

ABSTRACT

Title of Thesis: EVALUATION OF A SPACE
 ROBOTICS CONTROL CONSOLE
 USING EYE TRACKING GLASSES

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This thesis seeks to evaluate the human factors of the design of the space robotics control console to be used at NASA Goddard in the OSAM-1 mission, using eye tracking glasses to gain insights into the ways in which operators interact with the various console elements. An experiment was performed in which trained robot operators wearing eye tracking glasses executed a simplified task on the ground, representative of an attention-intensive in-flight task. As the OSAM-1 mission is not scheduled to launch until 2023, the configuration of this console is still somewhat in flux, so this task was repeated three times in different possible console configurations. Drawing on previous eye tracking literature in combination with the gathered eye tracking data, conclusions were developed about this particular console and task, and more broadly, insights were gained into robot control console design in general.

EVALUATION OF A SPACE ROBOTICS CONTROL CONSOLE USING EYE TRACKING GLASSES

by

Casey R Kracinovich

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Dedication

This thesis is dedicated to my late grandfather, Thomas Kracinovich, who only ever wanted me to do with my life what makes me happy.

And for Luna. May all nine of your lives last longer than your tail.

Acknowledgments

I would like to thank Dr. David Akin for being an almost unconditionally supportive advisor, as well as everyone at the Space Systems Lab. This thesis may not have specifically utilized the lab's resources all that much, but I am incredibly thankful for my time in a one-of-a-kind lab and for the awesome people I worked with. I particularly want to mention Nicholas Limparis for sending me what ended up being a crucial source late in my research, and for Daniil Gribok, for helping me to navigate the world of IT in the time of coronavirus. I should also mention the freshman ENAE100 team who were stuck with a graduate student mentor who just wanted to use them as Guinea pigs to prepare for his thesis.

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providing a home that I can always go back to, even during a pandemic.

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Table of Contents

Dedication	ii
Acknowledgements	iii
List of Tables	vii
List of Figures	viii
List of Abbreviations	x
1 Introduction	1
1.1 Motivation	1
1.2 Research Objective	2
1.3 Thesis Structure	3
2 Background	4
2.1 Manually Teleoperating Serial Manipulators	4
2.1.1 Joint vs Cartesian Space/Movement	4
2.1.2 Hand Controllers	5
2.1.3 Contact Operations	5
2.1.4 Camera Views	6
2.2 Eyes, Eye Tracking, and Eye Tracking Analysis	7
2.2.1 Image Mapping	9
2.2.2 Areas of Interest	10
2.2.3 Events	11
2.2.4 Heatmaps	11
2.2.5 Eye Tracking Metrics	12
3 Methodology	14
3.1 Screens/GUI Configuration	15
3.2 Test Subjects	19
3.3 Experimental Design	20
3.4 Task Performed	26
3.5 Data Gathering Methods	28

4	Results	31
4.1	Participant Background	31
4.2	Eye Tracking Glasses + Participants	31
4.3	Learning Effects	32
4.4	Console Configuration	33
4.5	Initial Patterns Observed	35
4.6	Eye Tracking Data Processing	36
4.7	Dealing With Incomplete + Inaccurate Data	38
5	Analysis	41
5.1	Attention on Each Screen	41
5.2	Transition Matrices, Paired Screens, and GUI Pivoting	46
5.3	Transitions vs Distance Travelled	48
5.4	Focus on EE-left over EE-right	53
6	Conclusions, Lessons Learned, and Future Work	57
6.1	Summary of Conclusions	57
6.2	Problems Encountered	58
6.3	Future Work	63
A	Task Performed	68
B	Interview Questions Asked	72
B.1	Pre-Test Interview	72
B.2	Post-Test Interview	73
C	Personal Screen Configuration	74
D	Time Taken per Subtask	79
E	Additional Figures Generated	81
E.1	Time Percentage per AOI	81
E.2	Time per Fixation per AOI	84
F	Institutional Review Board Paperwork	87
F.1	IRB Initial Application - Part 1	88
F.2	IRB Initial Application - Part 2	94
F.3	Recruitment Material	98
F.4	Introductory Questions	99
F.5	Post-Task Questions	101
F.6	Consent Form	102

List of Tables

3.1	Table describing the standard configuration	20
3.2	Table describing the altered configuration	23
4.1	Table containing operator background information	31
4.2	Minutes taken on each run for each participant	33
4.3	Standard set of events recorded	37
4.4	Percentage of usable data at various points in data processing	39
5.1	Breakdown of task segments for EE-left and EE-right analysis	54
C.1	Table describing the A1 configuration	74
C.2	Table describing the B1 configuration	75
C.3	Table describing the C1 configuration	76
C.4	Table describing the D1 configuration	77
C.5	Table describing the E1 configuration	78
D.1	Table describing the E1 configuration	79

List of Figures

2.1	Translational and rotational hand controllers	5
2.2	A camera view with an overlay on it.	7
2.3	An illustration of fixations and saccades across several screens	8
2.4	An example of a fixation mapped from the video recorded by the eye tracking glasses to a static image of the overall scene	9
2.5	A console with areas of interest on its screens	10
2.6	An example of a heatmap made from the data gathered in this research	11
3.1	The Motoman MH250 robot used in this experiment	14
3.2	Eight screen setup, labelled with numbered boxes	16
3.3	The end-effector cameras	17
3.4	A screenshot of the viz, clearly displaying a model of the MH250 . . .	18
3.5	A screenshot of the Word document, as it appears in on the PC . . .	18
3.6	A screenshot of the GUI as it was used in a data gathering run in this research	19
3.7	Standard configuration overall picture	21
3.8	Standard bottom left center screenshot, with blank space to the left and instructions to the right	21
3.9	Standard bottom right center screenshot, with the GUI to the left and viz to the right	22
3.10	Altered configuration overall picture	23
3.11	Altered bottom left center screenshot, with blank space to the left and instructions to the right	24
3.12	Altered bottom right center screenshot, with the GUI to the left and viz to the right	24
3.13	The operator’s view of the workcell from their console, blocked by the curtain	25
3.14	The hex cap “bathtub” and the end-effector, with the wobble socket circled in red	28
3.15	Tobii Pro Glasses 2, the eye tracking glasses used in this experiment .	29
4.1	Combined heatmap of all operator data in the standard configuration	35
4.2	Combined heatmap of all operator data in the altered configuration .	35

4.3	An illustration of the data processing workflow	38
4.4	An example of inaccurate mapping	40
5.1	Time percentages per screen, standard configuration	42
5.2	Time percentages per screen, altered configuration	42
5.3	Time per fixation per screen, standard configuration	44
5.4	Time per fixation per screen, altered configuration	44
5.5	Screen transition matrix, standard configuration	47
5.6	Screen transition matrix, altered configuration	47
5.7	Scatterplot of distances vs next fixations, standard configuration	49
5.8	Scatterplot of distances vs next fixations, altered configuration	49
5.9	Overall picture, participant A, personal configuration	52
5.10	Screen transition matrix, participant A, personal configuration	52
5.11	Percentage of time spent on EE-left and EE-right	55
C.1	A1 configuration overall picture	74
C.2	B1 configuration overall picture	75
C.3	C1 configuration overall picture	76
C.4	D1 configuration overall picture	77
C.5	E1 configuration overall picture	78
E.1	Participant A time percentage per AOI.	81
E.2	Participant B time percentage per AOI.	82
E.3	Participant C time percentage per AOI.	82
E.4	Participant D time percentage per AOI.	83
E.5	Participant E time percentage per AOI.	83
E.6	Participant A time per fixation per AOI.	84
E.7	Participant B time per fixation per AOI.	84
E.8	Participant C time per fixation per AOI.	85
E.9	Participant D time per fixation per AOI.	85
E.10	Participant E time per fixation per AOI.	86

List of Abbreviations

OSAM-1	On-orbit Servicing, Assembly, and Maintenance 1
AOI	Area of interest
SSRMS	Space Station Remote Manipulator System
EE-left	The left end-effector camera view
EE-right	The right end-effector camera view
GUI	Graphical user interface
DVR	Digital video recorder
IRB	Institutional Review Board

Chapter 1: Introduction

1.1 Motivation

Manually teleoperating a serial manipulator, and in particular manually teleoperating a serial manipulator in space from the ground, is a complex task which requires the operator to split their attention between command dialogues, data streams, and video feeds. These various elements are displayed on a robotic control console; a workstation with multiple screens containing the aforementioned elements, as well as a mouse, keyboard, and hand controllers. Though the input devices for teleoperation control are relatively straightforward to operate, it may be difficult, if not impossible, to fix mistakes made while remotely operating a robot in space, so it is imperative that the display elements of the console are arranged in the best possible configuration for the task to be performed. Ideally, using the information displayed on the console, operators should easily be able to maintain a mental model of the manipulator's position and environment, while simultaneously monitoring task-relevant telemetry and inputting commands.

It is possible that the scan patterns between these elements may be the defining factor in facilitating the operators' ability to absorb the necessary information, so it may be possible to gather the information needed to improve the operators' scan

patterns by tracking the operators' eye movements. Eye tracking is already widely used as a tool for evaluating user interfaces, in applications ranging from web design [1] to aircraft cockpits [18]. However, there are no known instances of using eye tracking to evaluate a robotic control console, let alone a console specifically meant for space applications.

The NASA mission, OSAM-1 (On-orbit Servicing, Assembly, and Maintenance 1), has a specific need for a well-designed space robot control console. OSAM-1 is a mission set to launch in 2023, with the goal of refueling the Landsat 7 satellite on orbit. Landsat 7 was not designed to be refueled, so capturing and refueling it while still on orbit is a complicated, multi-step process which will make use of a pair of serial manipulators on board the OSAM-1 spacecraft. Trained robot operators are tasked with developing procedures, and then operating the serial manipulators through the mission of refueling Landsat 7. In order to determine which console configurations are best for the OSAM-1 robot operators, a variety of evaluation methods should be considered; the hypothesis of this thesis is that eye tracking may be an effective way to generate metrics to evaluate the placement of information on multiple monitors for a robotic control station.

1.2 Research Objective

The objective of this research is to perform an eye tracking study on the console to be used by the OSAM-1 robot operators, and to develop conclusions about the human factors of the console for the task tested. This may be a somewhat limited

objective, but it is in service of a larger objective: to lay the groundwork for further research that can help answer questions regarding the ideal robotic control console configuration for the OSAM-1 mission as a whole, and for robotic control operations in general.

1.3 Thesis Structure

Chapter 2 presents key background information regarding robot operations and eye tracking. Chapter 3 will explain the methodology of the experiment performed. Chapter 4 will provide a broad overview of the results of the experiment and describe some of the data processing techniques used. Chapter 5 will apply a series of analysis techniques to the data gathered and discuss the takeaways. Finally, Chapter 6 will summarize the results of this research, describe problems encountered and lessons learned, and then suggest future work.

Chapter 2: Background

2.1 Manually Teleoperating Serial Manipulators

As mentioned before, manually teleoperating a robot is a difficult and attention-intensive task, which requires that operators be thoroughly trained. As such, there is a large amount of specialized expertise and knowledge needed. Below, a handful of robot operations concepts relevant to the research performed are explained.

2.1.1 Joint vs Cartesian Space/Movement

There are two ways of thinking about the pose (position and orientation) of a serial manipulator's end-effector: joint and Cartesian pose. Joint position is the configuration of each of the manipulator's individual actuators. In a typical manipulator consisting only of rotational (as opposed to "prismatic" or telescoping) joints, the manipulator's joint pose is represented by a list of angles which describe each individual actuator. Cartesian pose is the position and orientation of the manipulator's end-effector in space. The manipulator's Cartesian pose is represented by a set of translational coordinates for the end-effector's position and a set of angular coordinates for the end-effector's orientation. When commanding a manipulator to

move, it is common to either send a command in either joint or Cartesian space.

2.1.2 Hand Controllers

As an alternative to manually entering values in joint or Cartesian space, it is common to control a manipulator's pose using hand controllers. A typical setup consists of two hand controllers: rotational and translational, as seen in Figure 2.1. Each is used for three degrees of freedom, and typically directly controls the pose of the manipulator's end-effector.



Figure 2.1: Translational (left) and rotational (right) hand controllers.

2.1.3 Contact Operations

Any operations that involve a manipulator making contact with a fixed object are generally considered to be particularly difficult and possibly dangerous, for fear of causing damage to the manipulator, the target object, or both. A common way of dealing with this problem is compliance. This can take a few different forms; with the help of a force-torque sensor, a software control loop can provide compliance.

Alternatively, it can be mechanical, in the form of physical “springiness” in either the end-effector or the target object. In the case of the task performed in this thesis, compliance comes from a spring between the end-effector’s tooling and the body of the manipulator. Typically, during contact operations, the operator will need to closely monitor a display containing contact force and torque information.

2.1.4 Camera Views

Especially in situations where a robot cannot be seen directly by its operator, multiple camera views displaying its position from a variety of angles are extremely important [5]. Having multiple camera views from orthogonal, or at least significantly distinct, angles is particularly useful when performing operations which require precision. Additionally, camera overlays may be used in cases where precise alignment is needed. These take the form of fixed lines drawn over the video feed which help operators judge misalignments. The use of multiple camera views and overlays can be seen in the operation of the Space Station Remote Manipulator System (SSRMS), a manipulator on board the International Space Station. In operating the SSRMS, great care is taken to select and display the camera views which best capture the overall view of the manipulator and provide an advantageous viewpoint for determining if the manipulator is in danger of colliding with the structure of the space station. Overlays, meanwhile, are used for alignment purposes during tasks involving making contact using the end-effector [10] [6].



Figure 2.2: A camera view with an overlay (green dotted lines) on it.

2.2 Eyes, Eye Tracking, and Eye Tracking Analysis

Human eyes have two primary modes: saccades and fixations. Fixations, which as their name suggests are when the eyes are at rest, tend to indicate focusing on something and taking in information. Saccades are extremely fast movements during which the eyes move from one fixation to another [1]. Humans are effectively blind during saccades, meaning that we are only able to absorb information with our eyes while fixating. The one exception to this is smooth pursuit, which is when the eyes are able to smoothly follow a moving object [18].

During fixations, the in-focus field of view is surprisingly narrow; in-focus vision is a narrow circular cone of about two degrees, or “the size of a thumbnail at arm’s length” [19]. Outside of the in-focus view, vision becomes increasingly unreliable. Between blindness during saccades and our narrow field of view, discrete

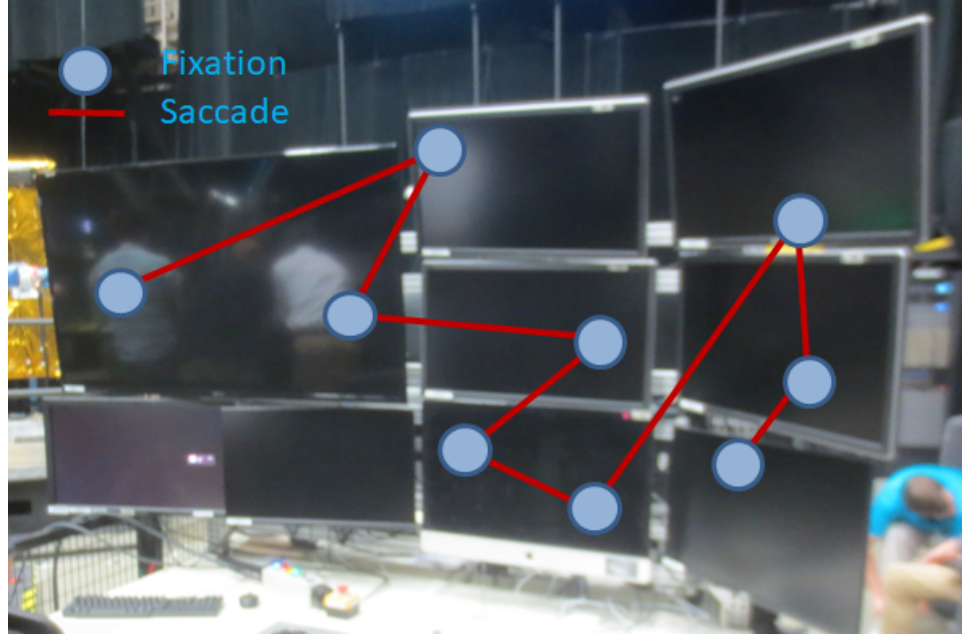


Figure 2.3: An illustration of fixations and saccades across several screens.

fixations of the eyes are a simple, yet effective way to estimate what data a subject has access to. This does not necessarily mean that the subject is *absorbing* whatever it is they are looking at, but it is safe to assume that if a subject's eyes never fixate in a given area, they have not absorbed the data that might be in that area.

