Collaborative product review using virtual reality interface devices performance studying

Mihir Radia
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Collaborative product review using virtual reality interface devices performance studying

by

Mihir Radia

A thesis submitted to the graduate faculty
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Major: Mechanical Engineering

Program of Study Committee:
Caroline Hayes, Major Professor
Rafael Radkowski
Stephen Gilbert

The student author, whose presentation of the scholarship herein was approved by the program of study committee, is solely responsible for the content of this thesis. The Graduate College will ensure this thesis is globally accessible and will not permit alterations after a degree is conferred.

Iowa State University
Ames, Iowa

2019

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ABSTRACT

The study presents two research questions: 1) Can stereoscopic 3-D visualization (like Virtual Reality) improve a design reviewer’s ability to detect errors when reviewing a product model over a traditional CAD system in which 3D product models are viewed on a flat 2D computer screen? 2) Can two collaborating individuals be more effective (faster time or detect more errors) during a product design review than one individual operating alone? The answer to the first question will help provide product design reviewers, managers, and software designers in product design firms decide what features to include, and whether it is worthwhile to purchase VR (Virtual Reality) tools to aid in design review, or whether more traditional CAD tools are just as effective. The second question will help scientists and managers understand whether collaboration really does increase success in product design reviews by increasing error identification or completing tasks faster than working individually. Design review is an important part of the design process: design reviewers aim to identify errors/defects as early as possible in order to save time and money. Various studies have been conducted to measure either user performance or user preference, or both, for VR versus traditional CAD interfaces in a variety of design tasks; however, there has been little quantitative research that has measured performance using VR versus CAD interfaces in a design review. The study used a low-cost desktop VR system as a test bed because of its potential to be used broadly in current work environments in any designer’s office without the need of a special room or large investment. An experiment was conducted to answer the research questions stated above. The investigation involved 16 participants who were asked to use four interfaces: CAD-view with individual interface, CAD-view with collaborative interface, VR-view with individual interface and VR-view with collaborative interface. They were asked to complete design review tasks employing
each interface. The tasks involved four model-based design review problems in order to identify errors in product models. The results of the experiment do not provide evidence to support the first question. But, the results from the second question indicate that two collaborating individuals will complete a task faster than an individual working alone. The author believes that the current desktop VR system used in the investigation did not provide sufficient hardware and software support to effectively test the two research questions. There were several issues expressed by participants such as seeing dual images, experiencing eye irritation, or sensing a “jerky” phenomenon. In subsequent investigations it may be worthwhile to build the experimental test bed on a VR-system that will better test the research questions.
CHAPTER 1. INTRODUCTION

This thesis investigates two research questions: 1) Can Virtual Reality (VR)-view improve a design reviewer’s ability to detect errors when reviewing a product model over a traditional CAD system? 2) Can two collaborating individuals be more effective (faster time or detect more errors) in a product design review than an individual alone? The effectiveness of this study is measured by two quantitative variables: the time required for task completion, and number of errors correctly identified in CAD product models. Errors were intentionally integrated into product models utilized in the study. NASA TLX was introduced to determine the perceived workload rate involved in different interfaces [27]. An answer to the first question will help provide knowledge for product design reviewers, managers, and software designers in firms that design products as they make decisions as to what features to include, and whether the purchase of VR tools is worthwhile. The second question will help design reviewers understand whether collaboration can increase success in product design reviews by effectively identify more errors, or more quickly completing tasks than when working individually.

1.1 Motivation

Design review is a process that allows designers to identify errors or problems in a product model and to verify a product against its requirements/specifications. Most product cost is committed during the early stages of the design process [4-5]. Hence, it is critically important to identify errors/defects during the early stages of the design review process to avoid unnecessary costs and delayed time-to-market. Traditionally, Computer-Aided Design (CAD) interfaces are commonly used to review product model designs during the designing process [10] using traditional CAD interface in which a 3D product model is viewed on a 2D computer screen. Users understand the 3D nature of the product model by rotating it and looking at its various
sides on a 2D screen. Designers employing this technology can successfully identify potential errors and locate interferences between parts; thereby, reducing production costs by not having to manufacture actual prototypes, and reducing design cycles—relative to sketches and clay models [11, 13, 14]. However, there are some drawbacks to traditional 2D CAD interfaces: the designer’s interaction with a model is limited by a 2D computer screen [16,17]. Design reviewers can still understand the 3D nature of the model from a series of 2D views, but they cannot use all typical modes of interaction with the world that includes 3D stereoscopic depth perception. In contrast, the stereoscopic image of a product model produced by virtual reality technology enables designers to interact with a model in a more natural and interactive environment [15,18,19]. Various usability studies [17,18, 19, 26, 33] have indicated that the better depth perception of models and the intuitiveness of Virtual reality interface improves a designer’s understanding of a CAD model, increasing user performance and rendering a preferred user interface. But, most investigations have not conducted quantitative performance design review measurements or statistical comparisons between performances while using VR versus CAD interfaces.

Communication plays an important role during a design review because it conveys ideas and messages among a group of designers who possess varying skills and interests [32]. Ostergaard, Wetmore III, Divekar, Vitali, and Summer’s [35] study showed that a group (five or six per team) is twice as effective as individuals in identify errors in 2D CAD drawings [35]. There is reduced productivity generated from a set of individuals if there are 3 or more people in the group. Another face-to-face collaborative study (two per team) showed that users preferred Mixed Reality over paper-based 3D drawings due to the 3D depth perception and high-level immersion of the MR [24]. While the collaborative versus individual approach has been
investigated in several domains, we are not aware that it has been quantitively studied in design reviews involving 3D CAD models.

1.2 Approach

An experiment was conducted to investigate the stated research questions utilizing 16 participants who were asked to use four interfaces: CAD-view with individual interface, CAD-view with collaborative interface, VR-view with individual interface and VR-view with collaborative interface. Individual participants or participant pairs were asked to identify errors in product models using four different experimental conditions. Product models and experimental conditions were systematically varied to balance the experimental design. The experimental hardware and software platform developed by the author to conduct this work was a proof-of-concept system.

A video recording of each session made it possible to determine the time necessary for each participant to complete a task. Participants were given a post-task questionnaire to complete at the end of each interface, and a debriefing questionnaire following the completion of all interface conditions. Additionally, they were asked to participate in a short interview at the end of the experiment. The purpose of the interview was to further clarify answers given on the debriefing questionnaire. The short interview was audio recorded and transcribed. Data was then collected from the questionnaires and video recordings.

It is anticipated that the results of this work will help managers, design reviewers, scientists, and software designers understand the effectiveness of the interfaces in product design reviews.
CHAPTER 2. LITERATURE REVIEW

The Literature Review is organized as follows: The first section (2.1) presents a brief background of design review along with literature stating the importance of design review in the product development process. The next two sections (2.2 and 2.3) provide the background of CAD and Virtual Reality interfaces used in design review, along with respective literature that explains the pros and cons of the interface, and develops the first research question. The final section (2.4) discusses the importance of collaboration in the design review by presenting literature that helped develop the second research question.

2.1 Design Review Process

Design review is a process that allows design teams to identify the most appropriate engineering design (based on product cost, manufacturing, and quality), errors, and oversights; thus, increasing the probability of project success. A Product Design Review team is typically a group of designers that plan, conduct, and evaluate a product design to assess where it meets a set of design objectives in a cost-effective and timely manner. An effective and thorough review saves time and cost through early problem detection. Decisions made during the design process have a significant impact on the life and total cost of a project, and the level of end-user satisfaction [1].

The product design process consists of a series of steps that progress from concept design to production design. The process consists of a number of phases from conceptualizing new product ideas through sketching, creating models, developing engineering designs, prototyping, testing, and supporting production, to rolling out new and improved products. Professionals engage in various types of product development processes. The Pahl and Beitz description of the design process [3] is accepted by many engineers and educators as a good model. They describe it as a
multi-phase process that progresses from the abstract (qualitative) to the concrete (quantitative) through a series of analysis and synthesis tasks [2]. The Pahl and Beitz design process is shown in Figure 1.

Figure 1: Pahl and Beitz design process
(Photo Credit: Image courtesy of Pahl and Beitz (1996) [3])
The Pahl and Beitz design process is primarily divided into four main phases: Planning and Clarifying task, Conceptual design, Embodiment design, and Detail design. The planning and clarifying task involves the gathering of product requirement/specification lists that indicate issues such as market demand, customer needs, economic trends, and company goals. In the Conceptual design stage, a rough functional product concept is created based on requirements and evaluated against technical and economic criteria. In the Embodiment design, functions specified in the conceptual model are embodied in a specific geometry using a 2-D or 3-D CAD model. The design is assessed in accordance with technical and economic criteria. The designer evaluates the design to identify errors, reduce product cost, and determine the time it will take to produce the product. The detailed design is the final stage of the design process: at this stage the design is finalized, and the full cost of the product and project is estimated. The design output is in the form of either a 2-D drawing or a 3-D CAD model, and the design material, parts list, number of parts, dimensions, and tolerances are specified to the manufacturer. The three measures of design process effectiveness are product cost, quality, and time to market [4].

2.1.1 Manufacturing cost commitment during design

Figure 2 shows that the percentage of cost committed over time during the design process. A relatively large percentage of product cost is committed during the early design stages. Ullman [4] indicates that about 75% of the manufacturing cost of a typical product is committed by the end of the conceptual phase process. Saravi, Newnes, Mileham and Goh [5] state that typically, 70-80% of the product cost is committed by the end of the conceptual design stage.
An example explaining the cost relationship between a design and manufacturing is shown in Table 1.

Table 1: Manufacturing cost with respect to design
(Source: Data reduced from K. Ulrich and S. A. Pearson [6])

<table>
<thead>
<tr>
<th>Coffee Maker</th>
<th>Number of Parts</th>
<th>Estimated Manufacturing Cost ($)</th>
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<tr>
<td>Proctor Silex</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• A6278</td>
<td>47</td>
<td>6.57</td>
</tr>
<tr>
<td>• A8737</td>
<td>61</td>
<td>7.48</td>
</tr>
<tr>
<td>Krups</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• 130</td>
<td>47</td>
<td>8.55</td>
</tr>
<tr>
<td>• 150</td>
<td>39</td>
<td>8.16</td>
</tr>
<tr>
<td>• 178</td>
<td>52</td>
<td>9.28</td>
</tr>
</tbody>
</table>

The costs shown in Table 1 are estimates drawn from 18 different automatic coffeemakers. The coffeemakers used in this study used identical brewing processes and were functionally similar. Variation in the manufacturing cost was driven by differences in material cost, number of parts, manufacturing process, and production cost which was determined during the design process in a hypothetical manufacturing system. Table 1 shows that the Proctor Silex (A6278) and the Krups
have the same number of parts (47), but the difference in product cost is 23.15%. Hence, the design decisions made early in the design process relate to cost commitment: if a commitment is made to a wrong design, it is going to have unfavorable cost implications. Similarly, if defects are not detected until the end of the manufacturing stage, a company must go back and rectify the design, costing both time and money. Hence, it is very important that errors are caught early in design reviews during the design process. Accordingly, the present research focuses on interfaces used in the product design process, where designers finalize the design of a product model using appropriate software, and identify weaknesses and errors.

The introduction of CAD software has revolutionized creative possibilities available to designers during the design process [12]. Hence, the next section provides a brief background of CAD software, along with the merits and limitations of CAD software in the design review process.

2.2 Computer-Aided Design

Computer-aided design (CAD) is a computer design software that allows designers to create complex 3D CAD models and modify designs on 2D computer screens. It is used in many industries such as aerospace, automotive, industrial equipment, architecture, engineering, and consumer goods. Design output is generally rendered in either a two-dimensional (2D) diagram or a three-dimensional (3D) model. Examples of 2D CAD diagrams or 3D CAD models are shown below.
A 2D diagram of a CAD model contains technical information about the product such as design material, parts list, number of parts, dimensions, and tolerances which are specified for the manufacturer; whereas, a 3D CAD model consists of the exact final product output. The 3D CAD model can also have the same properties as an actual physical object such as material, weight, size, and physical properties. This helps designers visualize the product before the start of actual manufacturing. Therefore, during the design process one of the key activities that most
high-level objectives build on is the review, and understanding the geometry of the design that is usually represented through 3D CAD models [8].

2.2.1 Computer-aided design in the design review process

Design teams have utilized CAD software to conceptualize, design, visualize, and validate the feasibility of proposed designs [9]. The use of CAD software as a tool to exchange ideas between design teams improves product development performance (time, quality, and productivity), which reduces errors and permits faster decision making [11]. Fitzgerald [13] reported that the use of CAD software in Chrysler cut the number of prototypes for each model, running anywhere from a dozen to a couple of hundred dollars ($500,000). Designers can view the model assembly in a CAD-view interface at an early stage of the design review process before creating actual prototypes, helping them detect shortcomings and interferences between relevant components [14]. Manufacturing the real-prototype of a model can be costly and time-consuming. Designers can identify or detect errors during the design development phase itself by reviewing a CAD design which will help them save money and time before the actual manufacturing. Fitzgerald [13] also found that the use of the CAD interface at all stages of the design process in the auto industry has reduced the design cycle (concept-to-production) time ranging from six months to a year when compared to sketches and clay models.

There are advantages to using a CAD interface in product design reviews as well as drawbacks. Ye [15] found that the conventional CAD system is not suited for supporting conceptual design activities like design review, and suggests that industry needs an interface that offers a natural and intuitive mode of human-computer interaction such as virtual reality technology. Additionally, Piegl identified ten challenges inherent in computer-aided design (CAD) interface.
One of which is related to the present study: the current CAD interface creates 3D CAD models and projects them onto a flat panel [16]. A two-dimensional interface, computer screen, or planar surface limits designer perception and understanding of the CAD model [17].

The advancement of technology makes it possible for a virtual reality interface to provide the designer with a 3-D depth perspective of a product model by visually engaging the majority of a designer’s field of view [19]. Ye [15] also indicates that Virtual Reality (VR) interface provides a more natural and interactive environment, thus enabling designers a more rapid and straightforward approach in conceptual design activities that prevail in the CAD interface. Virtual Reality (VR) interface gives the designer a sense of presence in a virtual world: stereoscopic viewing (left and right images) enables users to become immersed and interact using natural human motion [18].

The afore mentioned advantages make it possible to explore the use of Virtual Reality in product design review in the present study by identifying its protentional merits and drawbacks, as well as providing a brief background of Virtual Reality and various types of Virtual Reality systems.

