A COMPARISON OF 3D SHAPE RECOGNITION IN COMPUTER AIDED DESIGN BETWEEN VIRTUAL REALITY AND CONVENTIONAL TWO DIMENSIONAL DISPLAYS

by

Syed Faaiz Hussain

A Thesis

Submitted to the Faculty of Purdue University

In Partial Fulfillment of the Requirements for the degree of

Master of Science

Department of Computer Graphics Technology

West Lafayette, Indiana

May 2020

THE PURDUE UNIVERSITY GRADUATE SCHOOL
STATEMENT OF COMMITTEE APPROVAL

Dr. Tim McGraw, Chair

Department of Computer Graphics Technology

Dr. Paul Parsons

Department of Computer Graphics Technology

Dr. Christos Mousas

Department of Computer Graphics Technology

Approved by:

Dr. Nicoletta Adamo-Villani

ACKNOWLEDGMENTS

2

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

With the recent development of Virtual Reality technology, researchers are looking more into changing the way Virtual Reality is used in our daily lives in order to increase our productivity. One such application is the mapping of 3D spatial graphics in Computer Aided Design engineering where practitioners have been historically working on 3D models in a two dimensional environment. Researchers in Computer Graphics have proposed Virtual Reality as a more effective medium for CAD packages. This thesis carries out a user study to test whether or not 3D VR environments are more effective in relaying information to the users as compared to two dimensional displays such as computer screens by conducting a study to determine how users navigate and interact with complex CAD objects in the two different environments. The two environments make use of stereoscopic vision and monoscopic vision in order to compare the efficiency with which volunteers are able to notice subtle differences in objects. The motivation for this study stems from the fact that CAD in VR is largely an underdeveloped topic and the result of such a study could form a baseline and advocate for further research and development in this domain. The research question being addressed is "Does CAD in a three-dimensional Virtual Reality Environment(stereoscopic) allow for better understanding of shapes of complex assemblies as compared to CAD on two-dimensional (monoscopic) computer screens?" The findings of this study suggest that rather than just the display technique the kind of movements which objects undergo also contributes to the way users perceive the objects in 3D vs 2D spaces and uncover a set of directions which would be recommended for similar studies in the future.

Keywords: Shape Recognition, JND, Virtual Reality and CAD

CHAPTER 1.   INTRODUCTION

Computer Aided Design (CAD) forms an essential part of the manufacturing industry because of its ability to easily depict 3D models and integrate them with other 3D geometry. So much so that it is generally considered an essential skill to have in order to get into the field. In many universities around the globe such as Purdue and Lahore University of Management Sciences it is considered as an essential skill for engineers and is taught starting from freshman level classes and labs for fields like Aerospace Engineering, Civil Engineering, Electrical Engineering and Mechanical Engineering. Over the decades, CAD software has seen significant improvements in implementation such as the constant revamping of user interfaces. The images below are an example of these improvements in CATIA over the past two decades. The first image illustrates CATIA V4 which was launched in 1992 and the second image shows a bench in CATIA V6 which became available in 2003.

Notice the difference in the clustered UI from the 1992 model to a more open and comprehensible version in 2003 which represents one of the ways in which issues with existing CAD packages has been successfully identified and fixed. This paper aims to continue this tradition of improving user experience by studying stereoscopic VR packages as a possible replacement to the existing packages on computer screens. This could potentially allow even less cluttered UI on the screen and give users more space overall on their viewing device to understand 3D models. The area of stereoscopic study will largely focus on cognition and measuring a user's ability to distinguish dynamic objects in the two display techniques.
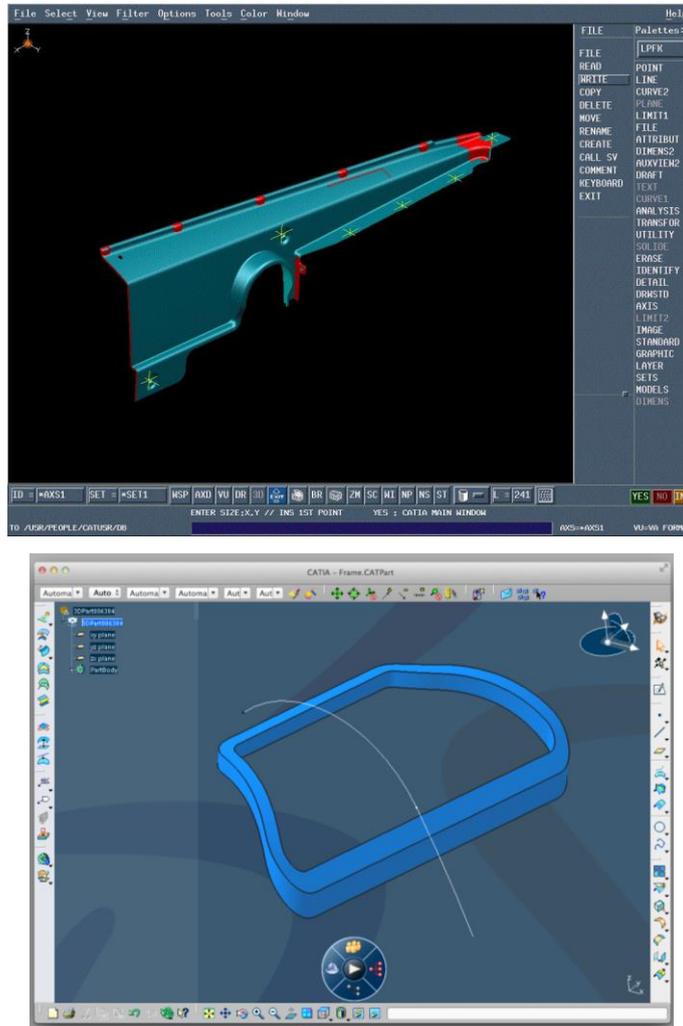
Figure 1.1 CATIA V4 and CATIA V6

1.1   Problem Statement

CAD is largely used on computer screens which are two-dimensional. Given the nature of the CAD environment is three-dimensional it raises a question as to whether or not this would be ineffective in relying information since mapping a three dimensional environment to a two dimensional screen requires a more selective display of the world and creates the requirement of additional user-interface tools in order to navigate the mapped environment.

One such three dimensional environment can be achieved by using CAD packages in Virtual Reality (VR). Virtual Reality can possibly provide a more effective way of communicating the shape and structure of a three dimensional model as compared to a two dimensional screen. The purpose of this study is to compare how well people can distinguish small changes between objects in Virtual Reality versus two dimensional displays.

1.2   Purpose Statement

The main purpose of this study is to examine if Computer Aided Design(CAD) in Virtual Reality is more effective as compared to conventional CAD on two dimensional screens in terms of depth perception. The study aims to perform an experiment on the perception of depth on volunteers across the two aforementioned mediums and aims to quantitatively examine and justify if one of the two mediums is better with regards to how depth is perceived within them. This study aims to lay the foundation for future studies into the CAD industry using the novel technology of Virtual Reality.

1.3   Motivation

The motivation for this study stems from the fact that VR equipment has become more affordable and easily available for non-professional users and this has opened up the door for more collaborative work in the classroom and in the industry now, since the benefits of using VR in such fields outweighs the costs/drawbacks.

The CAD package in VR itself could potentially help eliminate some of the active cognitive load on the users mind without so much as even adding a UI into it. This can easily be understood because of the fact that our usage of external cognition (Rogers ,2012) is made more efficient.One would no longer have to mentally "reprocess" the three dimensional figure into a specific two dimensional view which is projected onto the screen every time one tries to add any geometrical element to the product, hence one does not need to go through the process of re-imaging an object in two different (or more) kinds of views and can proceed with just the three dimensional mapping within our heads. **Figure 1.1** illustrates an example of a 2D sketch in CAD. Notice how the user is forced to sketch in 2D by default.
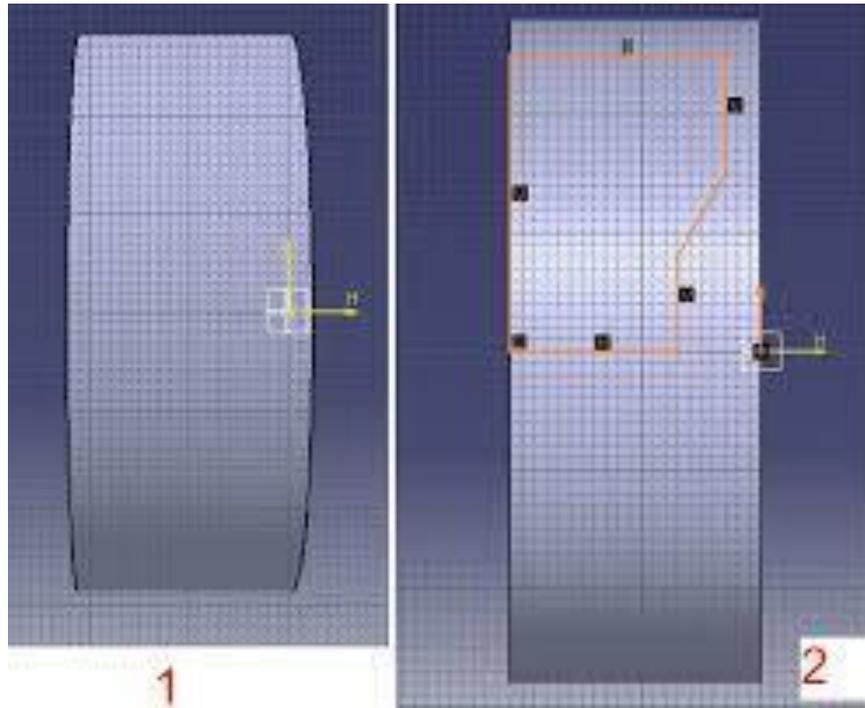
Figure 1.2 A top to down 2D sketch view

