USING A VISUALIZATION TOOL FOR STUDYING THE EFFECTS OF VIRTUAL ENVIRONMENTS ON ASSEMBLY TRAINING

By

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Title of Study: USING A VISUALIZATION TOOL FOR STUDYING THE EFFECTS OF VIRTUAL ENVIRONMENTS ON ASSEMBLY TRAINING

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Abstract: The objective of this research is to build and demonstrate the design on Virtual Reality (VR) environment to aid in the understanding of assembly & assembly planning for complex systems. To explain the research work, a Virtual Reality environment was created for assembly simulation of Treadmill parts used in a Spacecraft. This environment will account for space related constraint such as, gravity. This study will help in understanding the assembly of the VR model which might help an assembler to optimize the design related cost. Unity 3D is used for creating the VR environment along with Solidworks to create Treadmill parts. Text and image cues are offered to assist users while performing manual assembly. The assembly sequence followed by users will be compared with an optimized path sequence computed using a Genetic Algorithm for a collision-free layout.

To validate the research work, the virtual assembly simulation has been run on four distinct set ups using immersive (VIVE headset) and non-immersive (desktop) virtual reality systems. A series of user studies to achieve two primary objectives has been conducted: 1) Evaluation of simulated representations with respect to different analysis, 2) Identification of best layout in terms of correctness and elapsed time for a virtual environment. A visualization tool was employed to analyze the system and data collected from diverse set ups. An interactive visualization tool based on a Tree-Map visualization technique was developed to represent the hidden patterns in users' behavior when they perform different tasks in a virtual environment (using head-mounted VR tool and monitor based VR) which also help in concluding that immersive virtual reality with image cue appear to be the best set up in terms of correctness and time. In addition, using this interactive visualization tool, we show the intrinsic statistical relationships between/within diverse groups of participants in the form of chord diagrams.

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CHAPTER I

INTRODUCTION

The manufacturing sector plays a vital role in the national economy. According to the National Association of manufacturers, in 2015, this category contributed $2.17 trillion to the US economy [39]. So, it becomes important to come up with optimize manufacturing as even the tiniest mistake in design or layout can cost huge amount. Planning and training in assembly tasks can discover the most efficient way of product manufacture [42]. Use of prototyping is a vital step to conclude a product which helps in conceptualization of a design [45]. Virtual Prototyping (VP) predominantly used in industry all over the globe. VP supplies multifunctional evaluation at an economical price, equips engineers to examine downstream issues faced previously in the product design cycle, and may ease conveyance process design issues [14]. In this context, virtual reality (VR) emerges as a form of synergy between human and computer based on a wide range of inputs, like, haptic interfaces, advanced graphics, voice recognition and movement tracking. With various applications, VR-based systems are prominently used in the manufacturing area [41]. In addition, VR-based systems are finding applications in the medical sector as well, such as, VR based simulation for surgical training [12, 13].

The creation of VR based simulation environments holds the potential of improving the quality of training while decreasing the time needed for training. Within the last decade, there have been various attempts made in the virtual reality field to create an environment for assembly simulation [25-26, 30].

These approaches belong to various application sectors ranging from manufacturing to education and include collaborative approaches used to incorporate cyber physical components in advanced manufacturing [46]. Jayaram et al. [43] defined virtual assembly as ‘‘the use of computer tools to make or ‘‘assist with’’ assembly-related engineering decisions through analysis, predictive models, visualization and presentation of data without physical realization of the product or supporting processes’’. Virtual assembly provides in-depth information about the workflow followed for product development which can ease the efforts to identify and remove the steps. It can also help in modifying the order of the steps to make the process more productive. To verify the Virtual environment, an evaluation study can be performed which will make sure that the design is improved.

Another area of research involves information analytics and visualization methods. Some of the commonly used software packages in this area include Tableau [45], Alteryx and Qualtrics for visualizing surveys. However, these standard visualization approaches overlook the hidden patterns in users' conduct when they execute various tasks. Moreover, they also fail to find relationships among divergent groups of participants. To rectify these issues, we suggest building a visualization tool to decipher the collected evaluation data and extract meaningful results. Color is one of the most prevalent visual channels used in Visualization because of its merits in visual search and easy implementation. Color helps us break camouflage [43].

CHAPTER II

VIRTUAL ENVIRONMENT

2.1 Literature Review

A brief literature review of relevant research efforts is presented in this section.

2.1.1 Virtual Prototyping & Virtual Reality based applications

Virtual Prototyping (VP) is a method which involves computer aided modelling of a system, replicating and visualizing its performance under real-world functional conditions. Zorriassatine et al. [11] presented general survey of the available Virtual Prototyping techniques and they provided potential Small-to-medium enterprise users with a broad picture of the field of VP and identified various issues and information related to implementation of VP technology. Cecil et al. [15] also provided a detailed literature review on virtual prototyping research efforts in various engineering domains, including design and manufacturing. In [27], in-depth literature review on research efforts made in virtual prototyping (VP) were provided which covered design and manufacturing. This work explained how to approach Product and process design using Virtual Engineering.

Virtual Prototyping concept finds various applications in diverse types of domains for example, [12, and 13], Cecil et al. demonstrated the design and development of a VR based surgical environment (VSE). The paper covered the architecture of such a system and performed validation study which indicated that the VSE can ameliorate the understanding skills of residents. They employed the application of Next Generation Internet technologies which aided feasibility of surgeons and residents interacting with VSE from various locations. In [14], an integrated collaborative approach for Micro Devices Assembly (MDA) was demonstrated. This paper used collaborative manufacturing approaches in which the cyber modules focused on assembly planning and 3D Virtual Reality based simulation activities whereas, the physical components used outcomes of the cyber modules to perform physical assembly for target MDA activities. In their planning module, they used an Insertion Algorithm (IA) to minimize the travel distance of the assembly robot in accomplishing the tasks.

2.1.2 Virtual Reality in manufacturing field

Virtual Environments enable users to connect and interact with that environment as though they were physically present. In the past decade, various research works illustrated how Virtual Reality (VR) can be applied to assembly planning tasks. Al-Ahmari et al. [25] constructed a virtual manufacturing assembly simulation system (VMASS) with the objectives: a) to ease the investigation of the optimal translation of CAD data to VR software and b) integrates the various devices and software to build a system, which is helpful in feedback mechanism. Seth et al. [29] provided a review of the research in virtual assembly and categorizes the different approaches. They pointed out various applications of a virtual assembly/disassembly simulation such as, ergonomic evaluations, virtual training, tool and fixture design, virtual process planning, knowledge capture and representation etc. Similarly, Schenk et al. [26] merged assembly simulation and virtual reality, to build fully interactive and immersive 3D visualizations of assembly lines and factories. In this work, they performed dynamic online coupling of these tools at runtime. They have implemented two interfaces between virtual environment and simulation systems. They claimed that this work would help in case of emergencies, where, the factory operator can plan and test different plans of action. In this effort, the contributors incorporated user interactivity feature which help users to closely examine each action.

Validation is vital in the process of quality management which ensures that the process or product fulfils the purpose intended. David et al. [31] drafted a study to examine the validity of an immersive, interactive virtual pedestrian environment. Construct cogency was demonstrated through significant correlations between behavior in the virtual and real worlds within the child and adult samples. This work attempted to validate the Virtual design by asking all the users to provide ratings on how they viewed the environment. Later, they performed an examination of convergent validity with parent-reported measures of child temperament. In [32], Thomas et al. took a rudimentary step towards validating the Virtual Reality cognitive performance Assessment Test (VRCPAT), a virtual environment-based measure of learning and memory. VRCPAT software is a 3D VE programmed to simulate a city environment. The foremost aim of this research work was to appraise the construct validity of the VRCPAT using multitrait-multimethod matrix [35]. Similarly, Zeltzer and Pioch [30] described the task analysis, derived requirements, and validation and verification (V and V) process used throughout development of the prototype simulation. They showed that well-defined methods for validation and VE hardware and software verification could notably aid the development process for VE training systems.

2.1.3 Using Treadmill in Virtual Environment

Treadmill minimizes stress on the body than walking/ running on a normal surface. In the past few years, many researches have shown its significant role in virtual reality as well. Deutsch [19] provided this article to give an updated overview in developed and tested VR technology to improve walking for people post-stroke. He introduced the technology (Software and hardware) used to create VR system followed by an evaluation of the research on training methods to improve walking, with a priority on the software used for creation of the virtual environments. He sketched two tables one with the summary of Task, System Elements, and Outcomes of stroke walking Rehabilitation Studies and other with Summary of training elements and application of virtual walking studies. In [21], Betty et al. described the use of a treadmill-based virtual environment (VE) to investigate the influence of visual motion on locomotion. In addition, Sinitski et al. [22] examined walking speed changes for able-bodied transtibial amputee people on a self-paced treadmill in a multi-terrain virtual environment and examined gait differences between fixed and self-paced treadmill speed conditions. They have covered methods used within this research such as, demographics of Subjects, equipment used within the work, Virtual environment of a simulated pathway through a park-like virtual scene which had eight walking activities followed by Data analysis and Statistical analyses using R Version 2.14.2 using the lmer4 package. Further, Pavlović et al. [23] exhibited using of a Computer Aided Design software to facilitate designing of modern mechatronical (technology combining electronics & mechanical engineering) medical devices on an example of an instance of an infinite belt-Treadmill. In [24], Lee et al. suggested a novel design of Omni-directional treadmill. Their proposed system was simpler, lightweight and produced a high-power transmission efficiency based on suggested Omni-pulley mechanism. This work claimed to be different from conventional VR interface devices which provided only vision or tactile which opened its application in new locomotion interface devices to apply exercises of VE such as military training, games and gait rehabilitation.

2.1.4 International Space Station exercise countermeasures system

Due to long stays in International Space Station (ISS), astronauts face health issues. To overcome this problem, NASA pushes its astronauts to involve themselves in regular exercise. Moore et al. [16] presented a review about failure history for three countermeasure systems with the aim of recognizing lessons cultured that could help ameliorate future systems. They mainly focused on the Treadmill with Vibration Isolation and Stabilization System (TVIS), Cycle Ergometer with Vibration Isolation and Stabilization System (CEVIS), and the Advanced Resistive Exercise Device (ARED) was examined and evaluated with the hope of polishing future exercise hardware designs. Loehr et al. [17] kept their evaluation in twofold; firstly, to examine whether a slick-plate/contingency exercise surface (CES) could be helpful as a walking/running surface and could extract a heart rate >= 70% HR maximum and secondly, to determine the optimal hardware configuration, in microgravity, to simulate running/walking in a 1-g environment. They have explained the method opted for Slick Surface Evaluation and Slick Surface Configuration followed by results and discussion which concluded that CES could be utilized as a contingency countermeasure device in the following configuration: aluminium plate coated with Tufram, with the SPDs, booties worn over shoes, and the use of a handrail for stabilization. Moore et al. [18] examined the on-orbit understanding of ropes and cables in several exercise devices and explored the lessons learned from these hardware items, with the target of notifying future system design.

2.2 PROBLEM STATEMENT

Virtual Prototyping based approaches have become more widely used in industry today. The design of VR based digital mockups continues to be a complex process. With the advent of powerful information analytics and visualization methods, the creation of the Next Generation of integrated Virtual Prototyping and Visualization Analysis methods is possible.

In this context, there is a need to investigate the design of VR based approaches on different setups by considering human factors for validation.

2.3 RESEARCH OBJECTIVE

To explore a Virtual Assembly approach for different setups and study the user performance on assembly activities. We validate this approach using the process of the assembling of treadmills on immersive and non-immersive virtual reality system.

2.4 METHODOLOGY

2.4.1 TOOLS USED FOR VIRTUAL ENVIRONMENT

This part of chapter will cover the software used for creating Virtual Environment. Hu and Zhang [33] presented an advanced method of building virtual assembly applications, which took benefit of 3D game engine, and employed software component technique to construct a reusable component library. They briefly explained various advantages of using Unity 3D over traditional methods to build virtual environment. In this research task, Unity 3D is used for both the systems non-immersive & immersive virtual reality system. SOLIDWORKS is used for creating GameObjects which is deployed in our Virtual Environment.

2.4.1.1 NON-IMMERSIVE

In computer based simulation, mouse and keyboard are used to perform manual assembly along with a bunch of scripting in C#. To move a GameObject, user must click on it (Note: Add collider to make it clickable). Mouse click will trigger a C# script which will activate the script for manual assembly. In figure 1, we can see the keyboard controls used for manual assembly.

Figure 1: Keyboard usage for manual assembly

In figure 2, we can see the C# script which shows the functionalities assigned to controller. After the activation of manual assembly script, we can drag our interactable gameobject using keyboard and mouse as per above figure of "Keyboard usage of manual assembly" (refer figure 1). As soon as, this gameobject comes near its final position it will be captured automatically to the target location.

```
// Update is called once per frame
void Update () {
    float x = Input.GetAxis ("Mouse X");          // To mouse along z-axis using mouse
    float kx = Input.GetAxis ("Horizontal");      // To move back and forth
    float ky = Input.GetAxis ("Vertical");        // To move up & down

    transform.Translate (kx * Time.deltaTime, ky * Time.deltaTime, x * Time.deltaTime, Space.World);

    // This code will activate the snap drop zone for manual assembly using keyboard & Mouse
    if (Mathf.Abs(transform.position.x - gm.transform.position.x)< 0.4
        && Mathf.Abs(transform.position.y - gm.transform.position.y) < 0.4
        && Mathf.Abs(transform.position.z - gm.transform.position.z) < 0.4) {
        InvokeRepeating ("SnapIntoPlace", 0, 0.0001f);
    }
    else if (Mathf.Abs(transform.position.x - gm.transform.position.x) < 0.42
        && Mathf.Abs(transform.position.y - gm.transform.position.y) < 0.42
        && Mathf.Abs(transform.position.z - gm.transform.position.z) < 0.42)
    {
            gmChild.GetComponent<Renderer>().enabled = true;
    }
    else
    {
            gmChild.GetComponent<Renderer>().enabled = false;
    }
}

void SnapIntoPlace() {
    transform.position = Vector3.MoveTowards (transform.position, gm.transform.position, speed * Time.deltaTime);
    gmChild.GetComponent<Renderer>().enabled = false;
}

}
```

Figure 2: Code snippet of Manual Assembly C# script

In figure 3, we can see a user performing manual assembly using mouse and keyboard in non-immersive virtual assembly.

Figure 3: Non-Immersive Virtual Reality System (Computer Based Simulation) with its components

2.4.1.2 IMMERSIVE

HTC VIVE headset and controllers are used to perform Manual assembly in immersive environment. To run Unity 3D project for VIVE, Virtual Reality ToolKit (VRTK) needs to be imported in the Unity project, which is a collection of useful scripts and concepts to facilitate various solutions related to ease building of VR solutions. VRTK[1] provides facilities like movement within virtual space, interactions like touching, grabbing and using objects and body physics within virtual space such as, gravity and kinematics. STEAMVR[2] Unity asset needs to be imported within Unity 3D Project as, VRTK requires a supported VR SDK.

Figure 4: Fully Immersive Virtual Reality System (VIVE) with its components

[1] https://vrtoolkit.readme.io/docs/getting-started
[2] http://russellsoftworks.com/blog/steamvr_01/#setup

VRTK helps to touch and grab an interactable object within virtual space. If a user with controllers touch an interactable object then, the object color will turn into green which indicates that we can grab it using controllers shown in figure 5.

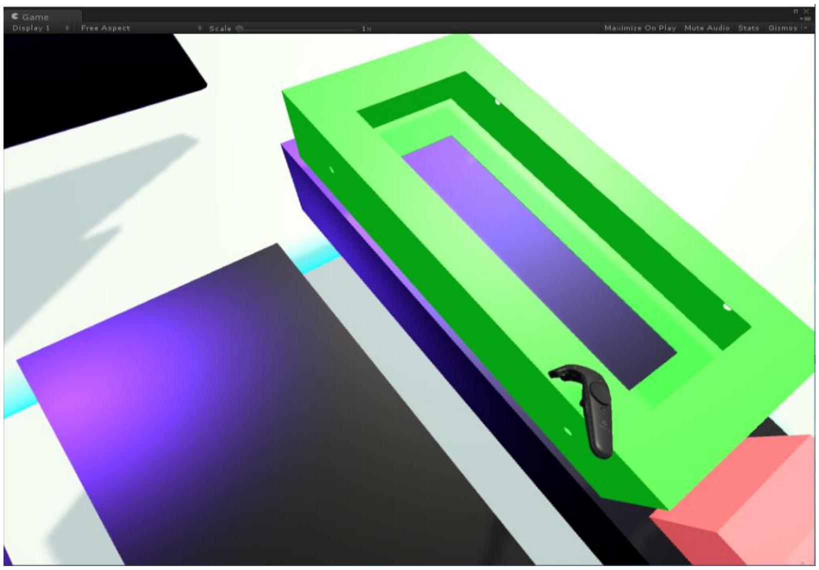

Figure 5: GameObject color turning green as soon as Controller touches the gameobject

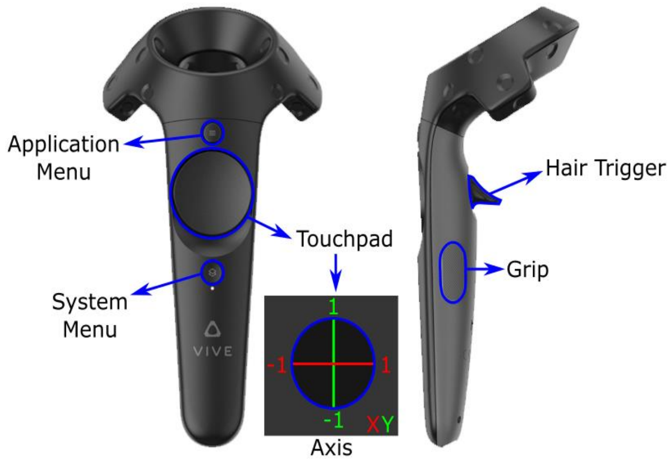

Figure 6: Handling input for VIVE using HTC controllers

To grab an interactable gameobject, user must move the controllers (refer figure 6) onto the gameobject until it finds the collider associated with it (interactable GameObject). GameObject will change its color (if applied by user) as soon as, controller finds its collider which will be an indication to the user that he/she can grab it. For manual assembly, we need a setup of a predefined zone where an existing interactable object can be dropped and upon dropping it snaps to the set snap drop zone transform position, rotation and scale. SnapDropZone[3] Game Object finds utilization in determining the target position of the dropped interactable object if it is unhanded within the drop zone collider range.

