DATA VISULIZATION IN AUGMENTED REALITY

by

Travis C. Samford, M. S.

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Travis C. Samford

APPROVED BY

Michael J. Findler, Ph.D., Chair

Anne Henry, MFA, Committee Member

Soma Datta, Ph.D., Committee Member

RECEIVED/APPROVED BY THE COLLEGE OF SCIENCE AND ENGINEERING:

Dr Said Bettayeb, Ph.D., Associate Dean

Ju H. Kim, Ph.D., Dean

Dedication

Dedicated to Margo Sikes for her continuous support during this process. Without her, this would not have been possible.

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ABSTRACT

DATA VISUALIZATION IN AUGMENTED REALITY

Travis C Samford

University of Houston-Clear Lake, 2019

Thesis Chair: Michael J. Findler, Ph. D.

During critical procedures with limited resources, astronauts are expected to operate at a high level of efficiency and effectiveness. Recently, NASA has begun development of an advanced space suit design with many technological upgrades that will make astronauts more efficient and effective during extravehicular activities (EVAs). These upgrades include the introduction of an informatics subsystem projected on the inside of the helmet in an astronaut's spacesuit. The current informatics system relies heavily on voice communication to a team member, "mission control," and an EVA partner. During an EVA, the astronaut needs access to two streams of data: the instructions on how to complete the EVA task and sensor readings on the health of the suit. The task data stream is a spiral notebook attached to the forearm, the system health display, and controls are embedded in the spacesuit's chest and must be monitored using a mirror on the forearm. The aim of this thesis is to reduce the workload of the astronaut user by leveraging an augmented reality display as part of the new informatics subsystem to increase efficiency and effectiveness. This includes two displays: the task display and

the suit consumables display. Two types of consumable displays were tested. One resembles the current astronaut display on their arm and the other has a sprocket design. The subjects were asked to complete an activity using one of these two consumable displays. The subject's performance was then compared between the two displays.

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CHAPTER I:

INTRODUCTION

Informatics is the science of information [1]. It is the study of collecting, processing, and communicating data between different systems. There are several disciplines that benefit from informatics, but they all have a focus on information and how it is represented, processed, and then communicated between a variety of systems. These systems can be human-to-human or human-to-computer, for example. The representation focuses on how data is stored. This could be in many formats such as ASCII for text, JPEG for images, and WAV for audio. Processing data is the transformation from one form to another. An example of a transformation is the indexing of a document by keywords. Once this document has been indexed, it can be effectively retrieved based on a given criteria. The data is then delivered to the requesting system in the appropriate format. An increasingly popular platform that will benefit from the collection, processing, and then displaying of data is augmented reality (AR). Leveraging informatics with AR tools can increase or extend a subject's abilities by presenting domain knowledge in a meaningful way in the right context.

AR is becoming more prevalent in the commercial and consumer space. There are two major forms of AR: see-through and monitor-based [2]. The first is a headset with a see-through display, the HoloLens is an example of this technology. The subject sees the real world and holograms are inserted into their environment on a transparent screen overlay. This technology is being used in maintenance and medical fields, where needed information is superimposed on the subject's environment. The second type is the monitor-based AR display, which is also referred to as window-on-the-world, where a subject can use technology like a smartphone to look through and see objects inserted into the real world. An example of this is the smartphone game Pokémon Go. The subjects walk around with their phone, and their phone's forward-facing camera takes images of what is in front of them. The game then takes that image and adds objects to the space that they are looking into on the phone. This creates the illusion that the user is looking into a window, using their phone to show objects that are normally hidden.

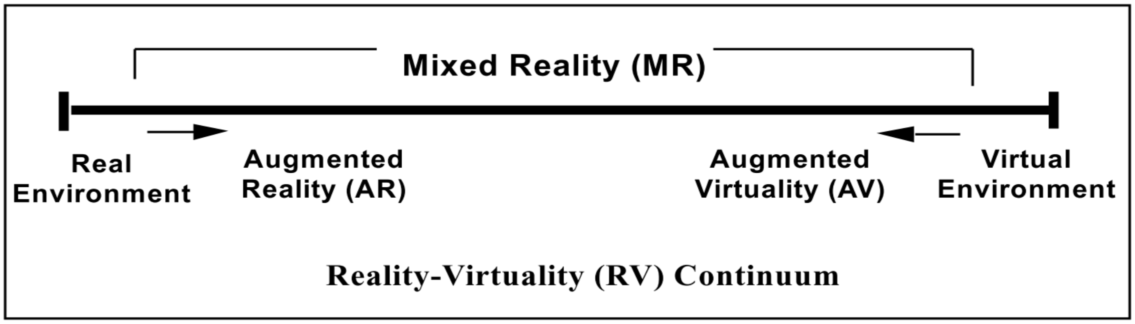

Figure 1RV Continuum [2]

There is a spectrum of these mixed reality technologies that go from the most realistic, set in the real environment, to the least realistic, set in virtual reality. Virtual reality is completely computer generated and blocks out the real world. AR leverages the real environment by overlaying information on top of it. Because of this, AR can be used to insert information for users while they perform tasks in the real world. This is especially important during time critical operations, such as an astronaut doing an EVA. During an EVA, an AR headset, using informatics to processes the environment around an astronaut, can display meaningful information, maintain their situational awareness and make them more efficient and effective at their task.

The NASA Spacesuit User Interface Technologies for Students (NASA S.U.I.T.S.) 2018 design challenge was an opportunity for student groups to be involved in the design of the new spacesuit[3]. This challenge focused on designing the informatics system of the suit Heads Up Display (HUD) using the Microsoft HoloLens® to simulate this environment. The system was responsible for displaying the needed information to successfully complete an EVA.

The current EVA workflow relies heavily on voice communication to a team member, “mission control,” and an EVA partner to guide the astronaut and collect information from them about their status. Each task that the astronaut follows is scripted through an EVA checklist. The checklist is usually an abbreviated version of the task the astronaut will complete during the spacewalk; the checklist is printed onto a small Cuff Checklist and worn by the astronaut on their forearm [3]. To monitor consumables, an astronaut must look through a mirror on their forearm to the Display and Control Module (DCM) on their chest.

NASA has an optional informatics computer assembly for the Advanced Extravehicular Mobility Unit (AEMU) [4]. This assembly adds a graphical user interface to the arm of the spacesuit. The interface displays suit status, timelines, procedures, and warning information, as well as providing an interface to control the suit camera for taking still images and video. In the future, they plan on adding navigation that will display maps with a GPS position, and a voice command system. The voice command system was completed in this version but was removed due to software changes in the final design. To use this system, the astronaut must stop their task and look at their wrist.

In the UHCL design of the NASA S.U.I.T.S. challenge, we set out to create a HoloLens display that increased a user’s efficiency and effectiveness when doing an extravehicular activity. Our design is driven by voice commands given by the subject, displaying information on their current task and updating them with their consumable information.

Voice can be used in situations when the user’s hands are full, or as a shortcut through complex menu navigations. Integrating the voice commands into the initial design reduces the visual load of the user. The use of voice commands eliminates the need to stop a task to free up a hand to provide input to the suit or navigate the menu system.

The use of a HUD allows the user to get information without looking away from the current task they are performing. The designed HUD is split into two interfaces. The first is a task display that shows the astronaut what their current task is and any information they may need to successfully complete the task. This information includes images, warnings about any difficulties they may face, holograms that indicate the area of interest for the work that must be done, and instructions read aloud to them by the HoloLens.

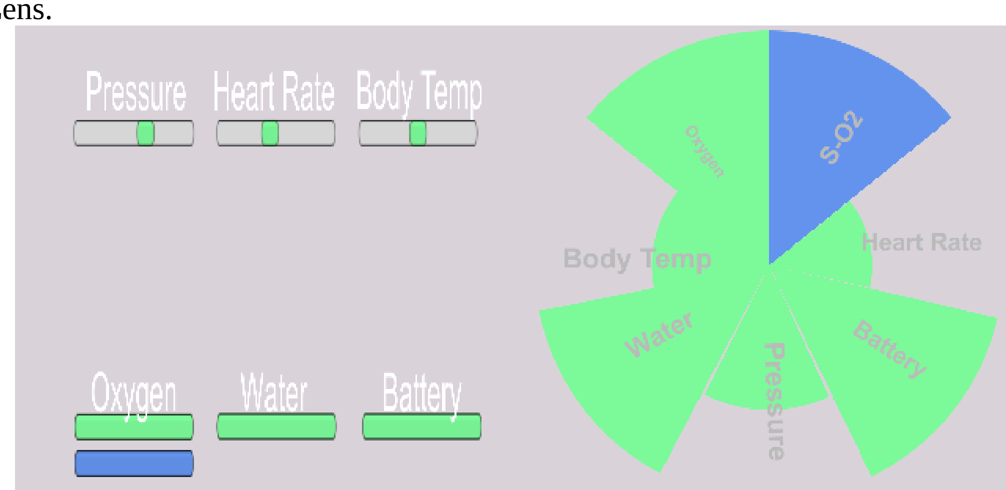

Figure 2 Left Traditional Display Right: Sprocket Display

The health user interface, the second display, informs the user of their suit's consumables. There are two designs for this display and their effectiveness is what this thesis is testing. The first utilizes a circular sprocket symbol design. This display allows users to glance at information that can be quickly relayed to "mission control" or make quick decisions based on what they see. The ability to assess their situation on a short glance decreases their mental load and allows them to more efficiently and effectively complete the task that they are working on. The second is a collection of slider bars meant to mimic the optional informatics system that displays some of the more important information shown on the sides of the display as bars, such as the oxygen and battery levels of the suit.