Figure 1.1 illustrates the fact that while trying to draw or add in any sort of geometry in CAD you must work in a two dimensional projection of the object in the specific view. The process itself is tedious with extra steps added. First of all you must select a specific view by using the following images of the menu with which the user can manipulate the viewing of the three dimensional model to their liking:
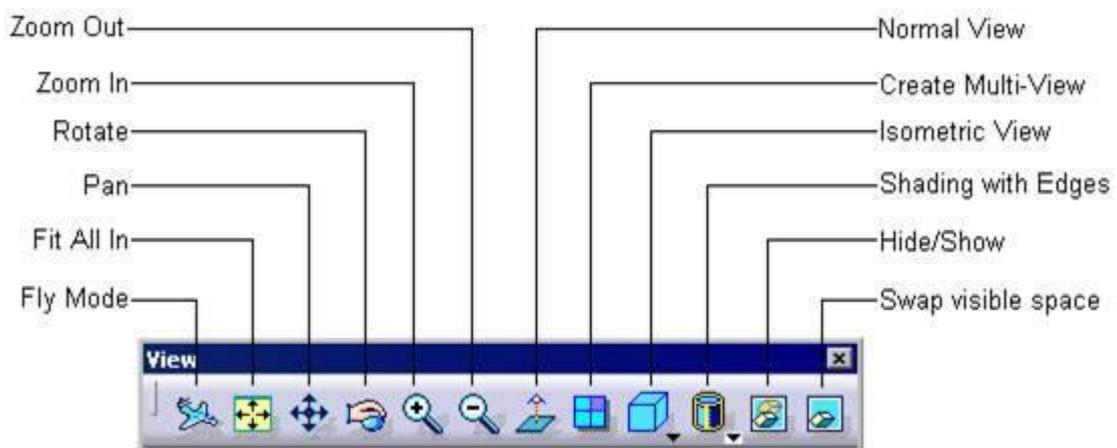
Figure 1.3 Viewing tools in Catia(A CAD package)

Figure 1.4 Extra options in the top view tools

The top of figure 2.2 shows us the different tools inside the CAD package for manipulating the camera view from the user's perspective, as one can clearly see it requires many different kinds of buttons that the user needs to learn in order to move or manipulate the position and view of the object.

An example of this would be the fact that moving, rotating and zooming all need different buttons in the CAD environment. Some of these buttons have further drop down options which only adds to the steep learning curve in the CAD package. One can also understand why these buttons would not be an absolute necessity in a Virtual Environment due to the fact that the user can move around and rotate themselves to get the appropriate angle to view the object, one can argue that this does indeed increase the physical load but it does not require any form of "familiarization' nor does it need us to look at a cluster of different and somewhat similar looking buttons which can be overwhelming, particularly for new users who are often first year engineering undergraduate students. Ofcourse one can argue that zooming in and out in VR would also require some sort of UI but assuming one has ample space it is not necessarily a must have in all cases.

1.4   Scope

The focus of this thesis is analysing how well users of VR and two dimensional screens are able to distinguish between objects with Just Noticeable Differences(JNDs). JND is defined as the minimum level of stimulation that a person can detect 50 percent of the time (Judd, 1932). For the purpose of this study the researcher is using their own custom-made CAD assembly viewing package for simulating both the VR and two dimensional media. Since directly comparing VR with two dimensional screens would present a host of lurking variables which would need to be dealt with (discussed in chapter 3) the study has been narrowed down to the specific aspect which distinguishes VR from two dimensional displays i.e. monoscopic display versus stereoscopic display.

1.5   Limitations

The attempt to control lurking variables and the scope of the project does leave the study with some limitations. These are mainly related to hardware constraints. For example one cannot control the resolution of the head mounted display would be fixed to 2160 x 1200 pixels. In addition to this our refresh rate i.e. frame rate would be fixed to 90 Hz and the field of view would be fixed at 110 degrees which also cannot be manipulated. These limitations are of the HTC Vive, the Head Mounted Display chosen for performing the experiment in this study.

1.6   Delimitations

Only two specific types of transformations/deformations are being tested namely rotation and translation. The rationale behind choosing these is that the researchers want to focus on some of the more commonly used geometry manipulations. The study focuses on largely undergraduate students who have very little experience in CAD modelling. It does not measure how people with varying degrees of experience in CAD respond/perform under the same circumstances. An actual CAD package was not used in an attempt to keep certain variables like field of view/ rendering style, lighting and other factors constant between the two display techniques as the researchers wanted to ensure that these would not play a factor in the findings of the research. JND in only one dimension (namely Z-axis) was tested since testing other dimensions would require a higher number of participants which may not be feasible to get for the purpose of this study. The only aspect being compared here is how the shape is perceived in the two display techniques not how well the volunteers are able to model their own meshes in the packages. The study also did not factor in how well volunteers can see i.e. the experiment may have been impacted if the users had variation degrees of minor visual impairment.

1.7   Assumptions

The researcher had to operate under certain assumptions in order to carry out this study. It had to be assumed that the volunteers are answering with accuracy and not with the intent of finishing the study prematurely. It also had to be assumed that wearing a head mounted display with an interpupillary distance set to zero would be able to mimic monoscopic vision. The researcher also has to assume that there is a strong relation between shape perception and JNDs.

1.8   Definitions

1. Virtual Reality: Virtual Reality presents a three dimensional computer generated environment using special hardware peripherals (Yu et al , 2006).

2. Virtual Environment: The VE is where all the interaction between a single or multiple users take place (Costello, 1997).

3. Just Noticeable Difference: JND is defined as the minimum level of stimulation that a person can detect 50 percent of the time (Judd, 1932).

4. Computational offloading : Letting a computer or machine keep memory stored for you instead of your brain.(Rogers ,2012).

5. Degrees of Freedom(DoF) : The total number of observations minus the number of independent constraints imposed on the observations.

1.9   Hypothesis

The hypothesis for this study is that there is a significant difference between how depth is perceived in CAD using VR(stereoscopic vision) as compared to how depth is perceived in CAD using computer screens(monoscopic vision). It is important to note that the hypothesis is not specifying which of the two mediums superior to the other in terms of depth perception hence this will be a two-tail test.

CHAPTER 2.   LITERATURE REVIEW

2.1   Methodology

The main databases used to compile the following literature review included multiple sources. The primary sources were IEEE Annual International Symposium,   IEEE Transactions on Visualization and Computer Graphics (TVCG) and Purdue Graduate School theses repository also known as "Hammer". These sources were used to determine experimental design, variables to measure and testing methods (Luo et al, 2007)(Bannister,   2019).

Data visualization techniques for collected data and the appropriate variables to measure were determined from previous work from online databases by processing queries related to perception in VR. In order to efficiently search for the appropriate terms for the online databases a concept is drawn up to better understand what sort of keywords would result in the acquisition of the appropriate articles.
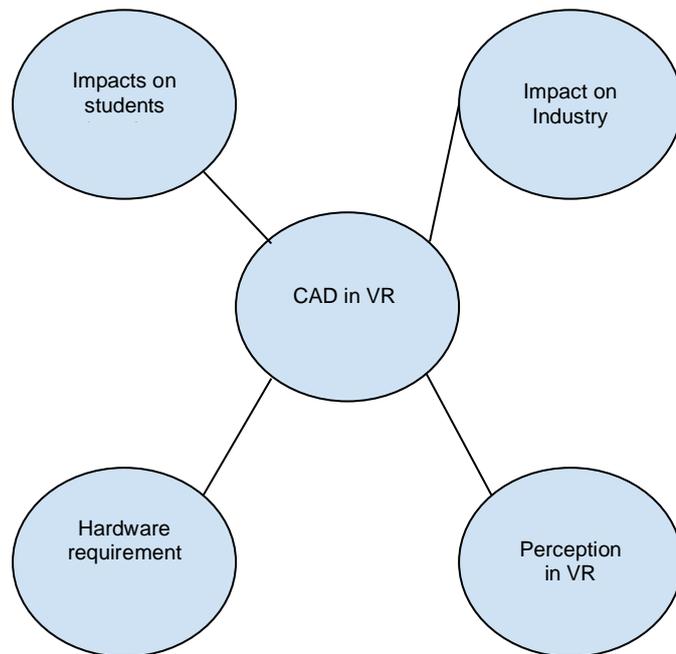
Figure 2.1 Concept map of key components in this research

Engineering village

Journal of vision

Search for Hardware
related issues in VR
and why VR is
relevant now

Search for user
studies in VR
and CAD.

Search for methods of
measuring shape
perception

Perception and VR
user studies and
Psychology

Search for links
between VR and
Perception

Search for Graphics
in visualization in VR

Wiley Online Library
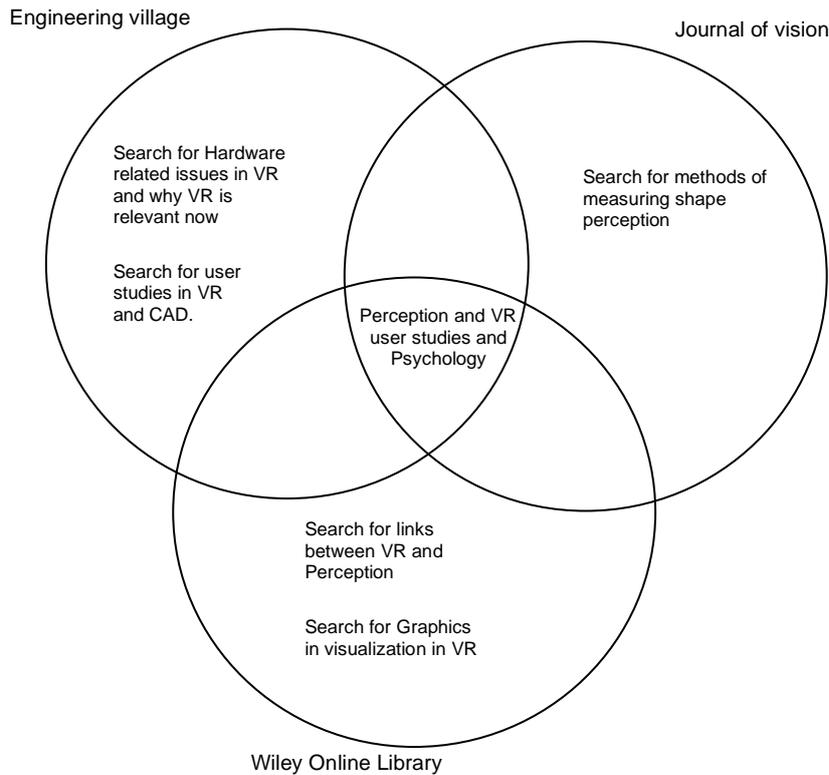
Figure 2.2 Keyword search in online databases for compilation of literature review

2.2   Computer Aided Design

3D Computer Aided Design packages are used in industry for professional use by many renowned companies such as Boeing, BMW, Porsche and Nokia. It is also taught in engineering courses at many high ranking universities throughout the world such as Purdue, Stony Brook University and Technical University of Munich. The software is typically taught as a part of Freshman or Sophomore year in engineering programs which are usually related to aerospace or mechanical engineering and then later reinforced through more advanced modelling courses at the undergraduate level. The reason is that there is evidence to suggest that students in engineering perform better by visualizing the design schemas of sketches as actual three dimensional models in CAD (Sanchez-Elez and Roman 2015).