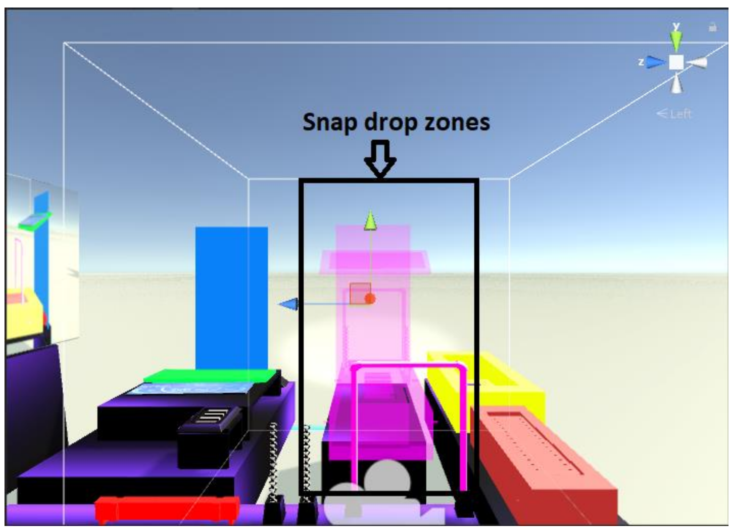

Figure 7: SnapDropZone GameObjects for Treadmill assembly

Snap drop zone is indicated with pink color (refer figure 8). So, whenever, we take our grabbed gameobject near snap drop zone it will be highlighted as in figure 8 which indicates that we can drop our gameobject.

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[3] https://vrtoolkit.readme.io/docs/snap-drop-zone

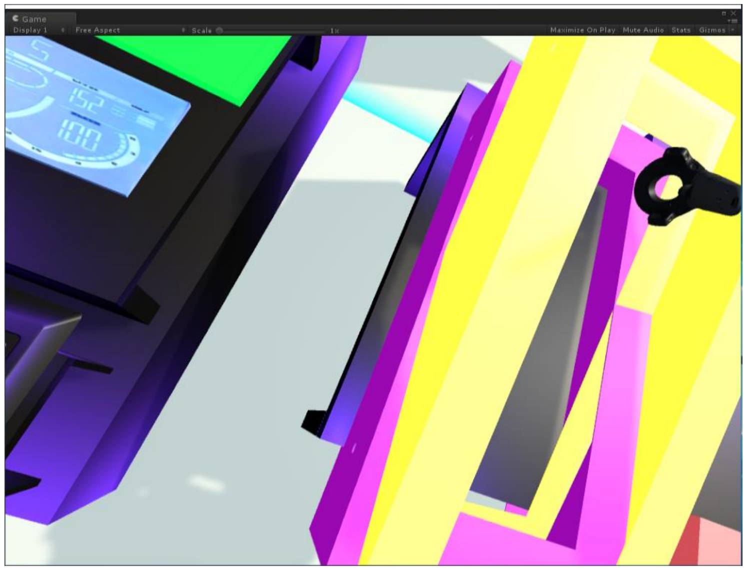


Figure 8: Pink color indicates the snap drop zone for housing (Yellow Object)

2.5 DATA COLLECTION

Data collection is performed by capturing data from user survey performed on immersive and non-immersive virtual reality system with text or image cue. Ten users were asked to go through the survey in which they were asked to perform manual assembly on HTC VIVE and desktop monitor. Each user was requested to show up for two days. The user study was divided into four distinct parts for each subject in which they did assembly: a) Immersive with text cue, b) Immersive with image cue, c) Non-immersive with text cue, d) Non-immersive with image cue. On the first day, he/she performed manual assembly on HTC VIVE using text or image cue followed by performing assembly on desktop using image cue if he/she performed assembly on VIVE with text cue. Similarly, if user performed assembly on HTC VIVE with image cue (refer figure 29) then, he/she did assembly on desktop using text cue. Following day, user accomplished

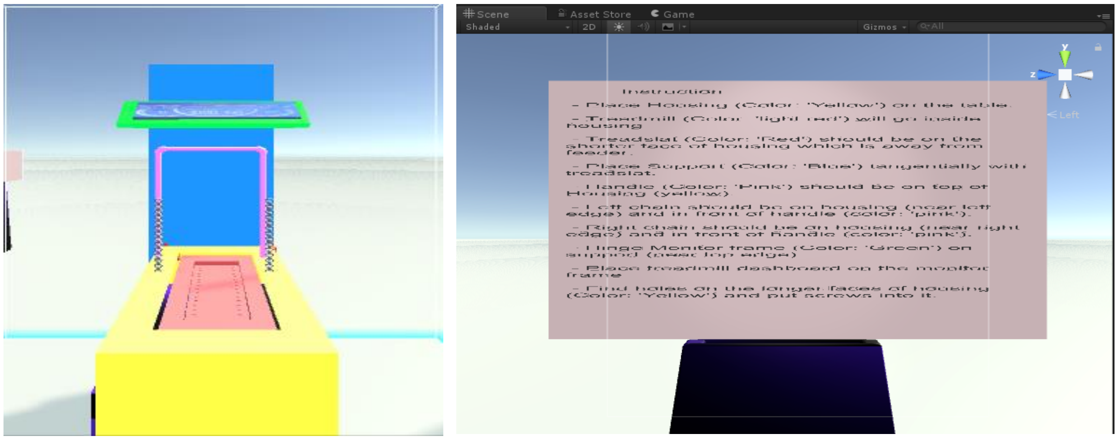


Figure 9: (Left Side) Image cue: This image will show the assembled parts of treadmill in both immersive & non-immersive VR System
(Right Side) Text cue: This blurred image shows text cue in immersive VR System (its visibility is clear in immersive)

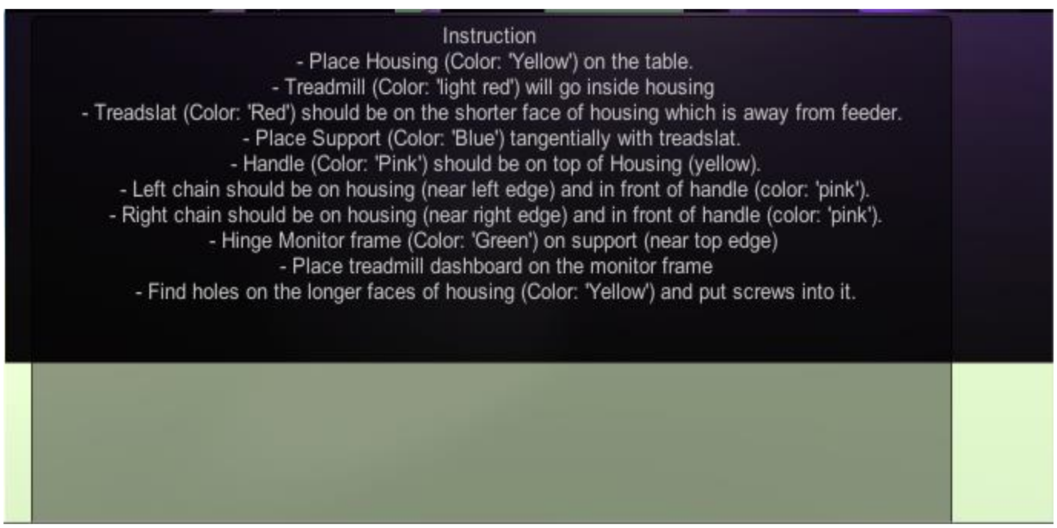


Figure 10: Text cue: This is used in non-immersive VR system

remaining parts for the user study.

2.6 DATA PREPROCESSING

From the Microsoft excel worksheet, user details, time taken, complexity of tasks and degree of correctness which were captured during user study are retrieved for further processing. This data is retrieved using PHP which was further utilized by JavaScript & D3.js to create various visualization methods.

2.7 HYPOTHESIS

In this research work, our analysis goals were to compare the user performance in immersive virtual reality system with non-immersive virtual reality system (2D screen) using text or image cue. Immersive virtual reality systems allow users to experience three-dimensional computer graphics applications from a first-person perspective and to interact using natural techniques with the help of controllers and HTC headset. Therefore, we can assert that immersive will give better performance in terms of correctness and time. Hence, we formulated our first hypothesis as:

H1: Using immersive virtual reality system will improve performance with respect to time and correctness in comparison with non-immersive virtual reality system.

Secondly, as images give a better understanding of instructions as compare to text. Therefore, we can come up with the statement that user performance in virtual reality system can be improve by using image cues instead of text. Hence, our next hypothesis will go like this:

H2: Image clue has statistically considerable influence on user performance as compare to text instructions.

We have developed our visualization tool to be able to investigate our formulated hypotheses. The description about visualization tool is described in Chapter 3 and the results that investigate the hypotheses are described in Chapter 4.

2.8 SUMMARY

This chapter covered topics related to virtual reality in which we went through literature review followed by identifying the problem statement which leads to the research objective. Within this section, we covered methodology which discussed about setups along with various software details being used for immersive and non-immersive. At the end, we formulated two hypothesis which will be answered by using interactive visualization tool developed in this research work.

In this research work, I have used Unity 3D with C# scripts along with VRTK plugins for creating virtual environment. For building interactive data visualization tool, I have used d3.js, HTML, css, JavaScript, jQuery and PHP.

CHAPTER III

INTERACTIVE VISUALIZATION APPROACHES

3.1 LITERATURE REVIEW

Data visualization helps people to understand the importance of data by portraying it in a visual setting as, text-based data can overlook patterns, trends and correlations. Ltifi et al. [1] categorized various information visualization techniques which have been developed to visualize large data sets. They classified visualization techniques into two groups: a) technical approach (oriented data structures) which consists of linear data [timelines], multidimensional data [Scatterplots], hierarchies [chord diagrams], networks and vectoral models. b) Interactive approaches (oriented user): approaches based on similarities and relevance. Blascheck et al. [2] provided an in-depth survey of visualization techniques for eye tracking. They presented an overview of visualization techniques for eye tracking data and described their functionality. They classified the visualization techniques using nine categories based on properties of eye tracking data, which included aspects of the stimuli and the viewer, and on properties of the visualization techniques. The survey illustrated various visualization approaches for eye-tracking data. In [3] Jalali focused on usage of Chord diagrams to enhance the level of abstraction when visualizing dense social networks in business processes.

The outcome displays a significant advantage of boosting the capability of people to discover more aspects of social networks in BPM area. He used interactive technique of chord diagrams to demonstrate social networks in Business Process Management. Scatter plots show how much one factor is influenced by another. Further, Etemadpour et al. [6] presented a direction for visualization designers who want to choose appropriate techniques for enhancing tasks involving multidimensional projection. They depicted real-world examples to display effective choices made while handling complex datasets requiring dimensionality reduction. A small set of variables may result into many scatterplots. Consequently, Scatterplot matrices (SPLOMs) can easily run out of pixels when presenting high-dimensional data. In [8] Dang et al. introduced a theoretical method and a testbed for assessing whether their approach can be useful to guide interactive exploration of high-dimensional data. Their testbed, ScagExplorer (name), which was developed to examine the expediency of handling huge collections of scatterplots.

There are various visualization tools created within last few years to enhance users understanding. Satyanarayan et al. [4] built Vega-lite, a high-level grammar which permit rapid specification of interactive data visualizations. It combines a traditional grammar of graphics, automatically producing visualization components including axes, legends and scales. It facilitates rapid exploration of design variations. The developers framed a tool which can pull comma separated values or JavaScript Object Notation (JSON) data to describe visualizations as mappings from data to properties of graphical marks like points or bars. Vaishnavi et al. [5] suggested a web based interface approach that visualizes various statistical tests and displays the distributions of data using color coding schemes. Saket et al. [7] presented VisExempler, a mixed-initiative prototype to show the feasibility of Visualization by Demonstration. The concept of Visualization by Demonstration does not require users to specify visualization techniques ahead of time. Instead, the paradigm will extract the visualization technique from the given demonstrations. In addition, the paradigm also extracts visualization mappings and parameters that match given demonstrations. The system recommends potential transformations (visual representation, data mapping, axes, and view specification transformations) from the given demonstrations. Kim et al. [10] introduced interAxis, a visual analytics technique to appropriately interpret, define, and change an axis in a user-driven manner. In this paper, they described (a) the overall design of the proposed visual analytics system, (b) the proposed interaction to steer the axis in a user-driven manner, (c) the underlying mathematical details to support the proposed user interaction, (d) the design rationale, and (e) the implementation details of the proposed system. Design study of LiteVis is explained in [38], it's a system for efficient decision support in lighting design. LiteVis closely combines global illumination-based lighting simulation, a spatial representation of the scene, and non-spatial visualizations of parameters and result indicators. This enables an efficient iterative cycle of simulation parametrization and analysis.

3.2 PROBLEM STATEMENT

Visualization techniques can be employed over statistical analysis to decipher and act on the gathered information from survey as, these graphical representations can convey complex ideas with clarity, precision, efficiency [5]. Visualization approaches are an effective way to access, evaluate, comprehend, explore and communicate data. The human visual system is high-bandwidth channel to brain. It can ease the efforts to see connections between multidimensional data sets which can be interpreted in the form of scatterplot.

There is a need to investigate the design of VR based approaches along with integrating such an approach with information analytical methods. This research seeks to address this problem in an integrated manner.

3.3 RESEARCH OBJECTIVE

To develop an interactive visualization tool for analyzing the users' performance. This information-analytical approach helps us to find the best possible setup and show the intrinsic statistical relationships between/within distinct groups of participants.

3.4 METHODOLOGY

This section includes the tools used for this research work.

3.4.1 TOOLS USED FOR BUILDING VISUALIZATION

Data-Driven Documents (D3) [52] is a JavaScript library for building interactive data visualizations for web. D3 allows to bind arbitrary data to a Document Object Model, and then employ data-driven transformations to the document. They illustrated various tools and coding parameters performed within/using D3. Authors provided the comparison with the existing tools. Due to faster page loads, supporting large datasets and dynamic behaviors for interaction and animation we are using D3 to sketch various data visualization methods.

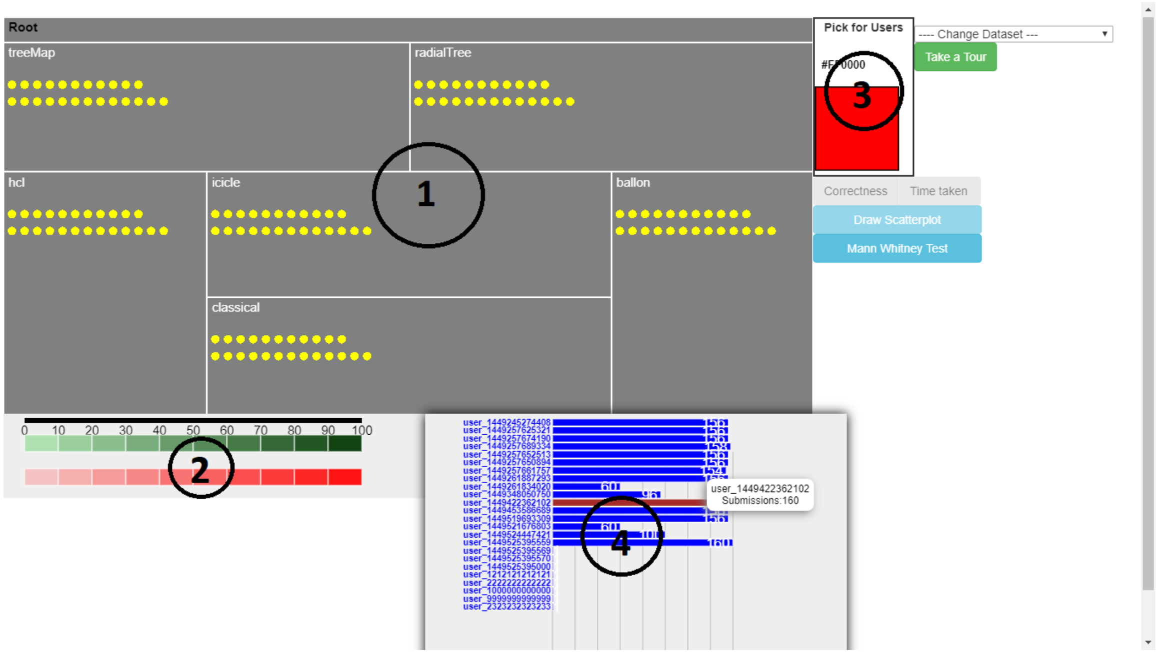


Figure 11: (Window 1): Data Visualization tool created in this research work

It is an interactive visual analysis tool for user survey data. Figure 11 shows the composition of different views within a window. This tool is composed of Treemap (refer section 3.4.1.1) which shows the correctness of each layout and shows the time taken to complete the tasks for the layout with respect to the maximum. User needs to mouseover the bars marked by “2” in figure 11. By clicking on any layout, a user can see the complexity of each subtask (refer section 3.4.1.1). In Figure 11, bar chart is marked with “4” which shows the count of submissions by individual users. If a user selects a bar from bar chart (refer section 3.4.1.3) then, he/she can change the color of bar using color picker which is marked by “3” in figure 11. Using this color picking feature, a user can be spotted in treemap (marked by “1” in figure 11) and simultaneously, it can be spotted in scatterplot (marked by “1” in figure 12).