The aim of this thesis is to identify the best way to visualize data on a spacesuit HUD using an AR simulation. It is proposed that if the sprocket design was used to display the data, then the astronaut would better understand the data being presented reducing their mental workload. This would allow them to perform tasks more efficiently and effectively. Additionally, when the sprocket is used, the astronaut will maintain situational awareness by quickly glancing at the condensed information for rapid decision-making, increasing safety of the astronaut and assuring mission success.

CHAPTER II:

LITERATURE REVIEW

Real-Time Dynamic Decision Making

This thesis aimed to increase an astronaut's performance and effectiveness while wearing this newly designed informatics AR system. The current system requires the astronaut to direct his full attention to the consumables for monitoring and configuration of the suit. The system sensor displays are on the space suit's stomach. To read these displays, the astronaut must look at them through a mirror on the arm of the suit. At the root of this problem is the astronaut's ability to take in information and make the best decision possible under time constraints in an extreme environment, where a bad decision could mean death. Research done by Lerch and Harter [5] focuses on cognitive support during instances of dynamic decision making, which they characterize as "a stream of interdependent decisions to be made in real-time." In this study, they aimed to find a way to increase a participant's rate of learning and performance. Some of the reasons they cited for poor performance were the complexity of growing decision branches, time constraints, and ineffective information filtering. They stress the importance of decision makers getting strong cues from their environment and reducing the amount of information that needs to be filtered out, which is the first level of situational awareness.

Situational Awareness

An integral part of dynamic decision making is maintaining situational awareness (SA). In a paper reviewing the concept of SA by Wickens [6], the three levels of SA are identified as perception, comprehension, and projection. The higher levels depend on the lower levels. A problem must first be perceived before it can be understood. Once the problem is understood, the consequences can be imagined, and proper steps can be taken to mitigate the issue. As an example, the astronaut would see their consumable go out of range and a warning pops up (perception). They would then know their oxygen is getting low (comprehension). The astronaut would then pull up the consumable submenu and switch to oxygen tank two (projection). Each level of SA can be increased by different types of information. Understanding the differences between the three levels can lead to better system design. Level one, perception, would be some sort of warning system. Level two could indicate what a warning means. Level three would be what the consequences of that warning will be, depending on how it is addressed. The idea of human control versus automation of a system, and how they interact with each other, is also introduced. This trade off decreases the workload of the user but also removes their SA of the underlying systems.

Humans and Automation

In his book, Thomas Sheridan [7] discusses human interactions with different levels of automation. He states that computers are better at responding quickly to control signals, while humans are better at making fuzzy judgment calls. A system should be designed to reduce mental workload, but not to the point of making the human's interaction trivial. If a human does not have enough interaction to keep them engaged, they may lose situational awareness. In this thesis, the focus is on increased performance and accuracy, the level of automation selects the data that is displayed, and how it is displayed, leaving decision making up to the astronaut. This allows for accurate and precise data visualization without causing overload or underload that disrupts situational awareness.

Data Visualization

Data visualization concepts are used to balance visual displays with the work that the astronaut is doing in the environment to increase their performance. In his book, Ware [8] states that visual systems are the highest bandwidth channel between humans and systems. Creating interfaces that meaningfully display data can leverage a human's ability to see patterns and diagnose issues that may go unnoticed otherwise. Data modeled well can also be interpreted very rapidly. This is especially important when reaction time and situational awareness is a key factor. Ware also talks about the stages of data visualization. The first is the collection of data, which is coming from the HoloLens data streams. Second, the data is then transformed in a way that the astronaut can understand. The third will be using the HoloLens to display the data in one of the designed interfaces leveraging AR, and the fourth is the human perceiving the data. Data visualization in AR comes with its own set of challenges.

Data visualization in AR

AR is unique in that it shares its interface with the real world. In their book, Schmalstieg and Höllerer [9] state that AR differs from conventional interfaces because it must interact with a real environment. AR, because of its interaction with the real world, is bound by the context of the user's current situation. The challenges that AR faces are similar to traditional visualization, with the primary challenge being data overload. When an astronaut is presented too much information, they can become overwhelmed, impairing their understanding of what is being presented to them. In AR, not only could this lead to data not being understood, but it could also cause the user to become disoriented with their surroundings, leading to an accident or injury. For this reason, the user interface should be as small possible while still being visible enough to communicate information effectively. AR allows developers to simulate a HUD and objects in the environment, such as holograms. One example of data visualization in AR is the NASA S.U.I.T.S. challenge where students were tasked to create a HUD that guides astronauts to complete tasks.

Nasa S.U.I.T.S.

The NASA Spacesuit User Interface Technologies for Students (NASA S.U.I.T.S.) 2018 design challenge was an opportunity for student groups to be involved in the design of the new spacesuit informatics system [3]. The challenge required the students to use the HoloLens to simulate a Heads-Up Display (HUD) of the spacesuit. They were required to design an interface that could effectively display procedures for the astronaut to follow while also displaying their biometrics data. The goal was to make astronauts more efficient and effective, as well as adding a level of autonomy during deep space flight. For this design, we looked at other NASA projects that had attempted to upgrade the informatics systems in the current suits. We found a paper on an optional informatics upgrade for the current Extravehicular Mobility Unit (EMU) utilizing a touch screen display that could be installed on the astronaut's arm called Advanced Spacesuit Informatics.

Advanced Spacesuit Informatics

In NASA's Advanced Spacesuit Informatics Software Design for Power, Avionics and Software Version 2.0 document [4], the current NASA spacesuit informatics system design is covered. This document discusses the various new physical displays, what type of information is to be displayed, and an outline for a voice command system that did not make it into the final design. The proposed system had simple voice commands that passed information to the GUI event system to simulate key presses. The system listens for an attention keyword, and then switches to a specific list of vocabulary phrases. If a keyword is not heard within 5 seconds, the system switches back to listening only for the attention keyword. This is similar in function to home assistants such as Amazon's Alexa or Microsoft's Cortana.

The system being used in this thesis is the AR headset HoloLens made by Microsoft using Cortana. The headset is used to create a simulation of the HUD the astronaut will have on their suit helmet.

Microsoft HoloLens

The HoloLens AR headset runs on the Windows Mixed Reality platform. The operating system is Windows Holographic (an edition of Windows 10 designed for the HoloLens). What follows is a description of the HoloLens capabilities and how they are leveraged in the project.

Input

The HoloLens AR headset includes gaze [10], gestures [11], and voice [12] in combination for the interaction system.

The gaze is the primary form of targeting and conveys the astronaut’s intent; using either gestures or voice will complete the interaction. It is important to note that the gaze is not calculated by tracking an astronaut’s eyes, it is calculated using a vector based on the position and orientation of their head. The gaze is represented on the HoloLens screen to the astronaut with a cursor. The cursor is placed in the world where the calculated vector first interacts with an object, whether it be real or a hologram. The cursor is represented with a dot, and when hovering over an interactable object, turns into a ring. Selecting the interactable object shrinks the diameter of the ring. This is used during the simulation to detect when an astronaut is looking at an area of interest, such as a hologram directing them what to do during a task.

Hand gestures allow users to interact in the AR environment of the HoloLens. Gaze is used to target, and gestures are used to act upon the target. There are two core gestures of the HoloLens, Air Tap, and Bloom. Air Tap is a simple tap of the index finger and thumb, which can be held to create more complex control types. The Bloom is a “home” gesture that is reserved for the HoloLens operating system to go back to the start menu. For this experiment, hand gestures were used to configure the system at the start of the application. Users were then given gloves that would cause the HoloLens to ignore hand gestures, because bloom could not be disabled, and was causing the program to be suspended during operation.

Voice input on the HoloLens is handled by the Windows speech recognition API; this is the standard way of handling voice input in all Universal Windows Applications. The HoloLens voice commands can be leveraged to interact directly with holograms instead of relying on gestures. In this project, all of the user’s interactions with the system are done with voice commands. A list of these commands can be found in appendix B.

Output (Of the HoloLens Display)

The output of the system is built on spatial mapping [13], spatial sound [14], coordinate systems [15], and spatial anchors [16].

Spatial mapping is achieved by the HoloLens hardware by automatically creating a geometric mesh that represents the real-world objects in a space. This mesh is then used to calculate where holograms can be placed and how they are perceived and interacted with in the simulation. This technology is leveraged in this experiment by placing generated holograms on interactable objects on the EVA kit. When the astronaut gets to the step that concerns this object, the hologram turns on in the correct spot.

Spatial sound is used to simulate 3D sound in a simulation. The sound can be used to indicate off screen events and give simulations a more lifelike feel. The astronaut receives most of their task commands as readable text and text-to-speech from the HoloLens.

Coordinate systems are used to accurately place holograms in the environment. HoloLens uses a collection of different coordinate systems to properly place and orient holograms in a simulation. These coordinate systems combine with the spatial mapping to calculate where the holograms should be.