2.3 Virtual Reality

Virtual Reality delivers a much stronger interactive and engaging environment than the CAD system. Virtual Reality (VR) consists of computer-aided reality, where a user immerses himself/herself in a 3D world using a unique head-mounted display (HMD) which shows visual effects directly in front of the user’s eyes. Due to these benefits, VR is used in many applications in computer-aided design, robotics, assembly planning, manufacturing layout, manufacturing
simulation and product maintenance [20]. There are generally three types of VR systems used in various industries and applications:

1) **Cave Automatic Virtual Environment (CAVE):** A virtual environment with a cube-shaped room in which a projected screen makes up the walls and floor. A user wears a heads up display and interacts using a wand or joystick. An example of a CAVE VR is shown in Figure 5.

2) **Head-mounted display (HMD):** A virtual reality headset that is worn on the head with a small display optic in front of each eye. An example of HMD is shown in Figure 6A.

3) **Single user workstation:** A virtual reality desktop computer that projects a 3D depth perspective of a model. A user can wear 3D glasses instead of HMD to interact with the model in a virtual environment and manipulates items using a stylus. An example of desktop VR system is shown in Figure 6B.

![Figure 5: Example of a VR CAVE [21]](image-url)
The CAVE and head-mounted displays (HMD) have existed since the early 90’s. The high cost and potentially significant floor-space requirements of these systems have created a substantial barrier for research activities and commercial adoption alike [8]. Hence, for our current work, we used the single user workstation VR system. The VR desktop computer used for the experiment was zSpace 200 by zSpace, Inc.

2.3.1 Virtual reality in the design review process

The application of virtual reality to enhance engineering design reviews has been a critical area of concentration for researchers since the innovation of modern virtual reality [29]. Freeman, Salmon & Coburn [8] evaluated CAD integration in virtual reality design review for improved interaction with an engineering model. The researchers found that the enhanced environment of VR improved the user’s ability to understand CAD geometry. The problems identified during the design review process can be addressed and resolved instantly with the help of virtual reality, and can save the project time and cost [32]. In turn, reduced time and cost leads to increased product development. Due to these advantages the auto industry has started using VR across a
number of applications including design, manufacturing, and training [25]. This is supported by Kim, Lee, Lehto, and Yun’s [30] study of automobile interior design. They showed that the use of VR during the early stages of development can help designers interact and evaluate design alternatives in the virtual environment without having to make a physical prototype (which can save time and money). The use of VR at General Motors allowed designers to detect and alter visual aspects of a design which they may not have seen until production [26].

The use of Virtual Reality helps industries support decision making and enables innovation. For example, during a design review meeting at TACOM, designers using VR interface were better able to visualize the fit of new equipment on currently existing vehicles than when using CAD interface [26]. Visualization of 3D CAD models in a VR environment requires less spatial reasoning skills due to stereoscopic viewing and intuitive VR model controls such as head-track displays, than when using the CAD interface [28].

The above research demonstrates that designers have benefited from VR interface in both academic and industry fields. Virtual Reality (VR) is recognized in the industry as an interface to increase efficiency in product design and manufacturing [20]. Recognizing these advantages, the next section presents studies comparing VR and the CAD interface in the design review process.

Casenave and Lugo [19] conducted an experiment to evaluate 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 researchers found that participants preferred the VR interface for design review because of head motion tracking that
allows for an intuitiveness of the VR environment, leading to a more natural engagement over the CAD interface; but, virtual reality in design review was as effective as the CAD interface in identifying errors.

Satter and Butler [17] conducted a usability study to measure user performance (navigation, error finding and repair, and spatial awareness) and user preference for a virtual environment in a design review when compared with CAD interface. The results indicated that VR interface in the design review process significantly improved user performance in navigation and error finding and repair, and users preferred the VR interface over the non-stereoscopic interface (CAD interface).

Toma, Gîrbacia, and Antonya [18] present an experimental study which compares the performance and usability of VR interface with a traditional CAD interface by modeling and assembling 3D CAD models. The results suggested that the VR interface was better for in-depth perception of 3D CAD models, but the modeling and assembling times were the same as the traditional CAD interface.

Johansson and Ynnerman [33] conducted an empirical study to measure learning as an important factor of performance while attempting to detect induced errors in a mechanical product using various displays: Immersive VR, Desktop-VR, and a traditional desktop system. The results showed that users performed best with the desktop-VR system by finding errors in the shortest time.
The investigations mentioned above conducted usability studies to measure either user performance or user preference, or both, for VR interface versus CAD interface conditions. However, most of the studies did not conduct a quantitative measurement of performance design review or make a statistical comparison between performance when using VR and CAD interfaces in a design review. Although, design review is recognized as important in identifying errors/defects in the early stages of the design process to save time and money. Thus, the main aim of this research is to quantitively measure the advantages of CAD interface vs. Virtual Reality interface in a design review.

Thus, the first research question of the present study is:

- Can Virtual Reality (VR)-view improve a design reviewers’ ability to detect errors when reviewing a product model over a traditional CAD system?

Thus, the results will help product design reviewers, managers, and software designers in firms that design products decide whether it is worthwhile to purchase VR tools.

Communication as well has a substantial role to play during the design review because it conveys ideas and messages between a group of designers with varying skills and interests [32]. Hence, the next section focuses on the importance of collaboration in the design review process.

**2.4 Collaborative Design Review**

A design review is a collaborative work where designers communicate with each other to review and evaluate a product model against its specifications/requirements. Communication is essential between the designers during the design review since it helps them identify and resolve
Various modes of communication are used during a design review such as face-to-face, speech-only, text-only, and teleconferencing. The research studies mentioned below indicate the importance of face-to-face as a communication mode in a design review.

Hammond, Koubek, and Harvey [34] stated that face-to-face interactions provide a broader mode of communication because it involves all five senses. Mediums such as video or audio alone limit the number of senses involved and result in decreased information transfer efficiency.

Emmit and Otter [36] suggested that in design review meetings, face-to-face communication is essential for design knowledge assimilation and a better design understanding between designers. Thus, for our current research work, the author chose face-to-face as a communication medium during collaborative design reviews. Below are findings from research studies that compare the effectiveness of collaborative versus individual reviews which relate to our current work.

Ostergaard, Wetmore III, Divekar, Vitali, and Summers [35] conducted a study using individuals versus groups to identify design flaws. The results showed that groups were twice as effective in identifying design flaws than individuals alone. The identification of these flaws was on a 2D CAD assembly drawing. It did not investigate whether this was true in a VR environment.
Wang and Dunston [24] conducted an experimental study to understand users’ experiences utilizing a Mixed Reality (MR) system and a paper-based 3D drawing in a face-to-face collaborative design review while performing an error detection task. User feedback suggested that 3D visual perception, high level of immersion, and visual quality enabled them to complete the task in a shorter time than the paper-based method, and was a useful aid in design error detection tasks.

One of the key activities in an engineering design review is to understand the geometry of a product model which is primarily represented through 3D CAD models [8], as discussed earlier. There appears to be an absence of empirical studies that have compared the effectiveness (time to task completion or error detection) of a collaborative interface versus an individual interface in a design review involving 3D models. The present study conducted a statistical comparison between the performance of collaborative versus individual interfaces in a design review. Thus, the second research question of the study is:

- **Can two collaborating individuals be more effective (faster time or detect more errors) in a product design review than an individual alone?**

Subsequent chapters of this thesis will present information about experimental setup, experimental preparation, results, discussion, and conclusion that will help answer to the two research questions.
CHAPTER 3. CONTRIBUTION

3.1 To the Project

This project focuses on the design and evaluation of Virtual Reality computer interface performance. The experimental design and questionnaires were adapted from a previous study [39, 40]. My contributions to the project are listed below:

• Experimental Design
  o Designed the experiment with four test condition interfaces, created a Graeco-Latin Square plan [31].
  o Created more approachable experimental tasks and questionnaires.

• Experimental Setup
  o Software
    ▪ The experiment had the same physical setup used in previous studies [41] with the addition of more functions to the software including assembly, disassembly, and rotation.
  o Conducting the Experiment
    ▪ Ran test participants under four different experimental conditions in which they jointly reviewed product design models and identified errors.
  o Analysis
    ▪ Analyzed data from the actual test to calculate time taken to complete each interface.
    ▪ Collected data and performed ANOVA analysis from post-task and debriefing questionnaires and performed data analysis to address the research questions.
3.2 To Science

This research is mainly addressed to designers, product managers and software engineers in manufacturing firms. The results of this work will help them make informed purchasing and software development decisions on whether to purchase/develop CAD or Virtual Reality design review software. This work helps designers and managers:

- Understand the impact of VR desktop systems in the product design review process.
- Understand the importance of the proximity of collaborating designers in a design review process.
CHAPTER 4. EXPERIMENTAL SETUP

The current set up consists of two identical design review work stations. An identical one used by [41] in his experiments.

4.1 Physical Setup and Hardware

Each design review work station consisted of a zSpace computer, virtual reality glasses, stylus, and two webcams. The computer used in the experiment was a zSpace 200 consisting of a monitor, controller, virtual reality glasses, and a stylus to control the application. Webcams were used to video-tape the experiment: one “front-view” camera to record the users face and movements, and one “over-head” camera to record the users screen. Video from the cameras were also used to collect time data. Design review work stations were separated by a soft wall. Design review partners serving as participants in the experiment could not see each other in their workstations.

Figure 7: Physical Layout of the Experiment
The zSpace virtual reality desktop system was used in the study. It is much smaller and more effective than many other immersive VR environments and is a viable option for most office workplaces. The zSpace monitor has an inbuilt infrared sensor that tracks the position of glasses to enable a stereoscopic display. The infrared sensors also enable the stylus to interact with objects in the virtual environment.

### 4.1.1 zSpace monitor

![Figure 8: zSpace 200 Monitor](Image courtesy of zSpace, Inc [42])

One of the 2 zSpace 200’s used in the experiment is shown in Figure 8. The zSpace monitor is a virtual reality desktop developed by zSpace, Inc. It has a 1920 * 1080 Full HD display which comes with an inbuilt infrared tracking camera. The head-tracked display enables the left and right images of the display to focus onto a single stereoscopic image when viewers use the virtual reality glasses. The tracking camera aligns the images with the user’s position and is based on the position and movement of the 3-D glasses.
4.1.2 Virtual reality glasses

![Head Tracking markers](image.png)

**Figure 9:** zSpace-Virtual Reality Glasses  
(*Photo Credit: Image courtesy of zSpace, Inc [42]*)

The virtual reality glasses used in the experiment are shown in Figure 9. They enabled users to see CAD models as 3-D stereoscopic objects in a virtual world. The tracking markers on the glasses are tracked by the infrared tracking cameras on the zSpace display, and when the user moves, the image on the display moves to match his or her viewing angle and head movement. The glasses are oriented to a right-handed coordinate system. The X axis projects from the right of the glasses, the Y axis projects up from the glasses, and the Z axis projects back toward the viewer’s head (See Figure 9).
4.1.3 Stylus

The stylus enables a user to interact with objects in the virtual environment. It is designed with 6 degrees of freedom to allow the user to manipulate objects in the virtual environment. The stylus includes a primary button and two left/right buttons that are programmable. A push of the primary button allows a user to “grab” objects in the 3-D VR space. Left/right buttons can be used to move forward or backward, respectively, and move objects in the virtual zSpace environment.

4.1.4 Webcams

The cameras used in this experiment are Logitech® HD Pro Webcam C920 with a 1920 x 1080 pixels resolution, shown in the Figure 11.
During the experiment, two webcams were used to videotape the process: one webcam pointed at the user (front-view webcam) and the other camera pointed downward at the user’s screen (overhead webcam) as shown in Figure 7. Hence, a total of 4 webcams were required for the experiment, and all sessions were videotaped. Figure 12 shows a simultaneous screenshot from all four cameras during an experimental recording session [41].

Figure 12: Screenshot of Camera Perspective View
(Photo Credit: Image courtesy of Cheng’s and Sadeghi’s usability study period [41])
4.2 Software Setup

The software used in this experiment was Vizard software that simulates a virtual environment using python scripting language. It is comprehensive virtual reality software that helps create VR applications created by WorldViz and uses a built-in Python scripting language. The typical workbench of Vizard is shown below.

![Vizard Integrated Development Environment (IDE)](image)

**Figure 13:** Vizard Integrated Development Environment (IDE)

The Integrated Development Environment (IDE) of Vizard is divided into 3 main pane windows which are explained below:

1) Editor: The Editor window helps to open and edit python files (.py)

2) Code Browser: The Code Browser pane window displays a hierarchical overview of all functions and classes within the current script. The Resources pane lists all the media files referenced by the script.

3) Interactive: The Interactive window gives direct access to the Python interpreter. It helps in viewing and displaying error messages generated by the Python interpreter.
Existing VR software was used to do a platform, allowing the creation of a virtual interactive environment using Computer-Aided Design (CAD) models. Vizard, a widely available lightweight CAD package and VR software, was used for testing purposes. Its built-in python package allowed users (e.g. design reviewers, or system programmers?) to check and navigate CAD models in the VR system. Although it did not have all the functions of a commercial CAD package, like Auto CAD and SolidWorks, the basic functions were sufficient to support the experiment. COLLADA format CAD files were used for this study.

This investigation used python scripts initially developed by [41]. The leading investigator of added functions to the existing code to enable product design reviewers to assemble, disassemble, and rotate CAD product models. The assembly sequence had been determined prior to the stage of design review study. Product design reviewers commonly identify assembly issues by first completely disassembling the product model, and then re-assembling it part-by-part to look for possible interference between parts. Rotation functions allowed participants to rotate the whole model 360 degrees in the virtual environment. The assembly and disassembly functions of a product model are illustrated in Figure 14.
4.2.1 Assemble and disassembly

![Image showing assembly and disassembly](image-url)

Figure 14: Assembly and Disassembly function
(Photo Credit: Screenshot from video recording during the Experiment)

The 2-D images shown in Figure 14 appear blurred because two images are rendered on the screen, one for the left eye and one of the right eye. When viewed through virtual reality glasses, each eye sees only one image which appears sharp and 3-dimensional.

4.2.2 Cursor

Each design review work station had its own stylus that used the software for product design review, enabling the user to interact with the same CAD product model. The lead researcher implemented a highlighted cursor that appeared as a “green” highlight around the part of the
model on the screen in order to help users see where their stylus was “pointing” on the CAD model. Without the highlighted cursors, the object in the CAD model would appear to move in unexpected ways, and the user would feel lost—just as one does in a 2-D environment when one’s cursor is not showing on the screen.