The significance of CAD is that it provides engineers with tools that allow them to computationally offload the image of a specific drawing/CAD part into a three-dimensional representation of the part. Offloading here means to allow computers to handle information so that it would not need to be used in active memory. In this sense, CAD is a very powerful tool, since it gives a means to form almost any kind of object the user can think of (Chang et al,1997) such as the F-16 assembly

in Figure 3.1. To accomplish this task some of the main features it incorporates are basic sketching of a part, surface modelling of parts, putting together complex parts in order to make an assembly and even digital mockup of assemblies to visualize how different parts would come together in a coherent manner during the manufacturing process. This is significant for memory and external representations , "External representations provide external memory aids" (Zhang,1997).

 Different parts and their assemblies in CAD afford the user to focus specifically on one part at a time without having to worry much about the dimensions of the other parts which would fit in the assembly (since a user can always just open up the other file containing that part and get that relevant information). This external representation also helps users "adjust" their internal representation of the object. The feedback a user gets from the external representation about the object can help in adjustments that need to be made about our assumptions regarding different parts which arise from our internal visualization of the part.
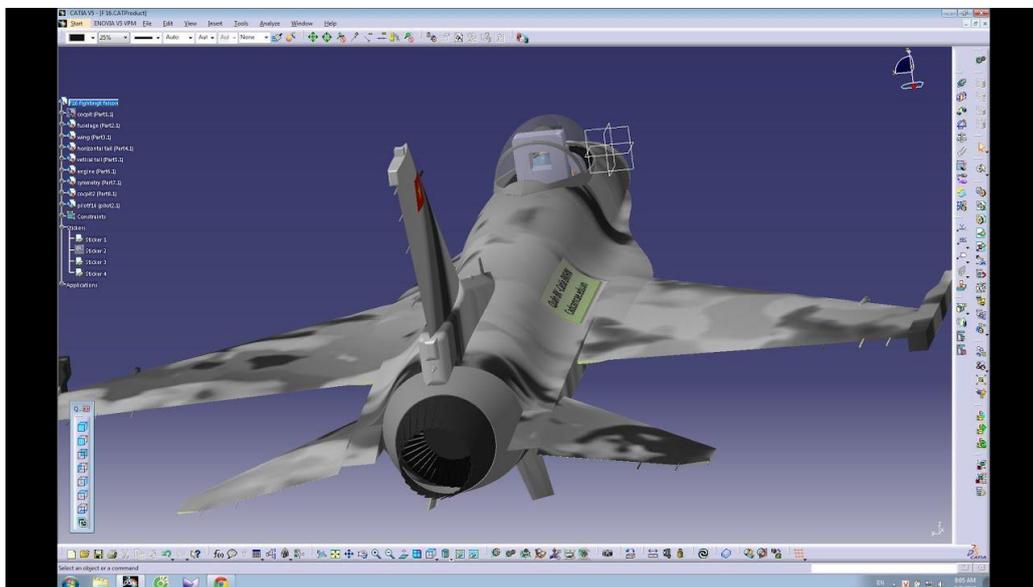
Figure 2.3 An F-16 Fighting Falcon in CATIA.

2.3   Virtual Reality

The first example of a device which implemented a Virtual Reality Environment was The Sword of Damocles designed by Ivan Sutherland during the 1960s at the Massachusetts Institute of Technology (Sutherland,1968). Until recently Virtual Reality had not enjoyed the same growth in popularity as conventional computers primarily due to the costs associated with the hardware needs for such an environment. For example the cost of a very primitive VR head device would be around

5 dollars and can be as high as 1300 dollars for more advanced high-end headsets like the HTC VivePro. The cost of a similar high-tech headset in 1990 was about $200,000. This price went down to $20,000 in just two years as companies like NASA began investing in the technology and contributed to its development (McGreevy,1991). This eventually led to VR becoming more common in household and non workplace/professional use (Monahan et al, 2008).

By the name itself Virtual Reality sounds like an oxymoron (contradicting terms) since the world "Virtual" means non real i.e. not physically existing and the word "Reality" is defined as the state of physically existing. VR in itself is just a computer generated three-dimensional immersive experience inside a "Virtual Environment"(VE). The VE is where all the interaction between a single or multiple users takes place. There are different kinds of VE's depending on the number of senses (touch, hearing, sight and smell) it simulates such as non-immersive, semi-immersive and fully immersive (Costello, 1997). The table below illustrates what falls into each category:

Table 2.1 Different types of Virtual Environments

Name	Non immersive	Semi immersive	Fully-immersive
# of Senses simulated	0-1	2-3	4
Examples	Most Augmented Reality applications	3-D Flight simulators on project screens 3-D Theaters Any HMDs without smell	HMDs with smell Sensorama (discussed later)

2.4   Virtual Reality versus two dimensional displays

The enhancement of VR hardware has also led to it being proposed as a substitute for desktop displays in some applications. One such example is the usage of VR applications (games) in teaching spatial orientation to teenagers who have mild intellectual impairments (Freina, 2015). Researchers argue that a fully immersive experience cannot be fully achieved by a desktop based application and VR provides a solution which is one step closer to truly immersive experience as compared to the former.(Gîrbacia, Beraru, Talabă & Mogan, 2014)

Proponents of VR argue that the user has more freedom to move about the environment and has a chance to develop a better mental model of the three dimensional world hence it is likely that shape perception in VR is better than shape perception in two dimensional displays (Leroy, 2009).

2.5   Shape perception

Shape perception is the organization, identification, and interpretation of information about objects in order to understand them (Spröte, 2016). Shape perception is relevant for CAD engineers because a user need to be able to understand the physical properties of an object in order to create and/or manipulate it as intended and shape perception plays an important part in understanding attributes about physical objects These attributes include : the stability of an object, the depth, the orientation and the curvature(Spröte, 2016). Each of these attributes would be important while designing models for objects which are developed and deployed in the real world like planes or cars. Therefore a three dimensional model needs to be represented accurately for it to be an effective visualization of an object in the real world.

The aforementioned evolution of VR in section 2.2 has resulted in psychological research in the realm of perception in VR. This kind of research has given rise to a number of questions about human perception in VR regarding shape and the environment. Psychologists have uncovered the fact that there are trade offs in using Virtual Environments. For example in VE it is easier to control the environment and get more realistic responses from users as opposed to the real world or two dimensional screens(Wilson and Soranzo, 2015).

This is primarily due to the fact that in VR it is easier to control stimuli as opposed to the real world. For example, one can control the amount of sunlight in a three dimensional scene with the alteration of some variable(s) but doing the same in the real world would be much more complicated. On the other hand, studies have also shown that it is also possible for users to significantly underestimate the size of shapes in Virtual Environments with users on average underestimating the size of an object by two fold(Loomis, 2002). Some researchers have directly compared shape perception between objects in the real world and objects in VR (Luo et al, 2007).

Given the importance of shape perception as discussed above this renders the issue as one worthy of studying. It could be crucial in determining which of the two display techniques would result in the most effective transfer of information regarding shape perception.

One question which needs to be tackled is how does one quantify shape perception? Or what method is there to measure differences in shape. One parameter which addresses this specific problem is called "Just Noticeable Difference". It is often referred to as the difference threshold. An example of the use of the difference threshold would be to hold an object of a specific weight in your hand and iteratively increase the weight until a noticeable difference is felt.

2.6 Perception in 2D VS 3D

In the past there has been research related to comparing perception and cognition in 2D environments versus comparing perception and cognition in 3D environments and the real world. Results of comparing on-screen stereoscopic visualization of 3D objects as compared to actual 3D objects suggest that the latter is more effective when evaluating information retrieval (Jansen, 2013). Researchers attribute this to the fact that objects in the real world have unique properties such as perfect visual realism and the ability to be physically touched (Jansen, 2013). Perfect visual realism means that stereoscopic images of objects mimic depth and realism by "stitching" two images together so that our eyes perceive them as close to the real object as technology allows. Going by this it may be meaningful to establish if 3D is one step closer to physical realism as compared to 2D. Research also suggests that 3D visualizations are not recommended for 2D screens (Shneiderman, 2019) as this may cause unwanted distortions and occlusions to the objects. However since the nature of CAD is 3D i.e. the data itself is 3D, creating a 2D representation would not be efficient.

An empirical study on 3D visualizations suggested that the effectiveness of an individual in a 3D environment is based on their spatial ability (Huk, 2006). This means that people with higher spatial ability are able to benefit more from the usage and interaction of 3D models whereas those who have a low spatial ability may find the use of 3D models to be more of a hindrance. According to data, the reason why this happens is because of different memory limits, that is to say that 3D objects would exceed the working memory limits of those who have low spatial ability (Huk, 2006) . Huk's study examined this particular phenomenon by acquiring test results of students who interacted with cell models in a hypermedia learning environment. This environment made the use of QuickTime-VR to display the models in a stereoscopic environment. The answer as to whether VR/3D environment would be more effective for learning would depend on the spatial abilities of the user. Therefore there is no evidence to suggest that 3D visualization would be more efficient than 2D without enhancing an individual's spatial ability or assessing that the user has enough spatial ability to benefit from such an environment.