Because fixations are the time in which eyes are capable of absorbing information, it is important that eye tracking software have a robust definition of what qualifies as a fixation. There are a variety of algorithms to detect whether the eyes are in a fixation, saccade, or smooth pursuit, which generally depend on metrics such as eye velocity and travel distance [14]. The algorithm used on the data gathered in this research is the Tobii I-VT (Attention) filter [15], which after heavily filtering the data, essentially defines fixations as a period of more than 60 milliseconds in which the eyes travel at most 0.5 degrees, at a speed of less than 100 degrees/second.

Once eye tracking information has been recorded, there are many tools for transforming and reducing it to a point where it can be more easily analyzed. The following subsections contain explanations of some tools to be used later in this thesis.

2.2.1 Image Mapping

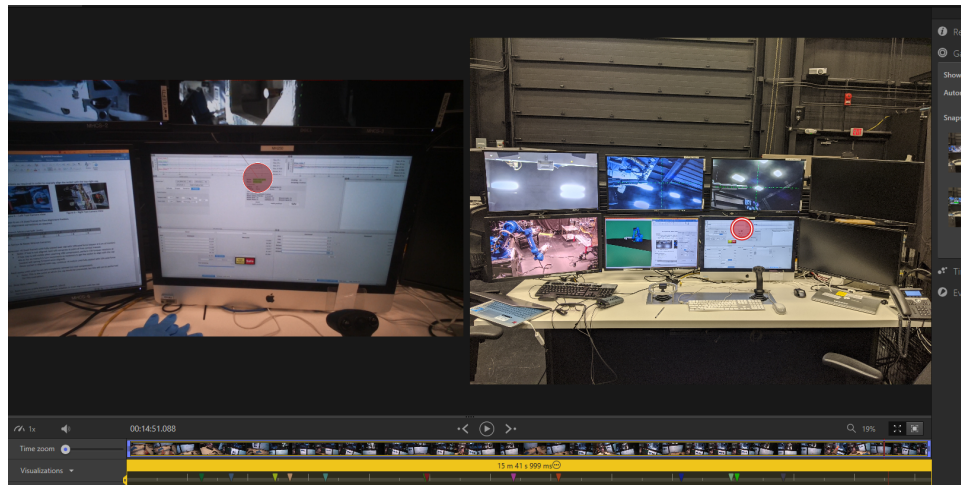


Figure 2.4: An example of a fixation (red circle) mapped from the video recorded by the eye tracking glasses (left) to a static image of the overall scene (right).

The simple first step is to map the data to an image. The eye tracking glasses used in this thesis record video and are able to tell where the subject's eyes are looking only in the context of the recorded video. In order to convert this to useful information, the data needs to be mapped to a static image of the visual scene, where eye location data becomes available as a set of coordinates on the image [7]. Image mapping can be done manually, but this is a tedious and time consuming task, so this was done automatically, using Tobii Pro Labs for this research. It is worth mentioning that automatic image mapping is generally reliable, but can

sometimes be incomplete or inaccurate.

2.2.2 Areas of Interest

Mapped images can be divided up into areas of interest, commonly abbreviated as AOIs. These are a useful tool for breaking down a visual scene into regions of reference for analysis, as software can automatically detect if a given fixation falls within an AOI on a mapped image [1] [19]. Upon mapping data into AOIs, several different useful metrics can be extracted, such as fixations per AOI, total time per AOI, and average time per fixation in a given AOI [16] [18]. Movements between AOIs may also be mapped into transition matrices which display the frequency or probability of transitioning between AOIs [2], or graphs which display the same information via graph theory [9]. AOI transitions may even be modelled as Markov chains [12], probability models in which the current state only depends on the previous state.



Figure 2.5: A console with areas of interest on its screens.

2.2.3 Events

Events are simply “timestamps” that can be exported along with other eye tracking data. Events can be used to indicate when a subject reaches a certain milestone in their task, and may mark the beginning or end of periods of particular interest in analysis.

2.2.4 Heatmaps



Figure 2.6: An example of a heatmap made from the data gathered in this research.

One common visualization of eye tracking data is the heatmap, a color-coded map overlaid onto the scene over which eyes are tracked [1]. Heatmaps are intuitive and easy to read, but it’s important to take note of what type of heatmap is being displayed. Heatmap types can be categorized in a few different ways:

- Fixation vs Duration: Fixation heatmaps count the number of fixations, while duration heatmaps count total time. Fixation and duration heatmaps may

differ dramatically if the length of fixations differs between different areas of the mapped scene [3].

- Absolute vs Relative: When a heatmap includes data from multiple data-gathering runs, absolute heatmaps simply add all data together, while relative heatmaps scale data according to the amount of data in the run [3].

Unless stated otherwise, the heatmaps in this thesis are relative fixation, meaning that they display fixations, scaled such that all included data-gathering runs are weighted equally.

2.2.5 Eye Tracking Metrics

Once eye tracking data has been gathered and reduced, there are many ways that it might be interpreted to draw conclusions about a given user interface. Poole and Ball (2006) [16] describe these many metrics and their uses. These include:

- Fixation frequency/fixations per AOI: More fixations in an AOI indicate that it is more attention-grabbing or simply that the information contained within is used more often.
- Fixation duration per AOI: Longer fixations in a given area indicate that the contained elements might contain more data by volume, or that the data might otherwise be more difficult to absorb.
- Proportional dwell time/total time per AOI: Total time spent per AOI gives a broad overview of overall attention which combines the information present

in both fixation frequency and fixation duration.

Chapter 3: Methodology

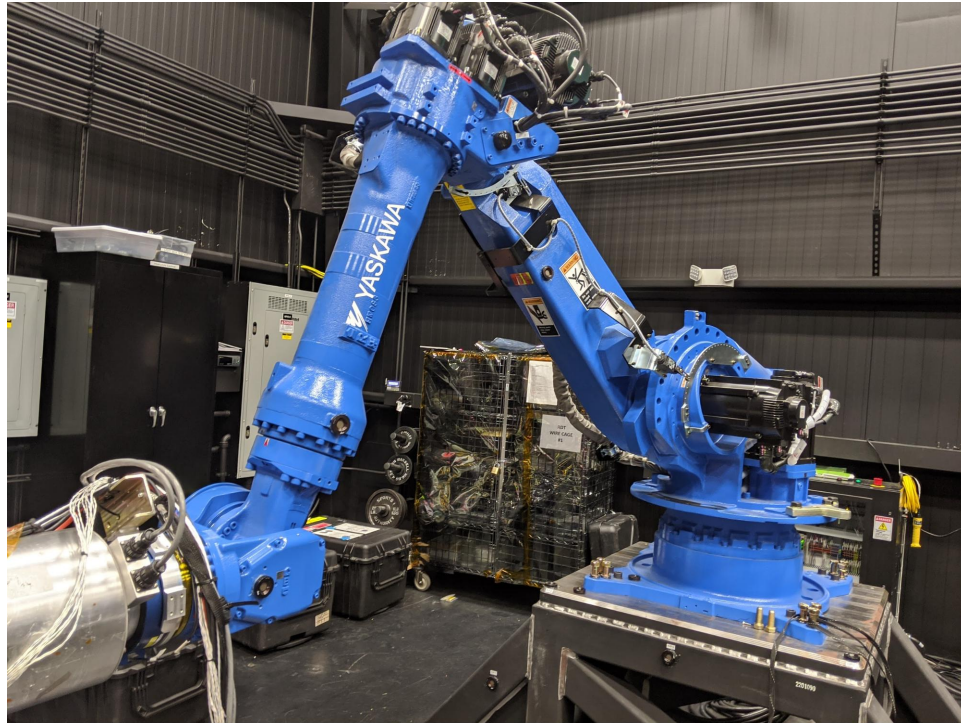


Figure 3.1: The Motoman MH250 robot used in this experiment.

In collaboration with NASA Goddard, an eye tracking test was performed on a group of OSAM-1 robot operators, which involved performing a training task on the OSAM-1 team’s Motoman MH250 robot while wearing eye tracking glasses. This task consisted of aligning the “wobble socket” end-effector (a hex socket on a compressible spring) of the MH250 with a hexagonal cap in a “cap bathtub”, and fully enveloping it with the end-effector. Currently, the OSAM-1 team does not

officially have a standard configuration for laying out the various data sources that operators need, such as GUI (graphical user interface) elements and camera views. The point of the experiment to follow, then, is to gather data which may point to an optimal arrangement for the various scenes on the monitors of the control station.

3.1 Screens/GUI Configuration

The console used for this experiment has 8 screens, as seen in Figure 3.2. When referring to a specific screen throughout this thesis, terms like “bottom center right”, or “top outer left” will be used to describe the screen’s position. Each configuration may have several different elements, which are described below:

1. An “overall” view, from a camera mounted on a nearby wall. The “overall” view contains both the entire robot and the cap bathtub.
2. A “safety” view, from below the hex cap bathtub, perpendicular to the end-effector.
3. A camera based on the left side of the end-effector that provides a view of the wobble socket. When viewed on the screen, an overlay (dotted green lines, as seen in Figure 3.2) helps the operator visualize a straight line from the end of the end-effector to the target hex cap. For brevity, this may be referred to as EE-left.
4. A counterpart to EE-left, on the right side of the end-effector. These views are orthogonal to one another. For brevity, this may be referred to as EE-right.

5. The display for inputs to a DVR (digital video recorder) used by the robot operators. This display contains several different facility camera views, including all four camera views used specifically for this task. This display was optional.
6. A PC displaying a robot control GUI, robot visualization (referred to as the “viz”), and instructions, which all together take up 2-3 screens. This will be elaborated on below.
7. There will often be at least one screen left blank.



Figure 3.2: Eight screen setup, labelled with numbered boxes. In the list above, the number for each description corresponds to the matching number for the screens here. It should be noted that video views can be arranged on any screen as part of the console set-up.

There were three primary elements displayed on the PC:

1. Viz: The “viz” is a visualization of the robot in an empty scene. Broadly, it has two uses for the task performed. It can be used as an additional camera view, having the ability to zoom and rotate to view all angles of the robot at will, but lacking any of the robot’s environment (while the viz can be used to display the robot’s environment, this feature was not used in this experiment). It can

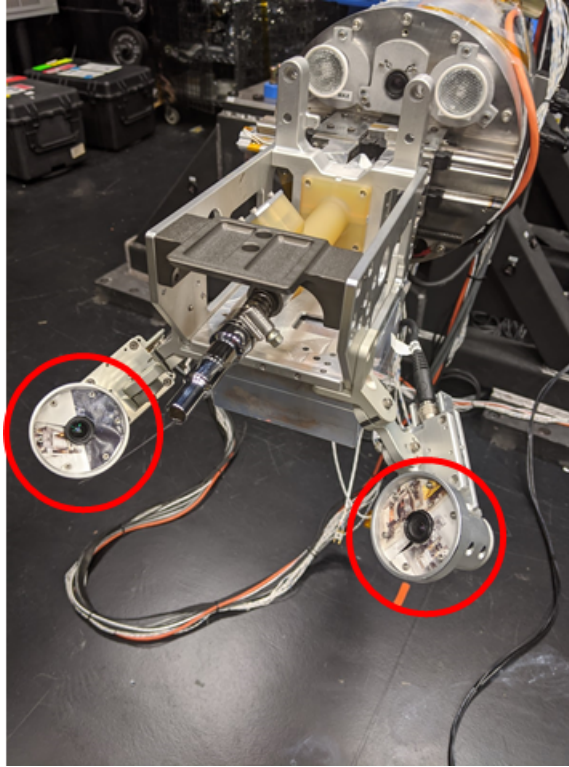


Figure 3.3: The end-effector cameras (circled in red).

also be used to display the orientation of the robot's coordinate axes, which can be particularly helpful in acquainting the operator with the operation of the hand controls.

2. Instructions: The instructions for the task being performed, open in Microsoft Word.
3. Graphical User Interface: The GUI used by the OSAM-1 team consists of several different elements which fulfil various functions for controlling the robot and displaying data. GUI elements are “dockable”, meaning that they can be rearranged within the primary GUI window, or can be split off into their own separate windows.

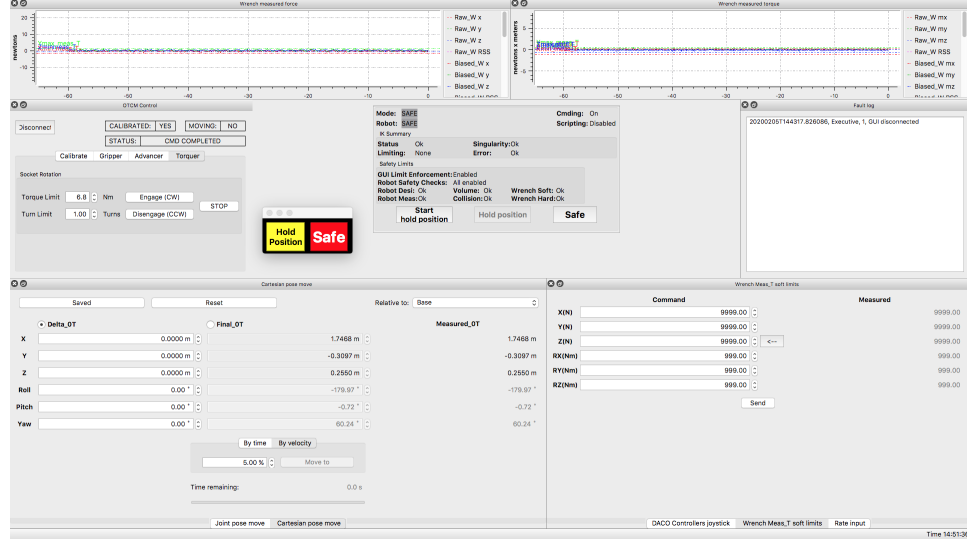


Figure 3.6: A screenshot of the GUI as it was used in a data gathering run.

3.2 Test Subjects

The test subjects for this experiment were a group of 6 trained OSAM-1 robot operators at NASA Goddard. Unfortunately, the data for one of these robot operators could not be used, as the eye tracking glasses were unable to calibrate for them. Therefore, there were ultimately 5 complete datasets to be analyzed. The robot operators will be referred to as participants A, B, C, D, and E. Previous experience as a robot operator varied from just a few months to as much as 12 years.