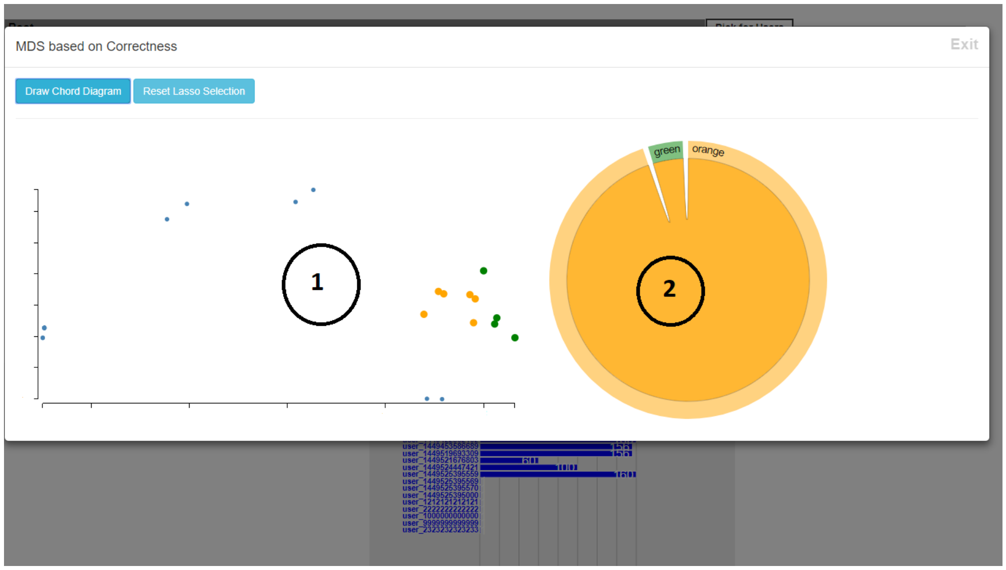


Figure 12: (Window 2): Data Visualization tool created in this research work

Four views have been employed, each view has certain aspect of the user survey data. In this interactive tool, all interaction operations on one view will be reflected in the other views as well. In addition, user can apply various interactive features such as, brushing (Lasso selection), zoom in & out, picking color and selection. This section will further highlight all the approaches which are used in this tool.

3.4.1.1 ZOOMABLE TREEMAP

Johnson, B. and Shneiderman, B. [54] found an approach for the visualization of hierarchically structured information. Treemaps are a form of space-filling layout where the area of each rectangle is proportional to its value. They divide the display space into a collection of rectangular bounding boxes showing the tree structure. These are ideal for displaying huge amount of hierarchically structured (tree-structured) data. The way rectangles are divided and ordered into sub-rectangles is dependent on the tiling algorithm such as, Squarified algorithm [55] which makes each rectangle as square as possible. In figure 13, we can see an example of tree map [4] with the description of hierarchy in the form of tree.

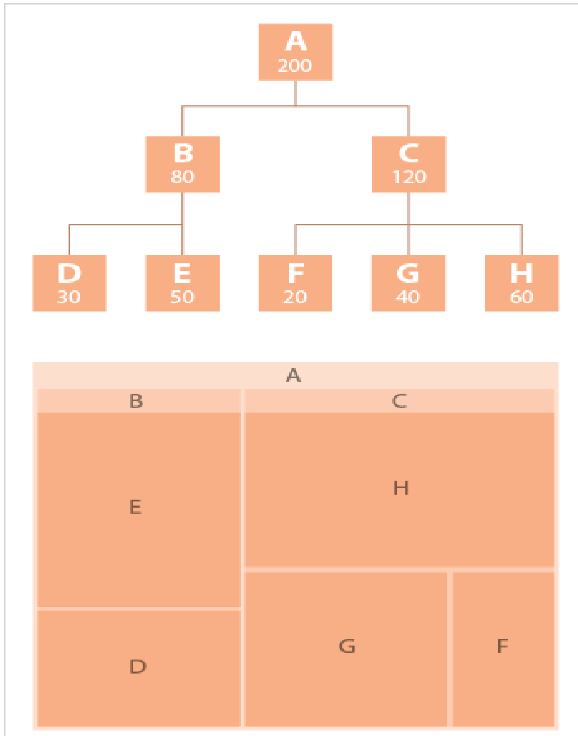


Figure 13: Treemap: An approach to show hierarchical data

Click to zoom to the next level. Click on the top light grey band to zoom out. This is highly influenced by Mike Bostock's Zoomable Treemaps[5]. In this treemap, the test data which has been used to build our visualization tool was collected from a user study done by Dang et al. [53] that studies the performance of users in terms of correctness and time when they explored six different tree layouts. The layouts are better illustrative of examples of trees with various features, node-link relationships, shape preservation, parent-child centering, and bundling angularity. Twenty-four users were subjected to answer quantitative questions with different complexities for all the layouts.

[4] http://www.datavizcatalogue.com/methods/treemap.html
[5] https://bost.ocks.org/mike/treemap/

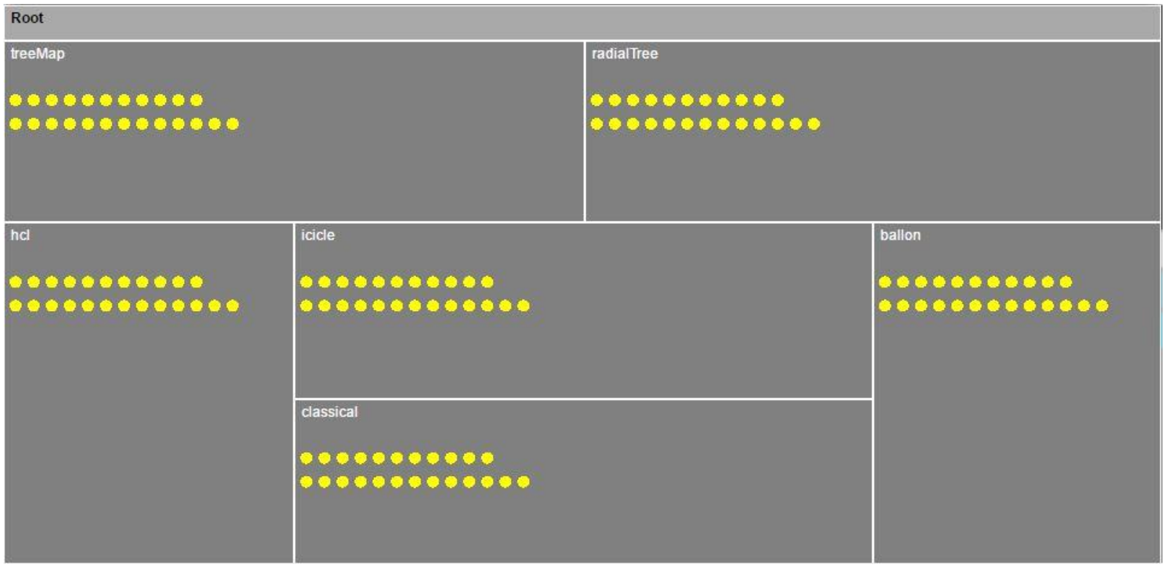


Figure 14: Zoomable tree map with circles showing users

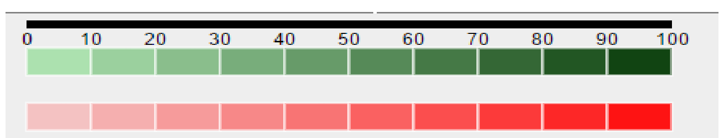


Figure 15: Mouse over on these bars to know the correctness and time taken for each layout

Three things can be concluded by observing zoomable tree map:

1. Correctness (refer figure 16): If a user, mouse over on the green bars (refer Figure 15) then, he/she can see the percentage of correct answers submitted by users for a layout. This approach will help a user (who will use this visualization approach) to identify the layout which is suitable to get the maximum correct responses.

Figure 16: Treemap showing the percentage of correct answers submitted for the layouts

Table 1 describes the results and it also interpret the usage of green color in figure 16. In this approach, if the rectangular portion is darker than the other rectangular portion then, it means that the correctness rate is higher for the darker portion as compare to the lighter one. In the above figure, a user can conclude that “hcl” will be the best possible layout to get the maximum correctness.

<table>
<tr><th>Name of the layout</th><th>Color</th><th>Interpretation of Correctness</th></tr>
<tr><td>treeMap</td><td>Light green</td><td>60-70%</td></tr>
<tr><td>ballon</td><td>Low Medium green</td><td>70-80%</td></tr>
<tr><td>radialTree</td><td rowspan="3">Medium green</td><td rowspan="3">80-90%</td></tr>
<tr><td>Icicle</td></tr>
<tr><td>classical</td></tr>
<tr><td>hcl</td><td>Dark green</td><td>90% +</td></tr>
</table>

Table 1: Interpreting the results of figure 16. Correctness

2. Time taken (refer figure 17): If a user, mouse over on the red bars then, he/she can see the percentile (ranging from minimum value to maximum value) of time taken to submit tasks by users for a layout. If a layout has dark red color then, it means the layout has more time-consuming tasks as compare to the layout which has a bright color.

Figure 17 Tree map showing the percentile of time taken to submit surveys for the layouts

In figure 17, a user can see different shades of red color which is interpreted in table 2. This table concluded that "hcl" has tasks which are less time consuming as, this layout has the lightest shade of red color whereas, "radialTree" has time consuming tasks as, this rectangular node is filled with dark red color.

Name of layout	**Color**	**Interpretation of Result**
Hcl	Light red	Least time needed
Icicle	Slightly darker than light red	
Ballon	Medium red	
Classical	Medium red	
treeMap	Slightly lighter than dark red	
RadialTree	Dark red	Most time consuming

Table 2: Interpreting the results of figure 17. Time

3. Complexity: User can see the complexity of all sub-tasks within the layout by clicking it. If the sub-tasks are light blue (sky blue) then, it falls under "easy" category whereas, if the color of sub-task is dark blue (sky blue) then, it can be concluded that the sub-task is complex.

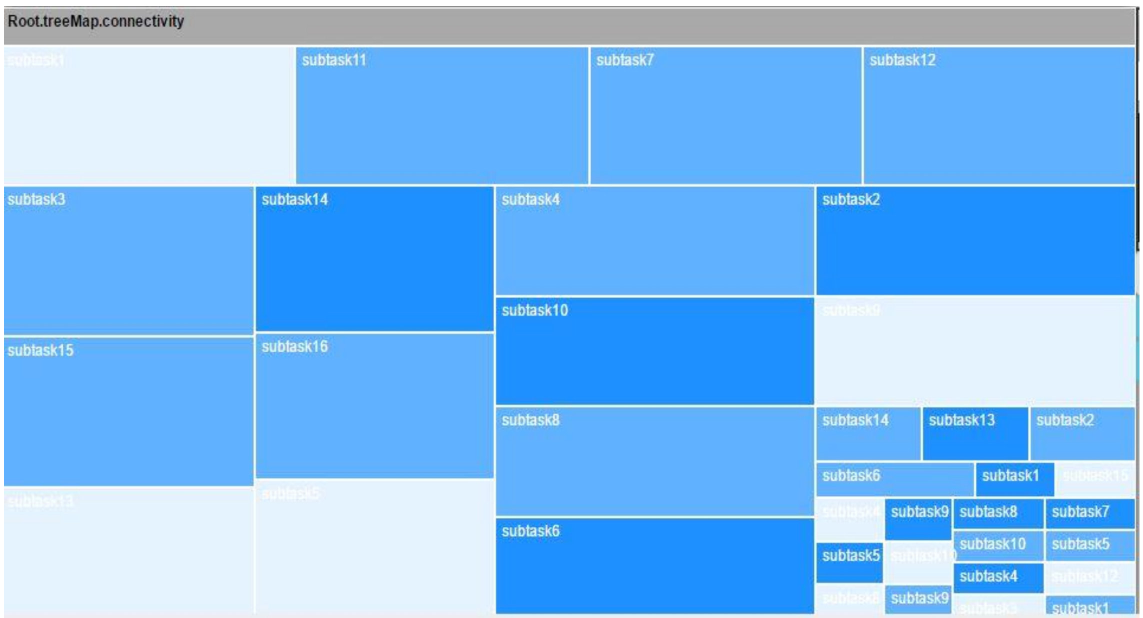


Figure 18 Zoomable Tree map showing the complexity of each sub-task within a layout (treeMap)

In figure 18, a user can see three different shades of blue color which indicates the level of complexity. A user can conclude that subtasks (Rectangular node) which are filled with light blue color are easiest in the difficulty level such as, subtask1 whereas, subtasks which are colored with dark blue are the most complex subtasks such as, subtask10.

3.4.1.2 MULTIDIMENSIONAL SCALING (MDS)

Multidimensional multivariate data can be described like [57], in which a set of observations S, where, the *i*th element S_i consists of a vector with n variables, $S_i = (S_{i1}…., S_{in})$. Multidimensional variables are those variables which are independent. In this research work, variables are independent of each other so, they can be termed as multidimensional data. We have two categories for multidimensional data where, first one has dataset from attribute for correctness and second consists of dataset from attribute with time. In figure 11, a user can see that there are six layouts which consist of many users. Suppose, we have n users who participated in the study whose submissions can be represented as a set of responses U, where, the jth user's response U_j consists of a vector with m variables which represents m sub-tasks performed by the user, Uj = $(U_{1j}, U_{2j}…...U_{mj})$.

In multiple dimensions, it's difficult to visualize them with an orthogonal visual structure as, it will be insufficient to do it. Therefore, Geometric projection techniques are used to visualize high number of dimensions. There are many visualization techniques which fall under this category such as, parallel coordinates and scatterplot matrices. Parallel coordinates are introduced by Inselberg [58], which is based on a system of parallel coordinates (refer figure 19) which induces a non-projective mapping between N-Dimensional and two-dimensional sets. Apart from parallel

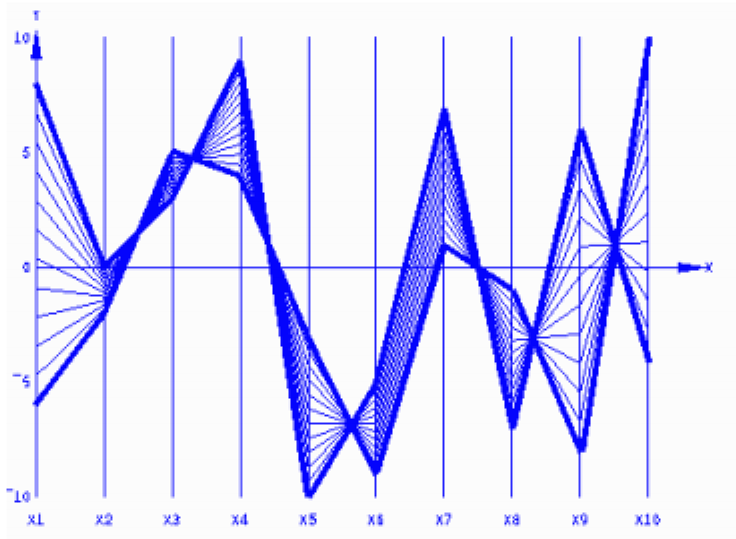


Figure 19: Parallel coordinates by Inselberg [58] display an interval of a line in R10

:

Coordinates, scatterplot matrix is considered as another visualization technique for multi-dimensional multivariate data. It presents all combination pairs of all dimensions and arrange them by a matrix [59]. In this visualization technique, each dimension is treated uniquely which can be seen in figure 20.

