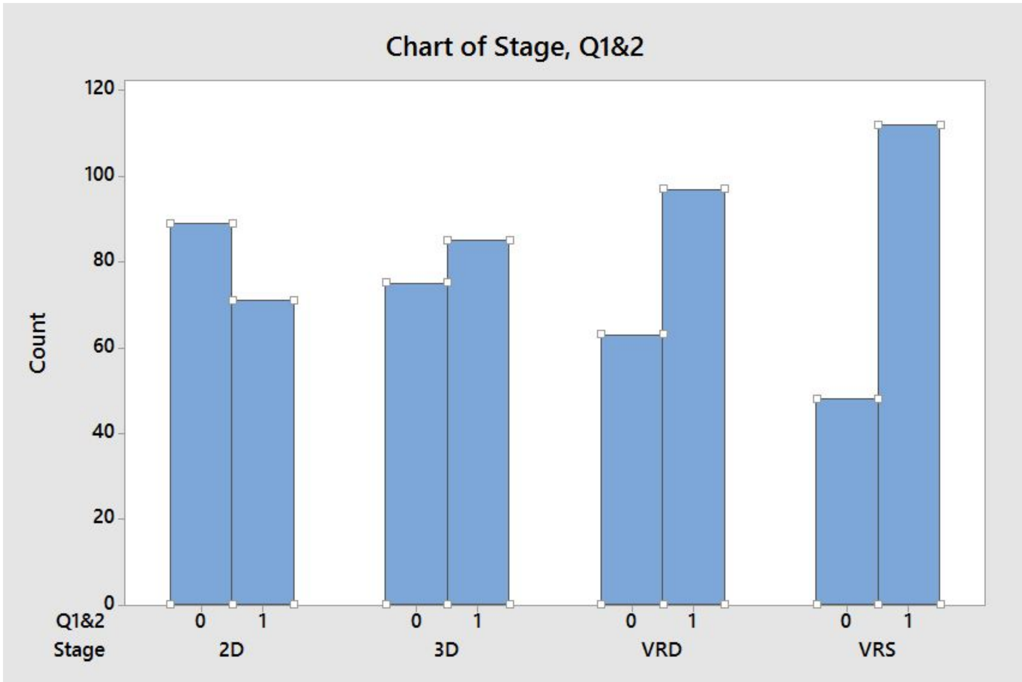


Figure 28: Experiment 2 Design Review Score Chart (0 = incorrect, 1 = correct)

Table 11: Experiment 3 Human Spatial Cognition Survey Results

Spatial Cognition Score (SCS)	4	6	8	9	10	11	12
Avg. Score	0.69	0.56	0.75	0.66	0.75	0.69	0.5
Avg. Time	67	76	52	90	57	68	53
Participants per SCS	1	2	1	6	7	13	10

than the keyboard but the joystick was not significantly higher than the keyboard.

The results of the human spatial cognition survey can be seen in Table 11. No correlation between spatial cognition score and design review score or duration was found.

4.5 Discussion

The results show there is not enough evidence to support **hypothesis 2a**, participants do not necessarily spend more time in VR design reviews when compared to non-VR design reviews such as with 2D and 3D renderings on a computer screen. This could be because with free POV participants are able to explore the assembly more naturally and quickly than with fixed POV in which they need to mentally visualize other POVs to explore the assembly.

The results show there is enough evidence to support **hypothesis 2b** where the duration of design reviews increase when assembly rotation is available to the participants. This is due to the increased amount of interactions available to participants at one time. Since the rotation is smooth in order to go from one angle to a desired rotation the assembly has to pass from one degree to the next, this can show to the subject areas that initially where not of interest and that will increase the time.

The results show there is enough evidence to support **hypothesis 2c**, where free POV movement results an increase in design review score as compared to a fixed POV environment. This shows participants had higher design review scores in VR environments than 2D and 3D environments, demonstrating the correlation of having highly realistic virtual prototypes and higher quality design reviews. This might be because the increase realism makes it easier to spot errors in the assembly and because the subject does not have to imagine how the assembly is from different POV because it has access to all desired POVs. This adds further support to the possibility of participants having excessive interaction in highly immersive environments to perform design reviews efficiently, with high quality and shortest duration.