In order to obtain approval for the use of human subjects, paperwork was submitted to and approved by the University of Maryland's Institutional Review Board (IRB). This paperwork can be seen in Appendix F. Because this experiment took place at NASA Goddard, it was originally planned to submit this paperwork to an IRB at NASA, but upon inquiring it was understood that there were no established protocols for submitting or approving IRB paperwork at NASA Goddard, at least

through the OSAM-1 team.

3.3 Experimental Design

The design of these consoles, as well as the tasks to be performed on them, have innumerable variables, and is already very much in flux, so it emerged that the best strategy might be to evaluate a simple, generic task in a handful of console figurations, so as to provide a guideline for future work. This approach has the additional advantage of making it easier to compare and contrast various console configuration variables, as many of the metrics measurable through eye tracking are far more useful when measured against metrics from other console designs.

Ultimately, three different console/GUI configurations were tested with each test subject. In order of testing for all test subjects, these are:

1. The operator’s personally chosen configuration. It was decided that this should be the first configuration that operators use, so that the operators are not influenced by the “standard” configuration in choosing their personal configuration.
2. A “standard” configuration, deemed by senior robot operators to be typical for the task to be performed.

	Outer left	Center left	Center right	Outer right
Top	Overall	EE-left	EE-right	Safety
Bottom	Blank	Instructions	GUI + Viz	DVR

Table 3.1: Table describing the standard configuration.



Figure 3.7: Standard configuration overall picture.

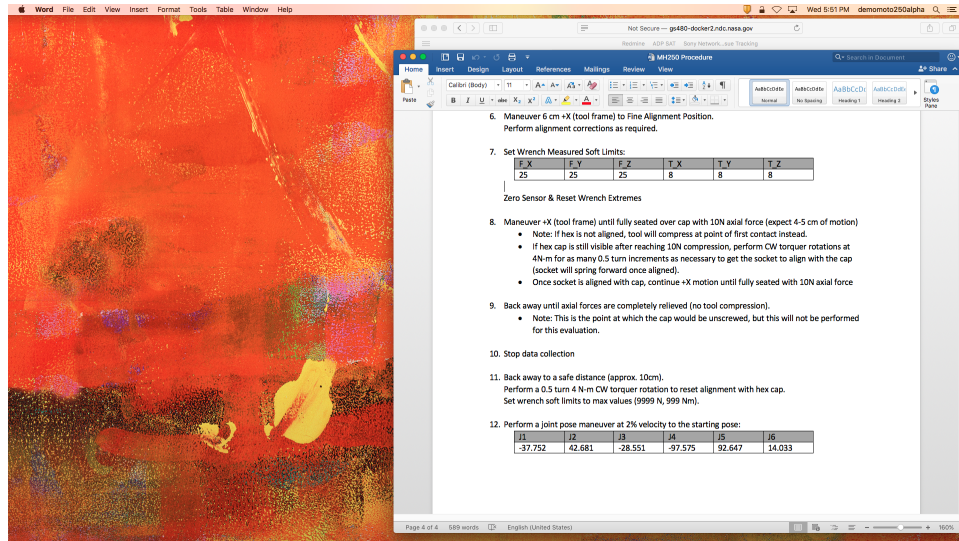


Figure 3.8: Standard bottom left center screenshot, with blank space to the left and instructions to the right.

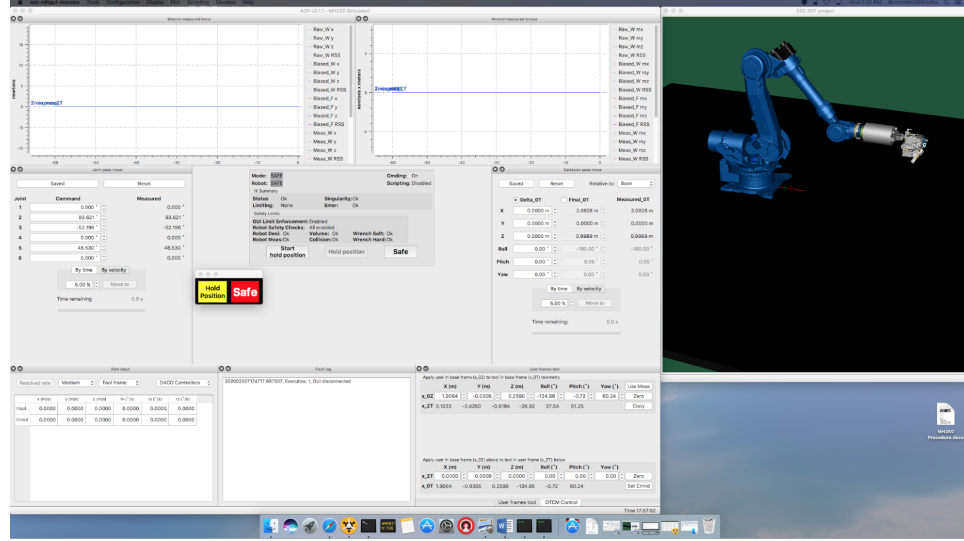


Figure 3.9: Standard bottom right center screenshot, with the GUI to the left and viz to the right.

3. An “altered” configuration chosen to be significantly different from both the standard configuration and all of the personally chosen configurations, while keeping certain configurable elements deemed to be essential. Originally, only the first two configurations were planned, but an additional run using this configuration was added to introduce more variation in the console configuration. The most noteworthy similarities to the “standard” are that the end-effector cameras stayed in the two top center screens of the console, the instructions and GUI stayed in the two bottom center screens of the console, respectively, and the force and torque plots remained on the top of the bottom right center screen. Beyond those similarities, an attempt was made to scramble the remaining GUI elements and camera views. Because it was thought that it might be particularly interesting to gauge the effects of a 2x3 layout rather than a 2x4 one, the rightmost column of screens was omitted. As shown in

Figure 3.8, the standard configuration put the instructions by themselves on a single screen, with the visualization and GUI together on a second monitor. Since the instructions are essentially a fixed width, the "altered" configuration placed the viz window on the unused portion of the instructions screen, giving the operator a full monitor for the GUI.

	Outer left	Center left	Center right	Outer right
Top	Overall	EE-left	EE-right	Safety
Bottom	Blank	Instructions	GUI + Viz	DVR

Table 3.2: Table describing the altered configuration.



Figure 3.10: Altered configuration overall picture.

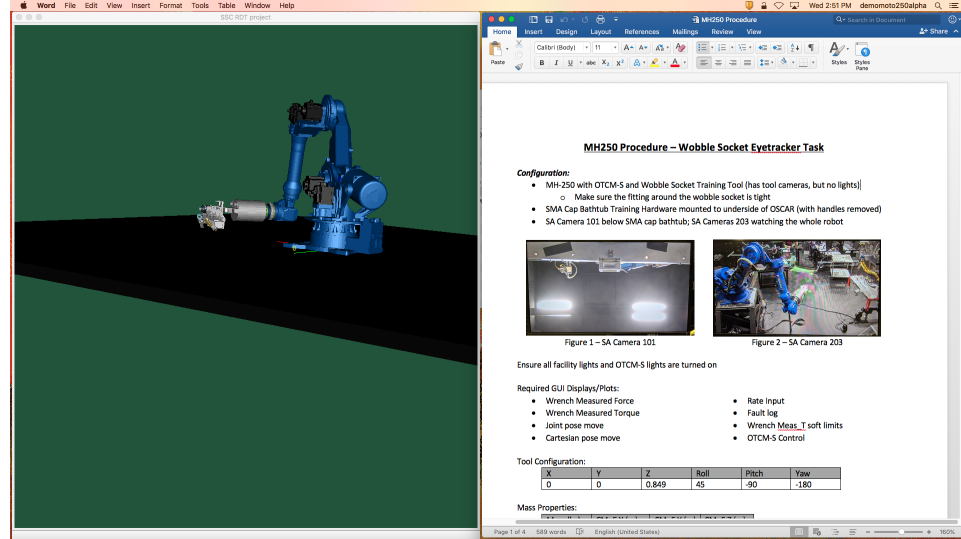


Figure 3.11: Altered bottom left center screenshot, with blank space to the left and instructions to the right.



Figure 3.12: Altered bottom right center screenshot, with the GUI to the left and viz to the right.

Throughout this thesis, specific data gathering runs may be referred by their operator letter and run number. For example, test subject C's third data gathering run (altered configuration) may be referred to as C3.

If an operator expressed that they were inexperienced with the task, they were allowed to start with a “dry run” before moving along to the recorded trials. In preparation for the personally chosen configuration, GUI layout was “scrambled” before each operator’s first run, and the screens were unmapped from their video feeds, forcing the operators to rearrange the console according to their own preferences, or at least use semi-randomly arranged GUI elements, in attempt to ensure that the operator’s personally chosen configuration was organically chosen. During all data gathering runs, a curtain was drawn between the operator and the robot, such they could only use the camera views on the console instead of being able to directly look at the robot.



Figure 3.13: The operator’s view of the workcell from their console, blocked by the curtain.

3.4 Task Performed

The test was a simple training task consisting of aligning the robot’s “wobble socket” end-effector over a fitting hexagonal cap, and pressing forward with 10 N of force. The complete instructions can be seen in Appendix A, but the overall task is summarized below:

1. *Move to approach position:*

A scripted joint movement, commanded from the keyboard into the GUI. This command, as well as all other joint movements, is sent by entering the desired joint space values into the joint movement dialogue one-by-one. This movement is from the manipulator’s initial resting position to an “approach” position.

2. *Move to coarse alignment:*

Another joint movement to the “coarse alignment” position, which is approximately 12 inches axially away from the cap. There were purposely minor inaccuracies built into the supplied joint space values, such that the operator would have to manually make corrections in the next step.

3. *Corrections to coarse alignment:*

Operators used hand controllers in Cartesian space to move the end-effector to visually correct the inaccuracies from step 2, using the overlays on the end-effector views to help visualize a straight line from the end-effector. The goal

of this step was to keep the end-effector approximately the same distance from the hex cap, but correct the rotational and translational inaccuracies such that the cap and end-effector become axially aligned.

4. *Move to fine alignment:*

Operators moved the end-effector approximately 6 inches towards the hex cap to reach “fine alignment”. Operators were allowed to perform this step using either hand controllers as before, or a Cartesian movement dialogue similar to the joint movement dialogue; most used hand controllers.

5. *Corrections to fine alignment:*

Similar to step 3, only applied to the fine alignment position.

6. *Press forward on cap until 10 N of axial force is measured:*

Operators used the hand controllers to contact the hex cap using the end-effector, and pressed forward, compressing the spring element of the wobble socket until 10 N of axial force was measured on the force display in the GUI.

7. *Rotate the wobble socket until it's aligned and springs forward to envelope the cap:*

Run the manipulator's torquer tool drive using the tool drive dialogue in the GUI. A simple button press corresponded to a 180 degree turn. When the hex in the socket aligned with the hex cap, it sprung forward, enveloping it, and the tool drive stopped rotating.

8. *Press forward on cap until 10 N of axial force is measured:*

Similar to step 6, only already seated on the hex cap.

9. *Back away until axial forces are completely relieved:*

Remove the wobble socket from the hex cap; the run is complete when all forces go to zero.

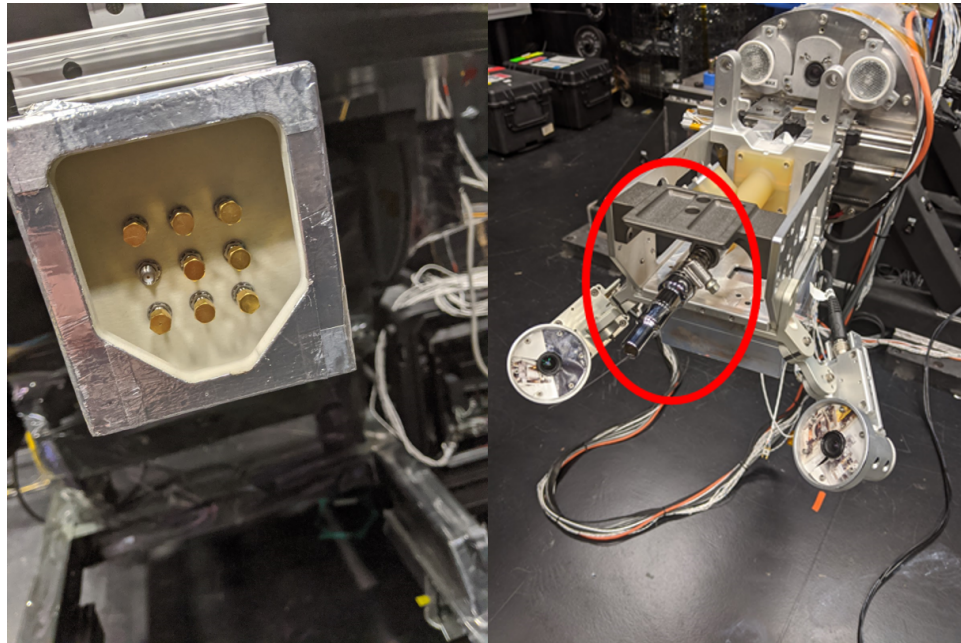


Figure 3.14: The hex cap “bathtub” (left) and the end-effector, with the wobble socket circled in red (right).

3.5 Data Gathering Methods

There are two primary types of eye tracking setups in common usage: screen-based (fixed to a computer/TV screen) and head-based (attached to the subject’s head; usually look a lot like glasses). Because this is an evaluation of a large, multi-screen control station setup, with multiple input sources (video streams, robot

control interface, etc), a screen-based solution was infeasible and a head-based setup was chosen: the Tobii Pro Glasses 2.



Figure 3.15: Tobii Pro Glasses 2, the eye tracking glasses used in this experiment [17].

Interviews were performed before and after the tests with each subject. Opening interviews were treated as an opportunity to introduce the participants to the eye tracking glasses, and determine which of the interchangeable nosepieces would best fit them. The operators were also asked if they wore contact lenses, and if those contact lenses were of a particularly strong prescription, as it was known from previous investigations that the glasses occasionally do not work if the subject is wearing strong prescription contact lenses. The operators were asked about their previous experience as robot operators, both broadly, and their experience with the task to be performed and the “standard” console configuration they would be using.

After the operators’ second and third runs through the task, they were asked whether they felt their performance was impacted by using a different console configuration. They were also asked about their comfort level wearing the glasses while

operating the robot, and whether or not it had an impact on their performance.

Chapter 4: Results

4.1 Participant Background

Table 4.1 contains the relevant background information from each participant:

Participant	Previous experience as a robot operator	Previous experience on this task
A	3.5 years	Once, 4 months ago
B	6 years	No
C	4 months	No
D	About 12 years	Years of experience on similar tasks
E	6 months	No

Table 4.1: Table containing operator background information.

4.2 Eye Tracking Glasses + Participants

Before running the task, all participants indicated that they did not expect the eye tracking glasses to affect their performance except Participant C, who thought they might slightly impede their ability to see the screen.

After running the tasks, the participants generally indicated that the glasses had little impact on their performance, though there were some minor complaints:

- Participant B said that the glasses sometimes blocked sections of their view, which meant that they sometimes needed to make extra head movements.
- Participant C also said that the glasses blocked sections of their view, and described a slight “glare” from the glasses. They believed the glasses were a minor distraction, but attributed this to having rarely worn glasses previously.
- Participant D said that the glasses were a very minor distraction, and also described mild discomfort from the glasses resting on their nose for an extended period of time.
- Participant E also mentioned discomfort from the glasses resting on their nose.