![Highlighted Cursor](image)

**Figure 15:** Each Stylus User’s Represented as a Highlighted Cursor  
*(Photo Credit: Screenshot from video recording during the Experiment)*

### 4.2.3 Use of software functions in the design review process

In a typical session, participants rotated the model 360 degrees to find a missing part on the outer surface of the CAD model. They would then disassemble the model in a pre-determined sequence to find either the misalignment or interference between the two parts. If they found any of the 3 errors, they notified the experimenter of the errors and the errors were recorded on the error recording sheet (Appendix C). Product models could be manipulated using various
functions by pressing buttons on the keyboard and stylus to find errors in a given product model. Below are the functions programmed into the keyboard and stylus for manipulating CAD models.

1. Keyboard Instructions
   a. Press the spacebar to remove one part at a time following a pre-set sequence.
   b. Press “Left Ctrl” to assemble one part at a time following a pre-set sequence.
   c. Press the “R” key to reassemble.
   d. Press “W” to rotate the model in the upward direction.
   e. Press “S” to rotate the model in the downward direction.
   f. Press “A” to rotate the model in the clockwise direction.
   g. Press “D” to rotate the model in the anti-clockwise direction.
   h. Press “H” to bring the model in the home position. (The home position is the center coordinate system in the virtual environment i.e., (x=0, y=0, z=0).

2. Stylus Functions
   a. Press the primary button to “grab” a component of the CAD model.
   b. Press either the left/right stylus button to move the model in either the forward (closer to view) or backward (farther) direction, respectively.
CHAPTER 5. EXPERIMENTAL PREPARATION

Participants were recruited to complete four tasks in pairs, using four different interfaces:

1) CAD-view with collaborative interface
2) CAD-view with individual interface
3) Virtual Reality (VR)-view with collaborative interface
4) Virtual Reality (VR)-view with individual interface

All tasks were model-based design review tasks. Participants were given a task description sheet to complete tasks (Appendix A). The order of tasks and conditions changed systematically to counter balance ordering and learning effects. This was to insure tasks and interfaces were paired systematically.

5.1 Objectives

The experimental design was developed to investigate two questions:

- Can Virtual Reality (VR)-view improve a designer reviewers’ ability to detect errors when reviewing a product model over a traditional CAD system?
- Can two collaborating individuals be more effective (faster time or detect more errors) in a product design review than an individual alone?

5.2 Independent Variables

The Independent variables were:

- Dimensionality (CAD-view, and Virtual Reality (VR)-view user interfaces),
- Collaboration (collaborative, and individual interfaces)
The CAD-view interface is a traditional 2-D interface in which the user views a 3-D model on a 2-D screen (x-y plane of a computer screen), as shown in Figure 16, and the Virtual Reality (VR)-view interface provides a three-dimensional space that helps the designer manipulate parts in a virtual environment, as shown in Figure 17.

Figure 16: CAD-view Software
(Photo Credit: Image courtesy of Brewster, Signe, 2013 [37])

Figure 17: Virtual Reality (VR)-view Software
(Photo Credit: Image courtesy of Report, Rich, 2013[38])
In collaborative interfaces, participants sit next to each other in a single collaboration cell; whereas, in individual interfaces, participants sit on opposite sides of a soft wall in a separate collaborative cell.

5.3 Dependent Variables

The dependent variables were:

- Completion time (minutes)

- Errors
  - Number of correctly identified errors
  - Number of missed errors
  - Number of falsely identified errors

- NASA TLX measures
  - Mental Demand
  - Physical Demand
  - Temporal Demand
  - Performance
  - Effort
  - Frustration

- Post-task Questionnaire

- Debriefing Questionnaire
  - Easiest
  - Most fun
Most preferred interface to use at work

Most preferred to least preferred interface

Participant errors can be *missed errors* or *falsely identified errors*. NASA TLX [27] includes six component measures: Mental Demand, Physical Demand, Temporal Demand, Performance, Effort and Frustration. These variables are also essential to understand participant workload.

5.3.1 Questionnaire

Participants were asked to complete two questionnaires: a post-task questionnaire and a debriefing questionnaire.

- A **post-task questionnaire** (Appendix B) was used after each trial experimental condition, and included two parts:

  1) NASA Task Load Index (NASA-TLX) for six measures: mental, physical and temporal demand, performance failure, effort, and frustration. NASA-TLX is a subjective, multidimensional assessment tool that rates the perceived workload needed to access a task, a system, or a team's effectiveness, or other aspects of performance. NASA-TLX measures are commonly used in Human Factors research and are, therefore, broadly understood by researchers.

  2) A questionnaire to assess collaborators’ perceptions of team cohesion, joint effort, social connection, team cooperation, and ease of communication when using the interface.
3) A debriefing questionnaire (Appendix B) was administered after participants had completed all four conditions. The questionnaire was used to assess differences among the four interfaces: those considered to be the easiest, most enjoyable, most preferable for professional work, and the most and least favorite.

5.4 Experimental Design

The experiment followed a 2 X 2 within groups design.

Tasks and interfaces were combined in a systematically varied manner to provide a counterbalance effect. This ensures that each task given to participants were paired with each interface condition an equal number of times. Also, there was systematic variation in presentation order for each unique task-interface pair. This type of counterbalance is a 4 by 4 Graeco-Latin Square [31], and shown in Table 2.

Table 2: Experimental and Training Design Matrix with A-E as interface conditions and 1-5 as Product models

<table>
<thead>
<tr>
<th>Groups</th>
<th>Training Period</th>
<th>Experimental Trial 1</th>
<th>Experimental Trial 2</th>
<th>Experimental Trial 3</th>
<th>Experimental Trial 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pair 1</td>
<td>E1</td>
<td>A2</td>
<td>D3</td>
<td>B4</td>
<td>C5</td>
</tr>
<tr>
<td>Pair 2</td>
<td>E1</td>
<td>C3</td>
<td>B2</td>
<td>D5</td>
<td>A4</td>
</tr>
<tr>
<td>Pair 3</td>
<td>E1</td>
<td>D4</td>
<td>A5</td>
<td>C2</td>
<td>B3</td>
</tr>
<tr>
<td>Pair 4</td>
<td>E1</td>
<td>B5</td>
<td>C4</td>
<td>A3</td>
<td>D2</td>
</tr>
<tr>
<td>Pair 5</td>
<td>E1</td>
<td>B2</td>
<td>C3</td>
<td>A4</td>
<td>D5</td>
</tr>
<tr>
<td>Pair 6</td>
<td>E1</td>
<td>D3</td>
<td>A2</td>
<td>C5</td>
<td>B4</td>
</tr>
<tr>
<td>Pair 7</td>
<td>E1</td>
<td>C4</td>
<td>B5</td>
<td>D2</td>
<td>A3</td>
</tr>
<tr>
<td>Pair 8</td>
<td>E1</td>
<td>A5</td>
<td>D4</td>
<td>B3</td>
<td>C2</td>
</tr>
</tbody>
</table>
The letters A-D were assigned to interface conditions where A was CAD-view with a collaborative interface condition, B was a CAD-view individual interface condition, C was a Virtual Reality (VR)-view with a collaborative interface condition, D was a Virtual Reality (VR)-view individual interface condition, E was a task that contained all interface conditions with an example product model (see product model 1 in Figure 19), and numbers 2 through 5 were randomly assigned to experimental tasks models (see product models 2-5 in Figure 20-23).

5.5 Experimental conditions

Four experimental conditions using all combinations of values of the 2 independent variables were formed and are as follows:

1) CAD-view with collaborative interface.

2) CAD-view with individual interface.

3) Virtual Reality (VR)-view with collaborative interface.

4) Virtual Reality (VR)-view with individual interface.

All experimental conditions had identical control functions. Participants manipulated the product model in the virtual environment by pressing various buttons on the keyboard and stylus.

The isometric view of the four experimental conditions is shown in Figure 18.
Schematic Diagrams of all Interfaces

**CAD-view with Collaborative Interface**

Participant A  Participant B

**CAD-view with Individual Interface**

Ceiling
Cameras

zSpace

3-D Glasses
Stylus

Participant A & B working respectively on their design review station

**VR-view with Collaborative Interface**

Participant A  Participant B

**VR-view with Individual Interface**

Participant A & B working respectively on their design review station

*Figure 18: Isometric View of all the Four Interface Conditions*
1. **CAD-view with collaborative interface**: Participants sat next to each other in a single collaboration cell. They used the underlying Virtual Reality CAD product model interface as shown in Figure 18, and shared one stylus.

2. **CAD-view with individual interface**: Participants sat on opposite sides of a soft wall in a separate collaborative cell and worked individually at their design review work stations. They used the same underlying Virtual Reality CAD product model interface used in the “CAD-view with collaborative interface.”

3. **Virtual Reality (VR)-view with collaborative interface**: Participants sat next to each other and were placed in a single collaboration cell. They used the Virtual Reality CAD product model interface, as shown in Figure 18, shared one stylus, and wore 3-D glasses.

4. **Virtual Reality (VR)-view with individual interface**: Participants sat on opposite sides of a soft wall in a separate collaborative cell and worked individually at their respective design review work station. They used the same Virtual Reality CAD product model interface used in the “Virtual Reality (VR)-view with collaborative interface.”
5.6 Product Models

**Figure 19:** Product model 1 (Training): (Quadcopter)

**Figure 20:** Product model 2: (Passenger Control Unit [PCU])

**Figure 21:** Product model 3: (Control Cursor Trackball [Trackball])

**Figure 22:** Product model 4: (Modular Equipment Tray [MET])

**Figure 23:** Product model 5: (Lightning Protection Unit [LPU])

Fig. 19-23 shows screen shots of models used in the experiment. The product models have different levels of errors which will be described later.
The number of parts and number of errors in each product model is shown in Table 3.

**Table 3**: Number of Parts and Errors in each Product Model

<table>
<thead>
<tr>
<th>Product Models</th>
<th>Number of Parts</th>
<th>Number of Errors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product model 1 (Training): (Quadcopter)</td>
<td>44</td>
<td>4</td>
</tr>
<tr>
<td>Product Model 2: (Passenger Control Unit [PCU])</td>
<td>68</td>
<td>5</td>
</tr>
<tr>
<td>Product Model 3: (Control Cursor Trackball [Trackball])</td>
<td>53</td>
<td>6</td>
</tr>
<tr>
<td>Product Model 4: (Modular Equipment Tray [MET])</td>
<td>229</td>
<td>6</td>
</tr>
<tr>
<td>Product Model 5: (Lightning Protection Unit [LPU])</td>
<td>53</td>
<td>5</td>
</tr>
</tbody>
</table>
5.7 Tasks

The task was to locate all the errors in a four model-based design review tasks. They were
designed for the experiment, and focused on: 1) making it possible for participants to become
familiar with the user interface; 2) understanding if dimensionality had any significant effect on
improving designer skill; and 3) understanding if change in participant proximity had any effect
during the design review process. Participants worked individually or in pairs based on the
interface conditions used to complete the task. The models used were provided by Rockwell
Collins, Inc. The 3 different types of errors are listed below and are pictorially shown in Figures
(24-26). The dotted red circle shows error location:

- **Misalignment Error**: Given parts of the model are not aligned with each other.
- **Missing part Error**: There are missing parts in the model like substrate, screw, threaded
  insert, etc. They can exist inside or outside the model.
- **Interference Error**: Certain models have interference between parts.

![Figure 24: Misalignment Error](image)
*Figure 24: Misalignment Error: The screw (red) is not aligned with its hole (dark blue).*

![Figure 25: Missing Error](image)
*Figure 25: Missing Error: There should be a screw in the hole (dark blue).*
Figures 26 and 27: Interference Error: The corner of the housing (yellow) overlaps with the screw (red).

<table>
<thead>
<tr>
<th>Levels</th>
<th>PCU</th>
<th>LPU</th>
<th>MET</th>
<th>TRACKBALL</th>
<th>QUADCOPTER (Training Model)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Easy:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Misalignment</td>
<td>X</td>
<td></td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>- Missing parts</td>
<td>X</td>
<td></td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Medium:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Misalignment (Inside)</td>
<td>X</td>
<td>X</td>
<td></td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>- Missing parts (Inside)</td>
<td>X</td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>- Interference</td>
<td>X</td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Hard:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Misalignment (Inside)</td>
<td>X</td>
<td></td>
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<td>X</td>
<td>X</td>
</tr>
<tr>
<td>- Missing parts (Inside)</td>
<td>X</td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>- Interference</td>
<td>X</td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

Figure 27: Types of errors in product models

All product models were categorized into three different error levels such as easy, medium and hard. The errors were classified based on the complexity of the error finding. Figure 27 shows the different error levels present in each product model.
5.8 Participants

We requested approval for up to thirty-six participants for the study. They were drawn from undergraduate students, graduate students, and faculty members who were familiar with the design reviewing process.

5.8.1 Beta test

Prior to administering the actual test, twelve participants (six pairs) were asked to run beta tests of the interface so experimenters could avoid mistakes, and to identify and resolve issues related to product models, training, instructions, procedures, and the questionnaires. Beta-test participants were not used as subjects in the study.

5.8.2 Actual test

There were no changes made to the experimental process following the beta test, and the experimenter became more familiar with the experimental procedure. Sixteen participants (eight pairs) were asked to participate in the actual test. They worked individually or in pairs to solve four different tasks using four different interface conditions. During the tasks, each participant, or participant pair was asked to use all four interface conditions to review product models and identify errors.

5.9 Procedure

5.9.1 Recruiting procedure

1) Prospective participants were solicited via emails to professors teaching the ME 415 course, physical flyers posted on bulletin boards in the College of Engineering, and personal communication with friends.
2) Interested participants were contacted via email and asked to fill out a demographic survey. They were further asked to review and sign a consent form, and to email the documents back to the experimenter in advance of the experiment.

3) The experimenter reviewed the demographic survey and consent form, and contacted the participant to set a time for the experiment.

5.9.2 Experimental procedure

The procedures are described as below. All sessions were videotaped.

1) Participants reviewed the signed consent form.

2) Participants were trained with a short practice session to become familiar with the CAD-view and VR-view interfaces. The same training example was used for both conditions (Figure 13).

3) Individual participants or participant pairs solved four model-based design review problems as described in Table 2. Each task was completed using different conditions. The participants reported errors to the experimenter, and the experimenter recorded the errors on an Error Recording Sheet (Appendix C).

4) Participants completed a post-task questionnaire after using each interface (Appendix B).

5) Participants completed a debriefing questionnaire after they completed all trails (Appendix B).