The results show there is not enough evidence to support **hypothesis 2d**. This shows assembly rotation may not have a significant effect on design review score whether in low immersion or high immersion environments. This means for designers that in order to review mechanical assemblies the rotation of the assembly is not an important factor for error finding. Additionally, in VR environments, having a static virtual prototype resulted in a not significant but observable improvement in design review scores. This shows there may be a point where excessive immersion can reduce the subjects ability to identify errors because they are taxed with manipulating the virtual environment. There are specific interactions which prove more valuable to the immersive experience than others such as the head motion tracking allowing participants to naturally explore their environment shows greater immersiveness than peripheral controllers to manipulate the environment. More natural and intuitive control schemes allow for better behavior inside a virtual environment due to its realism.

With regards to experiment 3, there is not enough evidence to support **hypothesis 3a**. This shows there is no significant difference in duration of design reviews between the three controller inputs used: gamepad, joystick, or keyboard. These might be because all are traditional interfaces and contribute similar value to a participant's level of environment manipulation. However, there is enough evidence to support **hypothesis 3b**, stating there is a significant increase in the average design review score specifically when using the gamepad versus the keyboard. This might be because, 28 of 40 participants reported over 10 hours of experience with the gamepad for video game use as compared to 20 participants reporting over 10 hours of use with a keyboard for specifically for video games and 5 participants reported over 10 hours for joystick use. This demonstrates participants are able to leverage previous experience with input controllers to effectively interact with the virtual environment, improving their design review performance. The joystick showed a higher than average design review score versus the keyboard but the result was not statistically significant. This demonstrates the increased variety of interaction a participant has with the gamepad proves valuable when manipulating objects and characters in virtual environments.

4.6 Summary

This chapter demonstrates there is a significant advantage to incorporating VR design reviews when compared to traditional methods partly due to the increased realism of the environment and virtual prototype. Additionally, the results show that immersion can affect the quality and duration of design reviews, thus it is important to achieve a balance in user interactions in a virtual environment to achieve efficient behavior. Nevertheless, the use of commercially available VR has the potential to increase the quality of engineering design reviews, potentially decreasing cost and duration of the overall product design process. This research demonstrates HMD VR provides an improvement in the identification of errors in mechanical assembly virtual prototypes when compared to 2D representations of engineering designs. Further research can be performed to explore what is the ideal amount of immersion for a subject to identify errors efficiently. Additionally, there is an opportunity to research innovative input controllers for interfacing with virtual environment as it is clear the keyboard and mouse setup is not ideal and the intuitiveness of the controller is key to allowing the participant to successfully perform design reviews without extensive training.

5 CHAPTER 5 OPEN PLATFORM FOR VIRTUAL REALITY DESIGN REVIEW WITH HMD

5.1 Introduction

This chapter details the front end design of online web platform open to public for VR enabled design reviews of 3D models using an HMD. The web platform provides a database of 3D models which can be viewed using the Google Cardboard platform and incorporates the virtual environment interactivity which was found to be most effective for performing VR design reviews; which is to allow the participant to move freely within the virtual environment and to have the 3D model remain static.

5.1.1 The Problem

While HMDs provide a more cost effective alternative to larger CAVE systems, the hardware necessary to render the virtual environment can still be a barrier to small or medium corporations who may want utilize this technology for a more streamlined product development process. A CAVE system in 2012 could cost up to $926k and at the time of writing an Oculus Rift costs $400 not including a computer with the ability to render the virtual environment, where an expensive and high performance graphics processing unit (GPU) is needed costing at least $750. This equipment is necessary to render a high resolution virtual prototype and to render the virtual environment at a speed which enables the user to navigate naturally without lag or decrease in resolution. In comparison the official Google Cardboard headset only costs $15 because it leverages the user's smartphone as the display. Today's smartphones include an accelerometer and a gyroscope which allow it accurately track directional prositioning of the user's POV. However, while theoretically possible, the accelerometer and gyroscope are not enough to accurately calculate positional tracking, where the user stands in 3D space in relation to the real world environment.

To achieve positional tracking where the user is able to change there position in the virtual environment an infrared camera and sensors are commonly used, this further requires the HMD to be connected to a computer with GPU for these calculations to be completed, limiting the portability and accesibility of VR setups.