4.3 Learning Effects

In interviews, operators consistently indicated that over the course of performing the task multiple times in a row, they got better at performing the task. Most operators performed the task twice in immediate succession on the personal and standard configurations, and then performed their third run in the altered configuration several weeks later. The resulting learning effects can be seen in the data in multiple areas; most operators spent significantly less time on subtasks that required direct operator input on their second run. Additionally, all operators spent more time looking at the screen with the instructions on it on their first run than on their second run. Operators were specifically told that they would not be evaluated based on how long they took to complete the task, but it is interesting to note that

all operators took less time for the task on their second run than on their first.

Participant	Personal Configuration	Standard Configuration	Altered Configuration
A	18:05	12:24	15:15
B	13:03	9:42	13:16
C	26:51	22:50	28:57
D	36:53	12:05	14:05
E	14:29	14:10	15:42

Table 4.2: Minutes taken on each run for each participant.

One operator observed that because the purposely inaccurate joint values in the coarse alignment joint move were the same during every run, they were able to make coarse alignment corrections far more easily with each subsequent run. Additionally, several operators mentioned that they were initially unfamiliar with the Cartesian orientation of the commands sent by the hand controllers, meaning that they greatly improved in subtasks that required use of the hand controllers as they performed additional runs. Due to the limited number of test subjects and available testing time, there was no opportunity to more carefully control or quantify the learning effects. This would be an important element in protocols for future, more detailed tests.

4.4 Console Configuration

During opening interviews, only one operator (participant B) indicated that their typical console configuration would be significantly different from the “stan-

dard”. This proved to be true in data gathering; in the personally chosen configuration round of testing, only participant B rearranged the screens in a way that meaningfully deviated from the “standard”. This is despite the fact that, as mentioned previously, the personally chosen configuration was the first round of testing, and that the console was purposely scrambled such that the operators had to arrange all of the screens and GUI elements themselves for the personal configuration.

Most participants detected only minor performance differences between the different console configurations. However, when transitioning to an unfamiliar configuration, most participants described some difficulty adjusting, particularly to the rearranged GUI elements in the “altered” configuration.

A few additional observations made by the operators regarding the various console configurations included:

- In the altered configuration, having the overall and safety views on the left side of the console felt further away from the operator than they were if they had been to their right.
- Also in the altered configuration, the force and torque graphs were somewhat smaller, which made them somewhat more difficult to use.
- In some cases when it was more convenient to do so, operators said they looked at the DVR display if it was on a side of the console that didn’t have a desired camera view.

4.5 Initial Patterns Observed

Figures 4.1 and 4.2 are a pair of heatmaps to give an overview of the eye-tracking results. These heatmaps include data from all participants on the runs in the standard and fixed configurations. Data from the personal configurations is not displayed, as the variations in configuration would make a composite display useless. These results will be discussed in greater detail in the next chapter.

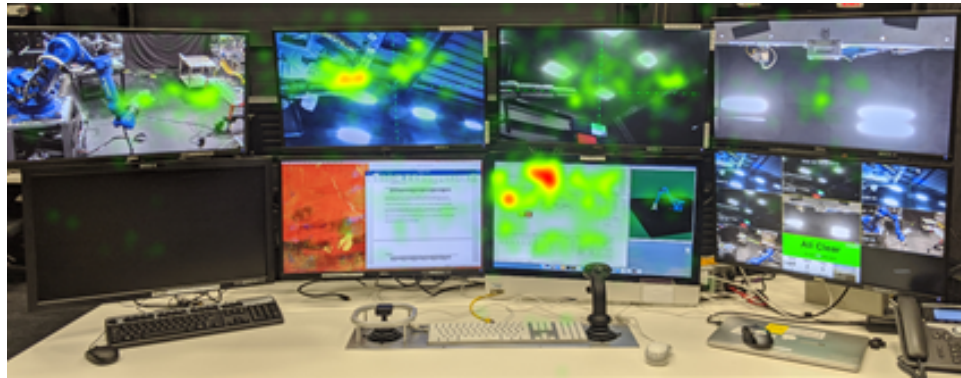


Figure 4.1: Combined heatmap of all operator data in the standard configuration.



Figure 4.2: Combined heatmap of all operator data in the altered configuration.

As seen in Figures 4.1 and 4.2, operators tended to focus their attention on three screens, regardless of the overall configuration: the screen showing the GUI,

and in particular on the force and torque plots, and the two screens showing end-effector camera view. Considering the task performed, it makes intuitive sense that these are the areas which received the most focus.

4.6 Eye Tracking Data Processing

In order to even begin to make sense of the data being processed, several steps were taken to transform it from its initial "raw" form. The first step in this process was to import it into Tobii Pro Labs, an analysis software designed for initial data processing of data from Tobii eye trackers. Upon being imported into Tobii Pro Labs, data was mapped, using the "automatic mapping" option to a wide view of the overall console and screenshot(s) of the PC screens and two different sets of images, both of which had AOIs denoting individual screens.

Additionally, all runs were given "events" corresponding to important points in the run. These events were used as markers for the purposes of breaking the overall task up into subtasks for analysis. The standard events recorded are:

Event Name	Placement in task
<i>start init move</i>	Beginning of initial robot movement
<i>end init move</i>	End of initial robot movement
<i>start move to CA</i>	Beginning of move to course alignment
<i>end move to CA</i>	End of move to course alignment
<i>start CA corrections</i>	Beginning of move to course alignment
<i>end CA corrections</i>	End of move to course alignment
<i>start move to FA</i>	Start of move to fine alignment
<i>end move to FA</i>	End of move to fine alignment
<i>start FA corrections</i>	Start fine alignment corrections
<i>end FA corrections</i>	End fine alignment corrections
<i>start move to contact</i>	Start move toward contact with hex cap
<i>make contact</i>	Contact is made between the end-effector and hex cap
<i>at 10N nonseated</i>	Measure 10 N in axial force, not seated on hex cap
<i>torque</i>	Tool drive is activated
<i>at 10N seated</i>	Measure 10 N in axial force, seated on hex cap

Table 4.3: Standard set of events recorded.

Most of these events are essentially “bookends” of various subtasks within the overall task, though there is one exception: “torque” is when the operator activates the tool drive, which may happen multiple times. For events such as “start move to FA” and “end move to FA”, even if the subject stopped their movement in the middle of this subtask, or even returned to a previous task, the “end move to FA” event would not happen until fine alignment was actually reached. In cases where subtasks were skipped, their corresponding events were added at the same time as the closing bookend for the previous subtask.

After being processed in Tobii Pro Lab, the data was exported as TSV (Tab Separated Value) files. The TSVs are run through a script to convert this data to MAT files (binary MATLAB data), which could be imported into MATLAB.

Once in MATLAB, data was pared down to only include successfully image-mapped fixations, before being further analyzed.

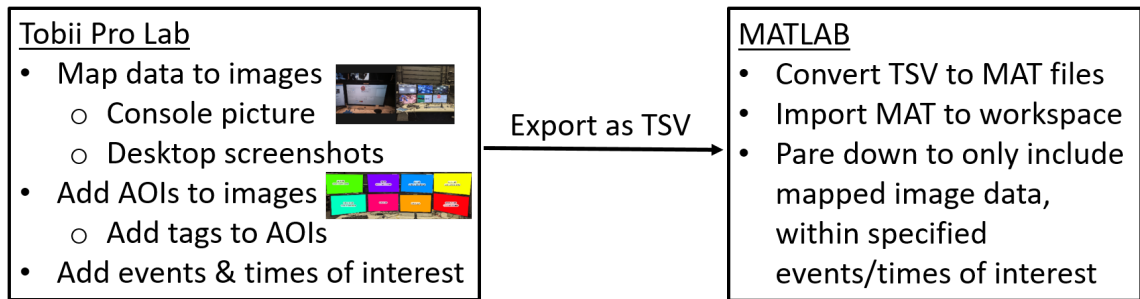


Figure 4.3: An illustration of the data processing workflow.

4.7 Dealing With Incomplete + Inaccurate Data

It is important to note that the eye tracking glasses are not perfect; on average, eyes are successfully tracked about 90% of the time. There are outliers however, most notably Participant D, whose percentage of tracked gaze samples dropped to as low as 67%. It would be infeasible to determine this empirically, but based on anecdotal observations in dealing with the eye tracking data, it seems that the eye tracking glasses were most likely to lose track of Participant D's gaze when they were looking at the top row of screens. Therefore, it could be assumed that Participant D has more fixations and overall time spent on the top row of screens than the data suggests.

Further complicating things, the mapping software is imperfect in its ability to map eye location to an image of the scene, meaning that the mapping to a given image is frequently incomplete, or even inaccurate. Therefore, in order to

supplement mapping to the overall view, the eye tracking data was also mapped to screenshots from the PC.

Participant	Run Number	Percentage of Tracked Gaze Samples	Percentage of Total Time Mapped-Only overall view	Percentage of Total Time Mapped-Overall view + PC screenshot
<i>A</i>	1	98%	87.1%	88.6%
	2	96%	83.4%	85.0%
	3	98%	91.9%	92.3%
<i>B</i>	1	98%	87.3%	88.6%
	2	98%	57.6%	69.3%
	3	97%	90.7%	90.9%
<i>C</i>	1	90%	72.7%	73.8%
	2	90%	58.3%	60.7%
	3	94%	87.4%	88.1%
<i>D</i>	1	67%	47.9%	53.7%
	2	83%	46.7%	55.3%
	3	67%	55.3%	56.1%
<i>E</i>	1	86%	78.8%	78.9%
	2	92%	52.8%	62.7%
	3	92%	66.0%	72.6%

Table 4.4: Percentage of usable data at various points in data processing.

Sometimes when mapping to more than one image, fixations were detected in different locations in each image, essentially meaning that eye tracking data sometimes indicated that eyes are in two places at once. This is a consequence of the occasional errors in image mapping; given mapping eye tracking data to two different images, if inaccurate mapping occurs when mapping to one image, but not the other, the resulting eye locations will conflict with one another. These conflicting periods were not insignificant; on average, they lasted approximately 12 seconds per

data-gathering run. It would be infeasible to fix all of these instances of conflict, as this would require manually determining the correct location on every instance of every run; in some cases there were more than 100 instances in a single run. Anecdotally in combing through the data, there seemed to be a roughly equal split between errors made mapping to the overall view and the PC screenshots, so it was decided that all instances of conflicting fixations should simply be removed. This resulted in a smaller amount of usable data, but the resulting data is more accurate.

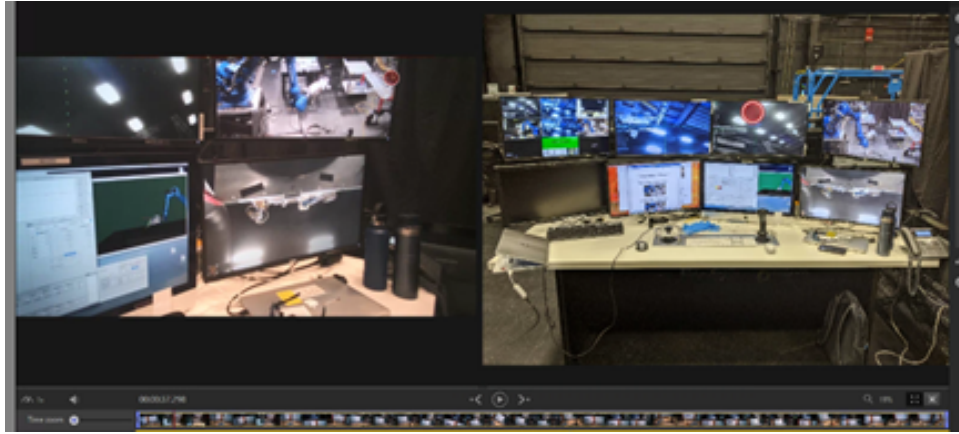


Figure 4.4: An example of inaccurate mapping. See the red circle in the left and right images, indicating the actual eye location (left), and the eye location as mapped to the overall view (right).

Chapter 5: Analysis

This chapter will apply a series of analysis techniques to the data gathered and discuss the takeaways. These analysis techniques will typically consist of a way of transforming the data gathered to generate a new data representation. These transformations will become increasingly complex over the course of this chapter, culminating in an exploration of a consistent finding from these data representations.

5.1 Attention on Each Screen

Figures [5.1](#) and [5.2](#) are charts breaking down percentages of time each operator spent looking at each screen in the standard and altered configurations. Composite results from the personal configurations are again not shown due to the differences in screen configurations. Similar data analyses for each of the test subjects individually are presented in Appendix E, and in that case the personal configuration can be accurately compared to the other two test cases.

Percentage of time spent looking at each screen in the standard configuration

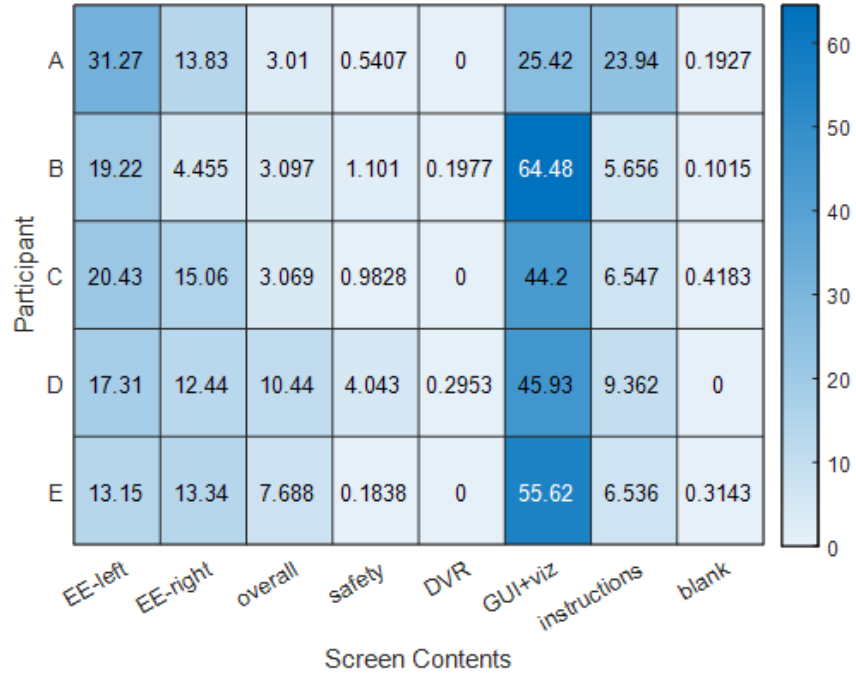


Figure 5.1: Time percentages per screen, standard configuration.

Percentage of time spent looking at each screen in the altered configuration

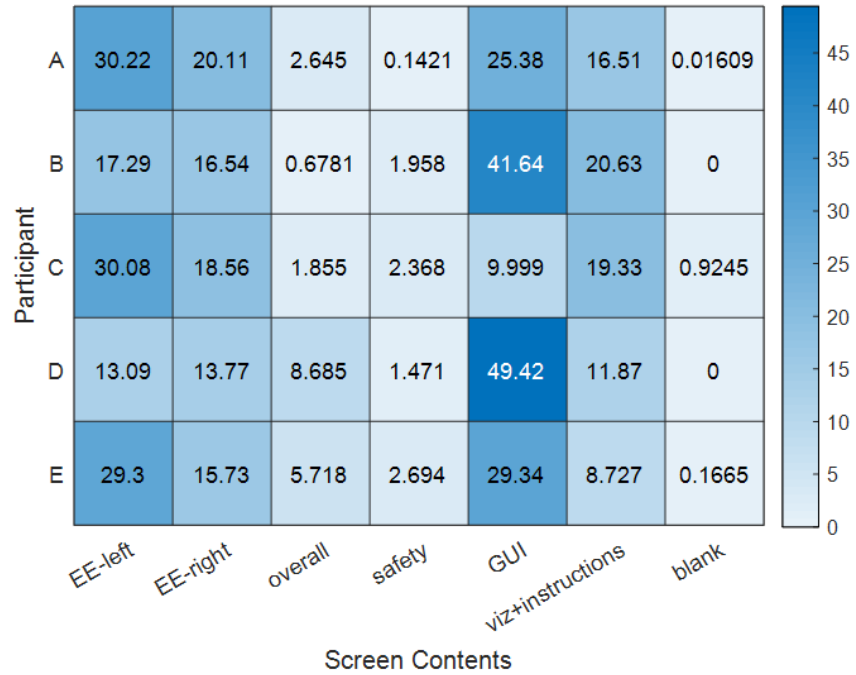


Figure 5.2: Time percentages per screen, altered configuration.