6) Participants were invited to participate in a short audio recorded interview after the entire questionnaire was completed, and they were asked to explain why they provided specific answers on the questionnaire those considered to be the easiest, most enjoyable, most
preferable for professional work, and the most and least favorite. Further explanations were requested if there were any unexpected questionnaire results (Appendix B).

### 5.10 Demographics

The demographic survey for 16 participants is mentioned below:

<table>
<thead>
<tr>
<th>Personal Details</th>
<th>Gender</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Male: 12 (75%)</td>
<td>Female: 4 (25%)</td>
<td></td>
</tr>
<tr>
<td><strong>Age</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>19-25: 14 (87.5%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>25-30: 2 (12.5%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>English Fluency</strong></td>
<td>Yes: 14 (87.5%)</td>
<td>No: 2 (12.5%)</td>
<td></td>
</tr>
<tr>
<td><strong>Background</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Education</strong></td>
<td>BS: 3 (18.75%)</td>
<td>MS: 10 (62.5%)</td>
<td>PhD: 3 (18.75%)</td>
</tr>
<tr>
<td><strong>College Major</strong></td>
<td>Mechanical Engineering: 6 (37.5%)</td>
<td>Industrial Engineering: 6 (37.5%)</td>
<td>Materials Engineering: 1 (6.25%)</td>
</tr>
<tr>
<td><strong>Work Experience</strong></td>
<td>Experience outside university as an intern or full-time employee</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>&lt; 1 year: 7 (43.75%)</td>
<td>1-2 years: 4 (25%)</td>
<td>&gt;2 years: 4 (25%)</td>
</tr>
<tr>
<td><strong>Physical Condition</strong></td>
<td>Eye Problem</td>
<td>Yes: 5 (31.25%)</td>
<td>No: 11 (68.75%)</td>
</tr>
<tr>
<td></td>
<td>Disability in your arms</td>
<td>No: 0 (0%)</td>
<td>Yes: 16 (100%)</td>
</tr>
<tr>
<td><strong>Design Meeting</strong></td>
<td>Collaborative work experience in class or in the workforce</td>
<td>Yes: 14 (87.5%)</td>
<td>No: 2 (12.5%)</td>
</tr>
<tr>
<td></td>
<td>Working in team experience</td>
<td>Yes: 15 (93.75%)</td>
<td>No: 1 (6.25%)</td>
</tr>
<tr>
<td></td>
<td>Design project experience</td>
<td>Yes: 11 (68.75%)</td>
<td>No: 5 (31.25%)</td>
</tr>
</tbody>
</table>

*Figure 28: Demographic survey*
<table>
<thead>
<tr>
<th></th>
<th><strong>Design review meeting</strong></th>
<th><strong>Virtual design review meeting</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Yes, several times:</strong></td>
<td>Yes: 3 (18.75%)</td>
<td>Yes: 4 (25%)</td>
</tr>
<tr>
<td><strong>Yes, not much:</strong></td>
<td>Yes: 7 (43.75%)</td>
<td>No: 12 (75%)</td>
</tr>
<tr>
<td><strong>No:</strong></td>
<td>No: 6 (37.5%)</td>
<td></td>
</tr>
</tbody>
</table>

Figure 28: (continued)

From the demographic survey, a majority of the participants for our study were relatively young. They were recruited from various undergraduate and graduate studies majors, almost all participants were drawn from engineering majors, except for one who was majoring in food science. Nearly 31.25% of the participants reported myopia (near sighted eye condition), but the participants wore glasses or contact lenses during the experiment. None of participants reported they had lazy eye, blindness in one eye or inability to see stereoscopic images. They had different skills and level of experience, that ranged from 6 months till 4 years, either as an intern or a full-time employee. Most of the participants were familiar with the design review process (62.5%), collaborative work environment (87.5%) or experience working in a team (93.75%).
CHAPTER 6. RESULTS

The results of the study are described in this chapter. The ANOVA analysis conducted were for repeated measures and the assumptions were met that the group and residual are normally distributed and have homogenous variance (Appendix G).

6.1 Experiment Video Record

6.1.1 Time to task completion

![Diagram A: Dimensionality](image)

![Diagram B: Collaboration](image)

![Diagram C: Four Interface Conditions](image)

**Figure 29:** Overall Task Time as Function of Interface (95% CI’s); “★”indicates a significant difference.
Table 4: Overall Task Time ANOVA analysis

<table>
<thead>
<tr>
<th>ANOVA Summary</th>
<th>Sum Sq</th>
<th>Mean Sq</th>
<th>NumDF</th>
<th>DenDF</th>
<th>F-Value</th>
<th>Pr(&gt;F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental period</td>
<td>13.678</td>
<td>4.559</td>
<td>3</td>
<td>15</td>
<td>0.5697</td>
<td>0.6434755</td>
</tr>
<tr>
<td>Product models</td>
<td>141.675</td>
<td>47.225</td>
<td>3</td>
<td>15</td>
<td>5.9012</td>
<td>0.0072282</td>
</tr>
<tr>
<td>Dimensionality</td>
<td>28.445</td>
<td>28.445</td>
<td>1</td>
<td>15</td>
<td>3.5544</td>
<td>0.0789086</td>
</tr>
<tr>
<td>Collaboration</td>
<td>155.100</td>
<td>155.100</td>
<td>1</td>
<td>15</td>
<td>19.3811</td>
<td>0.0005144</td>
</tr>
<tr>
<td>Dimensionality: Collaboration</td>
<td>5.738</td>
<td>5.738</td>
<td>1</td>
<td>15</td>
<td>0.7170</td>
<td>0.4104486</td>
</tr>
</tbody>
</table>

The time to complete each task was available from the video recordings made during the experiment. The results of the statistical analysis (shown in Table 4 and in the Figure 29B) reveal there was a significant difference in average task completion time between the Individual interface vs. Collaborative interface (p=0.0005144). Participants took less time to find errors when using the collaborative interface than when using the individual interface. It was observed during the experiment that collaborative interface participants talked with each other, discussing and dividing the workload. This helped them complete the task faster and detect errors more quickly.
Figure 30: Product model: Task Time as Function of Interface (95% CI’s); ★ indicates a significant difference.

Figure 30 shows that “Product Model 4: (Modular Equipment Tray [MET])” required significantly more time to complete than the others. It took on average 37 minutes longer because it was more complex and had a greater number of parts. While it is not desirable for product models to have different completion times, it does not affect the validity of the results for other variables because the design of the experiment systematically varied pairings of product models and interfaces to counterbalance the effects.
6.2 Errors

6.2.1 Correctly identified errors

**Figure 31:** Average number Errors Identified (0 means No Errors Identified, 95% CI’s)
Table 5: Identified Errors ANOVA analysis

<table>
<thead>
<tr>
<th>ANOVA Summary</th>
<th>Sum Sq</th>
<th>Mean Sq</th>
<th>NumDF</th>
<th>DenDF</th>
<th>F-Value</th>
<th>Pr(&gt;F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental period</td>
<td>0.3125</td>
<td>0.10417</td>
<td>3</td>
<td>15</td>
<td>0.15060</td>
<td>0.9277</td>
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<tr>
<td>Product models</td>
<td>2.9375</td>
<td>0.97917</td>
<td>3</td>
<td>15</td>
<td>1.41566</td>
<td>0.2772</td>
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<td>Dimensionality</td>
<td>2.0000</td>
<td>2.00000</td>
<td>1</td>
<td>15</td>
<td>2.89157</td>
<td>0.1097</td>
</tr>
<tr>
<td>Collaboration</td>
<td>0.1250</td>
<td>0.12500</td>
<td>1</td>
<td>15</td>
<td>0.18072</td>
<td>0.6768</td>
</tr>
<tr>
<td>Dimensionality: Collaboration</td>
<td>0.1250</td>
<td>0.12500</td>
<td>1</td>
<td>15</td>
<td>0.18072</td>
<td>0.6768</td>
</tr>
</tbody>
</table>

The ANOVA analysis (Table 5) and graphs (Figure 31 A and B) show that differences in the number of errors correctly identified by participants were not statistically significant, regardless which of the four experimental interfaces were used. However, there may be a trend towards correctly identifying more errors when using the VR-view than when using the CAD-view.
6.2.2 Missed errors

**Figure 32**: Average number of Missed Errors (0 means No Missed Errors, 95% CI’s)
The ANOVA analysis in Table 6 shows there were no statistically significant differences between the number of errors missed in product models. From the graph in Figure 33 it can be seen that “Product model 4: (Modular Equipment Tray [MET]) and Product model 3: (Control Cursor Trackball [Trackball])” had the highest number of missed errors, possibly because of the product model’s complexity. Participants must have missed errors during the model’s assembly and disassembly.
6.2.3 Falsely identified errors

Figure 34: Average number of Falsely Identified Errors (0 means number of Falsely Identified Errors, 95% CI’s)
Table 7: Falsely Identified Errors ANOVA analysis

<table>
<thead>
<tr>
<th>ANOVA Summary</th>
<th>Sum Sq</th>
<th>Mean Sq</th>
<th>NumDF</th>
<th>DenDF</th>
<th>F-Value</th>
<th>Pr(&gt;F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental period</td>
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<td>0.0938</td>
<td>3</td>
<td>15</td>
<td>0.1568</td>
<td>0.923666</td>
</tr>
<tr>
<td>Product models</td>
<td>17.6562</td>
<td>5.8854</td>
<td>3</td>
<td>15</td>
<td>9.8432</td>
<td>0.000776</td>
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<td>Dimensionality</td>
<td>2.5312</td>
<td>2.5312</td>
<td>1</td>
<td>15</td>
<td>4.2334</td>
<td>0.057453</td>
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<tr>
<td>Collaboration</td>
<td>0.7812</td>
<td>0.7812</td>
<td>1</td>
<td>15</td>
<td>1.3066</td>
<td>0.270924</td>
</tr>
<tr>
<td>Dimensionality: Collaboration</td>
<td>2.5312</td>
<td>2.5312</td>
<td>1</td>
<td>15</td>
<td>4.2334</td>
<td>0.057453</td>
</tr>
</tbody>
</table>

Figure 35: Product Models: Average number of Falsely Identified Errors (0 means number of Falsely Identified Errors, 95% CI’s); ‘★’ indicates a significant difference.

The ANOVA analysis is presented in Table 7. It is evident that the number of errors falsely identified in the product model were not statistically significant. The graph in Figure 35 shows that participants falsely identified the most errors in “Product Model 4: (Modular Equipment Tray [MET]),” possibly because it was more complex with a greater number of parts.
6.3 NASA-TLX

The NASA-TLX measures were assessed and analyzed using the multi-factor ANOVA analysis method.

6.3.1 Post-task questionnaire

The post-task questionnaire was comprised of questions to assess each participant’s perception of the task they had just completed. There were 6 NASA-TLX measures:

- Mental Demand
- Physical Demand
- Temporal Demand
- Performance
- Effort
- Frustration

All of the questions and their respective scales ratings are included in Appendix B.
6.3.1.1 NASA-TLX Mental Demand

“How mentally demanding was the task?” (Lower ratings are better)

![Graphs showing mental demand comparison between different interfaces: CAD-view vs. VR-view for Dimensionality and Individual vs. Collaborative Interface for Collaboration.](image)

**Figure 36:** NASA-TLX: Mental Demand Self-Assessment by Interface (0 means Very Low, and 10 means Very high, 95% CI’s)

**Table 8:** NASA-TLX: Mental Demand ANOVA analysis

<table>
<thead>
<tr>
<th>ANOVA Summary</th>
<th>Sum Sq</th>
<th>Mean Sq</th>
<th>NumDF</th>
<th>DenDF</th>
<th>F-Value</th>
<th>Pr(&gt;F)</th>
</tr>
</thead>
<tbody>
<tr>
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<td>2.2109</td>
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<td>3</td>
<td>15</td>
<td>0.53136</td>
<td>0.6677</td>
</tr>
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<td>Product models</td>
<td>7.2109</td>
<td>2.40365</td>
<td>3</td>
<td>15</td>
<td>1.73301</td>
<td>0.2031</td>
</tr>
<tr>
<td>Dimensionality</td>
<td>0.1953</td>
<td>0.19531</td>
<td>1</td>
<td>15</td>
<td>0.14082</td>
<td>0.7127</td>
</tr>
<tr>
<td>Collaboration</td>
<td>0.3828</td>
<td>0.38281</td>
<td>1</td>
<td>15</td>
<td>0.27600</td>
<td>0.6070</td>
</tr>
<tr>
<td>Dimensionality: Collaboration</td>
<td>0.0078</td>
<td>0.00781</td>
<td>1</td>
<td>15</td>
<td>0.00563</td>
<td>0.9412</td>
</tr>
</tbody>
</table>

The above results indicate that differences in the perceived mental demand imposed by 4 interfaces were not statistically significant. All participants experienced similarly perceived levels of mental effort when using collaborative or individual interfaces, or CAD vs. Virtual Reality interfaces.
6.3.1.2 NASA-TLX Physical Demand

“How physically demanding was the task?” (Lower ratings are better)

![Graph showing physical demand](image)

**Figure 37**: NASA-TLX: Physical Demand Self-Assessment by Interface (0 means Very Low, and 10 means Very high, 95% CI’s)

**Table 9**: NASA-TLX: Physical Demand ANOVA analysis

<table>
<thead>
<tr>
<th>ANOVA Summary</th>
<th>Sum Sq</th>
<th>Mean Sq</th>
<th>NumDF</th>
<th>DenDF</th>
<th>F-Value</th>
<th>Pr(&gt;F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental period</td>
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<td>0.5968</td>
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<td>15</td>
<td>0.4101</td>
<td>0.74810</td>
</tr>
<tr>
<td>Product models</td>
<td>4.2812</td>
<td>1.4271</td>
<td>3</td>
<td>15</td>
<td>0.9856</td>
<td>0.42597</td>
</tr>
<tr>
<td>Dimensionality</td>
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<td>5.2813</td>
<td>1</td>
<td>15</td>
<td>3.6475</td>
<td>0.07547</td>
</tr>
<tr>
<td>Collaboration</td>
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<td>0.2813</td>
<td>1</td>
<td>15</td>
<td>0.1942</td>
<td>0.66569</td>
</tr>
<tr>
<td>Dimensionality: Collaboration</td>
<td>1.5312</td>
<td>1.5312</td>
<td>1</td>
<td>15</td>
<td>1.0576</td>
<td>0.32007</td>
</tr>
</tbody>
</table>

The results above show that the physical demand using various interfaces and various experimental conditions were not great, and that the differences were not statistically significant.
6.3.1.3 NASA-TLX Temporal Demand

“How hurried or rushed was the pace of the task?” (Lower ratings are better)

![Figure 38: NASA-TLX: Temporal Demand Self-Assessment by Interface (0 means Very Low (Not Hurried), and 10 means Very high (Rushed), 95% CI’s); ⭐ indicates a significant difference.