Research around spatial ability has also suggested that multiple levels of spatial ability exist rather than a single one as in JND. Object manipulation spatial abilities such as spatial visualization and spatial relations are disjoint from perspective-taking spatial abilities. In other words a person's ability to manipulate objects from their own centre of vision is a different ability from their ability to manipulate objects from an imaginary perspective (Kozhevnikov, 2001). This study implies that the underlying spatial ability for both of these processes are not the same. Experiments involving the use of stimulus arrays to test both point of views of the users have been conducted to determine this outcome.

CHAPTER 3.   METHODOLOGY

3.1   Overview

CAD software companies are rolling out packages which incorporate VR experiences for users like Dassault Systems' 3D experience: however, direct comparison between the effectiveness of shape perception of VR and conventional two dimensional screens has been relatively undocumented. The goal of this experiment is to directly compare the two display techniques i.e. monoscopic and stereoscopic, and how users perform with regards to changes in shape. The study is a quantitative experiment whereby the researcher attempted to quantify how effective volunteers are at distinguishing minute differences in shape within the two display techniques. This experiment attempts to recreate similar experiences in both two dimensional CAD and VR in order to minimize the effect of lurking variables. The software used for development was Unity and the models used for comparison are all made in CATIA.

3.2   Research type

This study followed a 2x2 within subjects design for repeated measures i.e. two groups of participants were exposed to two different treatments one by one over a number of scenarios. This study is a controlled experiment. Shading, complexity of objects and lighting were controlled and the treatment consisted of different display techniques(stereoscopic and monoscopic displays).

The rationale behind testing each user for VR and for monoscopic vision analysis stems from the fact that individuals perceive shapes differently due to physical differences like subject height, eyesight and JND threshold. These differences between individuals can have a significant effect on the results of the study hence it's adequate to nullify the impact by having users being given both treatments i.e. within subjects. One factor under study in the experiment is the display technique in which the user carried out the study and the other factor being the kind of transformation done on an object. Each of the two factors have two levels. Transformation has translation and rotation whereas display technique is either monoscopic or stereoscopic. This relationship is described in the table below:

```
T  T
R  R
A  A
N  N
S  S
F
C  R
R  O
   T
   A
   T
```
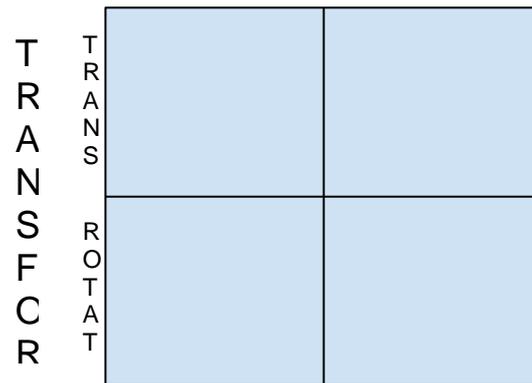
Figure 3.1 2x2 Experimental Setup

In summary, the volunteers performed two rounds of experiments one with each display technique. In each round, volunteers viewed two instances of the same object of which one would be dynamically changing according to the principles of Just Noticeable Differences and the other would be static. The goal is to measure the intensity of the stimulus it took for volunteers to notice any differences between the two objects. The dynamically changing object would have some small part of it either rotating or translating incrementally over time in small discrete steps which would be hard to notice in a single step.

3.3   Population

The sample population consists of Purdue University students who fit specified physical criteria as directed by IRB protocols, the volunteers must be able to walk freely without the use of any assistance or tools, the volunteers must not have a history of seizures, the volunteers must also be at least 18 years old and the volunteers must not have a major The research requires around 38 using power analysis by setting parameters of alpha = 0.1 and power = 0.8 the calculations regarding the power variables for the variables of interest will be shown in 3.5.

3.4   Sampling and Sample Size

Due to the logistics of the study the sampling technique used would be convenience sampling. In this regard the first 38(as calculated in the power analysis in 3.5) volunteers who registered for the study and met the physical qualifications described in the paragraph above would conduct the study. In order to ensure this the students who are interested in the study are required to fill out the

survey in appendix A. This allowed the researcher to filter out potential participants who do not meet the aforementioned physical criteria. Any volunteers who were under the age of 18 or those who could not move without the help of an instrument or those who had a history of seizures or those with major visual impairments were automatically disqualified from participating in the experiment for their own well being.

3.5   The Experiment

This section explains how the experiment was set up and carried out, how the researcher interacted with the volunteers, the data collection and analysis and overall breakdown of sampling and testing.

3.5.1   Randomly Sorted Groups

After the volunteers have been filtered and selected the users are segregated into two equal sized groups. This was done based on the order in which users volunteered for the study. For example volunteers number 1,3,5,7 etc would be assigned Group A whereas volunteers 2,4,6,8 etc would be assigned Group B. Volunteers in Group A performed the experiment in stereoscopic VR first whereas volunteers in Group B performed the experiment in monoscopic CAD first. This is done to cancel out any learning effect which may arise from "familiarization" (Rogers,2011).

3.5.2   Experimental Setup

In order to ensure that there are no lurking variables both display techniques had the exact same amount of light and the exact same background / environment as a standard CAD package. For this purpose the researcher chose to follow CATIA since it is the package taught at the introductory level course at Purdue. Both of the test applications were developed in Unity. The CAD models would be made inside CATIA and the researcher would use the exact same models for both VR and two dimensional CAD. A total of ten models would be used for the experiment. These models would be exported from CATIA and converted into OBJ files so that the objects may be used as assets in Unity. The objects were selected from an undergraduate CAD class from Purdue University and hence would represent objects that students would typically see in a classroom. The reason as to why CAD objects from a class are chosen is because our sample population consists of students and these types of objects is what they would be typically used to.

The two display techniques used in the experiment were the regular VR environment and the VR environment using a monoscopic rectangular display to depict a two dimensional screen similar to the ones on which conventional CAD applications are used. The only difference between the two display techniques was the style in which the objects were displayed. Other variables such as the field of view, initial depth/angle of objects, the relative position / orientation of the objects, the 3D space, the shading, the lighting and the rate of change (rotation or translation) of the object were all kept the same across the display techniques. A total of five distinct objects were used in the scenes. Each display technique had ten scenes which can further be classified based on the type of change the user was subject to i.e. rotation or translation. Each of the five objects were subject to both kinds of changes which made up these ten scenes. Thus the experiment had a grand total of twenty scenes. The figure below depicts a flowchart of the overall experiment.
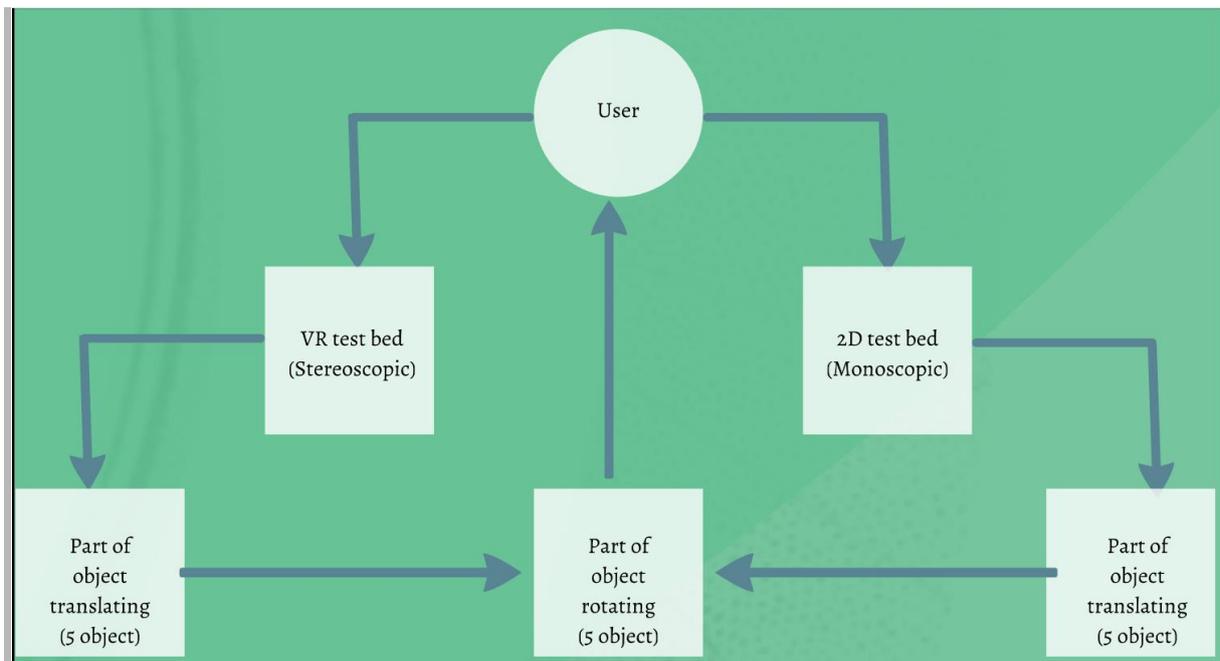
Figure 3.2 Experiment Outline

The volunteers viewed two instances of the exact same object, one of which were either rotating or translating in one-dimension (Z-axis) with respect to time and the other one remained unchanged in both display techniques. The goal is for the volunteers to indicate that there is a difference in the two objects as soon as it becomes noticeable to them. The next object appears when the user presses a designated button on the vive controllers(the trigger button) to indicate that they have noticed a difference between the two objects currently displayed on the screens.

The rotation / translation factor depends on the Weber-Fetchner equation (Weber, 1996). This ensures that the change in each dimension is proportional to the depth of the object from the screen. The equation would have the same effect as uniform rotation / translation.

$$\frac{\Delta S}{S} = \kappa$$

Equation 1: Weber-Fetchner equation

Historically this equation is relevant in just noticeable differences related studies where ΔS represents the minimum perceivable change i.e. the relative rotation / translation factor on an axis and κ is a constant overall rotation / translation factor. For example if one wants the rotation / translation factor along each axis to increase by only 1% then the researcher would set κ to be 0.01.