Anchors are used to represent important points in the HoloLens environment. Each anchor has its own local coordinate system and adjusts itself as needed. These anchors can be used to make persistent holograms that will load when an astronaut comes to a recognized space. This is used in reference to the EVA kit. Anchors are used to properly adjust and save the holograms positions between experiment runs.

CHAPTER III:

DESIGN

The Development Environment

This project was developed for the Microsoft HoloLens V1 AR headset. The Unity3D game engine V2017.2.1f1 was used as the development platform. Visual Studio 2017 express edition was the IDE was used for the coding environment. The HoloToolkit V2017.2 was also included in the project to extend Unity's built in AR features. For user interaction, the HoloLens voice recognition and text-to-speech features were used. Voice was used for the subjects to enter commands, and text-to-speech was used to guide subjects through the procedures.

Software

The software design has a layered architecture, consisting of four layers.

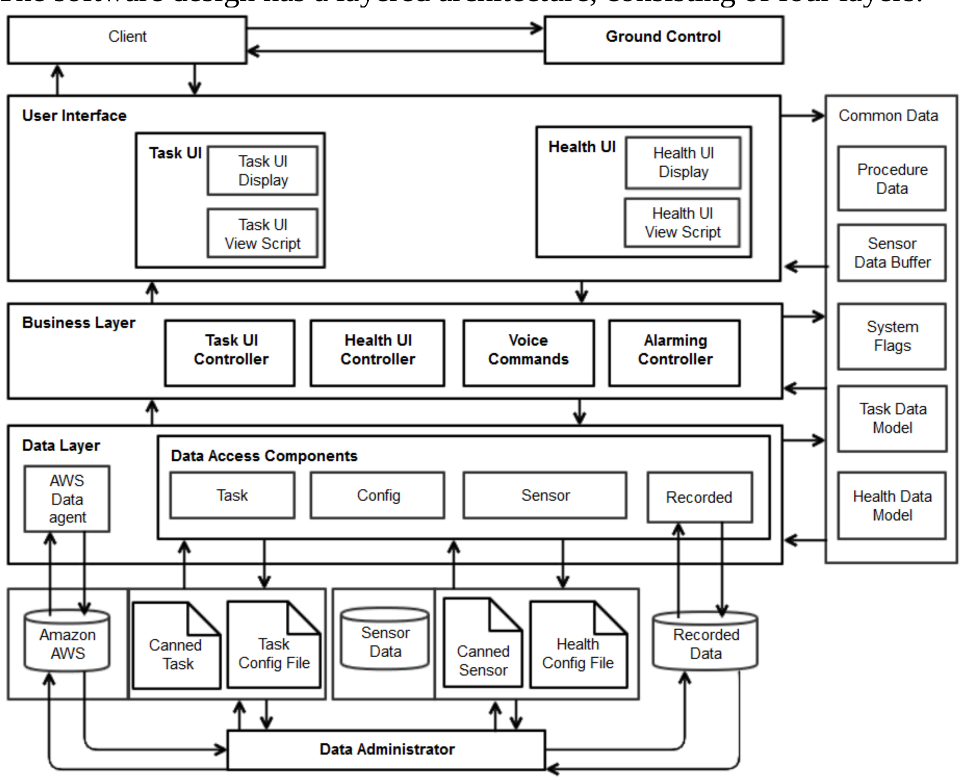

Figure 3 System Architecture

There is a shared layer to the architecture called the common data layer. This stores flags and configuration information about the system. The UI layer reads the data in this area to update the display. The business layer changes the flags and current data of the system in this layer, based on events from the UI layer. It also monitors the ranges of the data for the alarming system. The business layer instructs the data layer to populate the common data based on the configuration of the system.

The data access layer has several modules for receiving and converting data into objects; the system understands and defines the definitions of these objects. The system can retrieve data from Amazon Web Services in the form of a JSON file. There are also modules for reading .csv files and getting data from a local SQL server database. This layer receives instruction from the business layer to read and write into the common data. This layer also logs the results of the experiment in .csv files.

The business layer acts as a middleman to the data access layer and user interface layer. Based on the configuration of the system, it tells the data layer where to pull information for the experiment, and where to store it in the common data. This layer also handles the event requests from the UI layer above it. The business layer controls the state of the system and sets/clears flags as events occur. It monitors the ranges of values for the consumables display and sets warnings and alarms when the values go out of range. This layer handles the procedure creation and navigation, sending information to the text-to-speech system, and sets flags to turn holograms on and off.

The user interface level renders the current state of the system. The business layer sets the current values in the common data, and the user interface reads these values and displays them in a meaningful way. This interface has the concept of a HUD interface where the instructions for the procedure and consumable values are displayed at a fixed point relative to the headset's orientation, displaying fixed holograms in the 3D environment the subject is working in. The consumable interface has two versions to display the same data. The display to be used is chosen when the program is launched. These two types included a sprocket version that shrank as values decreased and grew as they increased. When these values went out of range, the colors would change from green to yellow for cautions, and then change to red for warnings.

Hardware

The project recreates NASA's EVA task board to test our system. Subjects are asked to step through two procedures. They are to pull a bad fuse and reroute the power on the board. This includes steps like locating objects of interest on the task board and interacting with them to complete the procedure.

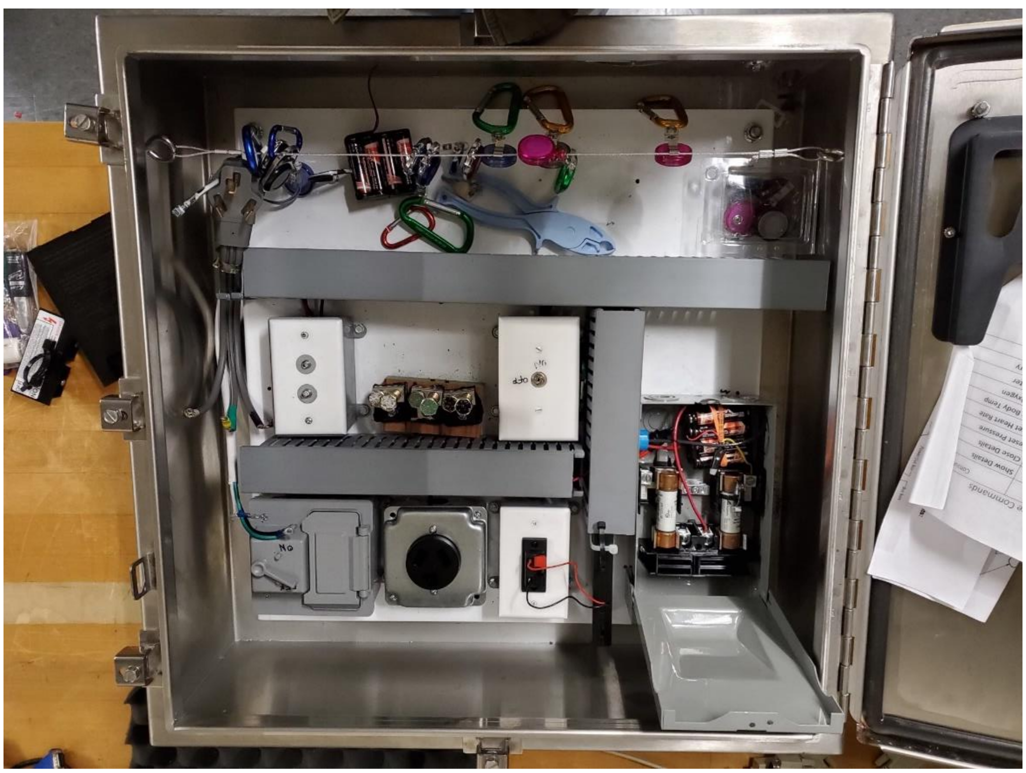

Figure 4 UHCL EVA Kit

Some of the task steps required tools. There is a fuse puller, backup battery packs, and power cables for rerouting power. The subjects were asked to wear gloves to mimic the environment that an astronaut works in. In an EVA, an astronaut cannot work with their bare hands, reducing their refined motor controls and their sense of touch.

Figure 5 EVA Kit Tools

Experiment

The current study was approved by the University of Houston Clear-Lake Review Board. The study was conducted on the campus, and subjects were recruited via flyer. 37 were a combination of undergraduate and graduate students and one was a professor.

The subject pool was split into two random groups. Each group was tested using one of two different versions of the health UI. One is in the shape of a sprocket with slices representing each consumable (UHCL Display). The other displays information in text and with bar charts (representation of NASA default). Both are color-coded the same and are in the bottom left of the subject's HUD.

The subject pool consisted of 36 subjects, mostly university students. Each display was tested by 18 subjects in an alternating order. This creates a completely randomized set of data. Their primary task was to complete the EVA procedures and as a secondary task, keep themselves alive by monitoring and maintaining their consumables. The secondary task is the task in which we are interested in testing.

The experiment is mixed in qualitative and quantitative measures of a variance model. The subjects were measured by their responses by instrumenting (automatic logging of subject interaction with the system) the HoloLens, asked to fill out a demographics survey and given a Questionnaire for User Interaction Satisfaction (QUIS) on their experiences. (Appendix C)

This experiment has many factors to consider, such as the users' experience with games and AR/VR systems. The users were also asked about the perceived quality of their experience with questions, such as: Were the displays confusing? Did you feel like the displays were a distraction? Could you read the text on the displays? The answers to these questions were then compared between the UI types.