Regardless of screen configuration, most time is usually spent on the GUI; this validates the central location of the GUI screen. EE-left and EE-right are often the next most viewed screens after the GUI, with EE-left nearly always more viewed than EE-right. Meanwhile, relatively little time is spent on overall and safety views, with the least overall time (other than the blank and DVR screens, which received a nearly negligible amount of attention) spent on the safety screen.

A broad trend is that more time is nearly always spent on the instructions in the altered configuration than the standard configuration. The primary reason for this is thought to be learning effects; as mentioned previously, all operators performed their tests on the personal and standard configurations in immediate succession, meaning that the operators had the best knowledge of the task during the standard configuration test. Having the viz grouped with the GUI in the altered view accounts for some of this, but in instances when the AOI data for the viz is viewed on its own, it is usually almost negligible. Other than this, the only other significant trend in the typical attention given to screens between the standard and altered views is that the overall view gets a few percentage points more attention in the standard configuration than the altered configuration.

Note that D3 has a particularly high percentage for the GUI and overall view, and particularly low percentages for EE-left and EE-right. This can be explained by the particularly low percentage of gaze samples in D3, which tend to be dropped more often when looking at the top row of screens, as was described in [Section 4.7](#).

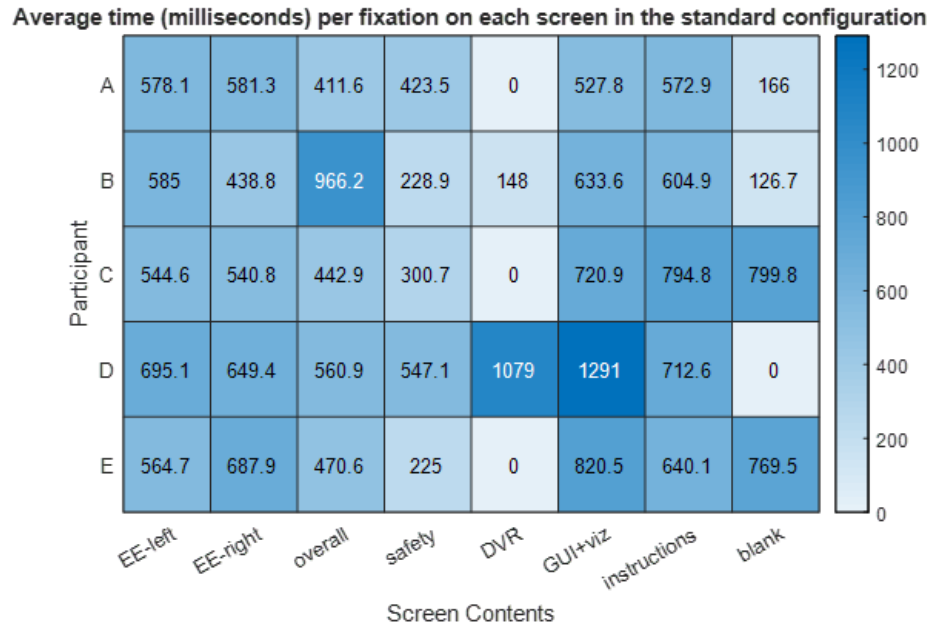


Figure 5.3: Time per fixation per screen, standard configuration. Note that "0" is used to denote that there were no fixations on a given screen.

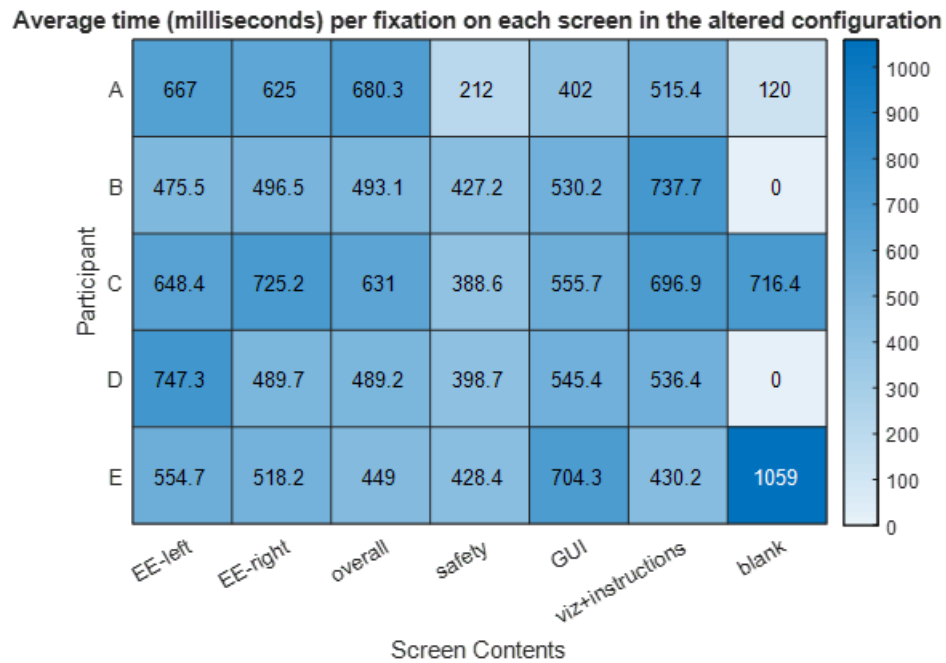


Figure 5.4: Time per fixation per screen, altered configuration. Note that "0" is used to denote that there were no fixations on a given screen.

Another simple representation of the data acquired is average time spent per

fixation per screen. The most immediate observation that can be made is that longer fixations tend to occur on the GUI, instructions, and end-effector views, while relatively brief glances are made at overall and safety views. This tracks with what one would expect given the information available on these screens; a smaller volume of task-relevant information can be drawn from overall and safety views than the precise alignment information on the end-effector views, the data readouts and inputs on the GUI, and the information in the instructions. On the blank and DVR screens, it is difficult to draw any conclusions about what information might be absorbed, as average time per fixation tends to vary dramatically, likely because there are fewer instances of these screens being looked at, and therefore fewer samples to average together.

An item of interest here is that eye tracking studies tend to indicate that users more familiar with a user interface tend to have longer fixations [18]. In this research, it might be expected that this effect would have the most noteworthy impact on the standard configuration, where the senior robot operators would be most familiar with the console. In line with this, note that participants C and E are the least experienced robot operators and generally have longer fixation times than other operators in the standard configuration, at least on the most viewed screens such as the instructions and GUI. In a surprising exception to this trend, participant D, who is the most experienced robot operator, has by far the longest fixation lengths while on the standard configuration.

5.2 Transition Matrices, Paired Screens, and GUI Pivoting

In order to better understand operators’ eye movements between screens, transition matrices were generated which mapped the number of transitions between the set of screens available on a given run. These matrices were generated by applying the following transformations and filters to the dataset from each data gathering run:

1. The data was filtered to timesteps containing fixations only.
2. If there was a gap between fixations larger than 1 second, the fixation at the start of that gap was removed.
3. Data was filtered to only contain the first timestep of each fixation.
4. Data was filtered to only contain fixations within the specified AOIs.
5. Each remaining fixation is stepped to the previous timestep, within a set of data filtered by steps 1 and 4, but not steps 2 or 3. The resulting fixations on either side of this step are saved coupled together as an “initial” fixation and a “next” fixation.

After being categorized by screen-to-screen pairing, each run was then normalized by the total number of transitions made, and then averaged together by configuration. The resulting matrices for the standard and altered configurations can be seen in Figures [5.5](#) and [5.6](#).

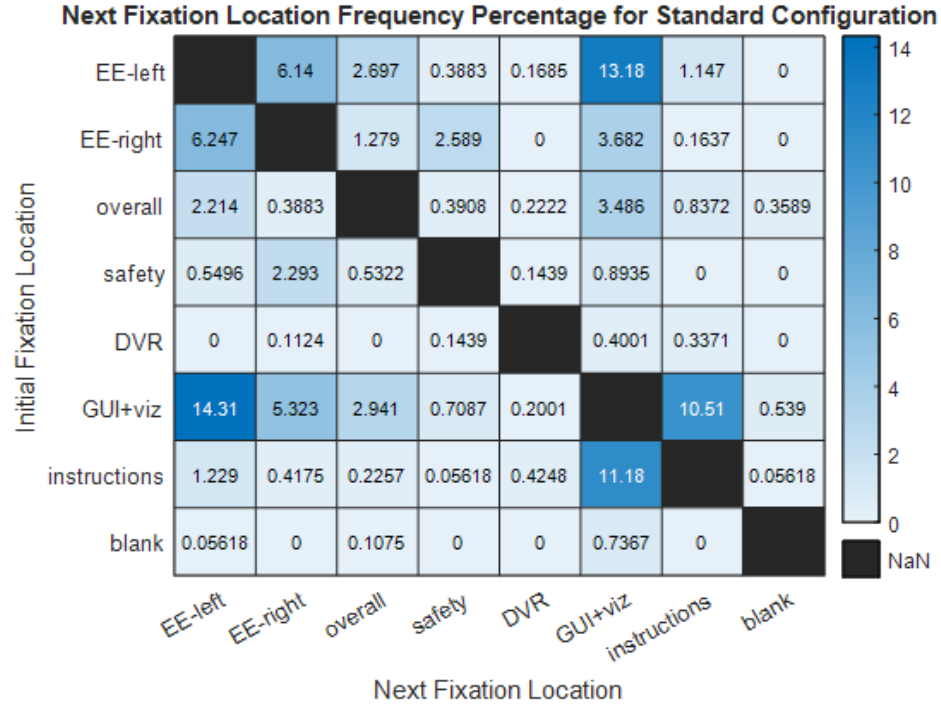


Figure 5.5: Screen transition matrix, standard configuration.

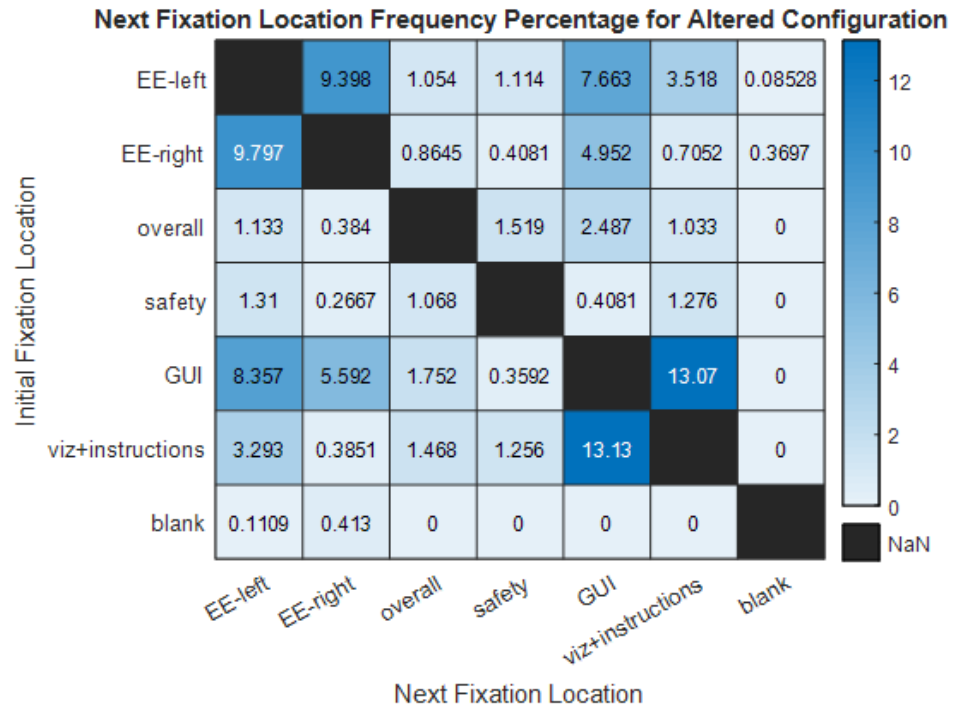


Figure 5.6: Screen transition matrix, altered configuration

An observation that can be made from this data is that frequent transitions most often come in pairs, where if there are frequent transitions from screen A to B, there will also be frequent transitions from screen B to A. Essentially, this means that most screen transitions involve operators “bouncing” between two screens. As was the case with the simple visualizations of time spent per screen and fixations per screen, the GUI almost universally got the most attention; nearly every screen consistently has transitions to and from the GUI, essentially making the GUI a “pivot” point around which the operator’s attention revolved. The other screens most often paired with the GUI are, in order from most to least frequent, are the instructions, EE-left, and EE-right. By far the most common screen pairing not including the GUI is EE-left and EE-right, which matches with the intended use of these views in tandem with one another.

5.3 Transitions vs Distance Travelled

Next, the transition frequencies defined in the previous section will be compared to the distance travelled between screens. Rather than using the centerpoint of screens to calculate distance travelled, distances were calculated based on the average location on screens on both ends of the transition, in order to capture the specifics of the typical behavior in transitioning between screens. In order to translate the pixel distances on the mapped images to real-world inches, some estimates were made, so the inch distances may not be perfect. It is estimated that the distances here are accurate within a 1.5 inch margin of error at most.

Average Fixation Transition Distances vs Next Fixation Location Frequency in Standard Configuration

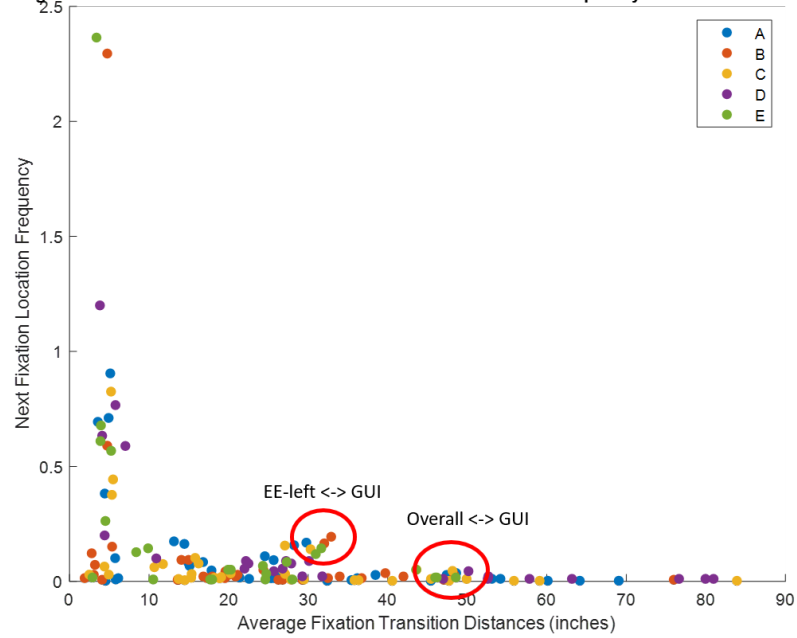


Figure 5.7: Scatterplot of distances vs next fixations, standard configuration (outliers circled in red and labelled).