3.5.3   Experiment Apparatus and Software

For the viewing apparatus the HTC Vive was used. This HMD is used for both stereoscopic and monoscopic display in the experiment. The only difference in the setup for the vive in the two experiments is that the monoscopic has a 2D screen which has a targeted texture rendered on it whereas the stereoscopic is just a regular VR scene.

Figure 3.3 HTC Vive VR Headset

3.5.4   Variables

The variable being measured here is the JND in the rotation / translation factor at which the user notices a difference between the two displayed models i.e. ΔS(This is also called the intensity of the stimulus). The experiment is subsequently subdivided into two types. In the first type the researcher would be testing for JNDs by translating i.e. the some part of the model would be translated along the z axis, whereas in the second type of experiment the researcher would be testing for JNDs the rotation of the sub components of the part i.e. some small part of the model would be rotating whereas the rest of the model would stay in the same place. The translation happens into the screen along the z-axis whereas the rotation occurs in the xy-plane about the z-axis. For translation the intensity of the stimuli was set to 1% of the initial z-depth of the changing object whereas for rotation it was set to 1% of the initial angle of the object along the z-axis. The part of the object which was to rotate/translate was set to be 3 units away from the user in depth and angled at 0 or 360 degrees. The reason why 360 was used here is one cannot use 0 which will give ΔS as 0 , so the best value to use here would be 360 as it is the minimum value which would give us a non zero stimulus intensity. The reason why the initial stimulus was set to 1% was because it was a small enough value so as to not abruptly change and give the user time to interact with both objects. It is also understandable as to why small values of ΔS would yield more accurate

results for this particular study as this would was more likely to yield a smaller difference between the recorded value and actual JND. The figures below show both of these occurrences.
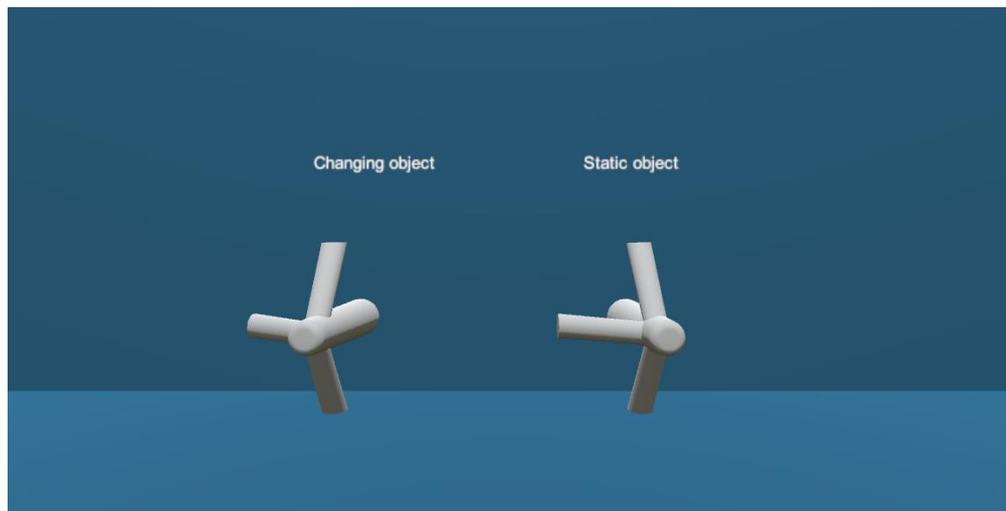
Figure 3.4 Translation scene before
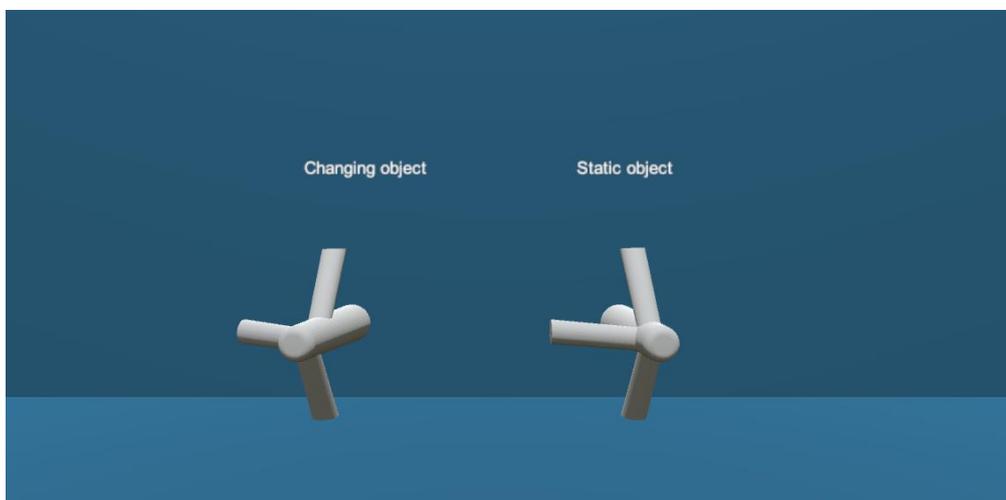
Figure 3.5 Translation scene after
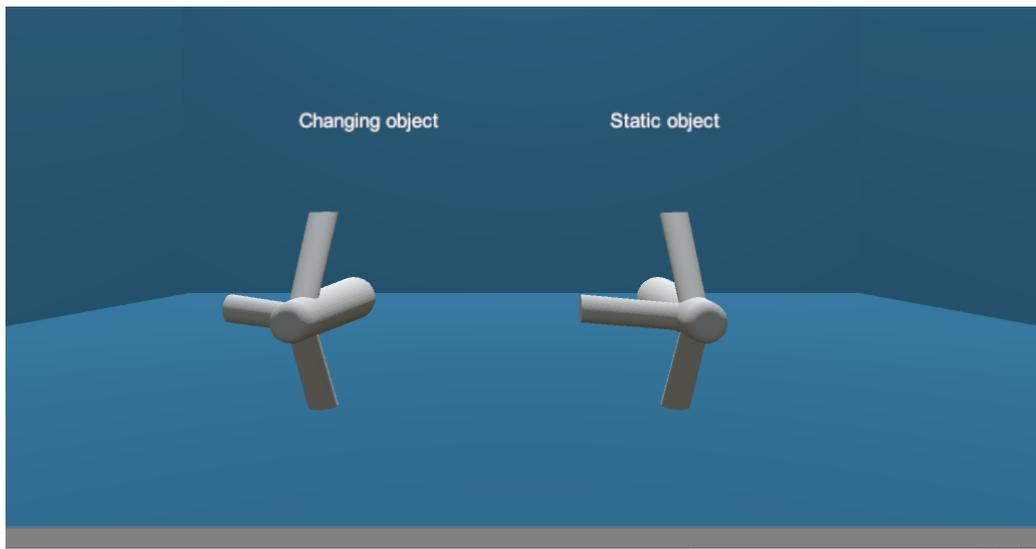
Figure 3.6 Rotation scene before
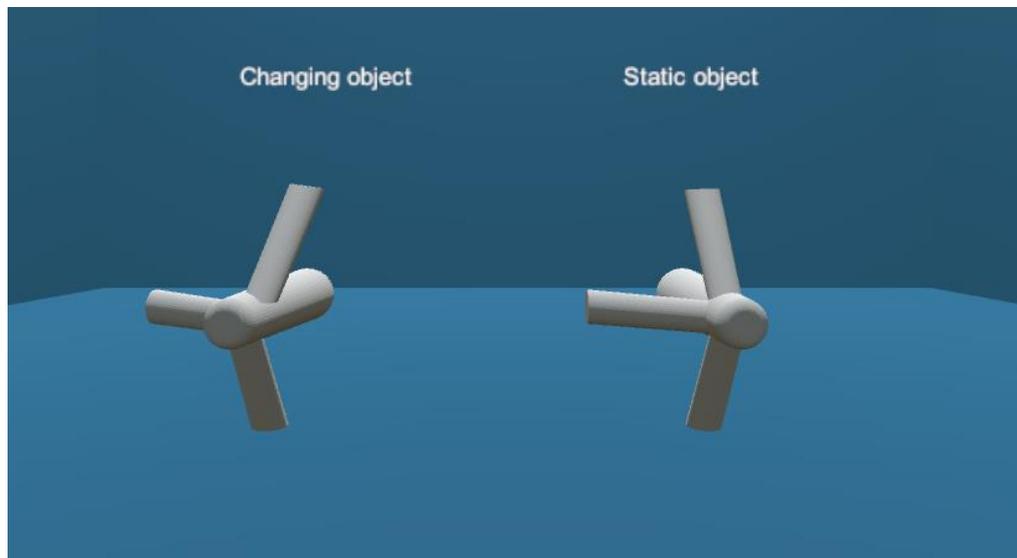
Figure 3.7 Rotation scene after

3.5.5   Hypothesis

The goal here is to find out if there is a difference in the JNDs between the CAD models in VR with respect to the CAD models on a monoscopic display. Consequently, the null hypothesis is that there is no significant difference between the average JNDs of CAD models in VR with conventional two dimensional screens. The alternative hypothesis is that there is a significant difference between the two averages.

3.5.6 Data collection and organization

As the volunteers interacted with the system and indicated when they noticed differences between the displayed objects. The time stamps at which they pressed the trigger button to switch scenes because the two objects no longer looked similar to them were recorded. These timestamps represent our target variable for analysis; this variable can be later translated into screen pixel values. The data also kept a record of the kind of scene the user was interacting with for a particular timestamp.

The data is sorted as such:

Table 3.1 Data collection

Scene Number	Volunteer Number	Scene Type	Type of Transformation	Time Taken

The variable Scene Number has a possible set of values from 1 to 10 each representing the scene number within either the stereoscopic application or the monoscopic application.

The variable Scene Type can either be monoscopic or stereoscopic, represented by either the letters 'M' or 'S' respectively.

The variable Type of Transformation can either be translation or rotation which can take up the values of 'T' or 'R' respectively.

The time taken is the variable of interest which will be the subject of the quantitative analysis and will be recorded as in terms of seconds.