At the time of the experiments lower cost options such as the Samsung gear VR or google cardboard, setups leveraging the use of a smartphone have the necessary high resolution screens to perform high quality design reviews but lack the ability to calculate its position within 3D space without an additional sensor to the gyroscope and accelerometer. This is because there significant error or drift when position is integrated twice from accelerometer data. For this reason HMDs which provide positional tracking use an external infrared sensor. The lack of positional tracking creates an experience where the user is able to change their viewpoint direction within the virtual environment but are not able to change their position which may aid the participant's ability to identify errors in virtual prototypes.

While current HMDs with positional tracking require an external infrared sensor, manufacturers are moving towards solutions which do not require being tethered to a computer in an effort to expand their market. For this untethered VR experience with positional tracking to be available on lower cost options is unknown. However, there is an opportunity to incorporate augmented reality technology to achieve this result. Augmented reality (AR) or mixed reality imposes virtual objects in the real environment. The HMDs in this space use integrated cameras to detect the 3D space around the user. Thus smartphone using HMDs already have the necessary equipment to achieve positional tracking by having at least one high quality camera.

5.2 Platform Front End Design

The web platform designed features a simple interface meant to be used with the Google Cardboard HMD which uses a smartphone. The user is first presented with a database and the options to upload a custom .stl file for design review. Once loaded, the user selects their model and is placed in the design review environment. It is at this point the user will put on the Google Cardboard and be able to view the loaded 3D model in VR. With the incorporation of three.ar.js code library the user is able to naturally move their head around the virtual prototype achieving the same level of interaction found to be best in experiment 2 where the user is able to have POV freedom while their virtual prototype remains static. The architecture of the web platform consists of an .stl database made with PHP and an HTML file as the stl viewer using the three.js library to render 3D models. This allows users to upload .stl models of virtual prototypes.

To complete this platform the backend architecture needs to be developed. The current setup including only the three.js library and Google Cardboard allows the viewer to see their .stl file in a VR HMD environment but are restricted to only directional tracking. The viewer has the ability to intuitively change their viewpoint of the environment, however they are lacking positional tracking where if they move their head forward to take a closer look at the object in review their point of view does not change. This restricts the viewers ability to inspect the 3D model. To add positional tracking, the three.ar.js library needs to be included for the smartphone camera be able to detect the 3D environment and calculate changes in position in relation to the surround objects. Using the augmented reality functions allow the software to anchor the

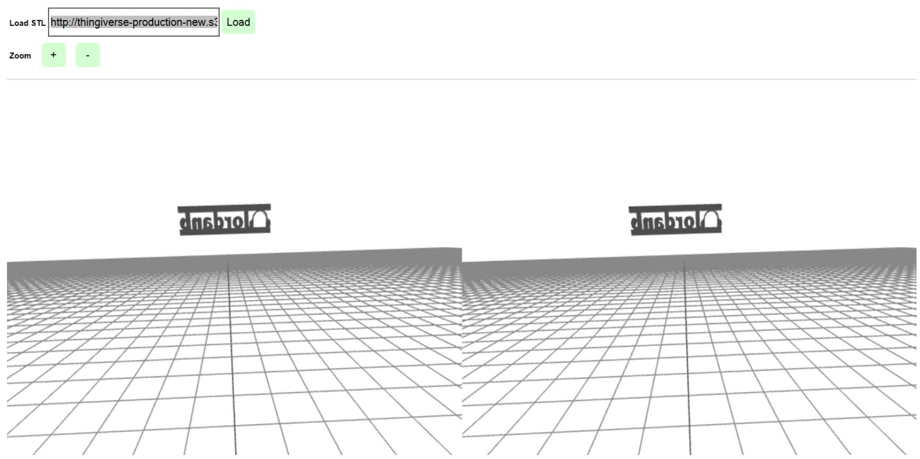


Figure 29: Web STL Viewer

3D model to a surface and allow the viewer to move around the virtual space without changing its position or orientation. A challenge in completing this is the granting of camera permission from a web platform as there are elements of web security.