For the quantitative measure, the HoloLens was instrumented to record when events occurred. Any time a user issued a command, the time as taken down and the values of the consumables were recorded. When the consumable values went out of range, the time was recorded, and the event type was logged. When users tried to issue commands out of context, such as a "close details" command when they were not in a detail screen, they were logged as errors and the time was recorded.

CHAPTER IV:

RESULTS

Demographics

All of the subjects that participated in the study were recruited from flyers distributed on the UHCL campus. Some of them were recruited by faculty in their classes. This led to most of the subjects being in the college age range with similar educational backgrounds. 18 of the students were undergraduate age, at 18 to 24. 17 of the subjects were graduate age 25 to 34, and 1 subject was a professor in the 55 to 64 age range.

The distribution of male to female subjects was almost equal. There were 19 male and 17 female subjects.

The subjects who required glasses were equal to those who did not. While some headsets do not allow for users to wear glasses, the HoloLens does. A user's vision should not be impaired while using the headset.

Subject's familiarity with AR was diverse. eight of the subjects answered that they had no experience with AR, while only three had a lot. nine of the subjects said they had an average amount of AR experience. 21 of the 36 subjects had a moderate and above experience with AR, and 28 of them had at least experienced AR.

Seven of the 36 subjects have never been exposed to VR while only three had a lot of experience. 19 of the subjects had moderate and above experience with VR and 17 below. Of the 36 subjects 29 of them have had at least been exposed to VR.

31 of the subjects currently play some form of video games. Only five subjects answered they do not play video games at all. 13 of the subjects frequently play video games. 27 of the subjects said that they play video games at least a moderate amount.

For demographics charts and the full table of answers by subject, see appendix A.

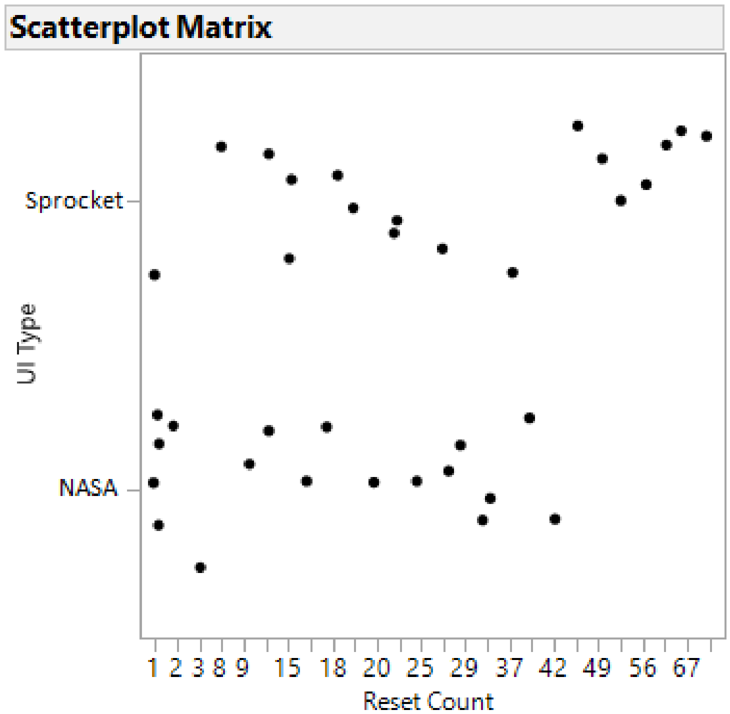

Figure 6 Reset Commands by UI type

When a health value goes out of range, the users are expected to reset them and promptly get back to work. This is done by opening a detail window and issuing a reset command on the proper value. Figure 6 shows the amount of reset commands a subject used while the study was being conducted. four subjects did not use the reset when using the NASA UI, while only one using sprocket UI failed to use the command. The top seven results are subjects using the sprocket UI. The average use of reset across NASA UI subjects was 17.2 with a total of 310. The average use of the reset across sprocket UI subjects was 33.11, with a total of 596 resets.

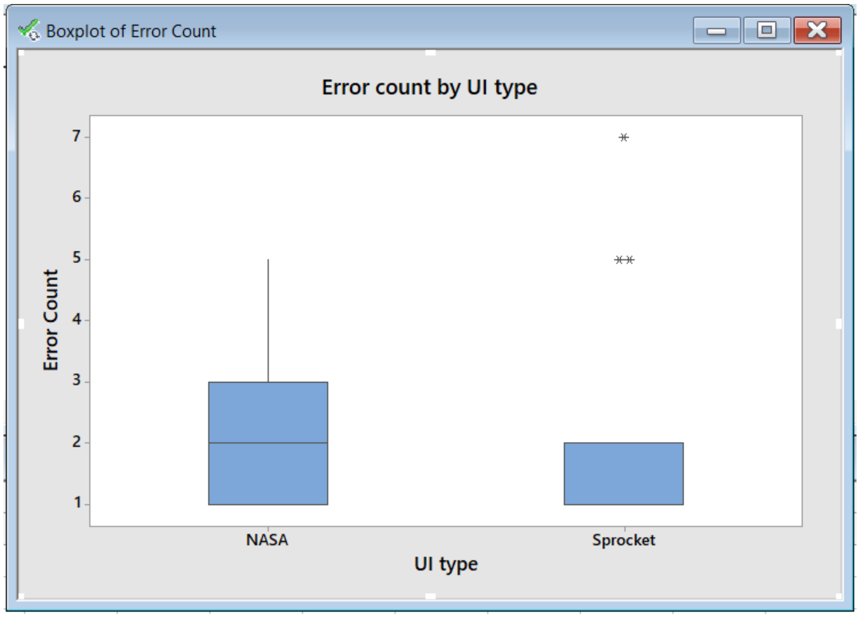

Figure 7 Errors made by UI Boxplot

```
Analysis of Variance

Source   DF   Adj SS    Adj MS  F-Value  P-Value
UI type   1   0.0886   0.08864     0.03    0.858
Error    26  70.6256   2.71637
Total    27  70.7143

Model Summary

      S    R-sq  R-sq(adj)  R-sq(pred)
1.64814  0.13%      0.00%       0.00%

Means

UI type    N   Mean  StDev       95% CI
NASA      13  2.154  1.345  (1.214, 3.093)
Sprocket  15  2.267  1.870  (1.392, 3.141)

Pooled StDev = 1.64814
```

Figure 8 One-way ANOVA of Errors Made by UI

An error indicates that a subject tried to issue a command in the wrong context. These include trying to clear warnings while in the task UI, trying to advance tasks while in the show details window, or trying to change to a state they are already in. This box plot demonstrates that most subjects that made an error made one to three errors. There were 13 subjects that made errors using the NASA UI and 15 using the sprocket. A total of 28 out of 36 of the subjects made mistakes. The three subjects that made the most mistakes were using the sprocket interface having five to seven errors. As shown in

Figure 8 doing a one-way ANOVA shows there is no statistical significance in this comparison.

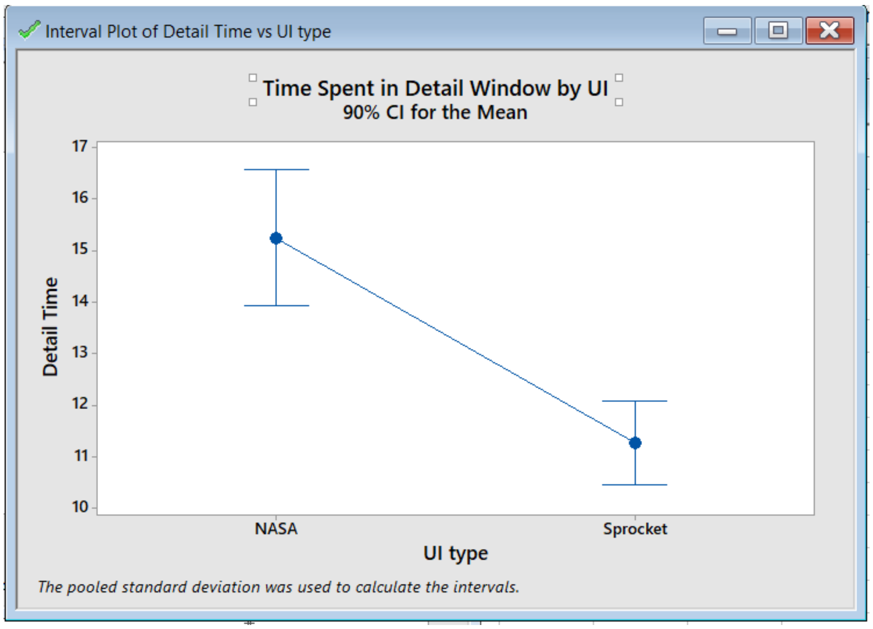

Figure 9 Interval Plot of Detail Time vs UI Type

```
Analysis of Variance

Source    DF   Adj SS  Adj MS  F-Value  P-Value
UI type    1    944.2  944.25    17.81    0.000
Error    297  15743.2   53.01
Total    298  16687.5


Model Summary

      S   R-sq  R-sq(adj)  R-sq(pred)
7.28063  5.66%      5.34%       4.07%


Means

UI type     N    Mean  StDev        90% CI
NASA       82   15.26   9.73  ( 13.93,  16.58)
Sprocket  217  11.273  6.116  (10.458, 12.089)

Pooled StDev = 7.28063
```

Figure 10 Average Time Spent in Details by UI Type

The subjects were measured on how long it took them to reset a value that has gone out of range. This is measured by the amount of time that passes between an “open details” command and a “close details” command. On average, the subjects that had the sprocket interface cleared warnings faster than those using the traditional NASA interface. There are three instances of clearing the warnings that took longer than 50 seconds that were associated with the NASA interface, while the highest sprocket time was 34 seconds. The average time it took for a subject to clear a warning using the sprocket UI was 11.3 seconds while the average NASA time was 15.3 seconds. A one-way ANOVA shows that there is a significant difference between the NASA and sprocket UI. With a P value of 0 the subjects that used the Sprocket design are significantly faster at clearing warnings than the subjects that used the NASA interface.