3.5.7 Measuring variables

Since the objective of this experiment is to measure JNDs for rotation and translation of a part of a 3D object two seperate measuring techniques would be needed for measuring the two JND thresholds in terms of seconds since the overall change in each of the scenes is constant with respect to the camera position.

The figure below demonstrates how the time take to notice the change in translation is to be measured:
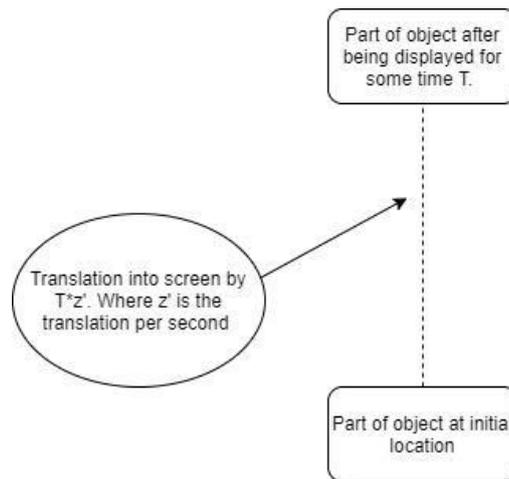
Figure 3.8 Translation in the positive z-axis of a part of an object

Similarly the rotation scenario would have some part of the object rotating about the z-axis in a clockwise direction about its own centre. The mechanisms for recording the time stamps in this scenario is the same as for a scenario where translation is the transformation of interest.

3.5.8 Data Analysis and Visualization

As part of the data analysis, based on the findings of both display techniques the researcher drew up side by side boxplots of two different comparisons. The first comparison is solely between VR and 2D i.e. between the different display techniques. The second comparison was between different techniques and the type of transformations within those techniques i.e. VR with Translation vs VR with Rotation vs 2D with Translation vs 2D with Rotation

The boxplots below were used to get the 50th percentile of the amount of change required for the user to detect that the two objects were not identical anymore. The 50th percentile is selected on the basis of how JND is defined i.e. amount of change which can be detected 50% of the time. Using the 50% JND percentile to perform analysis on such experiments is a common approach to doing quantitative analysis on such experiments (Szafir,2017).
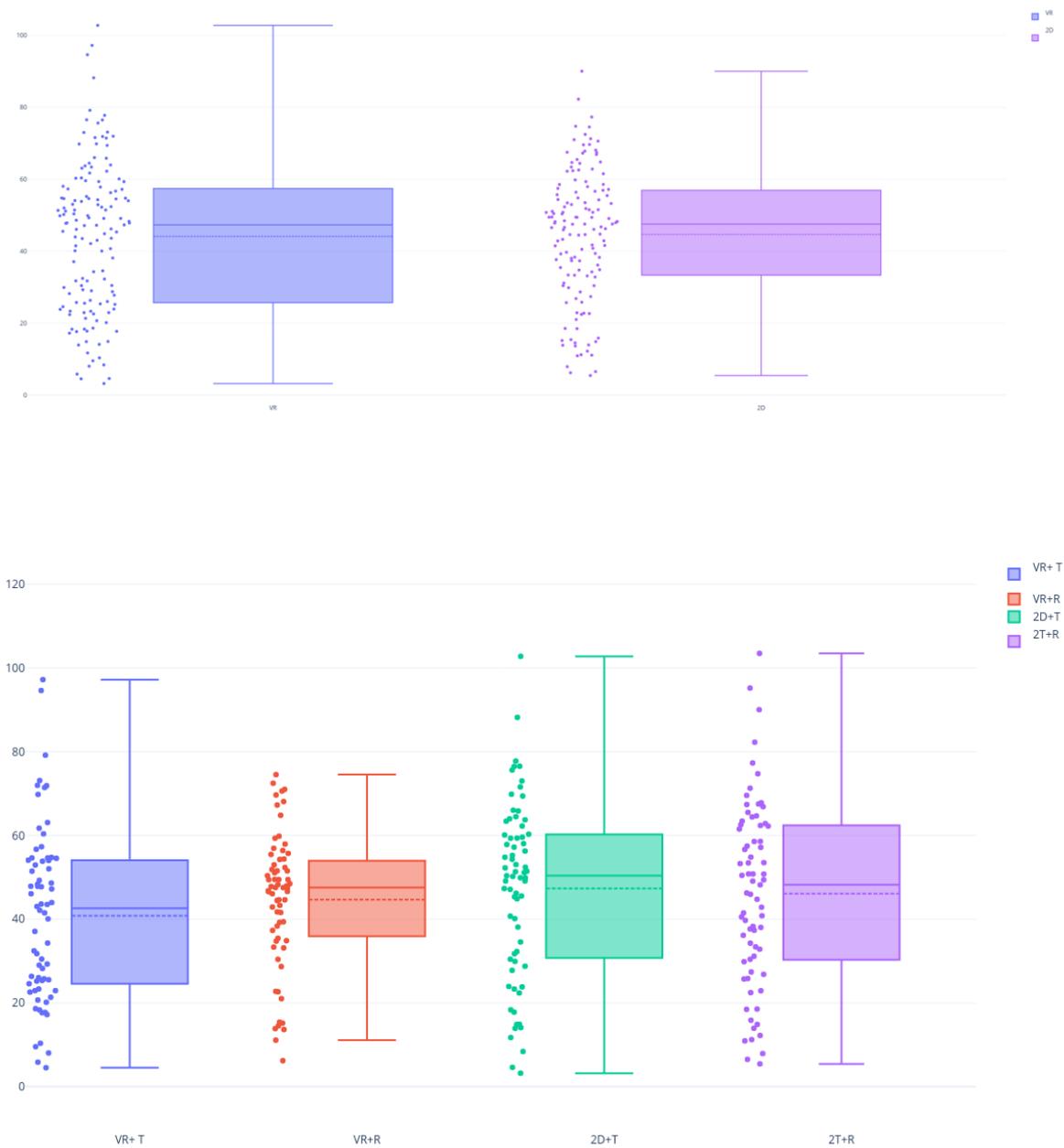
Figure 3.9 Side by Side box plots

One would be able to locate the JND at the 50% mark of change detection. From the four graphs one would get 4 JNDs. In general papers involving JND studies compare the difference JND level namely 25% percent threshold, 75 % threshold and the difference between them.

On the other hand for the hypothesis testing the researcher simply checked to see if there is a significant difference in the JND levels between stereoscopic CAD vs monoscopic CAD in both rotation and translation by looking at the mean/median of the data set.

In order to fully understand the contribution of different variables to the result. The researchers choose to fit a model onto the dataset. Since this experiment was a crossover design the researchers choose to use a fixed effects model in order to fully capture the contribution of different variables and individuals in this design.

This procedure was recommended by the Purdue Statistical Consulting Service as the optimal way of analyzing the effect of different variables. On advice from the SCS the researchers decided to fit two different models for this experiment. The first model is one which takes into account the kind of the effect of only the different display techniques and the variability within a subject. The second model takes into account the effect of the kind of transformation and the kind of scene where the transformation had occurred as well as the variability within a subject and different display techniques..

The models can be explained by the equation below:

$$M1: T = B0 + B1*S + B2*P + V + \varepsilon$$
$$M2: T = B0 + B1*S + B2*P + V + B\boldsymbol{3}*T + B\boldsymbol{4}*(S*T) + \varepsilon$$

Key:

T : Time taken to detect change

B0 : y-intercept of the linear model

    S : Represents the kind of Scene (Monoscopic or Stereoscopic) is being viewed by the user. Its value would be either -1 for Monoscopic or 1 for Stereoscopic.

B1 : Contribution of the kind of scene to the time taken to detect changes.

P : Represents a Period

B2 : Represents the contribution of each period

V : represents random effect which is taken into account by the software when fitting a model

ε : Is the error

T : Represents the type of transformation which would be represented by either -1(for translation) or 1 for rotation.

S*T : Represents the cross-over effect i.e. the effect of a particular transformation inside a particular display technique.

B4 : Represents the weight of effect of the aforementioned variable.

See figure 4.1 for a representation of the data in the model.

In the above two models , M1 represents the model where the researchers wanted to only explore the effect of each individual and the display technique being used. Whereas M2 represents the model where the effect of the kind of transformation taking place is also taken into account when fitting in the linear model. The respective values of Bi would let the researchers know exactly how much does each variable contribute to the overall time taken by the user to detect a change between the two objects being viewed.

Scene #	Time Taken(seconds)	Transformation	Type of Scene	Period
1	60.37787	1	-1	1
2	54.08479	1	-1	1
3	71.44379	1	-1	1
4	47.21568	1	-1	1
5	25.53447	1	-1	1
6	62.23972	2	-1	1
7	88.19958	2	-1	1
8	102.777	2	-1	1
9	118.3815	2	-1	1
10	71.58942	2	-1	2
1	48.62221	1	-1	2
2	105.5787	1	-1	2
3	94.61078	1	-1	2
4	97.21426	1	-1	2
5	34.29129	1	-1	2
6	63.97101	2	-1	2
7	50.20917	2	-1	2
8	77.76633	2	-1	2
9	69.8465	2	-1	2
10	65.84753	2	-1	2

Figure 3.10 Data Representation

3.6   Results

Due to the outbreak of the novel COVID-19 virus the experiment had to be discontinued midway since the VR equipment was being shared amongst the participants in order to prevent possible transmission of disease within volunteers. The initial targeted number of participants could not be met and the researchers could only accommodate 18 volunteers before the experiment was suspended due to increased risk.

3.6.1   Outliers

The researcher looked for two kinds of outliers, within display techniques and within display techniques crossed with transformation type on the recommendation of the SCS. Of the 18 participants 3 were excluded from the results because of the fact that their average time to complete the experiment in either display technique was too high and would skew the results of the experiment. This was accomplished by drawing initial box plots which contained the outliers, the researcher proceeded to remove the users data from the study.