Table 10: NASA-TLX: Temporal Demand ANOVA analysis

<table>
<thead>
<tr>
<th>ANOVA Summary</th>
<th>Sum Sq</th>
<th>Mean Sq</th>
<th>NumDF</th>
<th>DenDF</th>
<th>F-Value</th>
<th>Pr(&gt;F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental period</td>
<td>1.4063</td>
<td>0.4688</td>
<td>3</td>
<td>15</td>
<td>0.9366</td>
<td>0.44879</td>
</tr>
<tr>
<td>Product models</td>
<td>7.0313</td>
<td>2.3438</td>
<td>3</td>
<td>15</td>
<td>4.6680</td>
<td>0.01699</td>
</tr>
<tr>
<td>Dimensionality</td>
<td>1.1250</td>
<td>1.1250</td>
<td>1</td>
<td>15</td>
<td>2.2407</td>
<td>0.15517</td>
</tr>
<tr>
<td>Collaboration</td>
<td>3.7812</td>
<td>3.7812</td>
<td>1</td>
<td>15</td>
<td>7.5311</td>
<td>0.01506</td>
</tr>
<tr>
<td>Dimensionality: Collaboration</td>
<td>0.1250</td>
<td>0.1250</td>
<td>1</td>
<td>15</td>
<td>0.2490</td>
<td>0.62504</td>
</tr>
</tbody>
</table>

The ANOVA analysis in Table 10 shows there were significant differences in perceived temporal demands for the Individual interface and the Collaborative interface. The graph in Figure 38B demonstrates that the Collaborative interface graph had the highest perceived temporal demand, while the Individual interface had the lowest. This means that participants felt the most rushed when using the Collaborative interface, which contradicts the **Time to Task Completion** graph shown in Figure 29B (Pg. 47). The exact reason for this perception...
is unknown. A possible explanation is that during the collaborative interface the other participant was waiting to hand over the controls; most of the time the other participant was not able to do anything but talk about the product model.

**Figure 39**: Product model: Temporal Demand as Function of Interface (95% CI’s); ‘★’ indicates a significant difference.

There were also significant differences in perceived temporal demands between product models. The graph in Figure 39 shows that “Product model 4: (Modular Equipment Tray [MET])” was perceived as the most temporally demanding of the 4 product models. It was the most complex in design and had the highest number of parts, which is consistent with the **Time to Task Completion** graph in Figure 30 (Pg. 49). While it is not desirable for product models to have different perceived temporal demands, it does not affect the validity of the results for other variables because the design of the experiment systematically varied parings of product models and interfaces to counterbalance the effects.
6.3.1.4 NASA-TLX Performance

“How successful were you in accomplishing the task?” (Lower ratings are better)

![Image](image-url)

**Figure 40:** NASA-TLX: Performance Demand Self-Assessment by Interface (0 means Very Low (few errors), and 10 means Many (Rushed), 95% CI’s); “★” indicates a significant difference.

<table>
<thead>
<tr>
<th>ANOVA Summary</th>
<th>Sum Sq</th>
<th>Mean Sq</th>
<th>NumDF</th>
<th>DenDF</th>
<th>F-Value</th>
<th>Pr(&gt;F)</th>
</tr>
</thead>
<tbody>
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<td>1.8203</td>
<td>3</td>
<td>15</td>
<td>1.1322</td>
<td>0.367720</td>
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<td>15</td>
<td>9.8397</td>
<td><strong>0.006787</strong></td>
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<tr>
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<td>2.2578</td>
<td>1</td>
<td>15</td>
<td>1.4043</td>
<td>0.254445</td>
</tr>
<tr>
<td>Dimensionality: Collaboration</td>
<td>2.8203</td>
<td>2.8203</td>
<td>1</td>
<td>15</td>
<td>1.7541</td>
<td>0.205185</td>
</tr>
</tbody>
</table>

The ANOVA analysis in Table 11 shows a significant difference in perceived performance between the CAD-view and the VR-view. The graph in Figure 40A shows that participants perceived themselves as more successful (e.g.: lower number) when using the VR-view than when using the CAD-view. During the experiment it was apparent that participants using the VR-view collaborative could interact with the model in real-time and were able to visualize every part of the model more clearly than when using the CAD-view interface.
6.3.1.5 NASA-TLX Effort

“How hard did you have to work to accomplish your level of performance?” (Lower ratings better)

![Figure 41: NASA-TLX: Effort Demand Self-Assessment by Interface (0 means Very Easy, and 10 means Very hard, 95% CI’s)](image)

<table>
<thead>
<tr>
<th>ANOVA Summary</th>
<th>Sum Sq</th>
<th>Mean Sq</th>
<th>NumDF</th>
<th>DenDF</th>
<th>F-Value</th>
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<tbody>
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<td>15</td>
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<tr>
<td>Product models</td>
<td>2.03125</td>
<td>0.67708</td>
<td>3</td>
<td>15</td>
<td>0.63353</td>
<td>0.6048</td>
</tr>
<tr>
<td>Dimensionality</td>
<td>0.03125</td>
<td>0.03125</td>
<td>1</td>
<td>15</td>
<td>0.02924</td>
<td>0.8665</td>
</tr>
<tr>
<td>Collaboration</td>
<td>3.12500</td>
<td>3.12500</td>
<td>1</td>
<td>15</td>
<td>2.92398</td>
<td>0.1079</td>
</tr>
<tr>
<td>Dimensionality: Collaboration</td>
<td>0.12500</td>
<td>0.12500</td>
<td>1</td>
<td>15</td>
<td>0.11696</td>
<td>0.7371</td>
</tr>
</tbody>
</table>

The results of the ANOVA analysis revealed that the differences between interfaces in terms of perceived effort were not statistically significant.
6.3.1.6 NASA-TLX Frustration

“How insecure, discouraged, irritated, stressed & annoyed were you?” (Lower ratings were better)

![Graph showing frustration levels for different interfaces.](image)

**Figure 42**: NASA-TLX: Frustration Demand Self-Assessment by Interface (0 means not frustrated and 10 means very frustrated, 95% CI's)

**Table 13**: NASA-TLX: Frustrated Demand ANOVA analysis

<table>
<thead>
<tr>
<th>ANOVA Summary</th>
<th>Sum Sq</th>
<th>Mean Sq</th>
<th>NumDF</th>
<th>DenDF</th>
<th>F-Value</th>
<th>Pr(&gt;F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental period</td>
<td>8.9375</td>
<td>2.9792</td>
<td>3</td>
<td>15</td>
<td>1.430</td>
<td>0.2733</td>
</tr>
<tr>
<td>Product models</td>
<td>12.6250</td>
<td>4.2083</td>
<td>3</td>
<td>15</td>
<td>2.020</td>
<td>0.1544</td>
</tr>
<tr>
<td>Dimensionality</td>
<td>1.5312</td>
<td>1.5312</td>
<td>1</td>
<td>15</td>
<td>0.735</td>
<td>0.4048</td>
</tr>
<tr>
<td>Collaboration</td>
<td>0.0313</td>
<td>0.0313</td>
<td>1</td>
<td>15</td>
<td>0.015</td>
<td>0.9041</td>
</tr>
<tr>
<td>Dimensionality: Collaboration</td>
<td>0.5</td>
<td>0.5</td>
<td>1</td>
<td>15</td>
<td>0.240</td>
<td>0.6313</td>
</tr>
</tbody>
</table>

The results of the ANOVA analysis revealed that there were no statistically significant differences between interfaces in terms of frustration experienced.
6.4 Collaboration and Connection

In addition to NASA-T LX questions, other questions were asked of participants in order to assess their perception regarding interactions with their partners during the collaborative tasks. While answering questions, participants were asked to disregard individual interface conditions and focus on collaborative conditions.

6.4.1 Cooperation Effort

“To what extent did your solution truly feel like a joint effort?” (Lower ratings are more collaborative)

Figure 43: Cooperation Effort Self-Assessment by Interface (0 means a very much a joint effort and 10 means not at all a joint effort, 95% CI’s). ★ indicates a significant difference.
Table 14: Cooperation Effort ANOVA analysis

<table>
<thead>
<tr>
<th>ANOVA Summary</th>
<th>Sum Sq</th>
<th>Mean Sq</th>
<th>NumDF</th>
<th>DenDF</th>
<th>F-Value</th>
<th>Pr(&gt;F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental period</td>
<td>2.6650</td>
<td>0.8883</td>
<td>3</td>
<td>3.4122</td>
<td>3.3443</td>
<td>0.15649</td>
</tr>
<tr>
<td>Product models</td>
<td>9.0948</td>
<td>3.0316</td>
<td>3</td>
<td>3.4122</td>
<td>11.4130</td>
<td>0.02863</td>
</tr>
<tr>
<td>Dimensionality</td>
<td>5.6406</td>
<td>5.6406</td>
<td>1</td>
<td>3.0000</td>
<td>21.2353</td>
<td>0.01922</td>
</tr>
</tbody>
</table>

The graph in Figure 43A shows a statistically significant difference in cooperation effort between the VR-view and CAD-view collaborative interfaces. The participants felt they were cooperating more when using the VR-view interface. A probable explanation is that they were more drawn into the realistic environment of the VR-view and felt it was not that engaging, as compared to the CAD-view. There were also significant differences in cooperative effort between product models. “Product Model 4: (Modular Equipment Tray [MET])” seen in the graph in Figure 43B, received the highest rating due to the greater number of parts.
6.4.2 Interface: Seamless Collaboration

“How well do you feel the computer interface allowed you to collaborate seamlessly with your partner?” (Lower ratings are better)

Rough Collaboration

Figure 44: Interface—Seamless Collaboration Self-Assessment by Interface (where 0 indicates seamless collaboration and 10 means rough collaboration, 95% CI’s)

Table 15: Interface-Seamless Collaboration ANOVA Comparisons

<table>
<thead>
<tr>
<th>ANOVA Summary</th>
<th>Sum Sq</th>
<th>Mean Sq</th>
<th>NumDF</th>
<th>DenDF</th>
<th>F-Value</th>
<th>Pr(&gt;F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental period</td>
<td>6.6075</td>
<td>2.2025</td>
<td>3</td>
<td>3.5101</td>
<td>2.1144</td>
<td>0.2568</td>
</tr>
<tr>
<td>Product models</td>
<td>7.9805</td>
<td>2.6602</td>
<td>3</td>
<td>3.5101</td>
<td>2.5538</td>
<td>0.2097</td>
</tr>
<tr>
<td>Dimensionality</td>
<td>0.0625</td>
<td>0.0625</td>
<td>1</td>
<td>3.0000</td>
<td>0.0600</td>
<td>0.8223</td>
</tr>
</tbody>
</table>

The results above show that differences in seamless collaboration between interfaces were not statistically significant.
6.4.3 Interface: Limited Collaboration

“To what degree did the computer interface limit your ability to collaborate with your partner?” (Lower rating means less limiting)

Greatly Limiting

![Graph showing limited collaboration](image)

Not Limiting

**Figure 45:** Interface- Limited Collaboration Self-Assessment by Interface (where 0 indicates not limiting, and 10 means great limiting, 95% CI’s)

**Table 16:** Interface-Limited Collaboration ANOVA analysis

<table>
<thead>
<tr>
<th>ANOVA Summary</th>
<th>Sum Sq</th>
<th>Mean Sq</th>
<th>NumDF</th>
<th>DenDF</th>
<th>F-Value</th>
<th>Pr(&gt;F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental period</td>
<td>0.4858</td>
<td>0.1619</td>
<td>3</td>
<td>3.7171</td>
<td>0.1279</td>
<td>0.9383</td>
</tr>
<tr>
<td>Product models</td>
<td>15.2143</td>
<td>5.0714</td>
<td>3</td>
<td>3.7171</td>
<td>4.0071</td>
<td>0.1149</td>
</tr>
<tr>
<td>Dimensionality</td>
<td>0.3906</td>
<td>0.3906</td>
<td>1</td>
<td>3.0000</td>
<td>0.3086</td>
<td>0.6173</td>
</tr>
</tbody>
</table>

The above results show that differences in limited collaboration between interfaces were not statistically significant.
6.5 Debriefing Questionnaire

Participants completed a debriefing questionnaire once they had finished all tasks in order to compare the interfaces. Participants answered questions such as:

- Which interface was easiest to use?
- Which was the most fun?
- Which would you choose as a working professional collaborating with people in other locations?
- Please List the different computer interfaces from 1st favorite to least favorite.

“Which interface was easiest to use?”

![Bar chart showing participant preferences for “Easy to Use”]

**Figure 46**: Participant Preferences, Easiest to Use

The focus of the first two questions of the questionnaire were on the user’s experience with Virtual Reality and the CAD user interface. The above graph shows that the CAD-view collaborative and the Virtual Reality-view individual had similar “easiest-to-use” ratings.
“Which was the most fun?”

**Figure 47:** Participant Preferences, Most Fun

The graph above shows that the VR-view individual interface was rated as the most fun to use when compared to other interfaces.

“Which would you choose as a working professional collaborating with people in other locations?”

**Figure 48:** Participant Preferences, Working Professional

This question focused on distance technologies, and professional tools choices. The graph above reveals that the VR-view individual interface was the most frequently preferred professional tool.
“Please list the different computer interfaces from 1st favorite to least favorite”

The last question assessed participants’ most preferred interface. They were to rank the interfaces in order of the most preferred interface (1) to the least preferred interface (4). The graph below was created to visualize the data better and displays how the interfaces were ranked from the first favorite to least favorite.

![Composite Interface Rankings](image)

**Figure 49:** Participants Composite Interface Rankings
Each of the interfaces was assigned a preference score based on all participant rankings. The rating factor was multiplied by the number of rankings the interface received or the number of times it was ranked. For instance, if the most favorite interface had a rating of “4” and the VR-view individual interface was the most favorite for 6 participants, it scored “4 X 6=24.” Figure 48 shows the composite preference score for each of the interfaces.