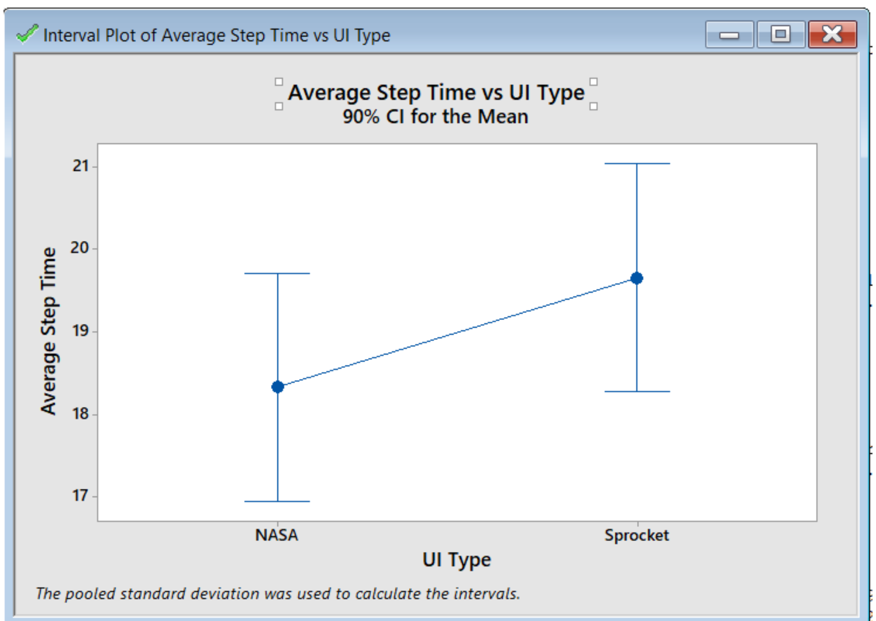

Figure 11 Average Time Between Steps by UI

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
UI Type	1	15.65	15.65	1.31	0.261
Error	34	407.29	11.98		
Total	35	422.94			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
3.46111	3.70%	0.87%	0.00%

Means

UI Type	N	Mean	StDev	90% CI
NASA	18	18.336	3.295	(16.957, 19.716)
Sprocket	18	19.655	3.619	(18.275, 21.034)

Pooled StDev = 3.46111

Figure 12 One-Way ANOVA of Average Time Between Steps by UI

The average time to complete a task step was taken by recording the subject's total time to complete the experiment and dividing by the total number of next step commands that the subject issued. The average completion time of a subject using the NASA interface was 1172 seconds, and 1271 using the sprocket interface. Most subjects were in the range of 65 to 67 next step commands. On average it took longer for subjects using the sprocket to finish a step with an average of 19.7 seconds, and 18.3 using the NASA UI.

Only subject 12 did not complete the experiment, causing them to have only 54 next step commands. This was a result of the system crashing near the end of the experiment. Because the completion time was shorter due to a crash, and the next step commands issued were proportional to the time the subject participated, the average is relatively the same with a completion time of 1080 seconds and an average step time of 20 seconds using the NASA UI. The one-way ANOVA of this data Figure 12 shows that there is no significant difference between the two UI types.

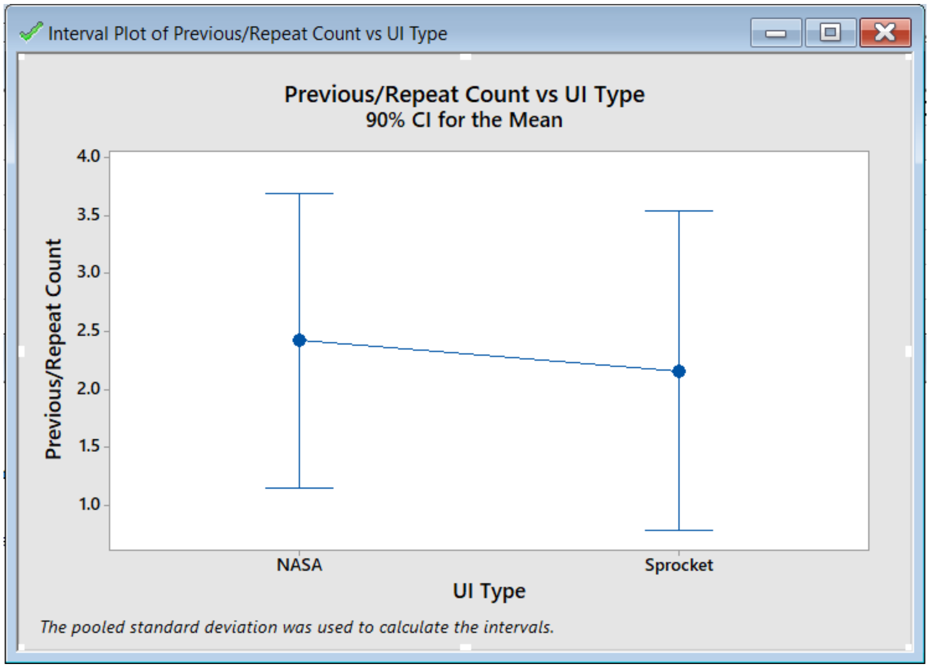

Figure 13 Amount of Repeat/Previous Step Commands by UI Type

```
Analysis of Variance

Source    DF   Adj SS   Adj MS  F-Value  P-Value
UI Type    1   0.2216   0.2216     0.06    0.806
Error     11  38.5476   3.5043
Total     12  38.7692


Model Summary

      S    R-sq  R-sq(adj)  R-sq(pred)
1.87199   0.57%      0.00%       0.00%


Means

UI Type    N   Mean  StDev        90% CI
NASA       7  2.429  2.299  (1.158, 3.699)
Sprocket   6  2.167  1.169  (0.794, 3.539)

Pooled StDev = 1.87199
```

Figure 14 One-Way ANOVA Amount of Repeat/Previous Step Commands by UI Type

When a user is confused about the current step, they have the option to issue a repeat step, which has Cortana read the step aloud to the subject or go back to the previous step. In the experiment, 13 subjects used these repeat commands at least once, seven subjects on the NASA UI, and six on the sprocket UI. Subject 21 had the most uses at seven, using the NASA UI.

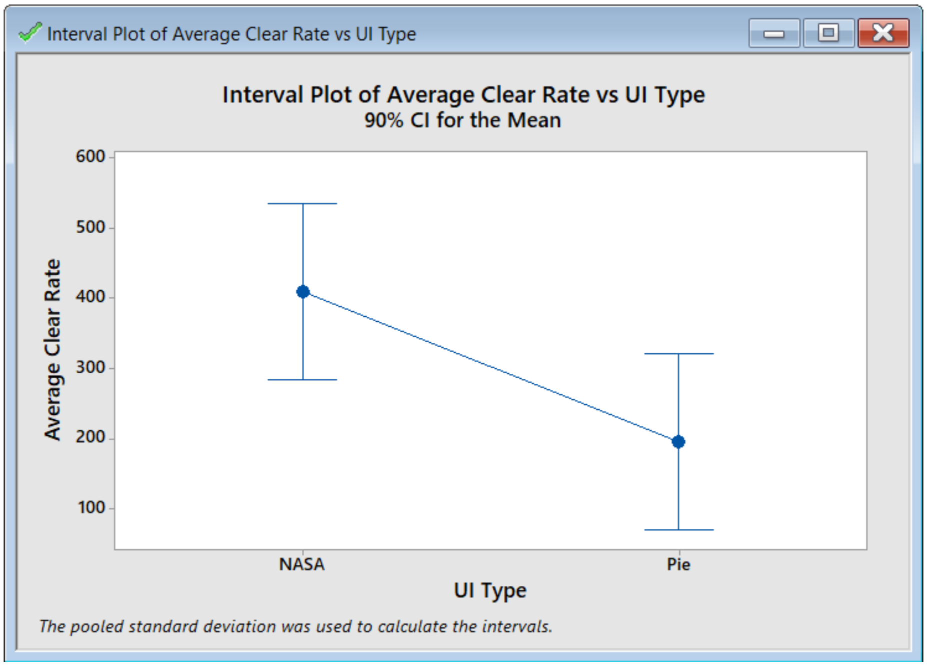

Figure 15 Interval Plot of Average Clear Rate vs UI Type

```
Analysis of Variance

Source   DF  Adj SS   Adj MS  F-Value  P-Value
UI Type   1  409379  409379     4.12    0.050
Error    34  3376521  99309
Total    35  3785899


Model Summary

      S    R-sq  R-sq(adj)  R-sq(pred)
315.134  10.81%      8.19%       0.01%


Means

UI Type   N   Mean  StDev      90% CI
NASA     18  409.4  390.1  (283.8, 535.0)
Pie      18  196.1  215.5  ( 70.5, 321.7)

Pooled StDev = 315.134
```

Figure 16 One-way ANOVA results for Average Clear Rate vs UI Type

For each warning that happens, the duration it is active is calculated and added to the running total time of active warnings. This is done for yellow and red states of each consumable. Once the running total time is calculated, it is divided by the total number of warnings. This total for each user was then grouped by UI type and compared using One-Way ANOVA (See Figure 20).