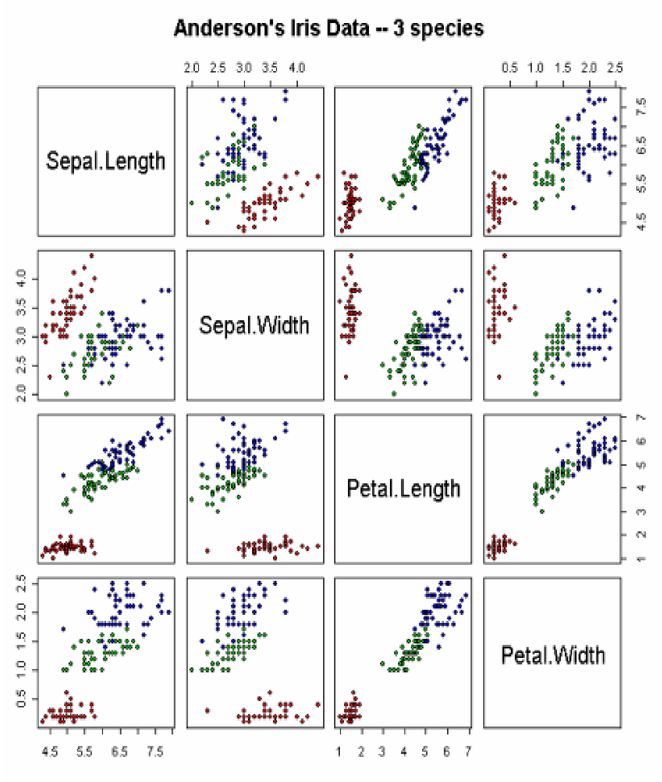


Figure 20: Scatterplot matrices [59]

Multidimensional scaling is an approach to visualize the degree of similarity of discrete cases of a dataset. This algorithm sights to position each object in multi-dimensional space so that similarities are preserved as much as possible from higher dimension to lower dimension. According to Davison [50], classical MDS is computed based on the results of Euclidean distance matrix. Using the Krislock et al. [51], Euclidean distance can be calculated based on the below formula.

$$d = \sqrt{\sum_{i=1}^{v} (p_{1i} - p_{2i})^2}$$

Figure 21: Formula for calculating Euclidean Distance

Where, the difference between two samples' scores is considered as inputs, and squared, and summed for v variables.

```
function findEuclideanDistance(x,y)   // where, x and y are two arrays
 {
 var euclideanDistance = 0;           // It will store the result
   for(var i=0;i<x.length;i++)
    {
     euclideanDistance = euclideanDistance + ((x[i] - y[i]) * (x[i] - y[i]));
    }
   return Math.round(Math.sqrt(euclideanDistance) * 100)/100;
 }
```

Figure 22: Code snippet for calculating Euclidian distance

In figure 22, x and y denote the multidimensional data which are the responses submitted by users. These multidimensional data can either be values of correctness or time taken for each sub-task by a user as explained earlier in this section. In figure 23, a user can observe that there are few data points which are stick together or close to each other which illustrates that considering all the tasks on the selected layouts, their performance is more similar. No labels are displayed for x- & y-axis as, these co-ordinates formed by using Euclidean distance and Multidimensional scaling results with no units.

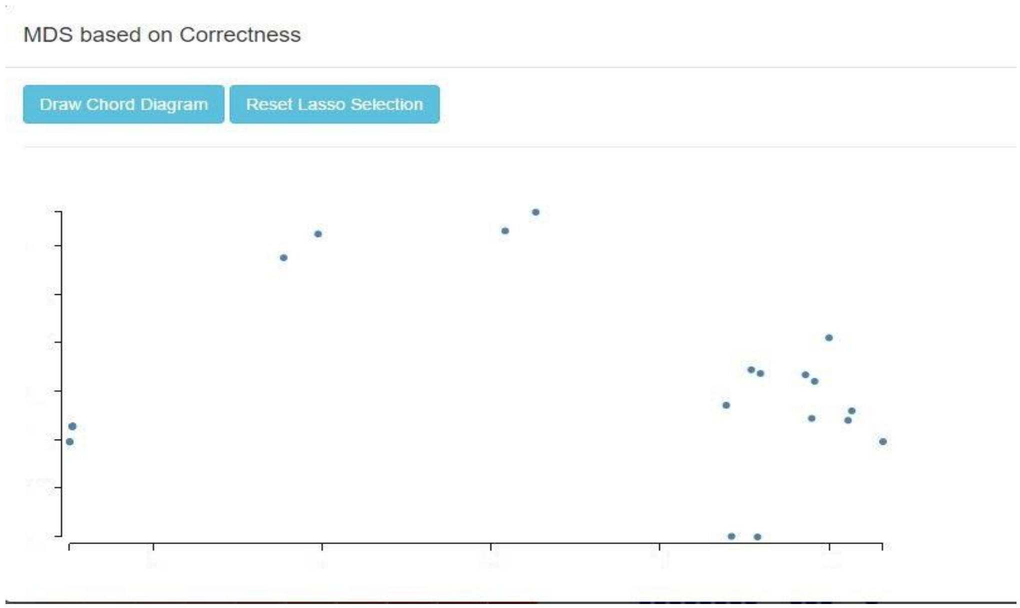


Figure 23: Scatterplot created from Multi-Dimensional Scaling after selecting layouts from treemap. These data points represent users' correctness value

3.4.1.3 BAR CHART

This horizontal bar chart presents grouped data with rectangular bars with lengths proportional to the values that correspond to them. In figure 24, each rectangle shows the number of surveys submitted by individual user. If length of the rectangular bar is larger than the other then, it can be concluded that larger ones' value is greater than the smaller one. These bars have clickable property which allow them to change color using color picker. This property helps in spotting user details from scatterplot and tree map. In figure 24, a user can also see the count of submissions as selective tooltip. In figure 11, a user can see the position of this bar chart.

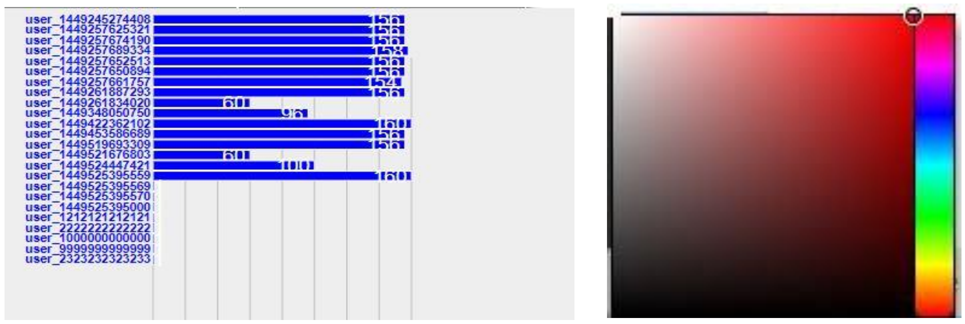


Figure 24: (Left hand side) Horizontal Bar chart illustrating number of surveys submitted by users, where, length of horizontal bar is directly proportional to its value (Number of surveys submitted)
(Right hand side) Color picker

3.4.1.4 USING LASSO SELECTION

This functionality is implemented with the help of lasso.js (D3 plugin) which allows user to tag elements on the SVG canvas by sketching a line over or around objects (refer figure 25). In this work, multiple lasso selections can perform which will lead to distinct groups formed by unique colors. This will help in spotting users (circles) of a group. This property of illustrating various groups with unique colors find use in identifying groups in the chord diagram. In this visualization tool, chord diagram is created based on Lasso selection where, each arc will correspond to the groups formed by multiple lasso selections. In figure 25, data points which are marked as “possible” will get selected whereas, “not possible” marked data points will remain as it is.

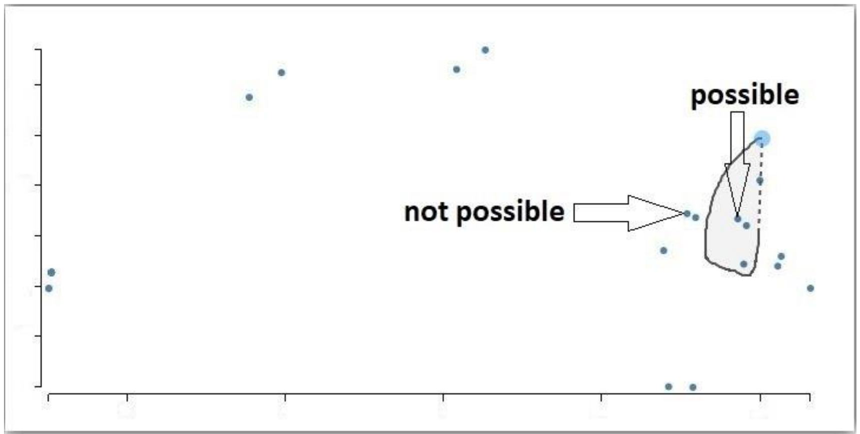


Figure 25: Lasso Functionality

In figure 26, we have a code snippet which shows that a function will be called as soon as, lasso ends. This function "selectForPValues()" (refer figure 27) will allow to change the color of

```
var lassoEnd = function(){
    //reset color of dots
    //style the selected dots
    lasso.items()
        .filter(function(d){return d.selected === true;})
        .classed({"not_possible" : false , "possible" : false,"selected" :true})
        .attr("r" , 5);

    //reset the style of not selcted dots
    lasso.items().filter(function(d){
        return d.selected === false;
    })
    .classed({"not_possible" : false , "possible" : false});

    // To call a function which will fill the color for selected circles
    selectForPValues();

};//end of lasso end
```

Figure 26: Code for calling function to create diverse groups formed by Lasso Selections

selected circles using lasso on each selection which means if a user perform lasso selection for the first time then, after lasso selection all selected data points will be filled with orange color. Further, if a user perform lasso selection again then, it will provide a different color for the selected data points. These different colors on scatterplot will help in identifying the groups in the chord diagram.

```
var counter =0;

var colorFormed = new Array("orange","green","blue","yellow","black",
                    "pink","blueviolet","brown","chartreuse");

function selectForPValues()
  {
    var index = document.getElementsByClassName("selected").length;
    for(var i=0;i<index;i++)
     {
       textVar = document.getElementsByClassName("selected")[i].id;
       document.getElementById(textVar).setAttribute("class","selected "+ colorFormed[counter]);
                    // This will fill the color for selected circles (user)
       document.getElementById(textVar).style.fill = colorFormed[counter];
     }
    counter++;      // This will change the color on each selection
  }
```

Figure 27: Code snippet of implementing distinct groups from Lasso

3.4.1.5 CHORD DIAGRAM

This section is divided into two parts where, first part gives a description of chord diagram and its advantage to show relationship between two groups. Further, second part explains the Mann-Whitney test used to find the statistical relationship whose results will be utilize for sketching the chord diagram created in this tool.

a) Description of Chord diagram

Keahey T.A. [56] asserted that chord diagram is effective to reveal networks of relations between individuals or groups. The thickness of each chord is directly proportional to the extent of traffic between the groups that are placed around the circumference. Jalali [3] explained the components of chord diagram to visualize networks. A chord diagram consists of arcs and chords in figure 28, we can observe that each chord has two edges connecting two arcs. The length of the edges is based on the weight of arcs connecting these nodes to each other.

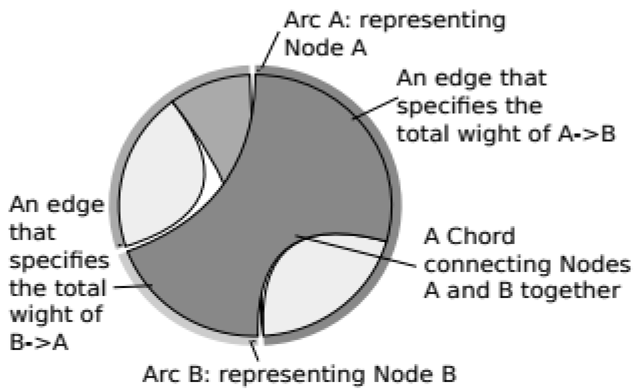


Figure 28: The structure of a chord diagram

These chord diagrams have three properties to help users to investigate relations easily as, it is difficult to identify them when there is a lot of chords in the network. Those properties are i) Interactivity, ii) Selective hints, and iii) colors.

b) Brief explanation of Statistical Relationship

In this research work, chord diagram is used to display the inter-relationships between data in a matrix which is created from values computed from Mann-Whitney test. According to Nadim [49], this statistical test can be used to compare two independent groups that don’t need large normally distributed samples. If the p-value is greater than 0.05 then, there will not be any direct connection between the two groups within the chord diagram as, it concludes that results were not statistically significant. In this tool, two chord diagrams are used for the following reasons:

i) To display relationship among layouts based on correctness and time taken,
ii) To show correlation among different user groups selected from Lasso selection.

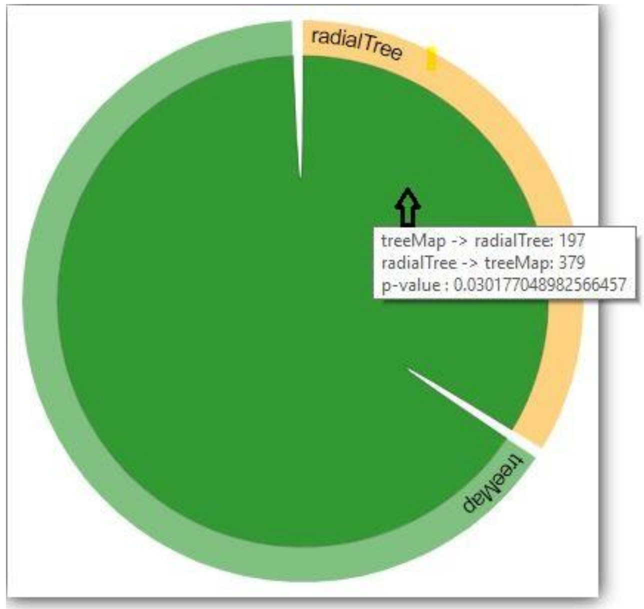


Figure 29: Chord diagram based on Mann-Whitney Test

Calculation of thickness for edges in chord: This is based on the values calculated using Mann-Whitney U test[6]. This test includes the calculation of a statistic, which is called U, whose distribution under the null hypothesis is known (Critical table for Mann-Whitney test).

$$U_1 = R_1 - \frac{n_1(n_1 + 1)}{2}$$

Figure 30: Formula for Calculating U in Mann-Whitney Test

In figure 30, n_1 is the sample size for sample 1, and R_1 is the sum of the ranks in sample 1. If the smallest U value among the pair is lesser than U critical value then, there will be a connection between the two in the chord diagram. The thickness of edge from source to destination within the chord diagram depends upon the U value. Suppose, there is a sample pair (1, 2) with U value = (U_1, U_2), $U_{min} = U_2$ and $U_{min} < U_{critical}$ then, sample 2 will have thicker edge

[6] https://en.wikipedia.org/wiki/Mann%E2%80%93Whitney_U_test

than sample 1 in sample1- sample2 connection within the chord diagram as, it has more significant impact on Mann-Whitney U test calculation. In figure 29, treeMap and radialTree are connected to each other because their p-value (0.03) is less than 0.05. In this chord, U value of treeMap is smaller than U value of radialTree which concludes that treeMap has more significant impact in Mann-Whitney U test therefore, edge from treeMap to radialTree is bigger than edge from radialTree to treeMap.

3.5 SUMMARY

This chapter described diverse topics related to interactive data visualization tool which is being used in this research work. This chapter deals with literature review which briefly summarized some related works done in data visualization subject. Further, we discussed about problem statement followed by research objective. Next, we had a brief explanation of Methodology which was about software being used to develop this novel interactive visualization tool.

CHAPTER IV

FINDINGS

This section deals with presenting results from user study conducted for virtual environment in immersive and non-immersive virtual reality system. In addition, this section will also interpret and conclude the user study using the visualization tools created within this research work.

4.1 SETUP FOR USER STUDY

User study was conducted for 10 users as discussed in the previous chapter. They were subjected to immersive (using HTC VIVE) and non-immersive (using Desktop) virtual reality systems with either image cue which will have two images (one with side view and other with front view) of the final assembled parts or text cue which will have instructions in the form of text. In table 3, users' assignment to different layouts has been mentioned which is divided into two parts (i.e., tasks for day 1 and day 2)

User IDs	Tasks for Day 1		Tasks for Day 2	
User_1	Immersive with text cue	Non-immersive with Image cue	Non-immersive with text cue	Immersive with Image cue
User_2	Immersive with Image cue	Non-immersive with text cue	Immersive with Text cue	Non-immersive with image cue
User_3	Non-immersive with text cue	Immersive with Image cue	Non-immersive with image cue	Immersive with text cue
User_4	Non-immersive with image cue	Immersive with text cue	Immersive with Image cue	Non-immersive with text cue
User_5	Immersive with text cue	Non-immersive with Image cue	Non-immersive with text cue	Immersive with Image cue
User_6	Immersive with Image cue	Non-immersive with text cue	Immersive with Text cue	Non-immersive with image cue
User_7	Non-immersive with text cue	Immersive with Image cue	Non-immersive with image cue	Immersive with text cue
User_8	Non-immersive with image cue	Immersive with text cue	Immersive with Image cue	Non-immersive with text cue
User_9	Immersive with text cue	Non-immersive with Image cue	Non-immersive with text cue	Immersive with Image cue
User_10	Non-immersive with text cue	Immersive with Image cue	Non-immersive with image cue	Immersive with text cue

Table 3: users' assignment to different layout

4.2 TASKS IN USER STUDY

This part of chapter will discuss about the collected data. Users were asked to perform manual assembly in immersive and non-immersive virtual reality system with the help provided in the form of text cue and image cue as discussed in the previous chapter. These tasks varies in complexity such as, performing manual assembly for small gameobject (like, screws) is difficult as compare to performing assembly for large gameobject (like housing) which can be seen in figure 31.