3.6.2   SAS Models

Each of the two models was put through SAS and the results were recorded. The code and result for model 1 i.e. the model which only takes into account the display technique being used are listed below.

```
DATA VRStudy;
     infile '\\Client\C$\Users\17657\Desktop\results.csv' dlm = ',';
     input Scene Time Transformation Type Subjects Period;
RUN;
PROC PRINT DATA = VRStudy;
    TITLE 'SAS NEW';
RUN;

PROC MIXED DATA = VRStudy;
     CLASS Scene  Transformation Type Subjects Period;
     MODEL Time = Type    / solution residual;
     RANDOM int/ subject = Subjects;
RUN;
```

Solution for Fixed Effects

Effect	Type	Estimate	Standard Error	DF	t Value	Pr > |t|
Intercept		44.7482	2.8686	14	15.60	<.0001
Type	-1	-0.2708	2.0825	263	-0.13	0.8966
Type	1	0	.	.	.	.

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Type	1	263	0.02	0.8966

Figure 3.11 SAS output 1

From this table the researcher can deduce that the equation of the model is :

M1 : Time Taken = 44.7482 - 0.2708*Type.

The negative b-hat value of Type suggests that any effect on time is largely because of the VR environment (as the VR was encoded as -1). To check whether the Type has a significant impact on the Time variable one has to perform an F-test on the given value by the SAS program using the degree of freedoms in numerators and denominators to check the F-critical value.

Density Plot
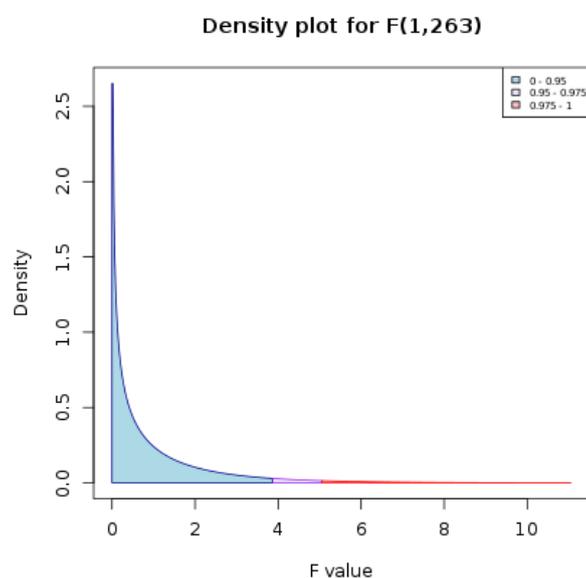
Figure 3.12 Density plot

The F-critical value is approximately 3.87 for DoF num = 1 and DoF den = 263. The F-value of the relationship model is 0.02. Since F-value < F-critical this implies that the relationship is not significant and hence the null hypothesis of the experiment stands and cannot be rejected. Thus there is no significant change in the average time taken in either of the display techniques in this experiment.

For the second model the SAS code and output are shown as below :

```
DATA VRStudy;
    infile '\\Client\C$\Users\17657\Desktop\results.csv' dlm = ',';
    input Scene Time Transformation Type Subjects Period;
RUN;
PROC PRINT DATA = VRStudy;
    TITLE 'SAS NEW';
RUN;

PROC MIXED DATA = VRStudy;
    CLASS Scene  Transformation Type Subjects Period;
    MODEL Time = Type Transformation*Type    / solution residual;
    RANDOM int/ subject = Subjects;
RUN;
```

Solution for Fixed Effects							
Effect	Transformation	Type	Estimate	Standard Error	DF	t Value	Pr > |t|
Intercept			44.7272	3.2000	14	13.98	<.0001
Type		-1	2.9170	2.9029	261	1.00	0.3159
Type		1	0	.	.	.	.
Transformation	1		0.03074	2.9507	261	0.01	0.9917
Transformation	2		0	.	.	.	.
Transformation*Type	1	-1	-6.4224	4.1457	261	-1.55	0.1226
Transformation*Type	1	1	0	.	.	.	.
Transformation*Type	2	-1	0	.	.	.	.
Transformation*Type	2	1	0	.	.	.	.

Type 3 Tests of Fixed Effects				
Effect	Num DF	Den DF	F Value	Pr > F
Type	1	261	0.02	0.8872
Transformation	1	261	2.35	0.1265
Transformation*Type	1	261	2.40	0.1226

Figure 3.13 SAS output 2

In this model the relationship between Transformation and Transformation * Type were also explored on the recommendation of SCS. The equation of the model came out to be :

Time = 44.7272+ 2.9170*Type + 0.03074*Transformation - 6.4224*Transformation*Type

The F-Critical value for Dof num =1 and Dof Den = 261 is approximately 3.877 since each of the F-values are less than the F-critical thus none of the variables have a significant effect on time.

3.6.3 Converting time to actual JND values

However it is important to note at this point that this analysis of JND also needs to take place with respect to the actual JND values. Therefore a second round of analysis is required whereby the time taken is converted into actual displacement/angle of rotation depending on the transformation. For this problem one only needs to examine the direct effect of JND vs display technique using a similar model to M1 and replacing the time term with the JND values after converting it to the appropriate values using Weber's equation.

For translation our S is set to 3 units because that was the initial position of the objects with respect to the z-axis from the user. Thus one can get delta displacement into the screen by multiplying time taken by 0.03(1% of the initial value at which the object was moving per second) this would imply that delta = (time taken)*0.03. Similarly for the rotation one would find the JND by simply converting the time taken to the change in angle by using delta = (time taken)*0.36. Over here the value used was 0.36 instead of 0.03 because the fact that the object facing the user has rotation of 360*Z where Z is an integer. The absolute non-zero magnitude for the objects would thus be 360 and 1% of 360 = 0.36. The main difference in this analysis would be that one must separate out rotation and translation from each other as they would have their own JND values thus one would need to run the model twice for each level of transformation. Doing so yielded the following results.

Solution for Fixed Effects						
Effect	Type	Estimate	Standard Error	DF	t Value	Pr > |t|
Intercept		18.6983	1.7708	137	10.56	<.0001
Type	-1	0.8311	2.2131	137	0.38	0.7078
Type	1	0	.	.	.	.

Type 3 Tests of Fixed Effects				
Effect	Num DF	Den DF	F Value	Pr > F
Type	1	137	0.14	0.7078

Figure 3.14 Results for Rotation JND

Solution for Fixed Effects						
Effect	Type	Estimate	Standard Error	DF	t Value	Pr > |t|
Intercept		8.0000	0.5679	137	14.09	<.0001
Type	-1	-0.8539	0.7097	137	-1.20	0.2310
Type	1	0	.	.	.	.

Type 3 Tests of Fixed Effects				
Effect	Num DF	Den DF	F Value	Pr > F
Type	1	137	1.45	0.2310

Figure 3.15 Results for Translation JND

The F values for these specific degrees of freedoms suggest that neither of the two transformation types are significant. Hence even when using JND values we would fail to reject the null hypothesis however the results do suggest that the underlying spatial abilities are not common.

CHAPTER 4.   CONCLUSIONS AND FUTURE WORK

4.1 Limitations of Experiment

There are a number of limitations in the experiment which could have possibly affected the outcome. First of all the number of participants was not enough to reach the determined power level (80%) due the risk of contact during the COVID-19 pandemic. In addition to this, many users stated that they had not been in a VR environment before and this was a particular concern during the experiment as it was a cause for distraction. Some users wanted to look around and explore the environment rather than focus on the experiment because of their curiosity. This could have potentially impacted the results by increasing the time taken by the users to detect changes as they were not focusing on the task at hand. This in turn would impact the JND values. The problem becomes more complex as some users spend more time distracted than others whereas those used to VR environments may not waste any time and their timestamps or JND values may end up being treated as lower tail outliers i.e. lower than acceptable values for the time or JND.

One way to counteract this problem could have been to introduce a demo or pilot study which would have assessed how users interact with the environment. The user's could have been allowed to train for as long as needed to get accustomed to the environment or until they reached a baseline of familiarization which would have been required for all participants. This pilot study which could have generated more data for power analysis and given a more accurate figure regarding the number of participants to be included. The researcher also believes that the users could have benefitted from being allowed to roam around unsupervised in each of the environments before starting the experiment.

4.2 Summary of Results

At the conclusion of the experiment it was determined that none of the measured variables had a significant difference on the JND values to detect changes between similar objects . The reason as to why could be that the researcher did not test the two display techniques across enough participants to have adequate data to be able to detect a significant difference. The Transformation and Transformation* Type variables are nearly significant and it is likely that they could prove to be significant if more participants are tested.

In spite of no new discoveries, this experiment has provided a framework which would allow future studies of similar nature to take place and analysis to be drawn from them. This study was conducted in an area which was relatively not well explored i.e. the overlap between CAD, virtual reality and perception. This experiment lays a study design which can be followed given that it has combined practices used in research from the relevant fields. This experiment answers questions like given some perception related problem which combines Virtual Reality and CAD, for example color perception, how would a researcher or a team go about designing an experiment, what sort of grouping would be needed, the method of collecting data, safety checks for individuals, what variables would need to be measured and the type of analysis which should be performed in order to accept or reject hypothesis.

Researchers can use this framework to analyze scenarios and variables not explored in this study. For example researchers may be interested in examining which rendering style of existing CAD packages would be the best with regards to existing packages. On the other hand future research work may expand on the given framework to make a direct comparison between 2D computer screens and Virtual Reality by accounting for the different factors which distinguish each display technique such as field of view and screen size.

This study would also open doorways to explore the topic from the lens of qualitative analysis since a number of participants did convey that they had enjoyed the overall experience in the proposed VR CAD environment as compared to the conventional monoscopic CAD environment. Future studies could be based on learning and engagement in the classroom utilizing the novel technology to provide a more captivating approach for engineering students to learn CAD or at least give the option to educators to combine the two in a manner which would help student's spatial memory and retention of perceived shapes.

VR CAD spaces can also introduce a largely unexplored topic - collaborative workbenches in CAD. Typically a CAD team is formed of different individual units. The smallest of which is the individual 3D modelling engineer. This engineer works mostly by themselves on an assigned part and usually does not have a 3D digital representation of other parts which may go in conjunction with their current parts due to the limitation of a fixed screen display. With VR involved such a shared workspace would be able to give the engineers real time feedback as to how their individual parts would work in the overall assembly of a particular product.