CHAPTER V:

DISCUSSION

Efficiency

When looking to analyze which user interface make the subjects more efficient, several factors were considered. When a subject is doing the experiment, their need to repeat or “go back” a task instruction is counted as a potential indication of distraction and to see how efficient a user is with their time. The higher the repeat count, the less efficient the subject completes the task. Any commands that result in an error reduce a user’s efficiency, as well as the subject’s average task completion time.

The total amount of users that issued repeat or previous step commands was 13. 54 percent of the users that had to redo steps were using the NASA interface. The highest amount was seven, by subject 21. Subject 21 responded that they had moderate experience with AR and VR and played games frequently. They also gave max positive responses about their experience. The total number of repeat and previous steps were 30 and 17 of them were using the NASA interface 57 percent total.

Of the 36 users, 28 of them made errors. The sprocket UI had 15 users make errors with the three top subjects making errors being five, five, and seven. Subject 1 made five errors and stated that they had no experience with AR or VR. Subject 20 made five errors and had a moderate amount of AR experience with a lot of gaming and VR experience. Subject 35 made seven errors and had very little experience with AR, VR, or Games. The NASA interface had 13 users who made errors, 46 percent of the total. The average amount of errors was two for both displays.

The sprocket UI required less users to repeat or use previous commands but did not perform as well as the NASA interface for making errors. The subjects who made the most errors responded on their demographics survey that they had little to moderate experience using AR/VR or playing video games. These results may be more conclusive with a larger pool of subjects.

Situational Awareness

Situational awareness is measured by how frequently the subjects clear their warnings over time. If a subject fails to clear warnings because they are too focused on the procedure of the EVA, it will be reflected in these values. It is important that the subjects clear warnings while also doing the EVA tasks. If the subjects are not monitoring their values consistently, they are not maintaining situational awareness with regards to their health.

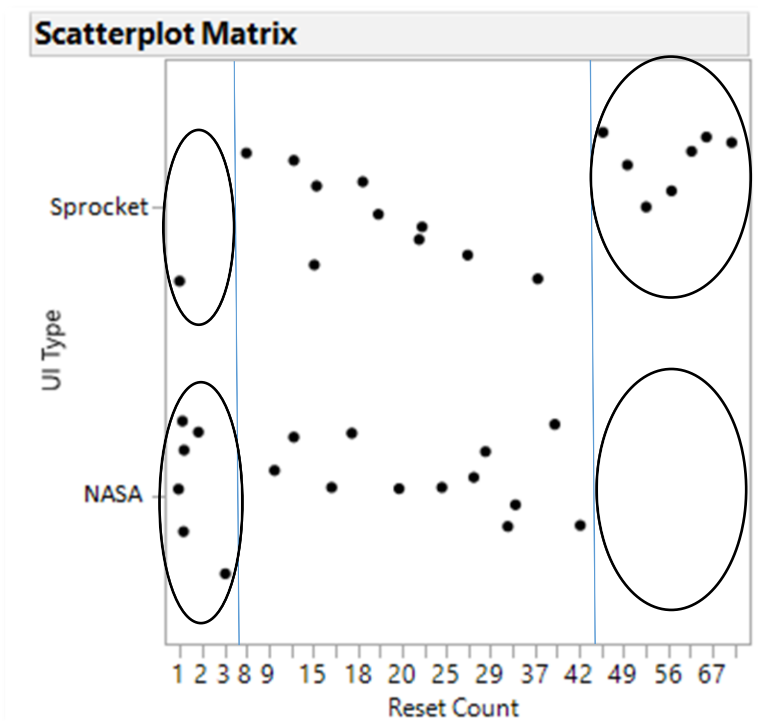

Figure 17 Resets by UI type

Looking at Figure 17, there is an obvious trend to the clearing of the consumable warnings, and how they differ between the user interfaces. The NASA interface has seven people who cleared less than three (3) warnings total, while the sprocket only has one person who ignored the warnings. The top seven subjects who cleared warnings were all using the sprocket interface.

A warning time was measured by the time it occurred until the time it was reset Figure 15. If a warning goes from yellow to red, the time that is being recorded is being counted for both. This is applying a double time penalty for the increased severity of the warning. These times are then added to a total warning time and then divided by them amount of warnings that occur. For a person who ignored the warnings completely, this time becomes large very quickly, and, since the warnings are never cleared, has a low divisor driving up their average. When using this method of comparison, the subjects using the sprocket interface outperform subjects using the NASA interface. Doing a one-way ANOVA analysis, you can see in Figure 16 of the average warning clear rate to UI type gives a P-value of .05 and F-value of 4.12. This is a statistically proven increase of situational awareness in the sprocket subjects over the NASA subjects.

The amount of time a subject had their detail window open was measured. There was a significant difference between the subjects using the sprocket versus the NASA UI. In Figure 11the one-way ANOVA shows that subjects using the sprocket were taking significantly less time to clear warnings in the detail window. This allowed subjects to spend minimal time away from the primary task and retain situational awareness. The sprocket design appears to be less jarring than the detail window for the NASA UI.

The sprocket interface increases situational awareness effectively over the NASA interface. The subjects using it were more aware of their warnings. More of these subjects cleared warnings at a higher rate, and when they cleared warnings they were more efficient at it. Only one of the subjects ignored the sprocket completely over the seven who had zero to three clears on the NASA interface. The subjects using the sprocket maintained their situational awareness and kept their average warning clear time below the NASA subjects.

Effectiveness

The effectiveness of the displays is measured using the average reset time of a warning, and many resets are being done during an EVA. The effectiveness for the consumables is measured by the same metrics as situational awareness. When someone is aware of their situation, they will be more effective at clearing the warnings.

The results of the warnings being cleared showed that the sprocket interface subjects were more likely to not ignore the warnings and to consistently clear them.

Future

Having specialized participants would increase the quality of the results. Finding people with a background in AR that are mechanically inclined would help get meaningful interactions with the system. Though this project could have many uses outside of this scenario, the test was focused on a situation where the subject would be highly trained on the system they were using. The visualization of data in a real time dangerous environment is not meant for untrained individuals that are not under real pressure. Stressing the importance of the experiment may help, but many of the participants were treating it like a game rather than a situation with life or death consequences, and the novelty of the headset often distracted them from their tasks.

CHAPTER VI:

FUTURE

AR is continuously improving. As this experiment is being conducted, the next generation of HoloLens has already been announced. The original HoloLens is not a consumer product and is the first generation of this type of device. Many of the subjects had issues using the device. The field of vision is restricted to 30 degrees, the headset does not always sit comfortably, and it can get hot or have performance issues after extended periods of use. The new headset is said to be much more stable, have a 90-degree viewing angle, and is more balanced for comfort. With these improvements, subjects would naturally perform the tasks better.

The sprocket design may benefit from a larger size, additional information on the display, or more interaction types. The current design is fixed on the HUD requiring the subject to use voice commands for interaction. This could be solved by either being able to pull the UI off the HUD and into the environment or adding some form of eye tracking. The submenus or detail menu is a scaled-up version of the sprocket that blocks the subject's vision when it is active. This was an intentional decision to keep subjects from doing tasks while they were in this menu to measure how effectively they cleared warnings and returned to their work. In practice, this is not an ideal design and would block an astronaut's vision while they are trying to work. The size of the sprocket does not allow for more information to be displayed. The idea was to increase a subjects reasoning power at a glance but if they needed additional information, they were forced to go into the submenu. A medium detailed design might be better where the size and color of the sprocket provides the glance information while some summary details could be added to the insides of the slices.

Doing more iterations of prototypes and small groups of user testing would have helped increase the quality and usability of the project. The current project had 4 pilot studies to refine the system to its current state. The tasks were often too complicated or not broken down enough for the users to complete them without assistance. Once broken down into very small incremental steps, users would complete two steps at once without realizing it and get confused. The tasks should take a certain level of concentration, but they were often difficult enough to distract the subjects from the consumables display entirely. Several uses experienced a learning curve where they would focus completely on the tasks until they were comfortable and only then realize that their consumables were going out of range. It was evident that the users were prioritizing the completion of the tasks over keeping their consumables values in the appropriate ranges.

Currently, the holograms may be more distracting than helpful. They overlay the object of importance, obscuring the subject's vision. Adding animations pointing to the object may be more helpful in conveying what the subject should do and where, versus having static holograms in the environment as a guide. Having a system for finding non-static objects of interest in the environment would help usability. The subjects got accustomed to having holograms being on all the objects they interacted with, but when they were asked to find a tool in a general area of a hologram, they got confused. Combining this with eye track would allow the system to find out where a subject was looking, versus where the object was and guide them to it.