4.3 COMPUTATION OF CORRECTNESS

The sequence followed by users were compared with the optimized sequence generated from genetic algorithm for our virtual assembly. Genetic algorithm [7] (GA) uses the idea of evolutionary of the fittest chromosome. GA creates its answer using three biology approaches known as: a) selection, b) mutation, and c) crossover. This algorithm keeps on enhancing its answer based on the three approaches until a better answer outcome.

[7] http://mnemstudio.org/genetic-algorithms- algorithm.html

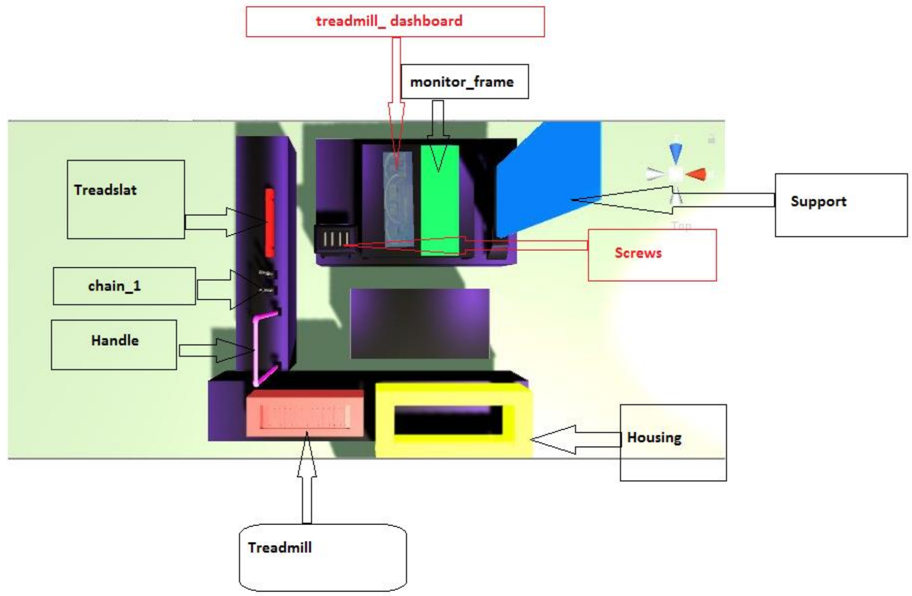


Figure 31: Top view of the virtual environment with labelled parts

In figure 32, we can see the nearest optimize sequence which was generated using Genetic algorithm for our assembly simulation in virtual environment.

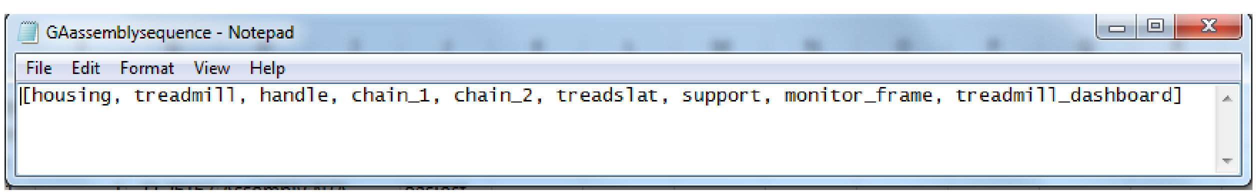


Figure 32: Optimized sequence generated using GA keeping precedence constraint

In this algorithm, screws were not included as inputs because they must be added at the end of the assembly sequence.

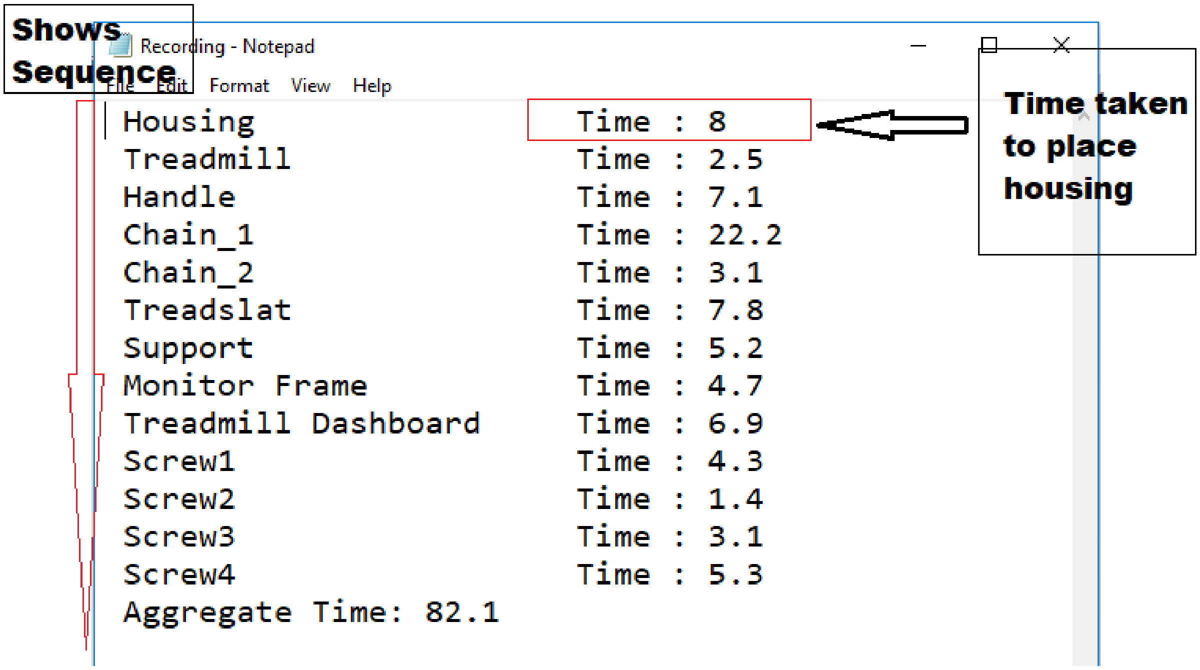
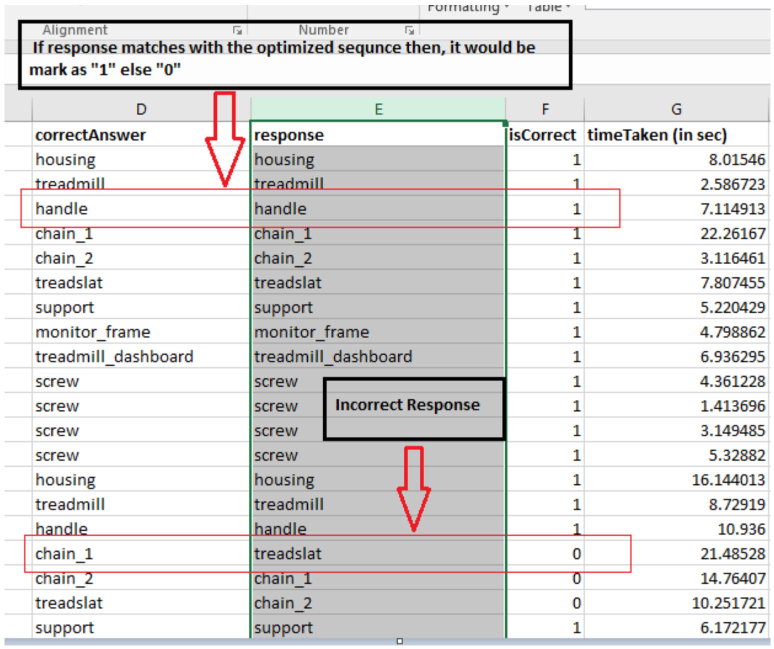


Figure 33: Data collection from user survey using C# script (Time in seconds)

In figure 33, user responses are captured sequentially along with the time elapsed to place the object at its destination. If the user responded sequence matches with the optimal sequence (GA optimal sequence) then, it would be mark with Boolean value as “1” (correct) else “0” (incorrect). Moving towards assigning the complexity for each task, it was found by user responses that placing small gameobjects such as, screws are more complex as compare to placing large gameobjects like, housing, treadmill, support etc. Figure 34 shows the calculation of correctness for user survey data.



If response matches with the optimized sequnce then, it would be mark as "1" else "0"

Incorrect Response

correctAnswer	response	isCorrect	timeTaken (in sec)
housing	housing	1	8.01546
treadmill	treadmill	1	2.586723
handle	handle	1	7.114913
chain_1	chain_1	1	22.26167
chain_2	chain_2	1	3.116461
treadslat	treadslat	1	7.807455
support	support	1	5.220429
monitor_frame	monitor_frame	1	4.798862
treadmill_dashboard	treadmill_dashboard	1	6.936295
screw	screw	1	4.361228
screw	screw	1	1.413696
screw	screw	1	3.149485
screw	screw	1	5.32882
housing	housing	1	16.144013
treadmill	treadmill	1	8.72919
handle	handle	1	10.936
chain_1	treadslat	0	21.48528
chain_2	chain_1	0	14.76407
treadslat	chain_2	0	10.251721
support	support	1	6.172177

Figure 34: Logic for finding correctness

4.4 HYPOTHESIS

We have formulated different hypothesis which are mentioned below:

H1a: Using immersive virtual reality (VR) system will improve performance with respect to time and correctness in comparison with non-immersive virtual reality system.

H1b: Using immersive virtual reality system with image cue will show better results in terms of performance as compare to non-immersive virtual reality system with image cue.

H1c: With the help of text cue in immersive VR system, we can achieve finer results as compare to using text cue in non-immersive VR system.

H2a: Image cue has statistically considerable influence on user performance as compare to text instructions.

H2b: Using image cue in immersive VR system can enhance user performance as compare to using text cue in non-immersive VR system.

H2c: With the help of image cue in non-immersive VR system can improve user performance as compare to using text cue in immersive VR system.

With the help of our interactive data visualization tool, these hypotheses are evaluated in section 4.6 which will conclude whether these can be accepted or rejected.

4.5 INTERPRETING RESULTS USING VISUALIZATION TOOLS

The purpose of this section is to draw conclusions and interpret the results using the visualization tool. Results can be interpreted using four views provided in the visualization (refer figure 35 & figure 36). Treemap (refer 4.5.1) will help a user to conclude which layout will be the best fit for the virtual assembly. Further, on click functionality of zoomable treemap will help a user to get the complexity level of each sub-task. This visualization tool also embeds bar chart which will give an overview of number of submissions by users in the user study.

Below link shows the Interactive Data Visualization tool created for this research work Link: http://cs.okstate.edu/~prated/visualizationToolVRUser.php

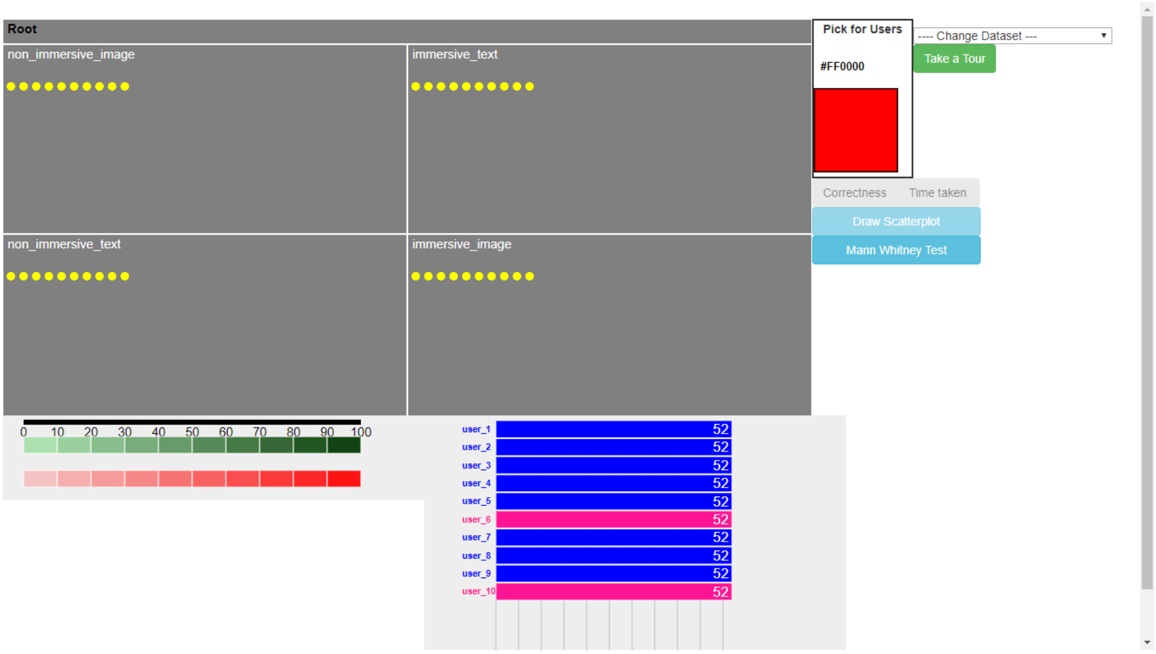


Figure 35:(Window 1) Data Visualization tool showing the results of our user study

In figure 36, a user can see scatterplot which shows the scaled overall performance of users in terms of either correctness or time taken. The highlighted green color data points are so close to each other which shows that their overall performance is close to each other.

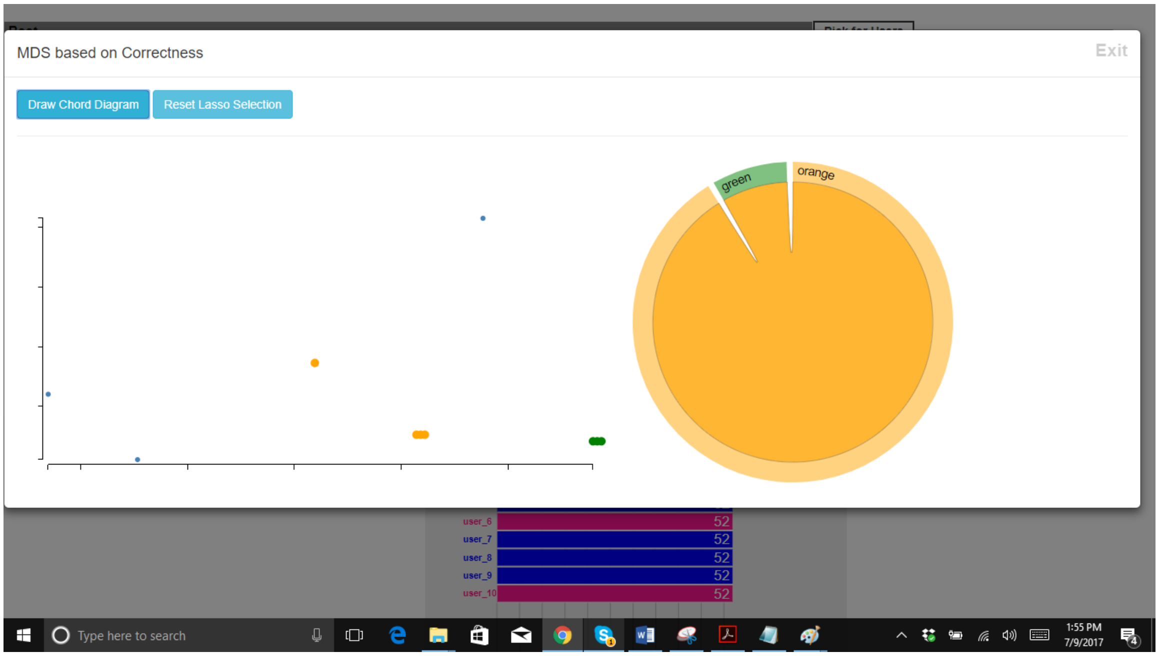


Figure 36: (Window 2) Data Visualization tool showing the results of our user study

4.5.1 VISUAL ANALYSIS USING TREEMAP

Zoomable tree map was built to fetch some significant visual information related to the user survey (input file: external csv file). User can understand the below mentioned information from zoomable treemap.

a) Number of users participated for a given layout.

b) Ratio of submissions for various layouts within a survey.

c) Complexity level of each task.

d) Percentage of correct answers given by users in a layout.

e) Percentile of average time taken to perform tasks for a layout.

1. Number of users participated for a given layout.

   From Zoomable treemap (refer 37), we can say that each layout has ten users which are represented by circles (yellow color).

Figure 37: Zoomable treemap showing users in the form of circles

2. Ratio of submissions for various layouts within a survey

In the treemap, area of any node corresponds to its value. From figure 37, a user can conclude that all four layouts have same count of task submissions because, area of all layouts are same.

3. Complexity level of each task

Using reference of the figure 38, tasks related to placing small game objects (such as, screws) are filled with dark blue color which shows that they are complex to perform as compare to tasks filled with light blue color which is used for large game objects (such as, housing, support, treadmill etc.). It also shows the number of tasks fall under small game objects category and large game objects category.