5.3 Summary

Through this development it is demonstrated that untethered design reviews are feasible at low cost and providing a high quality virtual prototype. Through the incorporation of three.ar.js augmented reality library the untethered HMD is able to produce positional tracking providing more immersion than without. This provides the opportunity for VR design reviews to take place at each design engineers desk without the need for dedicated space or computer hardware to be able to use other VR equipment. Due to the limited processing power of this hardware it is advisable that VR design reviews performed with the Google Cardboard be simple in nature and best done earlier in the process with less complex models. More complex virtual prototypes will still need considerable rendering abilities.

6 CHAPTER 6 CONCLUSION AND FUTURE WORK

6.1 Conclusions

This research demonstrates how VR via HMDs provides an improvement in design review quality versus traditional human computeer interfaces without the cost or space needed by traditional VR systems such as the CAVE. To reach this conclusion over 2 years of virtual environment development and validated by over 120 unique human trials. This conclusion was supported via three experiments: 1) tested the factors of point-of-view freedom and assembly rotation freedom in design review environments using abstract virtual prototypes and the peripherals used to visually render that environment to the viewer; 2) tested the factors of point-of-view freedom and assembly rotation freedom in design review environments using realistic virtual prototypes; 3) tested three different input control methods to measure their effect on a subjects ability to interact with a virtual design review environment and tasks. From these experiments it was found that having the ability to rotate the virtual prototype increases design review duration but does not necessarily increase the quality of the design review performed. Secondly, having point-of-view freedom (such as in VR environment) increases the quality of design reviews wherein participants identified more errors in virtual prototypes without an increase in design review duration. This may be a result of the intuitive interaction the HMD affords the viewers as there is more visual and spatial information to inspect of a virtual prototype but it is performed in a realistic fashion. Additionally, subjects demonstrated an increase in VR design review quality when using a gamepad or joystick when compared to the keyboard and mouse. The results of this study shed light on the effect the human computer interface and representation of a virtual prototype has on the ability of a viewer to navigate a virtual envinronment and mentally understand the spatial features of a virtual object.

These results illustrate the advantages of incorporating VR design reviews via HMDs industry product development processes. The use of HMDs versus traditional methods of rendering virtual prototypes allow for design engineers to have a more realistic rendering of their design. This leads to the opportunity of performing design reviews with more realistic virtual prototypes facilitating a better environment for identifying design errors. Additionally, the cost effectiveness and minimal space requirement of the HMD allow there to be one HMD for each engineer instead of one CAVE system for all engineers, alleviating the bottleneck of equipment availability to perform VR design reviews. This results in more design errors being found earlier in the process decreasing cost and time spent during the product development process. The design review assemblies used resemble realistic but simple assemblies such as a gearbox or rack and pinion, thus the results may or may not be applicable to exceedingly complex assemblies such as a complete automobile or airplane. Additionally, the results of the study are dependent upon the hardware configuration as the human computer interaction and results may vary if different setups are used.

The final part of this research was the online VR stl viewer for use with Google Cardboard. This tool provides a platform that utilizes the ideal interaction between the viewer and the virtual prototype, point-of-view freedom and a static virtual prototype. Utilizes the Google Cardboard platform lowers the barrier for performing VR design review via HMDs allowing a larger community of small and large organizations to take advantage of this technology and improve their product development process through low cost, highly immersive virtual prototype design reviews.

6.1.1 Contributions

This research yielded contributions in the form of two conference papers submitted to IDETC; "*Design Review Using Virtual Reality Enabled CAD*" DETC2017/CIE-67878 [4], "*Effects of Immersion on Virtual Reality Prototype Design Reviews of Mechanical Assemblies*" DETC2018/CIE-85936 [5].

6.2 Future Work

While the experiments demonstrate the effectiveness of HMD VR for design reviews, there is evidence of having excessive VR interactiveness for the user which may be superfluous to navigating the virtual environment and virtual prototype. Thus future work will explore this balance through VR environment design to identify additional factors of which can affect a reviewers ability to analyze the spatial information of a virtual object. There is an opportunity to incorporate viewing virtual prototypes through HMDs while in the CAD environment. Doing so may decrease the need for additional design reviews as the design engineers may have a better mental picture of the virtual prototype due to the interface they are using. Additionally, with the final task of this body research being completed through the combination of VR and augmented reality technology, further research is needed to understand what is the ideal intersection of the two for performing in situ design reviews using untethered VR equipment.

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