This project has potential applications in other fields. Having a series of panels that feature more complex tasks would be the next step in making this a commercial product. Using an image recognition tool to detect which panel the user is in and anchoring instructional holograms from the image would allow a subject to complete complex tasks efficiently and effectively with little background knowledge on the system they are working on. This system could be used in many applications where knowledge transfer is a barrier, such as maintenance on complex systems and other services. This would allow an expert to operate in a home location and monitor less experienced operators in the field.

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APPENDIX A:

DEMOGRAPHICS INFORMATION

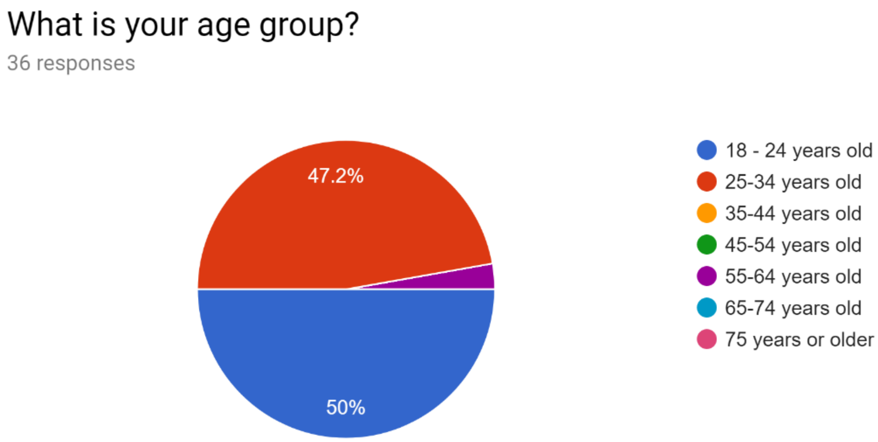

Figure 18 Age Group Sprocket Chart

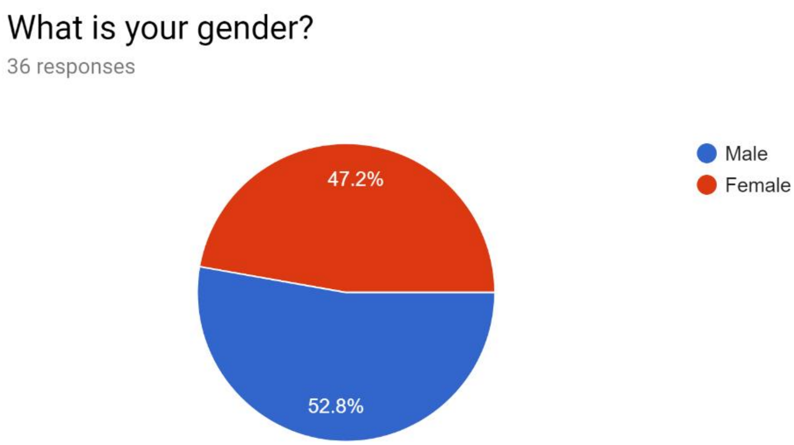

Figure 19 Gender Sprocket Chart

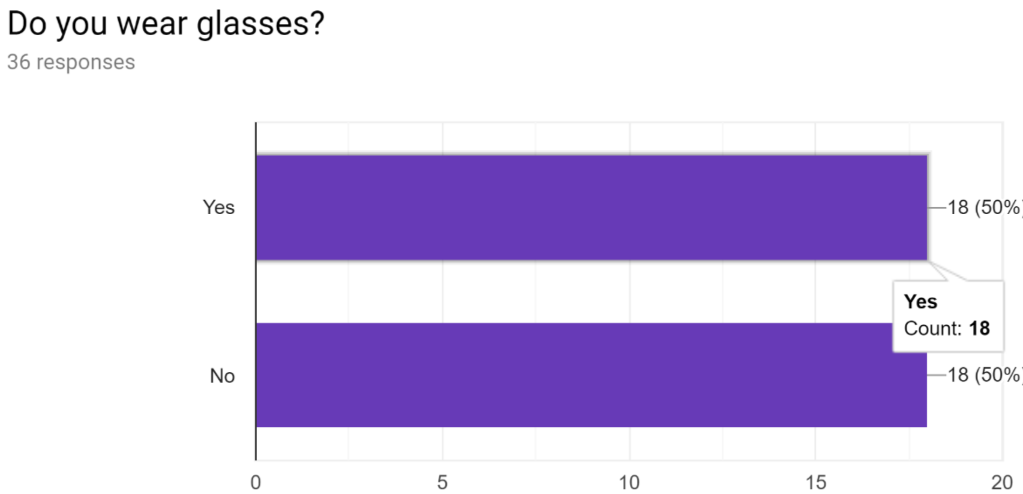

Figure 20 Glasses Bar Graph

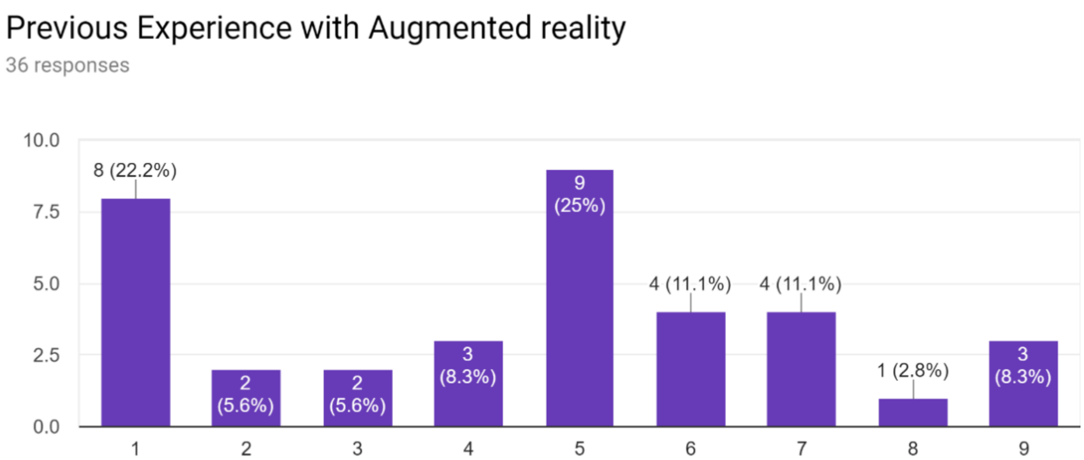

Figure 21 Augmented Reality Experience Bar Chart

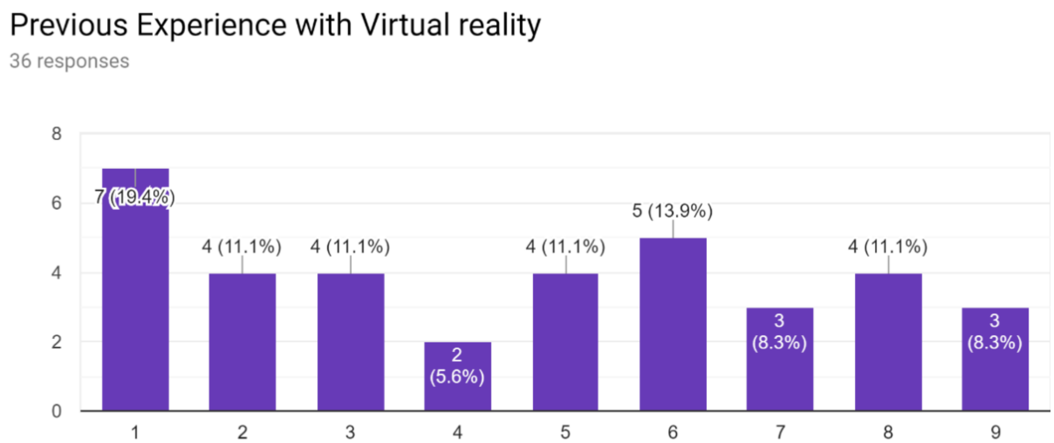

Figure 22 Experience with Virtual Reality Bar Chart

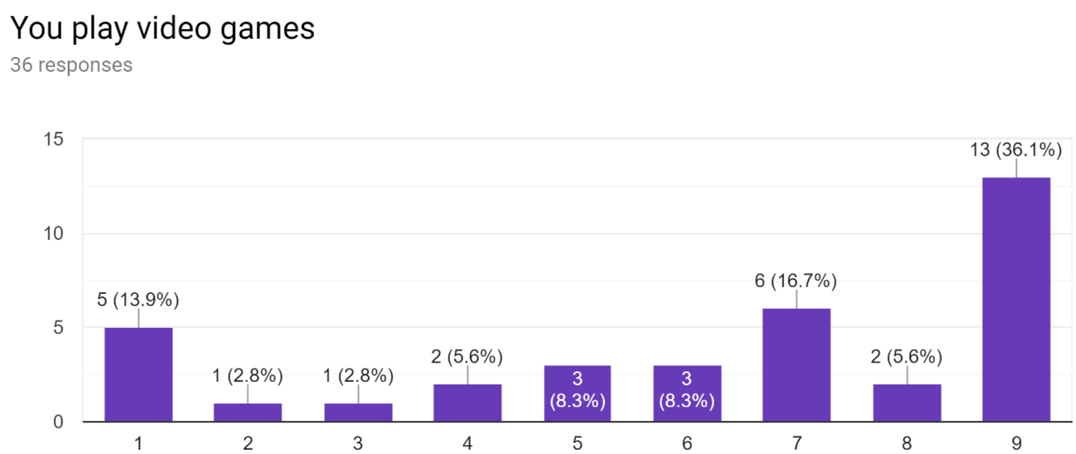

Figure 23 Video Game Experience Bar Chart

subject	glasses	age_group	highest_education	marital_status	employment	ethnicity	Race	gender	ARXP	VRXP	play_games
1	Yes	25-34 years old	College Graduate	Single/Never been married	Part-time	No	Asian / Pacific Islander	Male	1	1	7
2	No	25-34 years old	College Graduate	Single/Never been married	Part-time	No	White	Female	5	6	9
3	No	18 - 24 years old	College Graduate	Single/Never been married	Not employed	No	Asian / Pacific Islander	Female	9	8	7
4	No	25-34 years old	Some College	Single/Never been married	Part-time	No	White	Male	6	9	9
5	No	18 - 24 years old	College Graduate	Single/Never been married	Not employed	No	Asian / Pacific Islander	Female	4	4	5
6	Yes	18 - 24 years old	College Graduate	Single/Never been married	Not employed	No	Asian / Pacific Islander	Female	1	6	1
7	No	18 - 24 years old	College Graduate	Married	Not employed	No	Asian / Pacific Islander	Female	6	7	4
8	Yes	25-34 years old	Trade/Technical/Vocational Training	Single/Never been married	Not employed	Yes	Hispanic or Latino	Male	5	7	9
9	Yes	18 - 24 years old	College Graduate		Part-time	No	Black or African American	Female	2	2	1
10	No	25-34 years old	Trade/Technical/Vocational Training	Single/Never been married	Full-time	No	White	Male	5	3	6
11	Yes	25-34 years old	College Graduate	Single/Never been married	Part-time	No	Asian / Pacific Islander	Female	7	5	1
12	No	18 - 24 years old	College Graduate	Single/Never been married	Not employed	No	Asian / Pacific Islander	Female	7	8	8
13	No	25-34 years old	College Graduate	Married	Not employed	No	Asian / Pacific Islander	Female	4	3	1
14	Yes	25-34 years old	College Graduate	Single/Never been married	Not employed	No	Asian / Pacific Islander	Female	7	6	5
15	Yes	18 - 24 years old	College Graduate	Single/Never been married	Not employed	No	Asian / Pacific Islander	Female	7	7	9
16	No	18 - 24 years old	College Graduate	Single/Never been married	Not employed	No	Asian / Pacific Islander	Male	1	1	7
17	Yes	18 - 24 years old	Post Graduate Degree	Single/Never been married	Not employed	No	Asian / Pacific Islander	Male	9	5	9
18	Yes	25-34 years old	Some College	Single/Never been married	Not employed	Yes	Hispanic or Latino	Male	6	6	9
19	No	18 - 24 years old	College Graduate	Single/Never been married	Not employed	No	Asian / Pacific Islander	Female	1	1	9
20	Yes	25-34 years old	College Graduate	Single/Never been married	Part-time	Yes	Hispanic or Latino	Male	5	8	9
21	Yes	25-34 years old	College Graduate	Single/Never been married	Not employed	No	Asian / Pacific Islander	Male	6	5	8
22	Yes	18 - 24 years old	College Graduate	Single/Never been married	Not employed	No	Asian / Pacific Islander	Female	1	1	6
23	Yes	25-34 years old	College Graduate	Single/Never been married	Part-time	No	Asian / Pacific Islander	Female	1	9	3
24	No	25-34 years old	Some Post Graduate Work	Single/Never been married	Not employed	No	White	Male	5	1	9
25	No	18 - 24 years old	College Graduate	Single/Never been married	Not employed	No	Asian / Pacific Islander	Male	5	3	5
26	Yes	18 - 24 years old	College Graduate	Single/Never been married	Not employed	No	Asian / Pacific Islander	Male	8	8	6
27	Yes	18 - 24 years old	College Graduate	Single/Never been married	Part-time	Yes	Hispanic or Latino	Female	1	5	7
28	No	25-34 years old	Some College	Single/Never been married	Part-time	No	White	Male	1	1	2
29	Yes	25-34 years old	Some College	Single/Never been married	Not employed	No	Asian / Pacific Islander	Male	3	2	7
30	Yes	18 - 24 years old	Some College	Single/Never been married	Not employed	No	White	Male	5	1	9
31	No	18 - 24 years old	Some College	Single/Never been married	Not employed		White	Male	5	3	9
32	No	18 - 24 years old	High School Graduate	Single/Never been married	Part-time	Yes	Hispanic or Latino	Male	5	6	7
33	No	55-64 years old	Post Graduate Degree	Married	Full-time	No	White	Female	4	4	1
34	No	25-34 years old	Post Graduate Degree	Single/Never been married	Not employed	No	Asian / Pacific Islander	Male	9	9	9
35	Yes	25-34 years old	Some College	Single/Never been married	Not employed	No	Asian / Pacific Islander	Female	3	2	4
36	No	18 - 24 years old	Some College	Single/Never been married	Part-time	Yes	White	Male	2	2	9

Figure 24 Table of Demographics Information

APPENDIX B:

VOICE COMMANDS

Procedure	Consumables
Start Procedure	Show Details
Next Procedure	Close Details