Table 4: Showing complexity for each sub-task used for user study

Layout	Tasks	Sub-tasks	Complexity
Immersive_image	Large_gameobjects	All 9 sub-tasks	Easy
	Small_gameobjects	All 4 sub-tasks	Complex
Non-immersive text	Large_gameobjects	All 9 sub-tasks	Easy
	Small_gameobjects	All 4 sub-tasks	Complex
Immersive_text	Large_gameobjects	All 9 sub-tasks	Easy
	Small_gameobjects	All 4 sub-tasks	Complex
Non-Immersive_image	Large_gameobjects	All 9 sub-tasks	Easy
	Small_gameobjects	All 4 sub-tasks	Complex

All the tasks within each layout is same which means, tasks and sub-tasks for immersive_image is same as, tasks and sub-tasks used for other three layouts (non_immersive_text, immersive_text and non_immersive_image). Table 4 shows the detailed overview of complexity for each layout. In fig.38 and fig.39, a user can see the sub-tasks within large_gameobject and small_gameobject tasks.

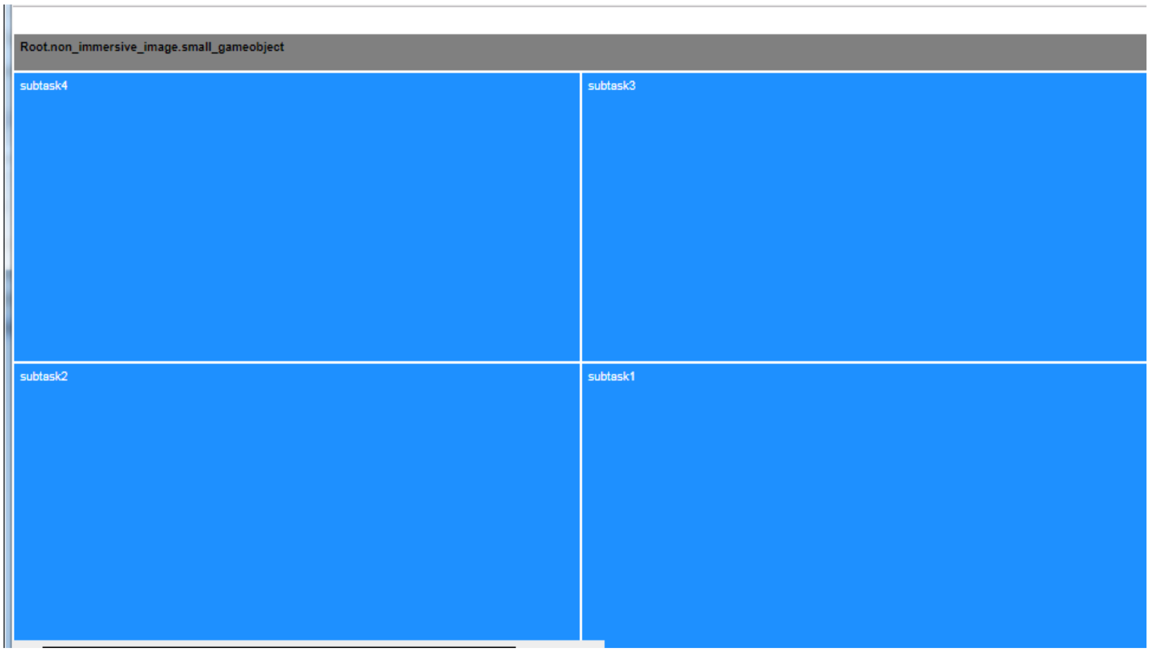


Figure 38: Zoomable treemap showing the complexity of task under small game_objects category

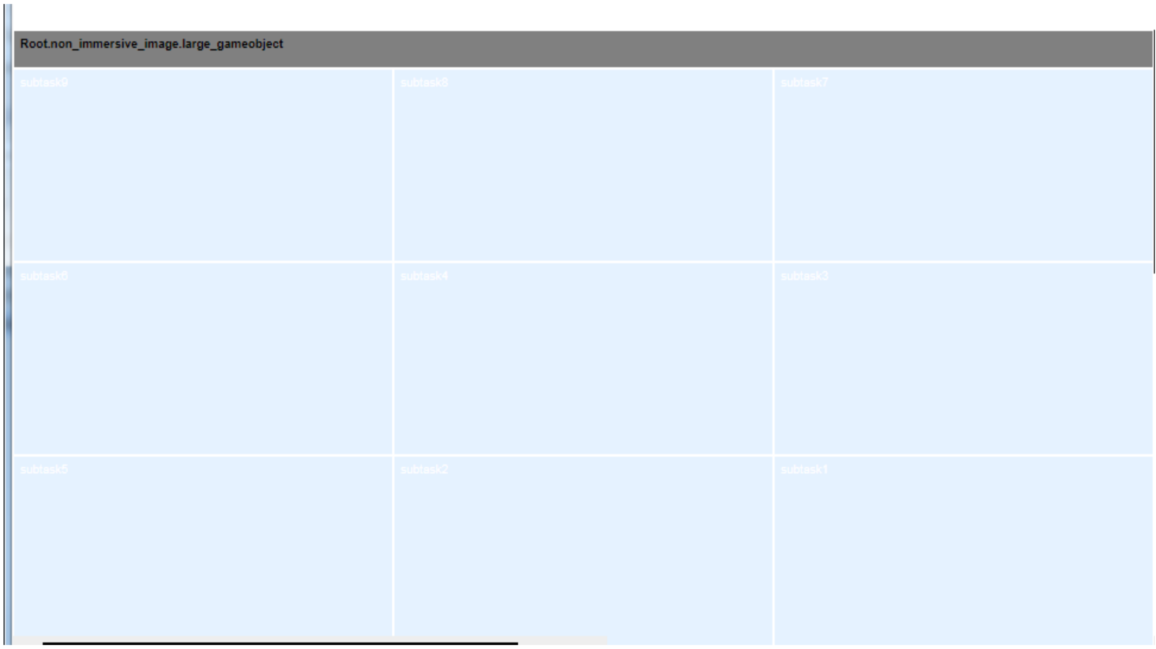


Figure 39: Zoomable treemap showing the complexity of tasks under large game_objects category

Using the reference from figure 39 which are related to complexity, a user can say that nine tasks are associated with large game objects category whereas, for small game objects category there are four tasks.

4. <u>Percentage of correct answers given by users in a layout</u>

In this visualization tool, a user can identify the percentage of correct answers provided by users for a given layout using bar (color: green) placed beneath the treemap. If the layout's color is dark green then, it means that the layout has more number of correct submissions as compare to the one which has light green color.

Figure 40: Zoomable treemap showing the percentage of correct submissions for each layout

In figure 40, one can assert that non-immersive and immersive virtual reality systems with image cues have higher percentage of correctness compare to non-immersive and immersive virtual reality systems with text cues.

5. Percentile of average time taken to perform tasks for a layout

Using this tool, a user can infer about the time require to finish tasks in a layout. This characteristic can be visualized with the help of bar (color: red) placed beneath the treemap. If the layout's color is dark red then, it means that the layout has more time-consuming tasks as compare to the one which has light red color.

Figure 41: Zoomable treemap showing the percentile of time taken for each layout

Figure 41 helps in concluding that immersive virtual reality systems consume less time for users to complete tasks in comparison with non-immersive. Layout "immersive_image" (immersive virtual reality systems with image cue) is filled with light color with respect to other layouts, which shows that it took minimum time to accomplish the tasks.

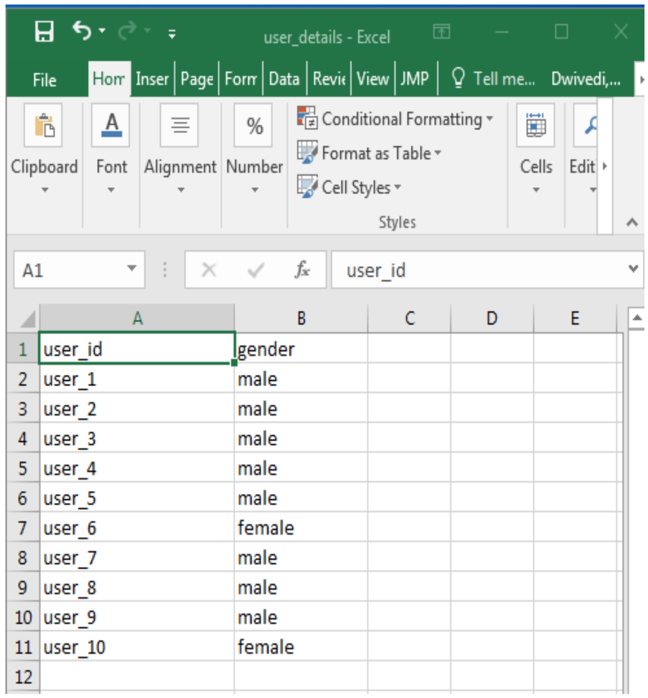
Which was the best layout?

According to the above interpretations, one can claim that "immersive virtual reality system with image cue" is the best layout for this manual assembly as, users consumed least time (refer figure 41) in this adjustment and this layout witnessed highest percentage of correct answers (refer figure 40).

4.5.2 VISUAL ANALYSIS USING BAR CHART

A user can understand two things from the bar chart used in this visualization approach.

a) <u>Gender of the subject in the user survey</u>: If gender of the subject is female then, bar will be filled with deep pink color otherwise, it will be colored with blue color. In user_details excel sheet (refer figure 42), we can change the gender parameter to some other parameter without changing the code structure for visually comparing different values.



	A	B	C	D	E
1	user_id	gender			
2	user_1	male			
3	user_2	male			
4	user_3	male			
5	user_4	male			
6	user_5	male			
7	user_6	female			
8	user_7	male			
9	user_8	male			
10	user_9	male			
11	user_10	female			
12					

Figure 42: Excel sheet shows the detail of users in the user survey

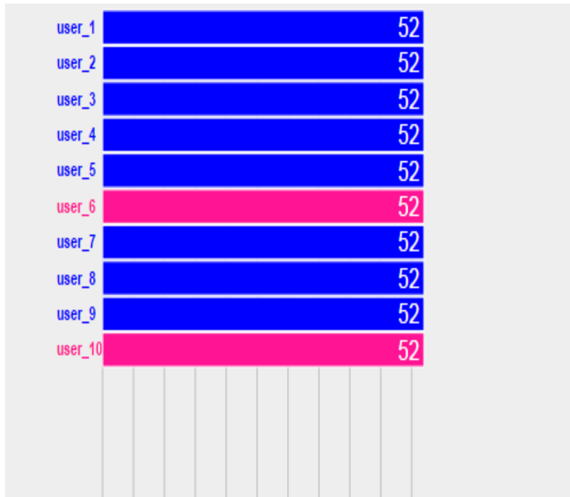


Figure 43: Bar chart showing count and gender of the users

Bar chart shows that all users have performed equal number of tasks, and the count is fifty-two which is also scribbled on each bar. Using this chart, a user can say that two out of ten users were female (user_6 and user_10) because, deep pink color symbolizes female gender.

4.5.3 FINDING STATISTICAL RELATIONSHIP AMONG DIFFERENT USER GROUPS USING CHORD DIAGRAM

Chord diagram uses Mann-Whitney U test to find whether two groups will relate to each other or not. In this chord diagram, a pair is formed only if they share meaningful relationship which means p-value < 0.05.

In this user survey, user group A which is marked with green color (#00ff00) has a meaningful relationship with user group B which is marked with red color. User group A consists of six users (user_1, user_2, user_5, user_6, user_8 and user_9) whereas, user group B has two users (user_4 and user_10).

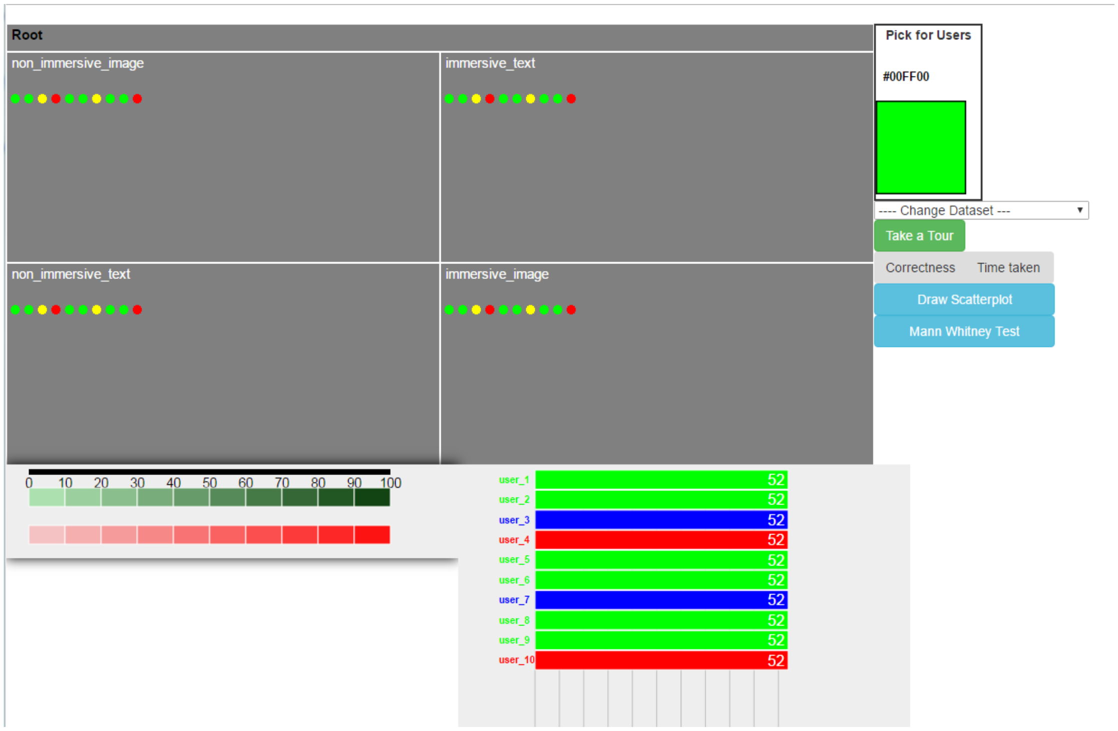


Figure 44: Highlighting User Group A (green color) and User Group B (red color)

In figure 44, scatterplot shows the two user groups formed in table 5. This figure locates users in both the groups (Group A & Group B) which will help us to create a chord diagram which can show that they share significant relationship.

Table 5: Details about users in Group A and Group B

Group A (Green Color)	**Group B (Red Color)**
1. User_1	1. User_4
2. User_2	2.User_10
3. User_5	
4. User_6	
5. User_8	
6. User_9	

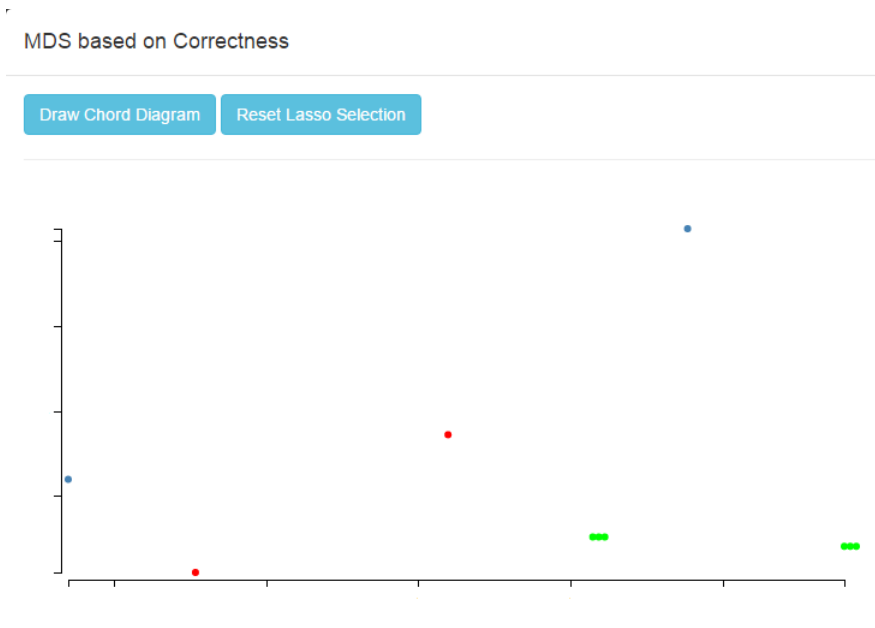


Figure 45: Spotting User Group A and User group B in the scatterplot

In figure 46, two groups can be seen where orange group represents user group B (red color) and green group represents user group A. Orange group contributes more significantly as compared to green group therefore, it makes larger arc. In Mann Whitney test, lesser the U-value of the group more will be its impact on p-value calculations.