The experiment overall failed in its objective to find a difference between the two display techniques and determine which was better. The similarities between the two display techniques for e.g. the average time to detect differences in both techniques was less than 0.5 seconds, was a surprising result. It may be due to the fact that researchers were able to control so many lurking variables that the experiences turned out to be similar. It may have been beneficial to record the number of years a user has used either of the two display techniques (VR or computer screens) as this may be a significant factor in determining how quickly a user adapts to the display techniques.

4.3 Discussion of Results

When compared with existing literature, this study, in the context of its limited results, does indicate that the underlying spatial ability for rotation and translation are disjoint and not common as there is a large difference between the F-values of both rotation and translation in the two display techniques.

From the Szafir paper the results of this study would be interpreted in the following way. JND may not necessarily be a robust way of measuring shape perception in the same manner as used in the experiment as the possibility exists that the framework on which JND is built upon may not necessarily apply to this particular use case. Hence there is a possibility that JND does not give a robust statistic to measure with a fair amount of confidence if there is a difference between the two display techniques. The generated model however does allow designers of CAD a way to quantify how dynamically changing shapes are perceived by users in the display techniques similar to how Szafir's model gives designers of webpages a way to quantify the level of discrimination between different colors of different shapes.

The high disparity among the user's time stamps and JND values can possibly be explained from the literature on varying spatial abilities within users (Huk, 2006). These can also be overcome by expanding the user's spatial ability using some of the established methodologies so that the users can get the maximum benefit out of a VR experience (Huk, 2006). Thus if the experiment was continued the result could be that one would have vastly different JND levels in both transformations. This would also imply that the assumption that rotation and translation have their own JND threshold levels and hence would need to be studied separately as done in this experiment (Kozhevnikov, 2001). This would also imply that not only would users have underlying spatial abilities for different kinds of transformations, but also that the same kind of transformations in

different directions (e.g. translation out of the instead of into the screen) could possibly also be disjoint.

Even though the results do not indicate a significant difference between the JNDs of the two transformations it is still possible for the VR display technique to outperform the 2D display technique in both transformations. For this to happen the experiment needs to be continued until the appropriate number of participants is reached. One possibility that could result from this practice is that the result could eventually become significant. If this were to happen it would re-establish the fact that VE give a more accurate representation of real world models as opposed to 2D environments (Wilson and Soranzo, 2015). If this were the case then one could state that VR is closer to perfect visual realism as opposed to 2D screens (Jansen, 2013). This would also mean that the results contradict previous literature that states that shape perception in VR is half as effective as that on 2D screens (Loomis, 2002).

APPENDIX

Pre test qualification survey : This survey is used to filter out volunteers who do not qualify for the experiment. This is done intentionally so as to exclude volunteers who may be minors or those who may experience discomfort or be at a heightened risk during the experiment.

Question 1)

Are you at least 18 years old?

    A) Yes

    B) No

Question 2)

Do you have any major visual impairment?(Requiring the use of glasses is not considered major visual impairment)

    A) Yes

    B) No

Question 3)

Can you walk without assistance?

    A) Yes

    B) No

Question 4)

Have you ever experienced any mild to high discomfort using a VR headset such as nausea?

    A) Yes

    B) No

    C) I have not previously use VR headsets

Question 5)

 Are you currently a Purdue University student?

    A) Yes

    B) No

Question 6)

Do you have vertigo?

    A) Yes

    B) No

REFERENCES

Bannister, N. A. (2019). *Computer Vision Syndrome in Head-Mounted Displays: Spontaneous Eye Blink Rate and Saccades* (Doctoral dissertation, Purdue University Graduate School).

Chang, T. C., & Wysk, R. A. (1997). Computer-Aided Manufacturing.

Costello, P. (1997). *Health and Safety Issues associated with Virtual Reality - A Review of Current Literature* [Ebook]. Leicestershire: Loughborough University. Retrieved from http://www.agocg.ac.uk/reports/virtual/37/37.pdf

Costa, R. T., Sardinha, A., & Nardi, A. E. (2008). Virtual reality exposure in the treatment of fear of flying. *Aviation, space, and environmental medicine*, *79*(9), 899-903.

Coyne, R. (2007). Thinking through Virtual Reality. *Techné: Research In Philosophy And Technology*, *10*(3), 26-38. doi: 10.5840/techne200710310

Davies, R. (2004). Adapting Virtual Reality for the Participatory Design of Work Environments. *Computer Supported Cooperative Work (CSCW)*, *13*(1), 1-33. doi: 10.1023/b:cosu.0000014985.12045.9c

Freina, L., & Canessa, A. (2015, October). *Immersive vs desktop virtual reality in game based learning. In European Conference on Games Based Learning* (p. 195). Academic Conferences International Limited.

Gîrbacia, F., Beraru, A., Talabă, D., & Mogan, G. (2012). Visual depth perception of 3D CAD models in desktop and immersive virtual environments. *International Journal of Computers Communications & Control*, 7(5), 840-848.

Huk, T. (2006). Who benefits from learning with 3D models? The case of spatial ability. Journal of computer assisted learning, 22(6), 392-404.

Jansen, Y., Dragicevic, P., & Fekete, J. D. (2013, April). Evaluating the efficiency of physical visualizations. *In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (pp. 2593-2602).

Judd, D. B. (1932). Chromaticity sensibility to stimulus differences. *JOSA*, 22(2), 72-72.

Kadam, P., & Bhalerao, S. (2010). Sample size calculation. *International journal of Ayurveda research*, *1*(1), 55.

Kozhevnikov, M., & Hegarty, M. (2001). A dissociation between object manipulation spatial ability and spatial orientation ability. *Memory & Cognition*, *29*(5), 745-756.

Lee, H., & Han, S. (2005). Reconstruction of 3D interacting solids of revolution from 2D orthographic views. *Computer-Aided Design*, *37*(13), 1388-1398.

Loomis, J. M. (2002). Using immersive virtual reality to study visual space perception, visual control of locomotion, and visually-based navigation. *Journal of Vision*, 2(10), 3-3.

Leroy, L., Fuchs, P., Paljic, A., & Moreau, G. (2009, February). Experiments on shape perception in stereoscopic displays. *In Stereoscopic Displays and Applications XX* (Vol. 7237, p. 723717). International Society for Optics and Photonics.

Luo, X., Kenyon, R., Kamper, D., Sandin, D., & DeFanti, T. (2007, March). The effects of scene complexity, stereovision, and motion parallax on size constancy in a virtual environment. In *2007 IEEE Virtual Reality Conference* (pp. 59-66). IEEE.

McGreevy, M. W. (1993). Virtual reality and planetary exploration. In *Virtual Reality* (pp.163-197). Academic Press.

Monahan, T., McArdle, G., & Bertolotto, M. (2008). Virtual reality for collaborative e-learning. *Computers & Education*, *50*(4), 1339-1353.

Potts, M. (1992, August 16). *VIRTUAL REALITY*. Retrieved November 22, 2018, from https://www.washingtonpost.com/archive/business/1992/08/16/virtual-reality/76720cb4-244e-4d98-9d09-d713f7216469/?utm_term=.1fb84825e96f

Raposo, A., Santos, I., Soares, L., Wagner, G., Corseuil, E., & Gattass, M. (2009). Environ: integrating VR and CAD in engineering projects. *IEEE Computer Graphics and Applications*, *29*(6), 91-95.

Reichelt, S., Häussler, R., Fütterer, G., & Leister, N. (2010, May). Depth cues in human visual perception and their realization in 3D displays. In *Three-Dimensional Imaging, Visualization, and Display 2010 and Display Technologies and Applications for Defense, Security, and Avionics IV* (Vol. 7690, p. 76900B). International Society for Optics and Photonics.

Rogers, Y. (2012). HCI theory: classical, modern, and contemporary. *Synthesis lectures on human-centered informatics*,5(2), 1-129.

Sanchez-Elez, M., & Roman, S. (2015). Learning Hardware Design by Implementing Student's Video-Game on a FPGA. *Frontiers in Education: Computer Science and Computer Engineering*, 27-30.

Shneiderman, B. Why not make interfaces better than 3d reality? I*EEEComput. Graph. Appl.* 23, 6 (Nov. 2003)

Spröte, P., Schmidt, F. & Fleming, R. *Visual perception of shape altered by inferred causal history*. Sci Rep 6, 36245 (2016) doi:10.1038/srep36245

Sutherland, I. E. (1965). The ultimate display. *Multimedia: From Wagner to virtual reality*, 506-508.

Sutherland, I. E. (1968). A head-mounted three dimensional display. Proceedings of the December 9-11, 1968, Fall Joint Computer Conference, Part I on - AFIPS 68 (Fall, Part I). doi:10.1145/1476589.1476686

Svarverud, E., Gilson, S. J., & Glennerster, A. (2010). Cue combination for 3D location judgements. *Journal of Vision*, *10*(1), 5-5.

Szafir, D. A. (2017). Modeling color difference for visualization design. IEEE transactions on visualization and computer graphics, 24(1), 392-401.

Weber, E. H. (1996). *EH Weber on the tactile senses*.Psychology Press.

Weidlich, D., Cser, L., Polzin, T., Cristiano, D., & Zickner, H. (2009). Virtual reality approaches for immersive design. *International Journal on Interactive Design and Manufacturing (IJIDeM)*, *3*(2), 103-108.

Wilson, C. & Soranzo, A. (2015). The Use of Virtual Reality in Psychology: A Case Study in Visual Perception. *Computational and Mathematical Methods in Medicine*, 2015.

Yu, F., Zhang, J.-F., Zhao, Y., Zhao, J.-C., Tan, C., & Luan, R.-P. (2010). The Research and Application of Virtual Reality (VR) Technology in Agriculture Science. *Computer and Computing Technologies in Agriculture III IFIP Advances in Information and Communication Technology*, 546–550. doi: 10.1007/978-3-642-12220-0_79

Zhang, J. (1997). The nature of external representations in problem solving. *Cognitive science*, *21*(2), 179-217.