Next Task	Reset Pressure
Repeat Task	Reset Heart Rate
Previous Task	Reset Body Temp
Start	Reset Oxygen
	Reset Water
	Reset Battery
	Continue

APPENDIX C:

DEMOGRAPHICS INFORMATION

Usability of the system

1. **Subject number**

____

2. **Characters on the User Interface**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	
hard to read	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	easy to read

3. **User Interface layouts were helpful**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	
Never	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Always

4. **Arrangement of information on User interface**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	
Illogical	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	logical

5. **Amount of information displayed on the user interface**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	
not enough	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	too much

6. **Use of terminology throughout system**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	
inconsistent	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	consistent

7. **Terminology relates well to the work you are doing?**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	
always	◯	◯	◯	◯	◯	◯	◯	◯	◯	never

8. **Instructions for commands or functions**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	
confusing	◯	◯	◯	◯	◯	◯	◯	◯	◯	clear

9. **Learning to operate the system**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	
difficult	◯	◯	◯	◯	◯	◯	◯	◯	◯	easy

10. **Time to learn to use the system**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	
slow	◯	◯	◯	◯	◯	◯	◯	◯	◯	fast

11. **Tasks can be performed in a straight-forward manner**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	
never	◯	◯	◯	◯	◯	◯	◯	◯	◯	always

12. **Ease of operation depends on your level of experience**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	
never	◯	◯	◯	◯	◯	◯	◯	◯	◯	always

13. **You can accomplish tasks knowing only a few commands**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	
with difficulty	◯	◯	◯	◯	◯	◯	◯	◯	◯	easily

14. **The system responded to voice commands**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	
never	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	always

15. **Additional Comments for Usability of the system**

The Consumables User Interface

16. **I can monitor the consumables with a quick glance**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	
with difficulty	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	easily

17. **Monitoring consumables while doing tasks**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	
difficult	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	easy

18. **Clearing warnings while doing task**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	
distracted	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	undisturbed

19. **Placement of consumable warning messages on the user interface**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	
confusing	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	clear

20. **I noticed a warning when it occurred**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	
never	◯	◯	◯	◯	◯	◯	◯	◯	◯	Immediately

21. **Clearing consumable warning messages**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	
difficult	◯	◯	◯	◯	◯	◯	◯	◯	◯	easy

22. **Accessing consumable details**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	
difficult	◯	◯	◯	◯	◯	◯	◯	◯	◯	easy

23. **The consumables voice commands were easily recognized by the system.**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	
disagree	◯	◯	◯	◯	◯	◯	◯	◯	◯	agree

24. **The color code for the consumables is easy to understand.**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	
difficult	◯	◯	◯	◯	◯	◯	◯	◯	◯	easy

25. **Additional Comments for Consumables Interface**

The Task User Interface

26. **Task U.I has clear sequence of screens.**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	
Confusing										Clear

27. **I went back a step.**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	
Never										Frequently

28. **I had to repeat a step**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	
never										frequently

29. **Read the Cautions/warnings related to current step.**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	
never										always

30. **I used the images related to current step.**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	
never										always

31. **Terminology used in the Task user Interface is related to the tasks.**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	
never										always

32. **Highlighting the current step helps user to clearly understand the task.**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	
not at all										very much

33. **Navigation from one step to other is taking minimum time.**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	
Inconsistent	○	○	○	○	○	○	○	○	○	Consistent

34. **User can perform the task correctly.**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	
never	○	○	○	○	○	○	○	○	○	always

35. **User can find all the information related to the step.**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	
never	○	○	○	○	○	○	○	○	○	always

36. **Holograms make the task process easier.**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	
never	○	○	○	○	○	○	○	○	○	always

37. **overall task User Interface.**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	
frustrating	○	○	○	○	○	○	○	○	○	satisfying

38. **Additional comments for Task Interface**