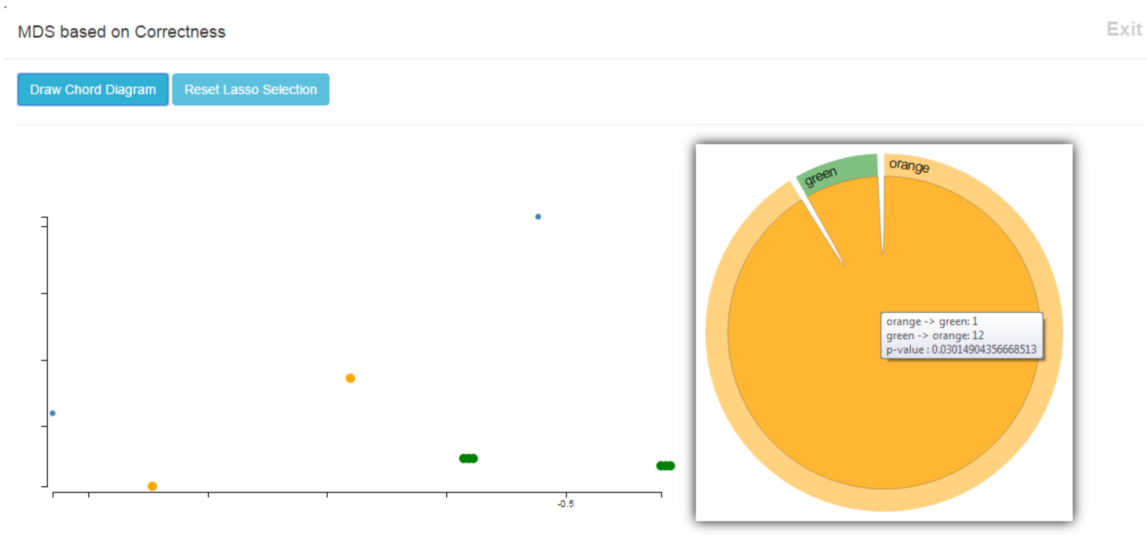


Figure 46: Chord diagram connection shows the significant connection between User Group A and User group B

VALIDATING CHORD DIAGRAM RESULTS

In figure 47 shows the input dataset of user group A and user group B (refer chord diagram of figure 46) which will be used for validation from online tool available for p-value calculation.

```
Index Chord 0 :                                  visualizationToolVRUser.php:967
[0.6153846153846154,0.6923076923076923]
Index Chord 1 :                                  visualizationToolVRUser.php:967
[1,1,1,0.8461538461538461,0.8461538461538461,0.8461538461538461]
```

Figure 47: (From console): Two input sets which represent user group A and user group B

Mann–Whitney U test (also called the Mann–Whitney–Wilcoxon(MWW), Wilcoxon rank-sum test, or Wilcoxon–Mann–Whitney test) technique used in statistics to examine differences between two independent groups on a continuous scale. This test is a non-parametric alternative to the t-test for independent samples [60]. Figure 48 depicts the result captured from online

Mann-Whitney test calculator which shows that the result shown in the chord diagram is close to the online p-value calculation (<0.05).

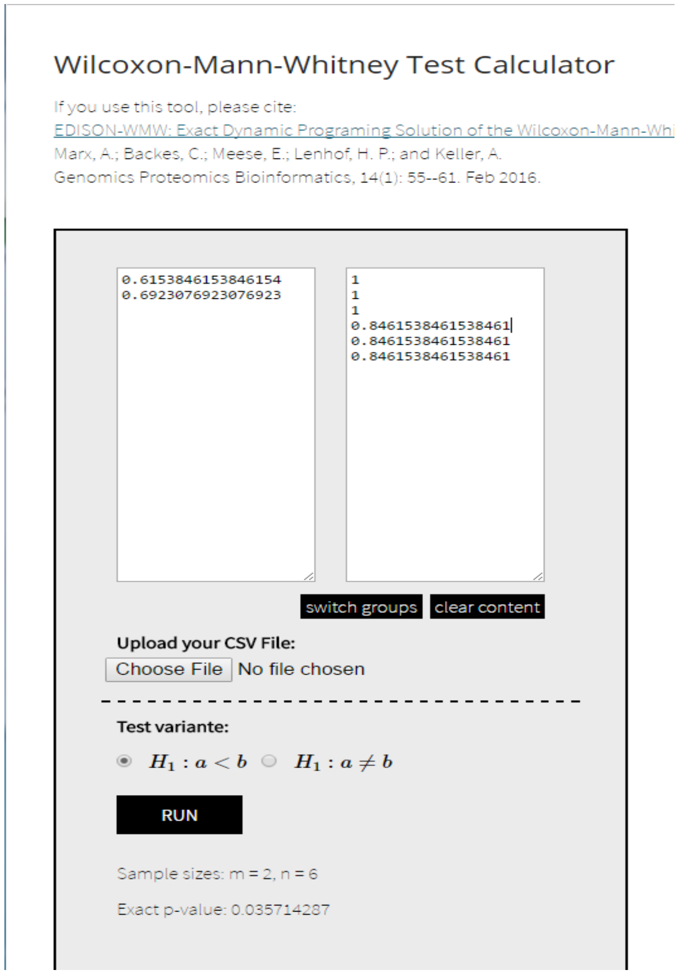


Figure 48: Online calculation of p-value using Wilcoxon-Mann-Whitney test for User Group A and B

FINDING STATISTICAL RELATIONSHIP BETWEEN LAYOUTS

Using chord diagram (refer figure 49), a user can conclude that non-immersive virtual reality system with text cue holds meaningful relationship with immersive virtual reality system with image cue. No significant relationship found for other pairs (p-values > 0.05)

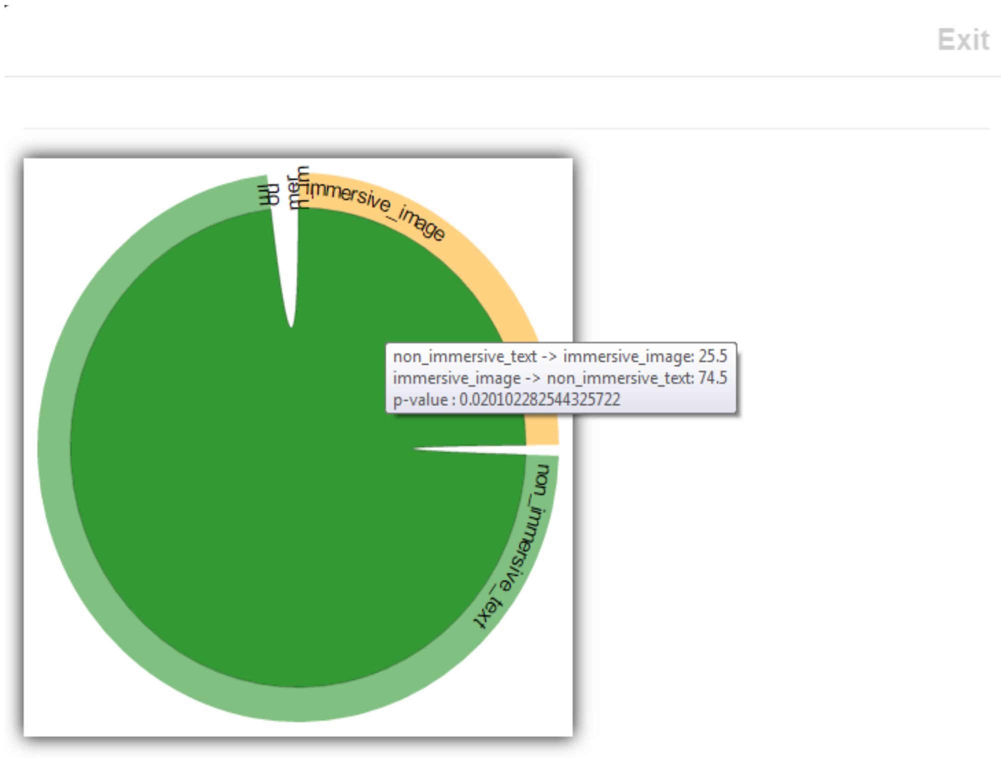


Figure 49: Chord diagram based on correctness

4.6 EVALUATION OF HYPOTHESES

H1a: Using immersive virtual reality system will improve performance with respect to time and correctness in comparison with non-immersive virtual reality system.

<u>Based on Correctness:</u>

Figure 50: Treemap showing correctness for Immersive and Non-Immersive VR systems

Immersive Virtual Reality System has more accurate results as compare to Non-Immersive VR System because, Immersive layout is filled with darker color as compare to Non-immersive.

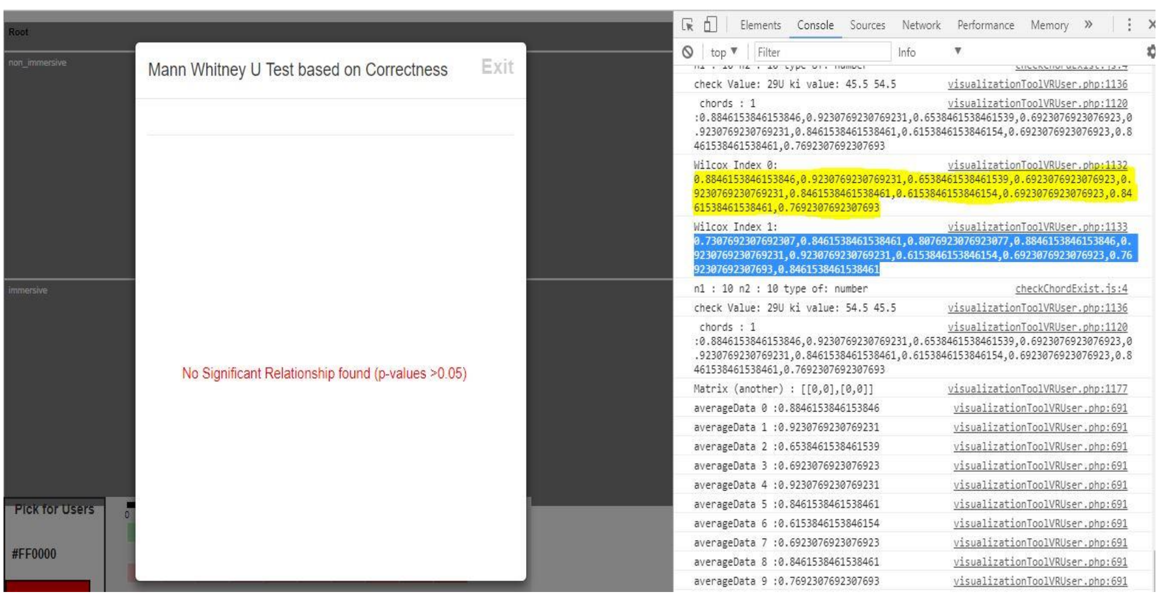


Figure 51: No Significant Relationship found between Immersive and Non-immersive virtual reality system

The results of figure 51 has been verified by online Wilcoxon Mann-Whitney U Test shown in figure 52.

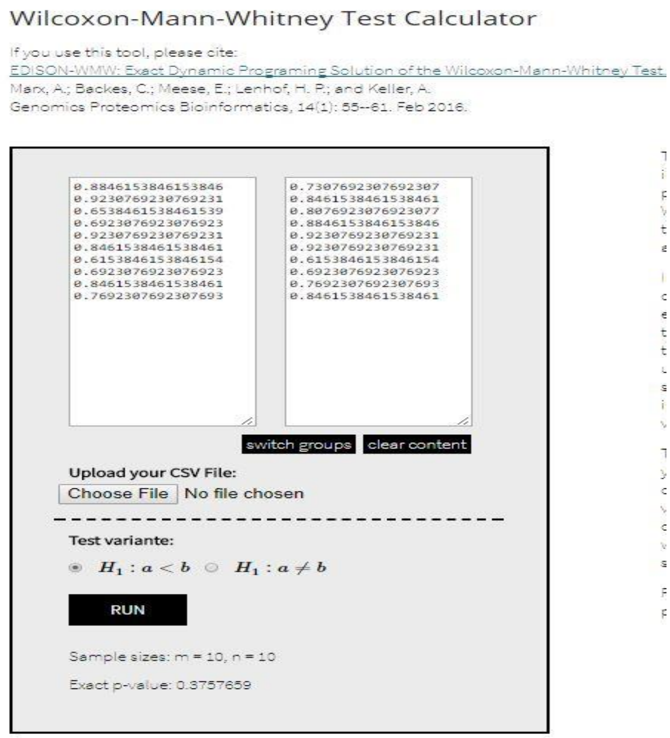


Figure 52: Verifying the results of figure 51

<u>Based on Time</u>

In figure, immersive layout is filled with light color therefore, we can conclude that Immersive is less time consuming as compare to Non-immersive.

Figure 53: Treemap showing time elapsed for Immersive and Non-Immersive VR systems

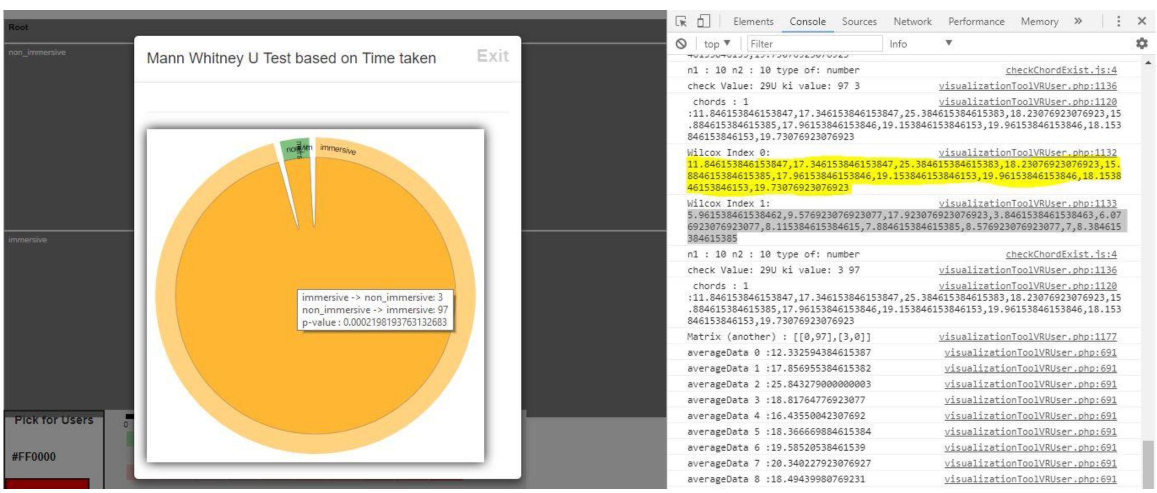


Figure 54: Significant Relationship found between Immersive and Non-immersive virtual reality system for Time

The results of figure 54 has been verified by online Wilcoxon Mann-Whitney U Test shown in figure 55.

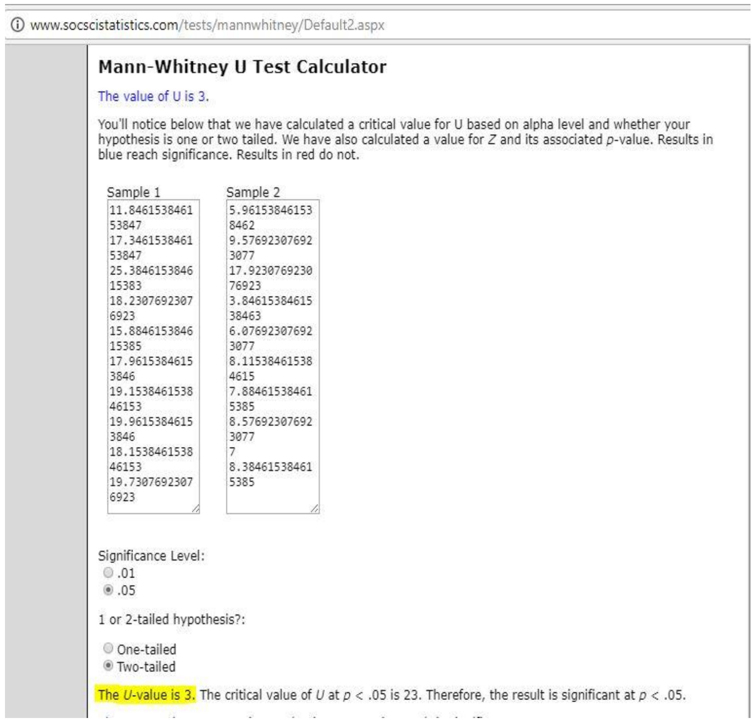


Figure 55: Verifying the results of figure 54

With the help of above results, we can conclude that the hypothesis H1a is partially accepted because user performance in immersive virtual reality system has statistically significant difference in comparison with non-immersive VR system only for the time parameter.

H1b: Using immersive virtual reality system with image cue will show better results in terms of performance as compare to non-immersive virtual reality system with image cue.

<u>Based on correctness</u>: I had performed pairwise comparison for immersive and non-immersive virtual reality system with image cue. With reference to figure 49, we can say that these two layouts don't have any significant difference among them.

<u>Based on time</u>**:** Figure 56 shows that immersive with image cue and non-immersive with image cue in pairwise comparison for time has significant difference among them.