<table>
<thead>
<tr>
<th>Ranking</th>
<th>Preference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Most favorite</td>
<td>4</td>
</tr>
<tr>
<td>2nd favorite</td>
<td>3</td>
</tr>
<tr>
<td>3rd favorite</td>
<td>2</td>
</tr>
<tr>
<td>Least favorite</td>
<td>1</td>
</tr>
</tbody>
</table>

The Virtual Reality individual interface was the most popular, while Virtual Reality with the collaborative interface was the second most popular. The least favorite among the participants was CAD with the individual interface.
### 6.6 Short Answer Responses

“What were the most frustrating part(s) about working on this task? For example, your partner, or the computer interface, the difficulty of the task, etc.”

“What were the most enjoyable/positive aspect(s) of working on this task?”

Table 18: Participants responses to the questions in post-task questionnaire

<table>
<thead>
<tr>
<th>Setup</th>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAD-view with individual interface</td>
<td><strong>Pros:</strong></td>
<td><strong>Cons:</strong></td>
</tr>
<tr>
<td></td>
<td>• Use of Stylus: [7]</td>
<td>• Controls (rotating movement, zoom-in and out): [8]</td>
</tr>
<tr>
<td></td>
<td>• Ease of interface in resetting and disassembly: [5]</td>
<td>• Difficulty of finding an error: [1]</td>
</tr>
<tr>
<td></td>
<td>• View of model from different perspective: [1]</td>
<td>• Difficult of task: [2]</td>
</tr>
<tr>
<td></td>
<td>• Thinking process: [1]</td>
<td>• Unfamiliar with design: [1]</td>
</tr>
<tr>
<td></td>
<td>• Finding errors: [1]</td>
<td></td>
</tr>
<tr>
<td>CAD-view with collaborative interface</td>
<td><strong>Pros:</strong></td>
<td><strong>Cons:</strong></td>
</tr>
<tr>
<td></td>
<td>• Collaboration [task easier, reassurance, another set of eyes]:</td>
<td>• Computer Interface [rotate and disassemble]: [6]</td>
</tr>
<tr>
<td></td>
<td>• Controls: [1]</td>
<td>• Finding Errors: [1]</td>
</tr>
<tr>
<td></td>
<td>• No positive effect: [1]</td>
<td>• Difficult of task: [5]</td>
</tr>
<tr>
<td></td>
<td>• Interface: [2]</td>
<td>• Partner was not responsive: [2]</td>
</tr>
<tr>
<td></td>
<td>• Assembly and disassembly: [2]</td>
<td>• Different views: [1]</td>
</tr>
</tbody>
</table>
**Table 18:** (continued)

<table>
<thead>
<tr>
<th>VR-view with individual interface</th>
<th><strong>Pros:</strong></th>
<th><strong>Cons:</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>• 3-D View model perspective: [8]</td>
<td>• Tricky Controls (zoom-in and out): [2]</td>
</tr>
<tr>
<td></td>
<td>• Easier head movements/side glances: [3]</td>
<td>• Computer Interface:</td>
</tr>
<tr>
<td></td>
<td>• 3-D glasses: [2]</td>
<td>• [1]</td>
</tr>
<tr>
<td></td>
<td>• Rotating: [1]</td>
<td>• Dual Images: [4]</td>
</tr>
<tr>
<td></td>
<td>• Experiencing new technology: [1]</td>
<td>• Irritation in eyes: [1]</td>
</tr>
<tr>
<td>VR-view with collaborative interface</td>
<td><strong>Pros:</strong></td>
<td><strong>Cons:</strong></td>
</tr>
<tr>
<td></td>
<td>• 3-D View helpful to rotate parts while disassembly: [2]</td>
<td>• Difficulty of task: [4]</td>
</tr>
<tr>
<td></td>
<td>• 3-D View model perspective: [6]</td>
<td>• Model is little sophisticated: [1]</td>
</tr>
<tr>
<td></td>
<td>• Collaboration: [5]</td>
<td>• 3D tools are demanding: [1]</td>
</tr>
<tr>
<td></td>
<td>• Glasses &amp; stylus: [1]</td>
<td>• Product model: [1]</td>
</tr>
<tr>
<td></td>
<td>• Different perspective of the partner: [2]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Experiencing new technology: [1]</td>
<td></td>
</tr>
</tbody>
</table>

The number in “[X]” indicates the number of times an item was commented on by each participant. Detailed comments by each participant is given in Appendix F.
6.7 Summary of Debriefing questionnaire

The desktop VR system had several hardware and software limitations which may have affected participant choices in the debriefing questionnaire. However, participant preferences reveal that the VR-view with the individual interface was rated the “most fun,” the “preferred collaboration tool as a working professional,” and the “most favorite.”

Reasons for preferring the VR-view over the CAD-view were naturalness, convenience and immediacy factor when using the VR-view interface. Participants liked that they were able to look at different sides/views of a part by moving their heads in the VR-view. This provided a very easy and natural way to view potential interferences between two parts that is not possible with a CAD view. In contrast, in the CAD-view they must use the interface controls to change views of a part.

Participants preferred the individual over the collaborative interface when using the VR-view, because when using the collaborative set-up, the VR desktop computer could register only one of the head trackers on the virtual reality glasses. This caused the viewing angle of the product model to flicker back and forth between the two participants, causing them to experience a jerky phenomenon.

For the question, “Which interface was easiest to use?” there was a tie between the VR-view with an individual interface and the CAD-view with a collaborative interface. It is notable that when using the CAD-view, participants preferred the collaborative interface, but when using the VR-view they preferred the individual interface. The question might arise: “Why was this
so?” When using the CAD-view interface, participants preferred the collaborative over the individual version--due to the communication, reassurance, and extra perspective offered by the other participant. As explained earlier, the hardware/software problem interfered with the effectiveness of the VR-view using a collaborative interface; however, there was no such problem with the collaborative CAD-view because participants did not need the virtual reality glasses in the CAD-view interface.
CHAPTER 7. DISCUSSION

This chapter is divided into two sections that discuss the two research questions.

7.1 Can Virtual Reality (VR)-view improve a design reviewers’ ability to detect errors when reviewing a product model over a traditional CAD system?

Based on the results of this experiment one cannot conclude that VR improves the design reviewers’ ability to find errors in a product model over that of a CAD-view. There were no significant differences between the VR-view and the CAD-view interfaces in 3 different error types such as the number of errors correctly identified, the number of errors missed, and the number of errors falsely identified.

However, the author is not convinced that stereoscopic 3-D viewing (VR-view) of a product model is not useful in general. There were several issues experienced by the participants that interfered with the effectiveness of the VR-view. Some participants complained that they saw dual images--one above the other--interfering with stereoscopic viewing, some reported eye irritation after using it for a lengthy duration; and some experienced a “jerky” phenomenon when using the VR-view with collaborative interface. The computer could register to only one of the two head trackers at a time on the two collaborating participants virtual reality glasses. This caused the viewing angle of the product model to flicker back and forth between the two participants, causing them to experience a jerky phenomenon. The jerky phenomenon occurred once every 10 minutes. Thus, the multiple hardware and software challenges experienced with the VR-view may have prevented it from being more effective.
However, there were other indicators suggesting that it may be worthwhile to continue investigating VR-viewing for use in product design review. The results also indicated that participants using the Virtual Reality (VR)-view interface perceived that they performed significantly better and those working collaboratively with a partner felt a stronger sense of cooperation in design review tasks than when using the CAD-view. Also, a non-significant trend was observed in that participants correctly identified more errors when using the VR-view interface. Hence, for future work it may be useful to look for a different VR system, or repeat the experiment using greater number of participants to determine whether the trend is significant and meaningful.

To summarize, the hardware and software issues may have interfered with the potential effectiveness of the VR-view interface. The author believes that the current desktop VR system used in the experimental platform did not provide sufficient hardware and software support to effectively test the research question.

7.2 Can two collaborating individuals be more effective (faster time or detect more errors) in a product design review than an individual alone?

Based on the experimental results, the author can provide evidence that two collaborating individuals are faster in completing a task in a product design review than an individual operating alone. There were no significant differences between any of the interfaces in 3 different error types, including the number of errors correctly identified, the number of errors missed, and the number of errors falsely identified.
However, when using the collaborative interface (in both CAD-view and VR-view) participants completed the task in significantly less time than when using the individual interface. The average time for each task was 4.46 minutes less when using the collaborative interface than when using the individual interface. The author of this thesis observed that when using the collaborative interface, participants talked with each other and divided the workload, helping them detect errors more quickly than individuals working alone.

Participants perceived that the pace of the task was significantly more hurried than when using the individual interface, even though they completed the task faster in the collaborative interface. The exact reason for this perception is unknown. A possible explanation is that when a pair of collaborating participants are working together, one participant is waiting to take control of the interface and is talking about the product model most of the time.

Apart from participants feeling rushed when using the collaborative setup, they also experienced a “jerky phenomenon” when using the VR-view with collaborative interface. These limitations may have interfered with VR-view interface effectiveness.

In summary, some of the results may have been affected by the limitations of the hardware and software systems used as the experimental platform. The particular desktop VR system employed may not yet be enough to provide a more effective comparison between individual and collaborative interfaces. Future experimentation calls for a better VR system where both participants comprising a pair do not have a competing head tracker in a collaborative interface.
CHAPTER 8. CONCLUSION

This thesis investigates two research questions: “Can Virtual Reality (VR)-view improve a design reviewer’s ability to detect errors when reviewing a product model over a traditional CAD system?” and “Can two collaborating individuals be more effective (faster time or detect more errors) in a product design review than an individual alone?” The experiment carried out for this thesis did not find evidence to support the first question.

To answer these questions an experiment was conducted with 16 participants who each used four interfaces: participants working individually using a CAD view of a 3D CAD model interface, participants working in pairs using a CAD view of a 3D CAD model interface, participants working individually using a stereoscopic view of a 3D CAD model interface, and participants working in pairs using a stereoscopic view of a 3D CAD model interface.

The data showed no significance differences between any of the interfaces (the CAD-view vs. the VR-view interfaces, and the individual vs. the collaborative interfaces) in terms of the number of errors identified, including the number of errors missed, and the number of errors falsely identified. The results from the second question indicated that when using the collaborative interface, participants completed the task faster than when using the individual interface.

However, the author believes the multiple hardware and software issues with the VR desktop used may have prevented the VR-view from being more effective; some participants experienced eye irritation, saw dual images, or sensed a jerky phenomenon. The VR-view
might help design reviewers detect more errors in a product model if an experimental platform free of these problems were used.

Furthermore, other results from this experiment suggest that it may be worthwhile to further explore these questions using different hardware and software. There was a non-significant trend for participants to correctly identify more errors when using the VR-view. One should consider repeating the experiment with a greater number of participants to determine whether the trend is meaningful and significant. Participants using the VR-view felt they performed significantly better, and those working collaboratively felt a stronger sense of cooperation than when using the CAD-view.

Given the results, the author believes that the current desktop VR system used in the study did not provide sufficient hardware and software support to effectively test the two research questions. Hence, further studies should also consider using a better VR system with fewer limitations.
CHAPTER 9. LIMITATIONS AND FUTURE WORKS

The experimental hardware and software platform developed by the author to conduct this work is a proof-of-concept system. As such, it has several shortcomings.

9.1 Limitations

- The current system had a number of hardware and software issues which are listed below:
  - **Dual images**: Left and right stereoscopic images were sometimes displayed incorrectly (one vertically above the other), causing dual images to appear when using Virtual Reality glasses.
  - **Eye Irritation**: Participants felt eye irritation when using the VR-view interface for an extended period.
  - **Jerky phenomenon**: The VR-desktop computer alternatively picked up the two participants' tracking sensors on their Virtual Reality glasses when they were used in the collaborative set-up. This caused the viewing angle of the product model to flicker back and forth between the two participants, causing them to experience a jerky phenomenon when using the VR-view with the collaborative interface.

Due to several limitations, a different VR-system needs to be explored with fewer shortcomings.
9.2 Future works

- There are several ways in which this work could be extended:

  o **Non-significant trend:** A non-significant trend was observed that suggests participants were able to correctly identify more errors when using the VR-view than when using the CAD-view. It may be useful to repeat the experiment with a larger number of participants to determine whether these trends are meaningful and insightful.

  o **Different VR-system:** The current software did not allow remote collaboration due to a software limitation. The single-user system that was developed would not be suitable for true design review applications, as design reviews are inherently a multi-user interactive activity. Hence, suitable software needs to be selected that allows multi-user interaction in a VR-environment.

Related research in the future should investigate the possibility of extending the concept of multi-user interfaces to other Computer-Aided Engineering (CAE) tools in addition to changing the hardware and software of the Virtual Reality system and increasing sample size. This would enable enhanced model interactions with a host of additional engineering design and analysis tools.
REFERENCES


[9]. Evans, Gabriel, (2018) "Development of a 3D conceptual design environment using a commodity head mounted display virtual reality system". Graduate Theses and Dissertations. 16576. https://lib.dr.iastate.edu/etd/16576


APPENDIX A. TASK DESCRIPTION

General information for use in all the scenarios

You will need to discuss that information in order to complete the tasks. Use the collaborative interface as needed to share information or discuss ideas. Jointly decide (1) what to do and (2) why.

Each scenario is designed to take approximately 10-15 minutes, though you are free to complete them sooner if you and your partner feel you have finished the task satisfactorily.

Tips for using the collaborative interface effectively:

- Go slowly. The system can’t process too many changes at once
- Click on “Unilowamain.py” to run the script and load the COLLADA file to the system.
- The loaded model can be manipulated using keyboard and stylus
  - **Keyboard Instructions**
    - Press the spacebar to remove one part at a time following a pre-set sequence
    - Press “Left_Ctrl” to assemble one part at a time following a pre-set sequence
    - Press the “R” key to reassemble
    - Press “W” to rotate the model in the upward direction
    - Press “S” to rotate the model in the downward direction
    - Press “A” to rotate the model in the clockwise direction
    - Press “D” to rotate the model in the anti-clockwise direction
    - Press “H” to bring the model in the home position
  - **Stylus Instructions**
    - Grab the stylus and press the primary button to grab a part
    - Press either the left/right stylus button to move the model either in the forward and backward direction respectively
Errors Type

- **Misalignment**
  - 2 Screws are not aligned with their holes
  - The connector holes are not aligned with their holes
- **Missing Parts**
  - The screw is missing
• **Interference**
  
  - Two parts collide with each other
Task#1, CAD-view with collaborative interface

Goal: Identify the errors in the given product model by collaborating with your partner and come up with a solution to find out all the level of errors in the model

Participant placement: side-by-side at same workstation

Interface: CAD

You & your partner share control of one stylus that controls a cursor that appears as a colored ray. You can use the functions above to explore the product models and find the level of the errors and identify the type of errors.