Average Fixation Transition Distances vs Next Fixation Location Frequency in Altered Configuration

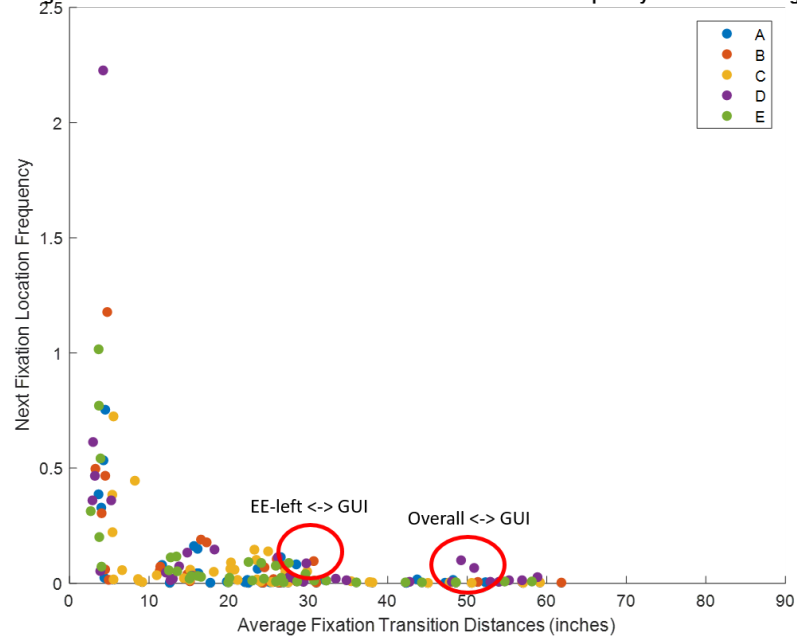


Figure 5.8: Scatterplot of distances vs next fixations, altered configuration (outliers circled in red and labelled).

The resulting plots mostly illustrate that there is an inverse relationship between the distance between screen transitions and the transition frequency, with some outliers. This is an intuitive result which indicates that in both the standard and altered configurations, screens are, for the most part, arranged such that the screens which need to be transitioned between frequently are closer together. It is important to note that the most viewed screens in these configurations (the central four) are functionally very similar to one another, and so this similar inverse relationship is to be expected. An alternative interpretation, though, is that operators simply transitioned more between adjacent screens because it was easier to do so. As with the transition matrices, datapoints tend to be paired; transitions from A to B and B to A occupy a similar space. There is some noticeable drift though; it is clear that operators do not usually make transitions from the same starting point or ending points.

Notable outlying paired data points include GUI and EE-left, and GUI and overall in both configurations. The relationship between the GUI and EE-left is thought to be the result of an unknown attractive quality in EE-left and will be examined in further detail in [Section 5.4](#).

It is easily understood why there would be at least somewhat frequent transitions between the overall view and the GUI; the GUI is essentially the center of focus for the operator, and the overall view is a broadly useful picture of the robot being operated. The distance between these views is similar in both the standard and altered configurations, though it is slightly closer in the altered configuration, where the overall view is on the bottom row of screens instead of the top. It is

noteworthy that there is actually a slightly higher transition rate between these two screens in the overall configuration than in the altered configuration. It is ultimately not clear what to make of this outlier; this may be an instance where it is simply a slightly longer transition distance than is proportional to the transition frequency.

There is a single data gathering run in which the GUI and overall views are adjacent: A1. Images of A1 and its transition matrix can be seen in Figures 5.9 and 5.10, respectively. In this configuration, there is no significant change in transition frequency between the GUI and overall views from any other configuration. There are also no outlying differences in any of the metrics such as time per fixation or overall time for the overall view when compared to the aggregated metrics for the standard and overall views. There is, however, a slightly higher overall time spent on the overall view in the personal configuration for participant A alone than in the other two configurations tested. This can be interpreted in two different ways: First, that operators will make the same number of transitions between two linked screens and pay the same amount of attention to the outlying screen, regardless of their distance. Second, that the distance relationship between these two screens is essentially meaningless in the gathered attention data. Regardless, this is only a single datapoint, so neither of these interpretations should be given too much weight.



Figure 5.9: Overall picture, participant A, personal configuration

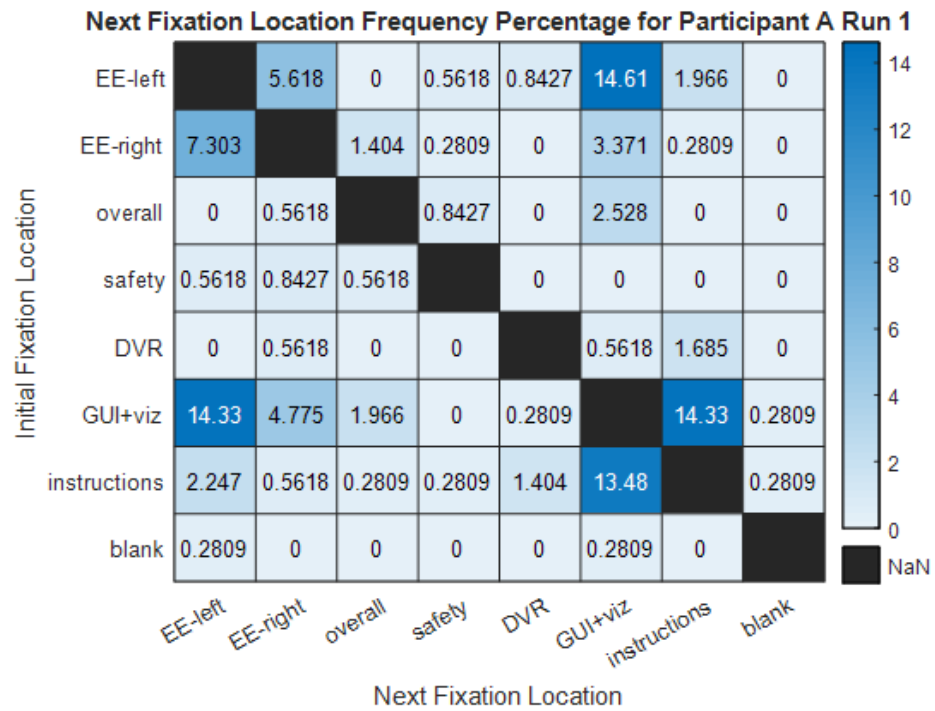


Figure 5.10: Screen transition matrix, participant A, personal configuration.

5.4 Focus on EE-left over EE-right

An interesting trend is the tendency to focus more on EE-left than EE-right, particularly given that in every configuration, EE-left is further from the GUI than EE-right. Of the 15 data gathering runs, there are only three in which more time is spent looking at the right end-effector than the left. These instances occur in no particular pattern; each is with a different operator in a different configuration (C1, D3, E2), indicating that they are most likely not linked to the differences in configuration or operator. Time per fixations on the EE-left and EE-right are usually roughly equal, which could be interpreted as meaning that operators absorb similar kinds of information on each screen, as would be expected, but are drawn to EE-left more often.

It is unclear what causes the focus on EE-left, as the two end-effector cameras are orthogonal and the views are meant to be complimentary to one another. It is possible that the quirks of the task being performed, such as the alignment changes needed, somehow favor EE-left. To examine this possibility, the overall task can be broken down into three segments, during each of which operators would be expected to have a different rationale for looking at the end-effector views. Table [5.1](#) breaks down these three segments.

Segment	Start Event	End Event	Assumed rationale for looking at end-effector cameras
1	<i>start init move</i>	<i>end move to CA</i>	No particular reason; may be used to supplement the overall view in confirming motion on the joint movements.
2	<i>end move to CA</i>	<i>make contact</i>	To bring the “wobble socket” in line with the hex cap after the misalignment at the end of the coarse alignment joint movement.
3	<i>make contact</i>	<i>at 10N seated</i>	To confirm that the “wobble socket” is aligned with the hex cap and to determine if the “wobble socket” has sprung forward to envelope the hex cap.

Table 5.1: Breakdown of task segments for EE-left and EE-right analysis.

Upon breaking down the task into these segments, the percentage of time looking at each end-effector view can be determined during each segment, using similar charts to those for the overall task.

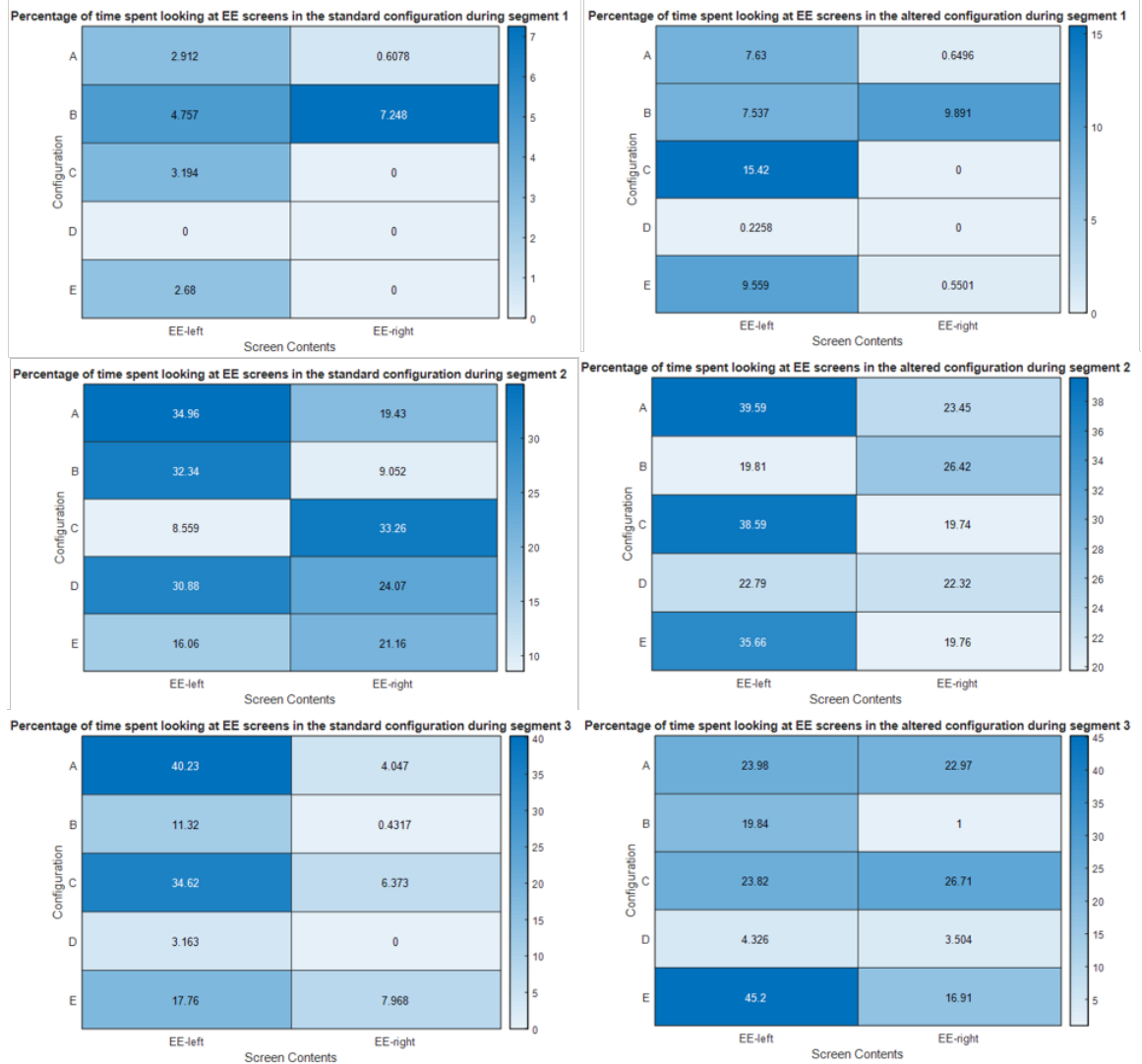


Figure 5.11: Percentage of time spent on EE-left and EE-right.

The primary takeaway from this data is that the focus on EE-left persists regardless of the rationale for looking at it. However, it seems that during segment 2, the gap between EE-left and EE-right is less pronounced. This is likely a result of the operators having to use both screens in tandem in moving into alignment, which may indicate that EE-left is simply seen as the “default” in checking the end-effector views.

Another possible explanation is simply that people, broadly speaking, tend to look at interface elements on the left before the right, and consequently tend to pay more overall attention to elements on the left rather than the right. It is a common finding in user interface design research that people tend to follow an “F-shaped” pattern in navigating an interface, where attention is initially drawn to the top and left elements of an interface, and that users are less likely to see elements of an interface if they are further down and to the right [1]. A limitation of this theory is that these are separate screens, and that these findings in user interface design research typically apply to single screens, and to webpages in particular, but it is possible that the instinct to “read” an interface from left to right extends to multi-screen displays. Operators might use EE-left as an entry point to viewing the end-effector, and only continue to EE-right if they require more data. If this was true, one might expect there to be more transitions from EE-left to EE-right than EE-right to EE-left, which does not hold true according to the transition matrices presented earlier in this chapter.

Ultimately, it is unclear what causes this phenomenon, and it may be an area which can be examined in further research. However, the implication that in a set of paired camera views, one of these views might be more useful, or even simply more attractive, could have broader ramifications in robotic console design. For example, it might be preferable to have the more attractive in a pair of views be more centrally located, or located adjacent to a dominant element of the overall console, such as the GUI in the case of this research.

Chapter 6: Conclusions, Lessons Learned, and Future Work

6.1 Summary of Conclusions

The most important conclusion of this research, which encompasses all of the conclusions to follow, is that eye tracking does appear to be an effective tool for evaluating a robotic control console. The open questions left by this research in combination with the experimental conclusions to follow illustrate that this may be a ripe area for future research.

The most certain conclusion that can be specifically drawn from the data gathered is that for the case of the task performed, on all console configurations, the GUI is the most important element of the console, attention-wise. Therefore, placing the GUI on a central screen of the console seems to be ideal, as in addition to garnering the most overall attention, it seems to be the screen that the operator’s attention tends to “pivot” off of. This conclusion is most likely immediately applicable to the vast majority of robotic control consoles, OSAM-1 included.

Very consistently throughout the tests performed, EE-left received more attention than EE-right; EE-left is even more strongly linked to the GUI for transitions than EE-right. Though it is unclear what causes this phenomenon, EE-left appears to be the default that operators use for assessing the status of the end-effector, only

moving to EE-right to draw a contrast to the data gathered from EE-left. This may have wider implications in robotic console design, as it possibly entails that among two paired camera views, one may be more attractive or possibly more useful, and therefore should be displayed in a more central location.

Broadly speaking, there was found to be a roughly inverse relationship between the transition distance between screens and the frequency of transitions between those screens, regardless of configuration. This may be just as much a result of well-arranged screen configurations as it is simply that it is easier to transition between adjacent screens; ultimately there is not enough variation in screen configuration data to make a definitive judgement.

6.2 Problems Encountered

Despite the interesting results, it is important to acknowledge that this research is ultimately an initial effort in the use of eye tracking to assess robotic control station configurations, and has identified numerous problems and complications. It is important to make these problems known, both to allow for more accurate judgements of the efficacy of this research, and to ensure that future experiments do not experience these problems. Some of these may have been mentioned elsewhere, but for accessibility, below is a list of all of the known problems encountered while gathering data for this study:

- There were originally meant to be 6 subjects for this study, but the glasses were unable to calibrate for one of them. The suspected reason for this is that

they had previously had LASIK eye surgery, as Tobii documentation mentions that eye surgery may leave scars on the cornea that interfere with eye tracking [11]. Interestingly, another subject for whom the glasses were able to calibrate for had also had LASIK.