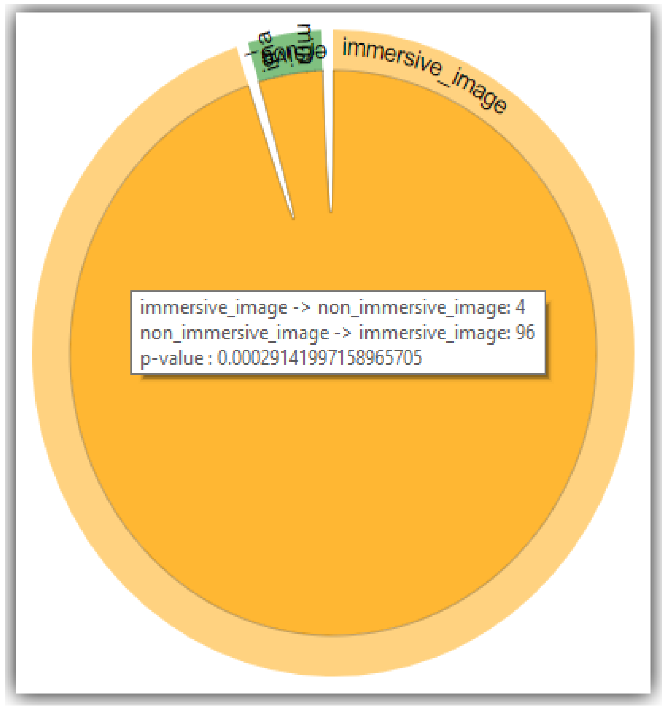


Figure 56:(For time) Chord diagram showing significant difference between immersive with image cue and non-immersive with image cue

With the help of above results, we can conclude that the hypothesis H1b is partially accepted.

H1c: With the help of text cue in immersive VR system, we can achieve finer results as compare to using text cue in non-immersive VR system.

Based on correctness: I had performed pairwise comparison for immersive and non-immersive virtual reality system with text cue. With reference to figure 49, we can say that these two layouts don't have any significant difference among them.

Based on time**:** Figure 57 shows that immersive with text cue and non-immersive with text cue in pairwise comparison for time has significant difference among them.

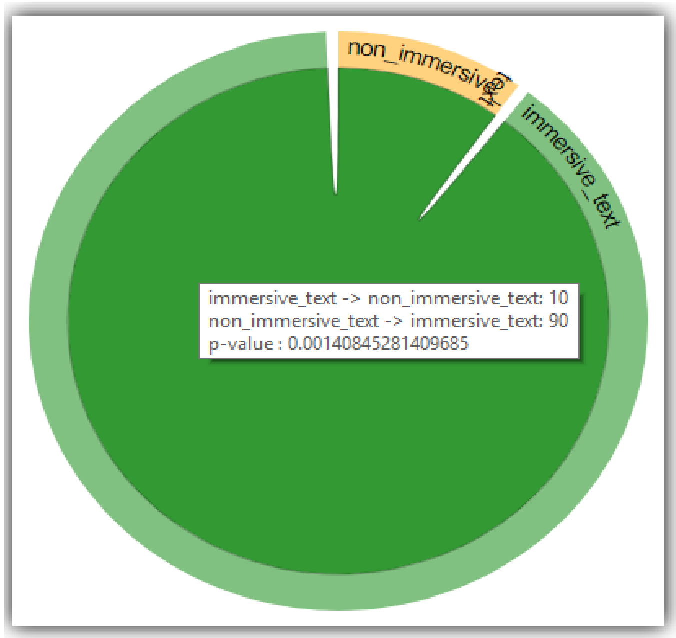


Figure 57: :(For time) Chord diagram showing significant difference between immersive with text cue and non-immersive with text cue

With the help of above results, we can conclude that the hypothesis H1c is partially accepted.

H2a: Image cue has statistically considerable influence on user performance as compare to text instructions.

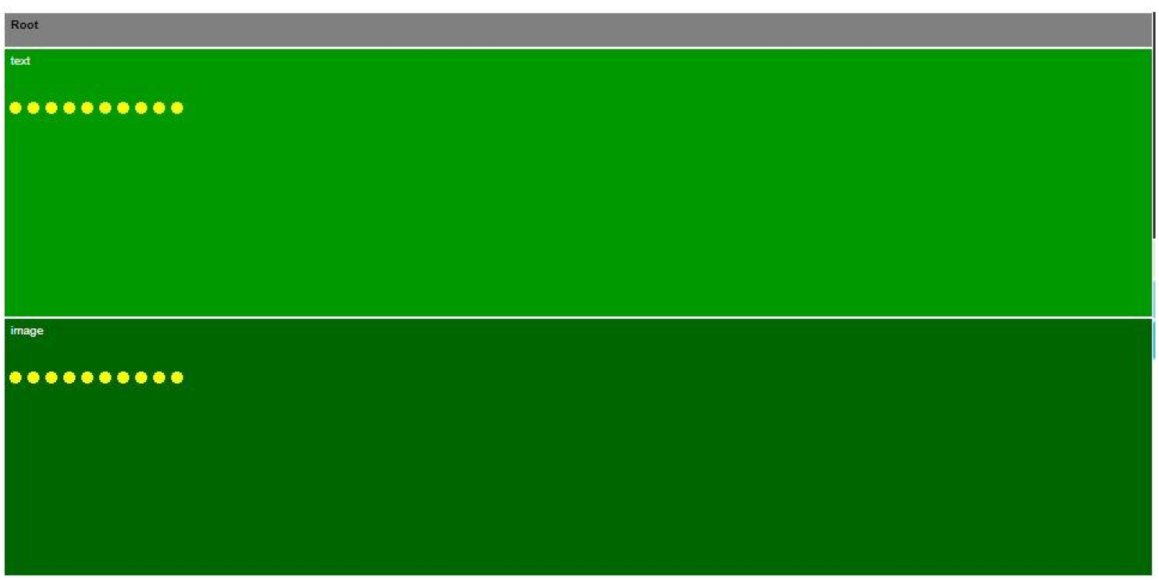


Figure 58: Treemap showing correctness for Text and Image cues

Image cue has more accurate results as compare to Text instructions because, image cue layout is filled with darker color as compare to Text instructions.

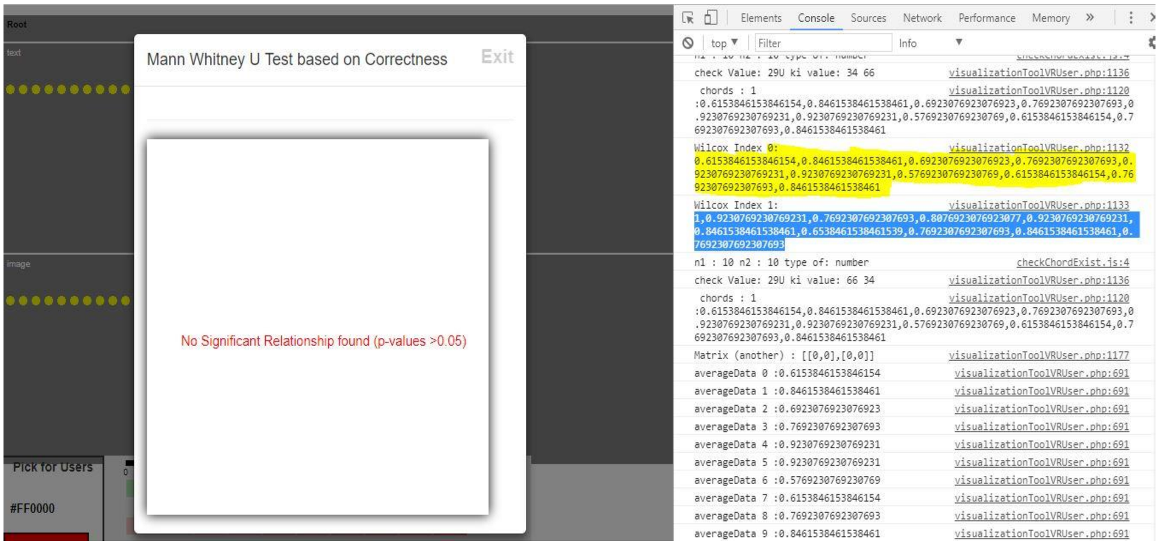


Figure 59: No Significant relationship found between Text and Images for Correctness

Figure 60: Treemap showing time elapsed for Text instructions and Image cue

As, Image cue layout is filled with light color therefore, we can conclude that Image cue is less time consuming as compare to Text instructions.

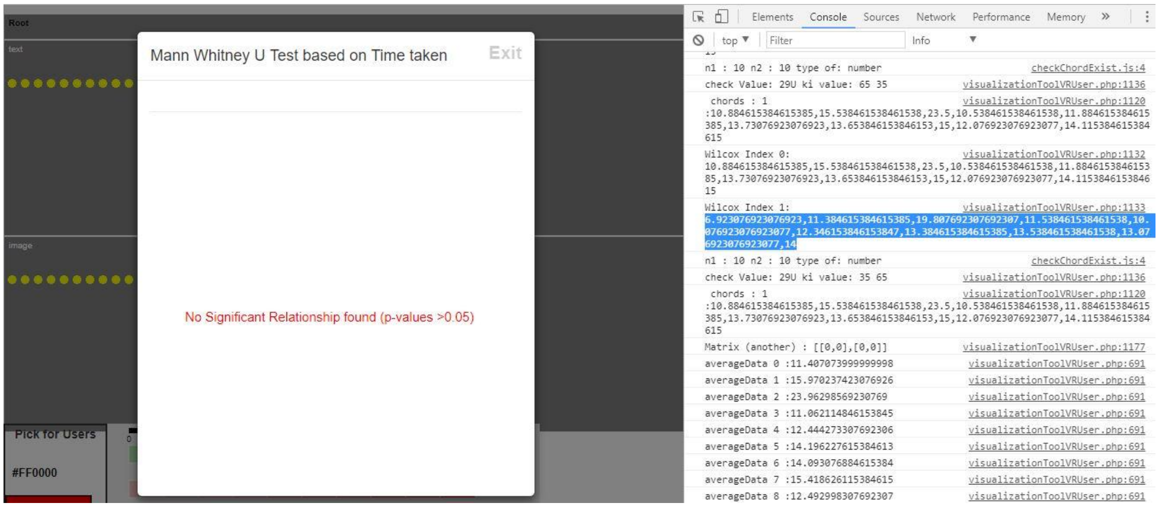


Figure 61: No Significant relationship found between Text and Images for Time

With the help of above results, we can conclude that the hypothesis H2a is rejected as they don't have any significant difference in the pairwise comparison.

H2b: Using image cue in immersive VR system can enhance user performance as compare to using text cue in non-immersive VR system.

Based on correctness: I had performed pairwise comparison for immersive with image cue and non-immersive with text cue. With reference to figure 49, we can say that these two layouts have significant difference among them.

Based on time**:** Figure 62 shows that immersive with image cue and non-immersive with text cue in pairwise comparison for time has significant difference among them.

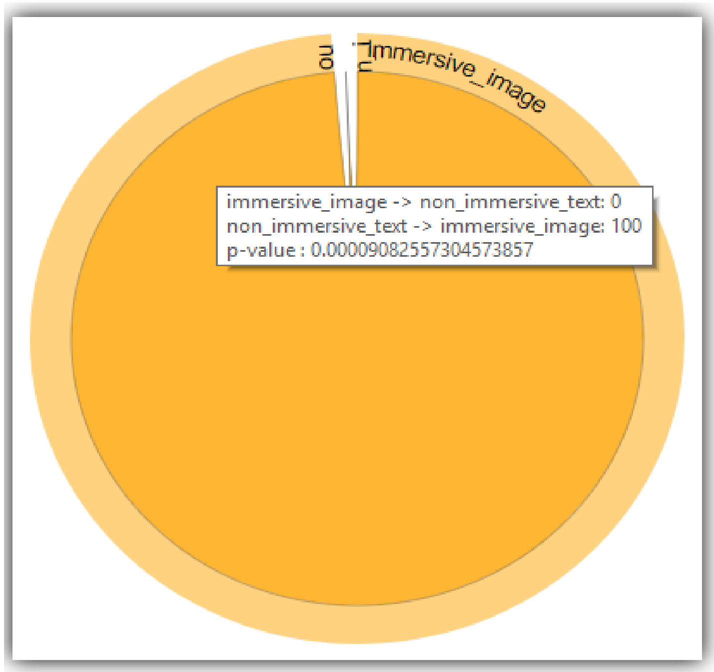


Figure 62: :(For time) Chord diagram showing significant difference between immersive with image cue and non-immersive with text cue

With the help of above results, we can conclude that the hypothesis H2b is accepted.

H2c: With the help of image cue in non-immersive VR system can improve user performance as compare to using text cue in immersive VR system.

<u>Based on correctness</u>: I had performed pairwise comparison for immersive with text cue and non-immersive with image cue. With reference to figure 49, we can say that these two layouts don't have any significant difference among them.

<u>Based on time</u>**:** Figure 63 shows that immersive with text cue and non-immersive with image cue in pairwise comparison for time has significant difference among them.

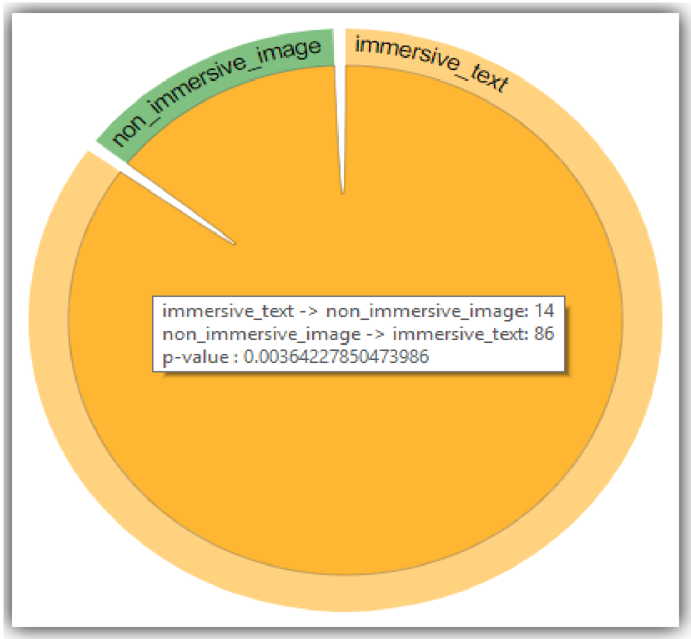


Figure 63: :(For time) Chord diagram showing significant difference between immersive with text cue and non-immersive with image cue

With the help of above results, we can conclude that the hypothesis H2c is partially accepted.

CHAPTER V

CONCLUSION

We have already seen that design phase plays a key role in manufacturing sector with the trending technology of VE, with its use, we can minimize the cost of physical prototyping and training inexperienced users. With this research work, we will conclude that designers can minimize the flaws related to the building of Virtual Environment (VE) by utilizing visualization approach. This approach can help VE designers to understand which layout would be best from users' perception with respect to following the correct sequence and consuming less time. In this research work, it can be concluded that immersive VR system along with image cues will be the best possible choice to perform manual assembly as, users took least time with respect to the other layouts to provide the flawless answers.

In addition to providing the best possible layout, this visualization tool also helps in identifying the relationship between user groups under the facts of correctness and time consumed to accomplish the tasks by using chord diagram which utilizes the logic of Mann-Whitney U test. These logics also help a user to identify whether a pair of layouts share significant relationship (p-value < 0.05).

Sr No	Links
(1)	Zoomable Treemap, https://bost.ocks.org/mike/treemap/
(2)	VRTK, https://vrtoolkit.readme.io/docs/getting-started
(3)	Mann Whitney Table, http://www.real-statistics.com/statistics-tables/mann-whitney-table/
(4)	Euclidean distance, https://en.wikipedia.org/wiki/Euclidean_distance
(5)	D3 lasso, https://github.com/skokenes/D3-Lasso-Plugin/blob/master/README.md
(6)	MDS Example, http://www.benfrederickson.com/multidimensional-scaling/
(7)	VIVE Tutorial, https://www.raywenderlich.com/149239/htc-vive-tutorial-unity
(8)	Snap Drop Zone, https://vrtoolkit.readme.io/docs/snap-drop-zone
(9)	Mann Whitney U test formula, https://en.wikipedia.org/wiki/Mann%E2%80%93Whitney_U_test
(10)	Genetic Algorithm, http://www.obitko.com/tutorials/genetic-algorithms/ http://mnemstudio.org/genetic-algorithms- algorithm.html
(11)	Mann Whitney test calculator, https://ccb-compute2.cs.uni-saarland.de/wtest/
(12)	Treemap Example, http://www.datavizcatalogue.com/methods/treemap.html

Table 6: Links

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APPENDICES

1. **Sample User Survey Data**

VR_User_Survey.csv

question,user,layout,correctAnswer,response,isCorrect,timeTaken (in sec),data,randomSeed,complexity

large_gameobject,user_1,immersive_image,housing,housing,1,8.01546,Assembly using VIVE with image cue,N/A,easiest

large_gameobject,user_1,immersive_image,treadmill,treadmill,1,2.586723,Assembly using VIVE with image cue,N/A,easiest

large_gameobject,user_1,immersive_image,handle,handle,1,7.114913,Assembly using VIVE with image cue,N/A,easiest

large_gameobject,user_1,immersive_image,chain_1,chain_1,1,22.26167,Assembly using VIVE with image cue,N/A,easiest

large_gameobject,user_1,immersive_image,chain_2,chain_2,1,3.116461,Assembly using VIVE with image cue,N/A,easiest

VITA

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