The errors that you need to identify are on the sheet labeled as “Error types”.

Show or tell your plan to the experimenter to complete the task.
**Task#2, CAD- view with individual interface**

**Goal:** Identify the errors in the given product model by collaborating with your partner and come up with a solution to find out all the level of errors in the model.

**Participant placement:** sitting on opposite of a wall using separated collaborative cells.

**Interface:** CAD

You have the product model and you can use the different functions of the keyboard and stylus to explore the product model and identify with errors. You can talk but not see each other.

Your coworker has the same product model and coordinates with you to identify the errors.

The errors that you need to identify are on the sheet labeled as "**Error types**".

Show or tell your plan to the experimenter to complete the task.
**Task#3, Virtual Reality (VR)- view with collaborative interface**

**Goal:** Identify the errors in the given product model by collaborating with your partner and come up with a solution to find out all the level of errors in the model

**Participant placement:** side-by-side at same workstation

**Interface:** Virtual Reality

You & your partner share control of one stylus that controls a cursor that appears as a colored ray. You can use the functions above to explore the product models and find the level of the errors and identify the type of errors.

The errors that you need to identify are on the sheet labeled as “Error types”.

Show or tell your plan to the experimenter to complete the task.
Task#4, Virtual Reality (VR)- view with individual interface

**Goal:** Identify the errors in the given product model by collaborating with your partner and come up with a solution to find out all the level of errors in the model.

**Participant placement:** sitting on opposite of a wall using separated collaborative cells.

**Interface:** Virtual Reality

You have the product model and you can use the different functions of the keyboard and stylus to explore the product model and identify with errors. You can talk but not see each other

Your coworker has the same product model and coordinates with you to identify the errors.

The errors that you need to identify are on the sheet labeled as “Error types”.

Show or tell your plan to the experimenter to complete the task.
APPENDIX B. QUESTIONNAIRE

1. Demographic Questionnaire

Thank you so much for accepting to participate in this experimental study.
Please answer to the following questions:

Personal Details:

1. What is your gender?
   ☐ Male ☐ Female

2. What is your age?
   ☐ 18 or under ☐ 19-25 ☐ 25-30 ☐ 30-35 ☐ 35-40 ☐ 40-45 ☐ 45-50
   ☐ above 50

3. Are you fluent in English?
   ☐ Yes ☐ No

Your background and degree:

<table>
<thead>
<tr>
<th>Degree type</th>
<th>Field of Study</th>
<th>Specialization</th>
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<tr>
<td>Bachelor (or similar)</td>
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<td>Master (or similar)</td>
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<tr>
<td>PhD (or similar)</td>
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Career background and position or job responsibility:

4. How many years of experience of working do you have? (including internship)
   Please explain your position and responsibility on your job:

Physical Condition:

5. Do you have any specific problem in your eyes?
   ☐ Yes ☐ No
   If Yes please explain the type of problem:
6. Do you have any disability in your arms or hands?
   - Yes
   - No

   If Yes please explain the type of disability:

   Meeting and Design Meeting:

7. Have you ever had the experience of collaborative work?
   - Yes
   - No

8. Do you have experience working in a team?
   - Yes
   - No

9. Have you ever been involved in design project?
   - Yes
   - No

10. Have you ever been in a design review meeting?
    - Yes, several times
    - Yes, but not too much
    - No, that's my first time

11. Have you ever had the experience of remote/virtual design review meeting (people in the meeting were located in different place)? [If Yes please answer the next question]
    - Yes
    - No

12. Please explain what type of software, tool or collaborative environment you used during the remote design review meeting and what type of difficulty you had with them [please mentioned all type of them even if you used different types in different meeting]?

Thank you for taking the time to complete this questionnaire
2. Post-Task Questionnaire

**Instructions:** Think about the collaborative task you just completed. Please consider the following questions with that task in mind. Place an “X” along each scale at the point that best indicates your experience with the display configuration.

**Note!** *This form has been designed so that the rating scale is always:*

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<thead>
<tr>
<th>Good/Easy</th>
<th>Bad/Difficult</th>
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**Mental Demand:** How mentally demanding was the task?

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<th>Very Low</th>
<th>Very High</th>
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**Physical Demand:** How physically demanding was the task?

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<th>Very High (Difficult)</th>
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(Easy)
**Post-Task Questionnaire**

**Temporal Demand:** How hurried or rushed was the pace of the task?

[ ] [ ] [ ] [ ] [ ] [ ] [ ] [ ]

Very Low (Not Hurried)  Very High (Rushed)

**Performance:** How successful were you in accomplishing the task? (Low score is best)

[ ] [ ] [ ] [ ] [ ] [ ] [ ] [ ]

Very Successful  Very Unsuccessful

**Effort:** How hard did you have to work to accomplish your level of performance?

[ ] [ ] [ ] [ ] [ ] [ ] [ ] [ ]

Very Easy  Very Hard

**Frustration:** How insecure, discouraged, irritated, stressed and annoyed were you?

[ ] [ ] [ ] [ ] [ ] [ ] [ ] [ ]

Not Frustrated  Very Frustrated

**Cooperation:** To what extent did your solution truly feel like a joint effort?

[ ] [ ] [ ] [ ] [ ] [ ] [ ] [ ]

Very Much a Joint Effort  Not at All a Joint Effort
Post-Task Questionnaire

**Connection:** To what degree did you feel disconnected from your teammate?

[Scale from Strongly Connected to Strongly Disconnected]

**Interface:** How well do you feel the computer interface allowed you to collaborate seamlessly with your partner?

[Scale from Seamless Collaboration to Rough Collaboration]

**Short Answer:** What were most frustrating part(s) about working on this task? For example, your partner, or the computer interface, the difficulty of the task, etc.

**Interface:** To what degree did the computer interface limit your ability to collaborate with your partner?

[Scale from Not Limiting to Greatly Limiting]
**Connection:** How much did you feel as if your partner was present with you, while working together on a solution?

![Connection Scale]

**Short Answer:** What were the most enjoyable/positive aspect(s) of working on this task?
3. Debriefing Questionnaire

1. I felt that all the computer interfaces were roughly the same in terms of usability, enjoyability, and productivity.
   A. Agree  B. False

2. Which interface was easiest to use?
   A. CAD with side-by-side  B. CAD with virtual  C. Virtual Reality with side-by-side  D. Virtual Reality with virtual

3. Which was the most fun?
   A. CAD with side-by-side  B. CAD with virtual  C. Virtual Reality with side-by-side  D. Virtual Reality with virtual

4. Which would you choose as a working professional collaborating with people in other locations?
   A. CAD with side-by-side  B. CAD with virtual  C. Virtual Reality with side-by-side  D. Virtual Reality with virtual

5. For which interface did you feel most connected to your partner?
   A. CAD with side-by-side  B. CAD with virtual  C. Virtual Reality with side-by-side  D. Virtual Reality with virtual

6. Please List the different computer interfaces from 1st favorite to least favorite.

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<th>Preference</th>
<th>Interface</th>
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<tbody>
<tr>
<td>1&lt;sup&gt;st&lt;/sup&gt; - Favorite</td>
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<td>2&lt;sup&gt;nd&lt;/sup&gt;</td>
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<td>3&lt;sup&gt;rd&lt;/sup&gt;</td>
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<td>4&lt;sup&gt;th&lt;/sup&gt;</td>
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Date: Location:
4. **Open Ended Interview Questions**

1) For your answers on debriefing questionnaire
   a. Which interface did you like/dislike the most?
      i. CAD with side-by-side
      ii. CAD with virtual
      iii. Virtual Reality with side-by-side
      iv. Virtual Reality with virtual
   b. Which interface made it easy/hard to use?
      i. CAD with side-by-side
      ii. CAD with virtual
      iii. Virtual Reality with side-by-side
      iv. Virtual Reality with virtual

2) Do you have any additional comments?
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<th>MET</th>
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APPENDIX D. CONSENT FORM

INFORMED CONSENT DOCUMENT

Title of Study: Collaborative Product Review Using Virtual Reality Interface Devices-Performance Studying

Investigators: Mihir Radia, Caroline Hayes

This form describes a research project. The information is intended to help you decide whether or not you wish to participate. Research studies include only people who choose to take part—your participation is completely voluntary. Please discuss any questions you have about the study or about this form with the project staff before deciding to participate.

This study is funded by Center for e-Design.

Introduction

The purpose of this study is to build a virtual workspace platform that will allow users at different sites to jointly review a product design.

You are being invited to participate in this study because you undergraduate students who have taken design courses like: ME 415 or designers employed at companies and you are fluent in English.

You should not participate if you are under age 18 or you are blind in one or either eyes (because you need stereo vision to see 3 dimensional displays in our study) or you are not fluent in English.

Description of Procedures

If you agree to participate, you will be asked to complete a demographic questionnaire that should take about 5 minutes; we will send this questionnaire by email and you have to return it to us as soon as you can. If it is determined you are eligible for the laboratory session, you may receive some additional emails to set time for experiment and some preparation documents before the experiment.

If you receive the additional emails, you will be asked to come to our lab for experiment (Mechanical Engineering Department, 2081, Black engineering building, Iowa State University). During the experiment you will use a collaborative environment for CAD/ Virtual Reality product design review in remote condition. You will work with another person who has been located in other site and you can just hear him/her. You will share a CAD/ Virtual Reality models and slides with partner. You can manipulate the CAD model with mouse, Virtual Reality model with stylus and head sensors. During the test you have to complete 3 pre-assigned task.

The experiment consists of 4 stages. The first will be the CAD with side-by-side, you will collaborate with your partner in CAD interface, you should discuss with another person about CAD model side-by-side. The second will be CAD with remote settings, you and your partner will be using separated workspaces. You can use your voice to communicate with your partner and perceive him/ her as cursors on the shared CAD model. You will be asked to complete a
fault finding task during this process to test this interface’s performance. The third will be Virtual Reality with glasses stage, which will take you about 30 minutes to complete, by side-by-side communication.

You can use your voice to communicate with your partner and perceive each other by the stylus of their partner on the virtual Virtual Reality model. You can also manipulate (drag and zoom, in and out by controlling their head movement) and point on the virtual models using different color stylus.

The fourth will be the same interface setting as the third one, but by using separated workspaces. What’s more, we set an assembly and disassembly function in this interface for you, you can just hit space to activate it or reset. Additionally, we have also set a zoom in and zoom out function, you can press and hold the letters A and Z respectively on the keyboard. You will also complete a task during this process. And after each trial, you will be assigned to complete a post-task questionnaire and you will also complete a debriefing questionnaire and a short interview after you have finished all trials, your interview will be videotaped and analyzed.

During the experiment cameras will videotape you. The short interview will be audio recorded and transcribed. (Please see Confidentiality part for more information) We will also record your computer use activities within the virtual workspace software application while you are completing study tasks in our lab – any computer activities (web browsing, etc.) outside of the software application will not be recorded.

Risks or Discomforts

While participating in this study you may experience the following risks or discomforts:

- Probably there is some risk of arm fatigue because of holding stylus and eye fatigue because of Virtual Reality glasses. Also there is some possibility of motion sickness however that is more commonly associated with immersive environment and the environment under study is not immersive.

Benefits

If you decide to participate in this study provide the opportunity for you to experience working in remote collaboration environments with new technology, which is a direct benefit to you. It is hoped that the information gained in this study will benefit society by aimed at developing Virtual Reality collaborative tools, and also to inform decisions about what features to include in these tools. The results of this work will also enable organizations to make informed decisions about investments concerning appropriate and effective virtual collaboration tools.

Costs and Compensation

You will not have any costs from participating in this study. You will not receive any compensation for only completing the demographic survey. You will be compensated $22
for participating in the laboratory portion of this study. You will need to complete a form to receive payment. Please know that payments may be subject to tax withholding requirements, which vary depending upon whether you are a legal resident of the U.S. or another country. If required, taxes will be withheld from the payment you receive.

Once you come to the laboratory at the scheduled time arranged, if you decide to not continue your participation in the study, you will still receive full compensation for the participation.

Participant Rights

Participating in this study is completely voluntary. You may choose not to take part in the study or to stop participating at any time, for any reason, without penalty or negative consequences.

If you have any questions about the rights of research subjects or research-related injury, please contact the IRB Administrator, (515) 294-4566, IRB@iastate.edu, or Director, (515) 294-3115, Office for Responsible Research, Iowa State University, Ames, Iowa 50011.

Confidentiality

Records identifying participants will be kept confidential to the extent permitted by applicable laws and regulations and will not be made publicly available. However, federal government regulatory agencies, auditing departments of Iowa State University, and the Institutional Review Board (a committee that reviews and approves human subject research studies) may inspect and/or copy study records for quality assurance and data analysis. These records may contain private information.

To ensure confidentiality to the extent permitted by law, the following measures will be taken: Data and video/audio recordings collected during this observation study will be retained for 3 years in a secure area in IOWA State university which only authorized researchers involved with this study will have access. The personal or identifying information collected during your participation will be secure and will be used in general sense and individual participants will not be identifiable in results or publications. Hence in publications and presentations no personally identifiable information will be shown.

We may use your images from the video recordings when results are shared through publication or presentation, however in this case we will blur your face.

The participants will be associated with numbers, so the data will be labeled with the participant’ number.

Electronic data will be stored on a laptop with password protection and an external storage hard drive with password protection for a copy of the data, the hard drive will be in a locked office. The data stored on laptops or external hard drive will be protected by encryption.
Questions

You are encouraged to ask questions at any time during this study. For further information about the study, contact:

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Graduate Research Assistant  
Department of Mechanical Engineering  
Iowa State University of Science and Technology  
Room 2081, Black Engineering  
Building Phone: +1 (515) 735-6239  
maradia@iastate.edu

Caroline Hayes  
Chair, Department of Mechanical Engineering  
Lynn Gleason Professor of Interdisciplinary Engineering  
Iowa State University of Science and Technology  
2025 H.M., Black Engineering Building  
Office Phone: +1 (515) 294-7121  
Fax: 515-294-3261  
cchayes@iastate.edu

Consent and Authorization Provisions

Your signature indicates that you voluntarily agree to participate in this study, that the study has been explained to you, that you have been given the time to read the document, and that your questions have been satisfactorily answered. You will receive a copy of the written informed consent prior to your participation in the study.

Participant’s Name (printed)

______________________________

Participant’s Signature:  
Date:
APPENDIX E. PARTICIPANT RECRUITMENT POSTER

Collaborative Virtual Reality Computer Interface Devices Performance Studying

Participants will conduct reviews of product designs on CAD and Virtual Reality computer Interface devices.