- None of the nosepieces supplied with the Tobii glasses provided an appropriate fit for participant D, and as a result the glasses sat too high on their head, meaning that there were a lower percentages of vision samples than would have been preferred. Typical gaze sample percentages for all other subjects were at least 90%, while this participant’s gaze samples were 67%, 83%, and 67% percent, respectively. Data from this subject, though useful, was somewhat limited.
- All but one operator chose a configuration very close to, if not identical to the “standard” for their personally chosen configuration, meaning that an entire round of testing was essentially redundant. Based on exit interviews and other discussions with the team, this is thought to be a result of having been trained by the senior robot operators, who designed the standard configuration.
- Over the course of their runs through the task, operators learned the task and performed better. This may have impacted the data in several areas, such as spending less overall time looking at the instructions, and having a far easier time correcting for the purposely misaligned coarse alignment. One subject suggested that it may have helped to move to a differently misaligned coarse alignment each time, so as to prevent the operator from learning the required

alignment corrections.

- Because testing took place over the course of more than a month in an active work area, changes were sometimes made to the console and workcell which may have had an impact on data collection and operator performance. It is recommended that future testing onsite at NASA Goddard take place during the most compressed timeline possible so as to prevent changes to the workcell environment and console.
 - The camera for the overall view was mounted on a wall, but its pan, tilt, and zoom settings could be controlled remotely. At one point between testing, the camera's setting were changed and attempts were made to return it to its original configuration. These attempts were mostly successful, but it is worth noting that the overall camera view may not be identical between all runs.
 - The camera for the safety view was not mounted to anything, but was instead simply placed on the ground below the hex cap bathtub. Its position remained fairly consistent, but shifted somewhat over the course of the experiment. Again, mostly successful attempts were made to return the camera to its original configuration.
 - Screen resolution of the bottom center right screen had been changed between when most of the operators did their second and thirds testing rounds. This wasn't caught until after most of the third round data had already been gathered, but upon discovering this, it was decided that this

would be treated as a feature of the altered screen configuration. For the first two rounds for all subjects, the resolution was 2560x1440. For the final round for all subjects, resolution was 2048x1152.

- The screens were sometimes tilted somewhat differently between testing rounds.
- Some instructions for the task were omitted, ignored, misinterpreted, or otherwise incorrectly implemented.
 - Gravity compensation setting was not specified in the instructions; some operators assumed it should be set on, others proceeded without it. Midway through D1, the operator decided that it should be set on, and added it to the instructions, assuming it had been erroneously left out. It was later discovered that gravity compensation had been left out intentionally by the robot operator who wrote the instructions. Gravity compensation may have had some impact on the ease of operating the robot, though the subjects who performed the task without it did not seem to have been impacted.
 - Though the instructions said to do so, the end-effector light was not turned on by some operators. In some cases, the subject or researcher realized that the lights had not been turned on midway through the task, and the lights were promptly turned on, but there were cases where the lights were kept off for the entire run. This may have impacted the operator’s ability to see the wobble socket making contact with the hex

cap.

- Some operators skipped instructions by blending them together. For example, there are several cases where operators performed corrections to the fine alignment while also moving to fine alignment, allowing them to essentially skip a step in the instructions. This blending and compounding of user errors typically escalated over the course of a data gathering run, and was complicated by the fact that some users sometimes needed to return to previous steps. The result of this problem is that particularly for the later steps of the task, it was all but impossible to accurately partition many of the data gathering runs into subtasks for the purpose of analysis.
- It was discovered that during D1, the fastener keeping the hex cap in the “bathtub” had come loose, leading to the hex cap spinning freely when the tool drive was activated. The operator briefly paused and recording was temporarily stopped to fix this problem.
- It was planned to perform additional tests with this set of test subjects, or to increase the size of the subject population. Due to the shutdown of NASA Goddard due to the coronavirus pandemic, further human testing was not possible, and is still infeasible at the time of writing.

6.3 Future Work

The research performed here is explicitly meant to be a baseline for future work to build upon. In addition to accounting for the problems encountered, future work should be consciously designed to answer specific questions raised by this research, in contrast with the experiment performed, which was essentially designed to answer the very broad question of how robot operators' eyes behave while performing a task. Many hypotheses can be drawn from this data, which will be elaborated on below through a series of ideas for future experiments, in rough order from most immediately feasible to least. Note that it may be advantageous for a future researcher to draw on elements of many of these ideas in designing a new experiment.

1. Build on this research by repeating the same basic experiment but with more test subjects, and measures taken to quantify or remove the observed learning effects, and mitigate the various other problems encountered in collecting data. Performing with more test subjects may remove what biases may occur in the limited population studied in this research, as well provide additional data for dealing with learning effects. However, there is a highly limited population of trained robot operators available, so it may be necessary to expand beyond exclusively using robot operators as test subjects. It may in fact be interesting to examine data gathered from non-robot operators for reasons beyond the advantages of testing with more subjects. Because the experiment performed involved operating expensive hardware, it would be preferred that any exper-

iment involving non-robot operators be simulated, rather than actually being run on a physical robot. Future versions of this experiment may also benefit from considering additional participant characteristics, such as handedness, or considering new areas of analysis, such as whether it is easier for subjects to transition between screens vertically or laterally.

2. An important conclusion of this research is that screens tend to be paired, attention-wise. The most frequently occurring pairs were EE-left and EE-right, the GUI and instructions, and the GUI and EE-left. It is important to note that in literally every data gathering run performed, screens containing the GUI, instructions, and the end-effector views were in the same position relative to one another. The configuration used makes intuitive sense; it is only natural to assume that as the most important cameras views, the end effector cameras should be front and center, and that the GUI, most notably the force and torque displays, should be as close as possible to the end effector screens, particularly during contact operations. It also makes intuitive sense that the instructions should be near the center of the console, and as close as possible to the GUI, where commands are entered. However, experiments should be performed to determine just how essential this configuration is by scrambling the screens more dramatically. It is hypothesized that there is a quantifiable benefit to grouping more frequently transitioned screens closer together, so experiments in this vein may be used to test this hypotheses.

- (a) One test with a scrambled configuration should specifically break apart

the most commonly paired screens. It is always a possibility that part of the reason transitions occur so commonly between two screens is at least in part simply because they are close together, and not because they are naturally linked in the data that operators gather from them. In particular, because the GUI is generally the "pivot" which most other screens are paired with, this may entail moving the GUI to a corner of the console, surrounded primarily by less often used screens.

- (b) To specifically test the relationship between the end-effector views and force and torque displays on the GUI, an experiment could vary the position of the force and torque displays relative to end-effector camera views, and have the subjects perform contact operations, paying close attention to how long it takes the operators to notice that they're in contact, while in various configurations. This test might take some inspiration from the standard display intrusion test. A limitation of this is that it may be dangerous for hardware, and could not be performed with the current OSAM-1 simulation software, as it lacks the ability to simulate contact operations.

- 3. Early in the analysis for this research, it was anticipated that breaking the data analysis for the overall task into smaller subtasks and contrasting performance on these subtasks to one another might yield particularly interesting results. Because of the length of the overall task and the variables which occur and compound over its course, it became difficult to consistently divide the length

of all data gathering runs into discrete subtasks in the first place, let alone compare and contrast these subtasks among different runs. As a result, this area of analysis was largely dropped in favor of primarily analyzing each data gathering run as a whole. In order to better isolate smaller subtasks and so facilitate analyzing data on a subtask-by-subtask basis, it may be preferable to have operators perform several very small tasks, as opposed to one long one. For example, this could entail individually performing all of the subtasks from the experiment performed here, but at the end of each subtask, data collecting would stop and the robot would be reset to a standardized position for starting the next subtask. The difficulty here is that these subtasks-based trials would likely be time intensive and require significant help from the robot operators.

4. This research was highly limited in that it only involved collecting data on a single, relatively simple training task. The task was selected because it was a simple training task which bears some resemblance to some of the more attention-intensive tasks to be performed on OSAM-1, but more realistic tasks may be better for evaluating the console's usefulness in flight. Ideally, various tasks should be evaluated which run the gamut of teleoperation tasks, both specifically on OSAM-1, and generally in teleoperation of serial manipulators. Particularly in regards to OSAM-1, these tasks should utilize as many different types of camera views and GUI elements as possible, to evaluate the consoles to their fullest possible extent. It may also be advantageous to introduce other

flight-like complications, such as a delayed signal.

5. Cognitive load is a metric of working short-term memory used in a given task, which researchers have been working to establish a relationship to eye movements [4]. Recent approaches to estimate cognitive load involve using an eye tracking system to monitor pupil diameter and microsaccades (tiny eye movements smaller than a saccade, during a fixation) [13]. Regardless of a specific link to cognitive load, changes in both pupil diameter and microsaccades have been shown to correlate with task difficulty [8]. Future experiments could use these metrics, which can be gathered using the same eye tracking system used in this research, to determine if there is a link between either cognitive load or task difficulty and screen configurations.

Testing has revealed the complexity and painstaking nature of eye tracking, particularly with the extreme visual field of the OSAM-1 control station configuration, but the results indicate that there is some useful information to be gathered from the procedure, and in particular point to areas which can be explored in greater detail. The human element makes the data gathered extremely noisy and sometimes difficult to interpret; this is compounded by the fact that for this particular area of study, there is a very small available population of potential test subjects. The best way forward is simply to gather more data and try to plan and execute future experiments as well as possible.

Appendix A: Task Performed

The following pages contain the procedure given to robot operators for the experiment performed. This procedure was written by Zakiya Tomlinson.

MH250 Procedure – Wobble Socket Eyetracker Task

Configuration:

- MH-250 with OTCM-S and Wobble Socket Training Tool (has tool cameras, but no lights)
 - Make sure the fitting around the wobble socket is tight
- SMA Cap Bathtub Training Hardware mounted to underside of OSCAR (with handles removed)
- SA Camera 101 below SMA cap bathtub; SA Cameras 203 watching the whole robot

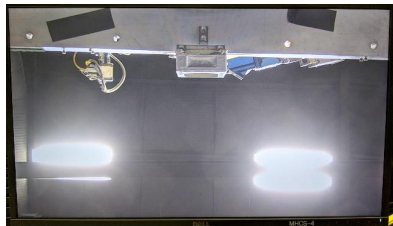


Figure 1 – SA Camera 101

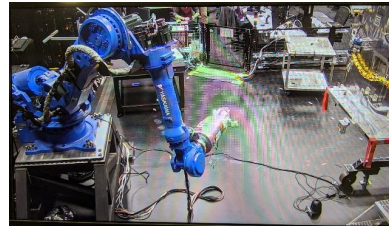


Figure 2 – SA Camera 203

Ensure all facility lights and OTCM-S lights are turned on

Required GUI Displays/Plots:

- | | |
|---|--|
| <ul style="list-style-type: none"> • Wrench Measured Force • Wrench Measured Torque • Joint pose move • Cartesian pose move | <ul style="list-style-type: none"> • Rate Input • Fault log • Wrench Meas_T soft limits • OTCM-S Control |
|---|--|

Tool Configuration:

X	Y	Z	Roll	Pitch	Yaw
0	0	0.849	45	-90	-180

Mass Properties:

Mass (kg)	CM_E X (m)	CM_E Y (m)	CM_E Z (m)
30	.01	.005	.5

Do not select a scene for the Visualization (OSCAR is incorrectly placed in the red scene)
 Set the Visualization robot payload to the MFT2 (closest cousin to the Wobble Socket tool)
 Configure tool cameras with crosshairs overlays, with the centerline aligned with the tooltip.
 Do not have the terminal window with the deployer or yiax application visible during data collection
 (both contain information that should not be recorded for an external source).
 Make sure the walkway gate to the workcell is tied shut with the “DO NOT ENTER” sign in place.
 Add notes (if applicable) to Test Ticket [#18640](#)
 Joint pose tolerance: +/- 0.01 degrees.

Procedure:

1. If the robot is not already at the position below, perform a joint pose maneuver at 2% velocity to:

J1	J2	J3	J4	J5	J6
-37.752	42.681	-28.551	-97.575	92.647	14.033

2. Begin data collection.

3. Perform a Joint Pose Maneuver at 2% velocity to:

J1	J2	J3	J4	J5	J6
-9.635	49.997	-50.322	-18.682	91.032	44.923

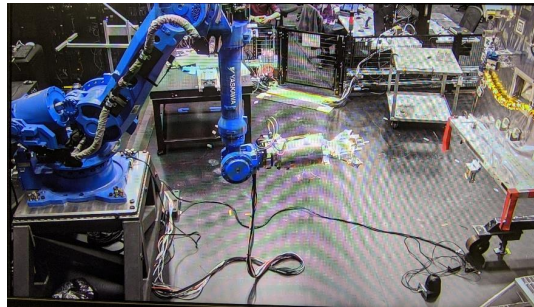


Figure 3 – SA Camera 203 View

4. Perform a Joint Pose Maneuver at 2% velocity to Coarse Alignment:

J1	J2	J3	J4	J5	J6
-20.558	34.908	-17.011	-23.958	77.459	56.745

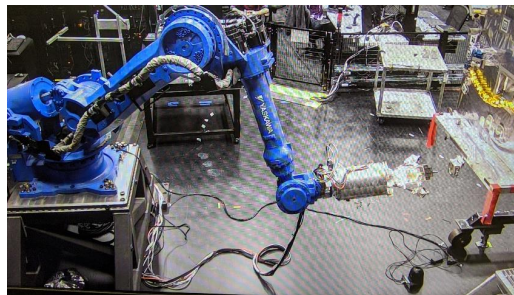


Figure 4 – SA Camera 203 View

5. Perform corrections as required in order to coarsely align the socket with the top-right cap.

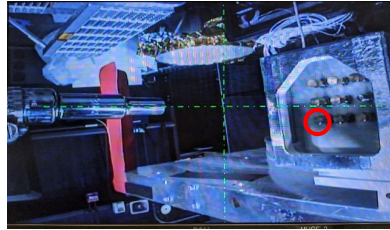


Figure 5 – Left Tool Camera View



Figure 6 – Right Tool Camera View

6. Maneuver 6 cm +X (tool frame) to Fine Alignment Position.
Perform alignment corrections as required.

7. Set Wrench Measured Soft Limits:

F_X	F_Y	F_Z	T_X	T_Y	T_Z
25	25	25	8	8	8

Zero Sensor & Reset Wrench Extremes

8. Maneuver +X (tool frame) until fully seated over cap with 10N axial force (expect 4-5 cm of motion)
- Note: If hex is not aligned, tool will compress at point of first contact instead.
 - If hex cap is still visible after reaching 10N compression, perform CW torquer rotations at 4N-m for as many 0.5 turn increments as necessary to get the socket to align with the cap (socket will spring forward once aligned).
 - Once socket is aligned with cap, continue +X motion until fully seated with 10N axial force
9. Back away until axial forces are completely relieved (no tool compression).
- Note: This is the point at which the cap would be unscrewed, but this will not be performed for this evaluation.
10. Stop data collection
11. Back away to a safe distance (approx. 10cm).
Perform a 0.5 turn 4 N-m CW torquer rotation to reset alignment with hex cap.
Set wrench soft limits to max values (9999 N, 999 Nm).