*Are you a designer employed at a company? Have you taken design courses like ME 415?*

*Do you have experience reviewing product or device designs?*

If you answered YES to one of these questions, you may be eligible to participate in our research study.

The purpose of this research study is to compare CAD and Virtual Reality design tools.

You will be asked to use both computer interfaces to review product designs. The experiment and questionnaire will require approximately 90 minutes (or less). Participants will receive an incentive payment of $22.

Participant will schedule a time to come between January 9th - May 5th. The study is being conducted at Room 2081, Black Engineering Building, Iowa State University, Ames, Iowa, USA.

Anticipated experiment period: **January 9th – May 5th**

**Contact Information**

Mihir Radia: (515)735-6239  maradia@iastate.edu
Appendix F. SHORT ANSWERS STUDENT RESPONSES

Below are the comments from each participant to the short answer questions in post-task questionnaire.

“What were the most frustrating part(s) about working on this task? For example, your partner, or the computer interface, the difficulty of the task, etc.”

- **Group 1:**
  - CAD-view with individual interface
    - Participant 1: “The computer interface (especially rotating the parts to view them at different angles).”
    - Participant 2: “Zoom and unzoom the model, controlling movement of model.”
  - CAD-view with collaborative interface
    - Participant 1: “The controls to rotate and disassemble the parts.”
    - Participant 2: “Computer Interface.”
  - VR-view with individual interface
    - Participant 1: “Zooming out and in were a bit tricky.”
    - Participant 2: “Computer Interface.”
  - VR-view with collaborative interface
    - Participant 1: “The rotating moments.”
    - Participant 2: “Computer Interface.”

- **Group 2:**
  - CAD-view with individual interface
    - Participant 1: “Determining the errors, unfamiliar with design so limiting my guesses as to where errors could appear etc.”
    - Participant 2: “The Interface wasn’t great, the lack of zoom and defined edges.”
  - CAD-view with collaborative interface
    - Participant 1: “Finding errors vs other design flaws.”
    - Participant 2: “Design flaws and lack of zoom on body.”
  - VR-view with individual interface
    - Participant 1: “3-D visual can get disorienting (Double vision at times/angles) trouble finding errors vs design.”
    - Participant 2: “When I tried to bring a part closer, I would get double vision.”
  - VR-view with collaborative interface
    - Participant 1: “Design flaws not true errors no ability to zoom into features for detail.”
    - Participant 2: “I wasn’t sure what my partner was seeing, hard to describe errors.”
• **Group 3:**
  o CAD-view with individual interface
    ▪ Participant 1: “Difficult to find error.”
    ▪ Participant 2: “Difficulty of the task.”
  o CAD-view with collaborative interface
    ▪ Participant 1: “Computer Interface limits team performance.”
    ▪ Participant 2: “Difficulty of the task.”
  o VR-view with individual interface
    ▪ Participant 1: “Irritation in eyes.”
    ▪ Participant 2: “Difficulty of the task.”
  o VR-view with collaborative interface
    ▪ Participant 1: “Irritation in eyes, physically demanding.”
    ▪ Participant 2: “Looking at screen from an angle.”

• **Group 4:**
  o CAD-view with individual interface
    ▪ Participant 1: “Difficulty of the task.”
    ▪ Participant 2: “The operation to zoom in/out the model.”
  o CAD-view with collaborative interface
    ▪ Participant 1: “Difficulty of the task.”
    ▪ Participant 2: “The computer interface to show whenever I want.”
  o VR-view with individual interface
    ▪ Participant 1: “Difficulty of the task.”
    ▪ Participant 2: “The model is a little sophisticated.”
  o VR-view with collaborative interface
    ▪ Participant 1: “Difficulty of the task.”
    ▪ Participant 2: “Difficulty to work simultaneously with my partner.”

• **Group 5:**
  o CAD-view with individual interface
    ▪ Participant 1: “**Didn’t answer.**”
    ▪ Participant 2: “Computer Interface.”
  o CAD-view with collaborative interface
    ▪ Participant 1: “Difficulty of the task.”
    ▪ Participant 2: “Difficulty of the task.”
  o VR-view with individual interface
    ▪ Participant 1: “**Didn’t answer.**”
    ▪ Participant 2: “The part.”
  o VR-view with collaborative interface
    ▪ Participant 1: “Computer Interface.”
    ▪ Participant 2: “The model was being doubled.”
• Group 6:
  o CAD-view with individual interface
    ▪ Participant 1: “I didn’t find it frustrating.”
    ▪ Participant 2: “The errors were too miniscule to be identified.”
  o CAD-view with collaborative interface
    ▪ Participant 1: “It’s better to work independently.”
    ▪ Participant 2: “Partner had different views or dwelled on her ideas.”
  o VR-view with individual interface
    ▪ Participant 1: “Part is too big. Took long time to analyze.”
    ▪ Participant 2: “3-D tools are demanding.”
  o VR-view with collaborative interface
    ▪ Participant 1: “I didn’t find it frustrating.”
    ▪ Participant 2: “Nothing I guess.”

• Group 7:
  o CAD-view with individual interface
    ▪ Participant 1: “Aligning object with keyboard controls as the rotation axis was not passing through center of the CAD model.”
    ▪ Participant 2: “Move or spin the model.”
  o CAD-view with collaborative interface
    ▪ Participant 1: “Partner was silent the whole time.”
    ▪ Participant 2: “Difficulty of the task.”
  o VR-view with individual interface
    ▪ Participant 1: “No perfect rotation of CAD model. Alignment was difficult. Some artifacts were there after zooming in much.”
    ▪ Participant 2: “The glasses.”
  o VR-view with collaborative interface
    ▪ Participant 1: “Interaction with 2 3D glasses took time to sync.”
    ▪ Participant 2: “Difficulty of task.”

• Group 8:
  o CAD-view with individual interface
    ▪ Participant 1: “The computer Interface could have been better on the zooming aspect of the task.”
    ▪ Participant 2: “Operating the task.”
  o CAD-view with collaborative interface
    ▪ Participant 1: “Finding errors.”
    ▪ Participant 2: “Difficulty of the task.”
  o VR-view with individual interface
    ▪ Participant 1: “Difficulty of the task.”
    ▪ Participant 2: “Glasses weren’t comfortable.”
  o VR-view with collaborative interface
    ▪ Participant 1: “3-D interface was not in balance.”
    ▪ Participant 2: “Adjusting to Glasses.”
“What were the most enjoyable/positive aspect(s) of working on this task?”

- **Group 1:**
  - CAD-view with individual interface
    - Participant 1: “The basic rotation motions.”
    - Participant 2: “The stylus use in controlling.”
  - CAD-view with collaborative interface
    - Participant 1: “The collaboration made the task easier.”
    - Participant 2: “Didn’t answer.”
  - VR-view with individual interface
    - Participant 1: “The 3-D view was very convenient to view the parts from different angles.”
    - Participant 2: “The model is 3-D and is more imaginable than 2-D.”
  - VR-view with collaborative interface
    - Participant 1: “The 3-D view was very helpful to rotate parts while disassembly.”
    - Participant 2: “3D imaging.”

- **Group 2:**
  - CAD-view with individual interface
    - Participant 1: “Ease of interface in resetting and disassembling”
    - Participant 2: “The stylus was cool and easy to use.”
  - CAD-view with collaborative interface
    - Participant 1: “Communication, reassurance.”
    - Participant 2: “Another set of eyes to bounce opinions off.”
  - VR-view with individual interface
    - Participant 1: “Easy slight adjustments in the part angle quick glances vs full keyboard movements.”
    - Participant 2: “The 3D was really cool, very neat experience.”
  - VR-view with collaborative interface
    - Participant 1: “Collaboration and attention to detail.”
    - Participant 2: “The 3-D was cool and allowed for a more natural inspection feel.”

- **Group 3:**
  - CAD-view with individual interface
    - Participant 1: “Getting to know the assembly/sub-assembly in 3-D.”
    - Participant 2: “Cool controls.”
  - CAD-view with collaborative interface
    - Participant 1: “The team effort eases the effort.”
    - Participant 2: “Controls.”
  - VR-view with individual interface
    - Participant 1: “The zoom when I move towards the screen.”
    - Participant 2: “3D glasses.”
  - VR-view with collaborative interface
• Participant 1: “To be able to work as a group.”
• Participant 2: “3D glasses, stylus.”

• Group 4:
  o CAD-view with individual interface
    ▪ Participant 1: “Watching the model from different perspectives.”
    ▪ Participant 2: “The interface to pick up given part of the model.”
  o CAD-view with collaborative interface
    ▪ Participant 1: “None.”
    ▪ Participant 2: “No positive effect when working together.”
  o VR-view with individual interface
    ▪ Participant 1: “Model moves with 3-D glasses.”
    ▪ Participant 2: “I can rotate the parts with pen as I like.”
  o VR-view with collaborative interface
    ▪ Participant 1: “Control the perspectives.”
    ▪ Participant 2: “The 3-D perspective to the parts.”

• Group 5:
  o CAD-view with individual interface
    ▪ Participant 1: “Didn’t answer.”
    ▪ Participant 2: “The feeling of finding errors.”
  o CAD-view with collaborative interface
    ▪ Participant 1: “Partner gives an extra perspective.”
    ▪ Participant 2: “Difficulty of the task.”
  o VR-view with individual interface
    ▪ Participant 1: “Didn’t answer.”
    ▪ Participant 2: “Being able to experience new technology.”
  o VR-view with collaborative interface
    ▪ Participant 1: “Different perspective of the partner.”
    ▪ Participant 2: “Experiencing new technology.”

• Group 6:
  o CAD-view with individual interface
    ▪ Participant 1: “I was able to analyze each and every part. Interface is good. I enjoyed using stylus.”
    ▪ Participant 2: “Had me thinking and applying my brain.”
  o CAD-view with collaborative interface
    ▪ Participant 1: “Interface is good.”
    ▪ Participant 2: “Less strenuous with team work.”
  o VR-view with individual interface
    ▪ Participant 1: “Interface is good.”
    ▪ Participant 2: “I got a new perspective of seeing things.”
  o VR-view with collaborative interface
    ▪ Participant 1: “With time, I enjoyed working together.”
    ▪ Participant 2: “Its fun finding solution with friends.”
• **Group 7:**
  o CAD-view with individual interface
    ▪ Participant 1: “Working with the virtual wand and using it just as a person handles an object with wand.”
    ▪ Participant 2: “Disintegrate the models to see details.”
  o CAD-view with collaborative interface
    ▪ Participant 1: “The interface which gives a better perspective to visualize DFM.”
    ▪ Participant 2: “Disintegrate the model.”
  o VR-view with individual interface
    ▪ Participant 1: “Coordinating the eyes and the wand in hand to reach all the corners of the model, even peek to look inside.”
    ▪ Participant 2: “Look around product moving your head.”
  o VR-view with collaborative interface
    ▪ Participant 1: “Working this time.”
    ▪ Participant 2: “3-D model.”

• **Group 8:**
  o CAD-view with individual interface
    ▪ Participant 1: “It was very easy to assemble and disassemble the parts with just a single button.”
    ▪ Participant 2: “Finding the errors.”
  o CAD-view with collaborative interface
    ▪ Participant 1: “Disassembly.”
    ▪ Participant 2: “Difficulty of the task.”
  o VR-view with individual interface
    ▪ Participant 1: “The 3-D view gives a better understanding of the model than the 2-D view and is less annoying.”
    ▪ Participant 2: “Sensor in the glasses.”
  o VR-view with collaborative interface
    ▪ Participant 1: “Better understanding of the individual parts.”
    ▪ Participant 2: “Assembling and disassembling.”
APPENDIX G. ANOVA ASSUMPTION GRAPHS

1. Group anova assumption

   ![Normal Q-Q Plot](image1)
   ![Residuals vs Fitted](image2)

   Group-Normality
   Group-Homogenous variance

2. Error term anova assumption

   ![Normal Q-Q Plot](image3)
   ![Residuals vs Fitted](image4)

   Error term-Normality
   Error term-Homogenous variance
APPENDIX H. IRB APPROVAL MEMO

IOWA STATE UNIVERSITY
OF SCIENCE AND TECHNOLOGY

Date: 12/22/2016

To: Mihir Radia
Black Engineering Building, Room 2081 Iowa State University
Ames, IA 50011

CC: Dr. Caroline Hayes
2025 Black Engineering

From: Office for Responsible Research

Title: Collaborative 3D Computer Interface Devices Performance Studying

IRB ID: 16-475

Approval Date: 12/22/2016

Date for Continuing Review: 12/21/2016

Submission Type: New

Review Type: Expedited

The project referenced above has received approval from the Institutional Review Board (IRB) at Iowa State University according to the dates shown above. Please refer to the IRB ID number shown above in all correspondence regarding this study.

To ensure compliance with federal regulations (46 CFR 46 & 21 CFR 56), please be sure to:

- Use only the approved study materials in your research, including the recruitment materials and informed consent documents that have the IRB approval stamp.

- Retain signed informed consent documents for 3 years after the close of the study, when documented consent is required.

- Obtain IRB approval prior to implementing any changes to the study by submitting a Modification Form for Non-Exempt Research or Amendment for Personnel Changes form, as necessary.

- Immediately inform the IRB of (1) all serious and/or unexpected adverse experiences involving risks to subjects or others; and (2) any other unanticipated problems involving risks to subjects or others.

- Stop all research activity if IRB approval lapses, unless continuation is necessary to prevent harm to research participants. Research activity can resume once IRB approval is reestablished.

- Complete a new continuing review form at least three to four weeks prior to the date for continuing review as noted above to provide sufficient time for the IRB to review and approve continuation of the study. We will send a courtesy reminder as this date approaches.

Please be aware that IRB approval means that you have met the requirements of federal regulations and ISU policies governing human subjects research. Approval from other entities may also be needed. For example, access to data from private records (e.g., student, medical, or employment records, etc.) that are protected by FERPA, HIPAA, or other confidentiality policies requires permission from the holders of those records. Similarly, for research conducted in institutions other than ISU (e.g., schools, other colleges or universities, medical facilities, companies, etc.), investigators must obtain permission from the institution(s) as required by their policies. IRB approval in no way implies or guarantees that permission from these other entities will be granted.

Upon completion of the project, please submit a Project Closure Form to the Office for Responsible Research, 202 Kingland, to officially close the project.

Please don’t hesitate to contact us if you have questions or concerns at 515-294-4586 or IRB@iastate.edu.