12. Perform a joint pose maneuver at 2% velocity to the starting pose:

J1	J2	J3	J4	J5	J6
-37.752	42.681	-28.551	-97.575	92.647	14.033

Appendix B: Interview Questions Asked

B.1 Pre-Test Interview

The following is the loose script for the opening interview:

1. *Introduce and explain the eye tracking glasses.*
2. Do you wear contacts? If so, would you say that it is a particularly strong prescription?
3. *Have subject try on the eye tracking glasses, and try out different nosepieces, selecting the one they will use for the test based on a combination of comfort and centering glasses on eyes.*
4. *Attempt to calibrate the glasses.*
5. Do you think the glasses will in any way impede your performance?
6. Describe your experience as a robot operator.
7. *Explain the task to be performed.* Have you done this task before? How many times/how recently?

8. *Show the subject an overall picture of the standard console configuration.* Have you used this console configuration before? Would you say that it is conventional for the task to be performed?
9. *Show the subject a screenshot of the GUI configuration to be used.* Have you used this GUI configuration before? Would you say that it is conventional for the task to be performed?
10. A quick disclaimer: Data gathered will not be attributable to you. We will not publish your identity. Any results that involve data from specific participants will refer to you as participant A, B, etc. Also, don't rush, go at your own pace, go as you normally would. I may be timing you, but the purpose of this test is not to evaluate you based on speed.

B.2 Post-Test Interview

The following is the loose script for the post-test interview:

1. Do you think there was a significant difference in your performance due to having performed this test multiple times?
2. Do you think the console configuration had an impact on your performance?
3. Do you think wearing the eye tracking glasses had an impact on your performance?

Appendix C: Personal Screen Configuration



Figure C.1: A1 configuration overall picture.

	Outer left	Center left	Center right	Outer right
Top	DVR	EE-left	EE-right	Safety
Bottom	Blank	Instructions	GUI + Viz	Overall

Table C.1: Table describing the A1 configuration.



Figure C.2: B1 configuration overall picture.

	Outer left	Center left	Center right	Outer right
Top	Safety	EE-left	EE-right	Safety
Bottom	DVR	Instructions	GUI	Viz

Table C.2: Table describing the B1 configuration.



Figure C.3: C1 configuration overall picture.

	Outer left	Center left	Center right	Outer right
Top	Overall	EE-left	EE-right	Safety
Bottom	Blank	Instructions	GUI + Viz	DVR

Table C.3: Table describing the C1 configuration.



Figure C.4: D1 configuration overall picture.

	Outer left	Center left	Center right	Outer right
Top	Overall	EE-left	EE-right	Safety
Bottom	Blank	Instructions	GUI + Viz	DVR

Table C.4: Table describing the D1 configuration.



Figure C.5: E1 configuration overall picture.

	Outer left	Center left	Center right	Outer right
Top	DVR	EE-left	EE-right	Overall
Bottom	Blank	Instructions	GUI + Viz	Safety

Table C.5: Table describing the E1 configuration.

Appendix D: Time Taken per Subtask

Participant	Run Number	Move to approach position	Move to coarse alignment	Corrections to coarse alignment	Move to fine alignment	Corrections to fine alignment
A	1	34.6	20.0	2:15.7	31.7	???
	2	35.1	20.5	2:06.6	46.1	???
	3	36.6	20.6	2:13.4	33.3	1:14.8
B	1	35.4	19.9	28.1	18.6	16.9
	2	36.1	16.6	20.8	17.0	14.1
	3	33.5	19.8	24.3	37.1	14.8
C	1	33.1	22.5	3:44.0	38.9	???
	2	31.1	16.5	2:20.0	1:24.6	49.7
	3	31.3	17.4	4:55.0	1:15.7	2:16.8
D	1	37.7	17.0	1:41.1	30.4	???
	2	37.9	18.6	1:37.1	45.2	27.9
	3	32.7	18.5	1:07.9	19.6	1:36.0
E	1	35.1	22.8	3:23.9	1:24.9	1:24.9
	2	34.2	20.5	4:17.5	1:48.3	1:48.3
	3	34.6	17.6	1:57.2	1:41.3	???

Table D.1: Table describing the E1 configuration.

The events which form the bookends of these subtasks were recorded manually using the Tobii software, which allowed events to be entered by watching playback from the glasses recordings and pressing buttons events occurred. Note that in cases where “???” is listed instead of a time, lines between tasks were blurred, making it extremely difficult to assess a beginning and end time to tasks. Also note that times

for later subtasks are not included, as in many data-gathering runs lines between tasks become increasingly blurred as the task continued, to the point where it would be impossible to simply express the amount of time that the later subtasks took.

Appendix E: Additional Figures Generated

E.1 Time Percentage per AOI

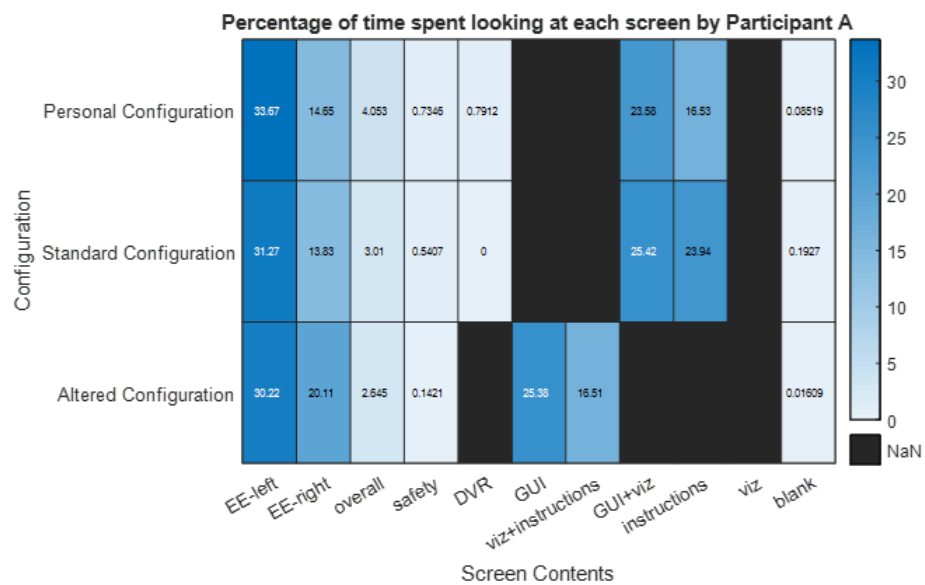


Figure E.1: Participant A time percentage per AOI.

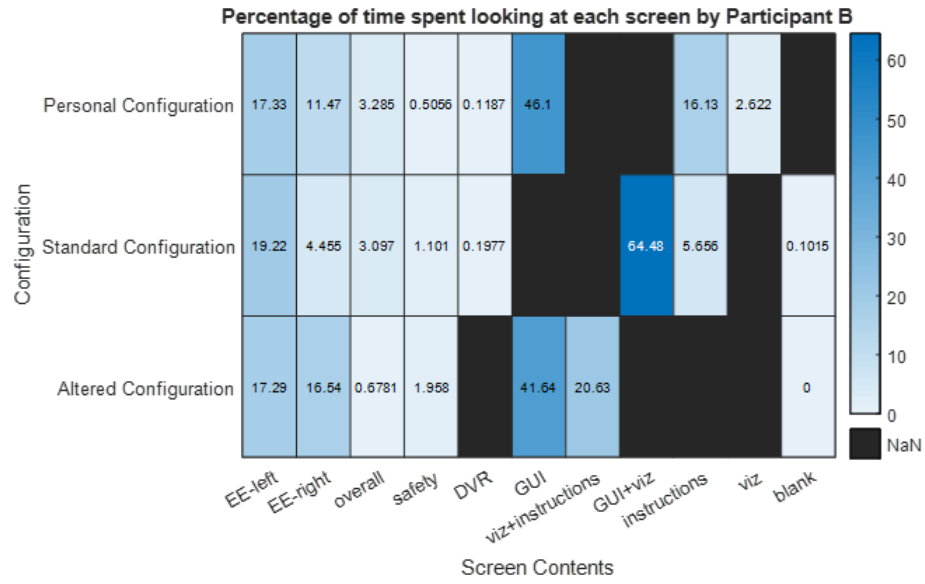


Figure E.2: Participant B time percentage per AOI.

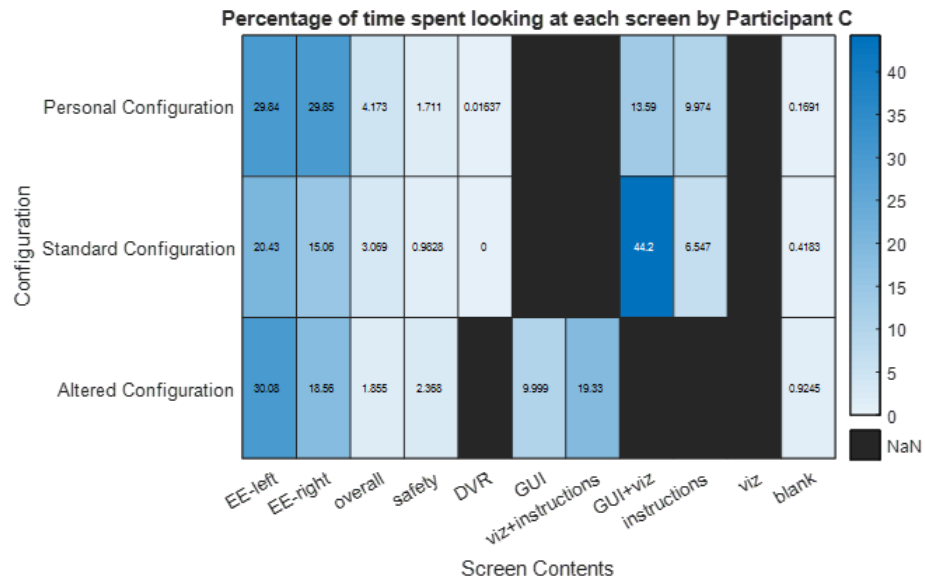


Figure E.3: Participant C time percentage per AOI.

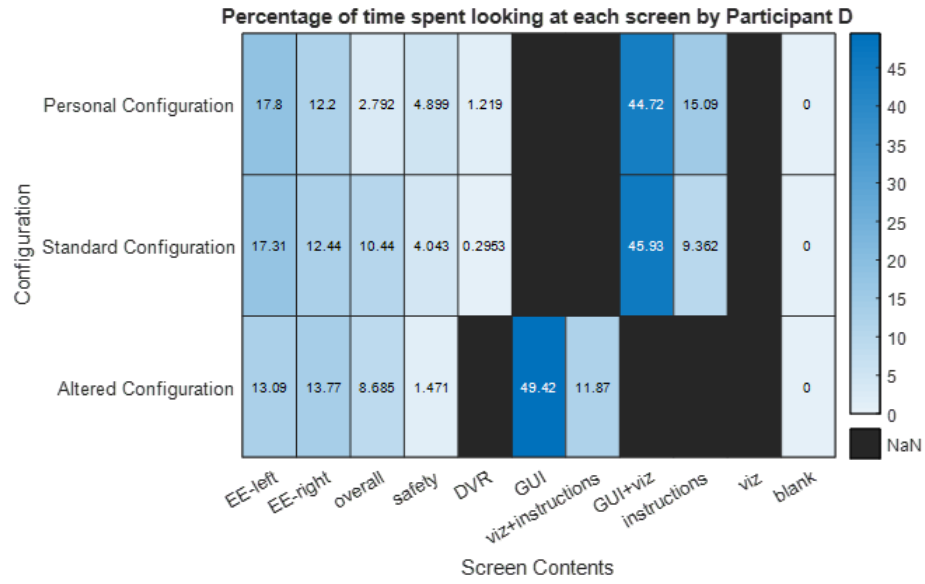


Figure E.4: Participant D time percentage per AOI.

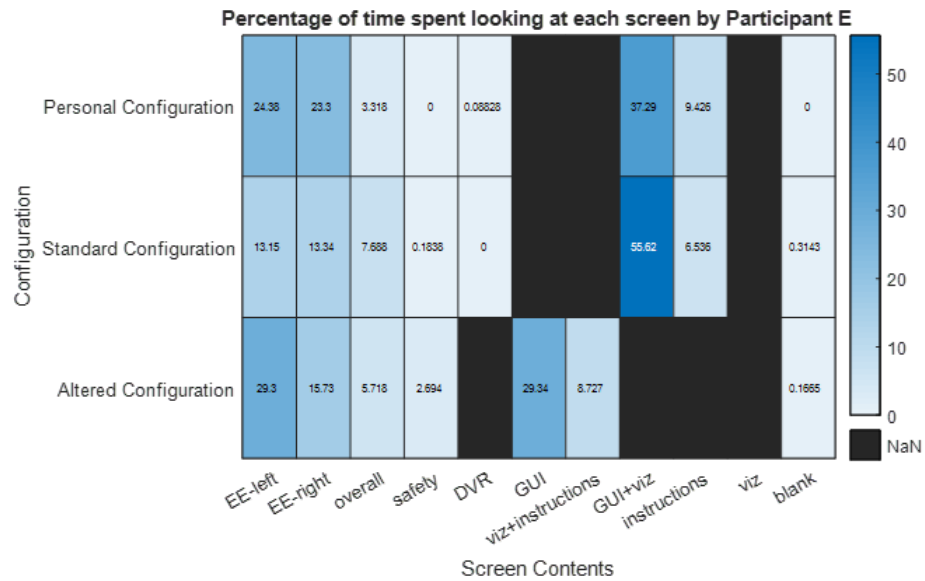


Figure E.5: Participant E time percentage per AOI.

E.2 Time per Fixation per AOI

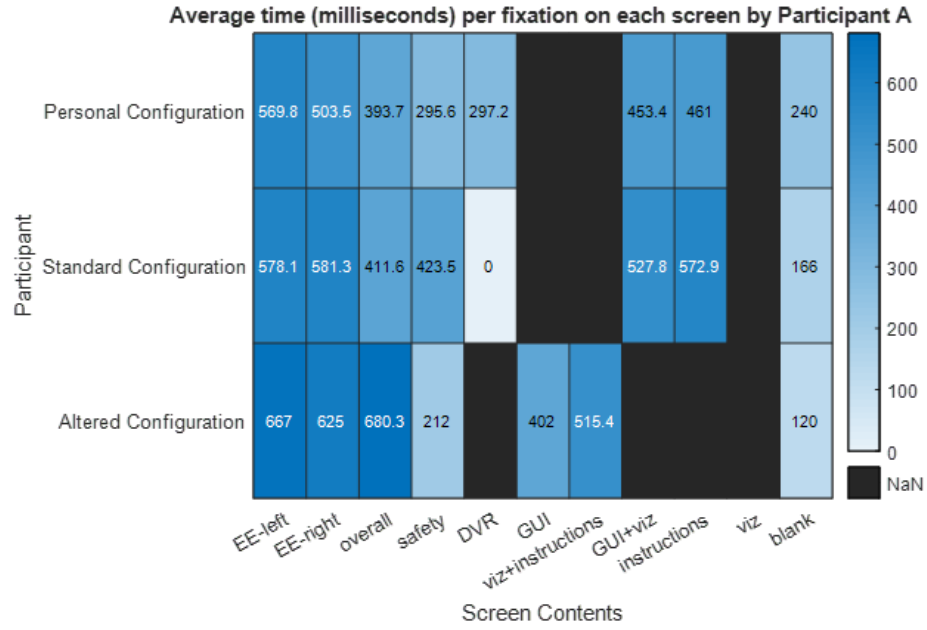


Figure E.6: Participant A time per fixation per AOI.

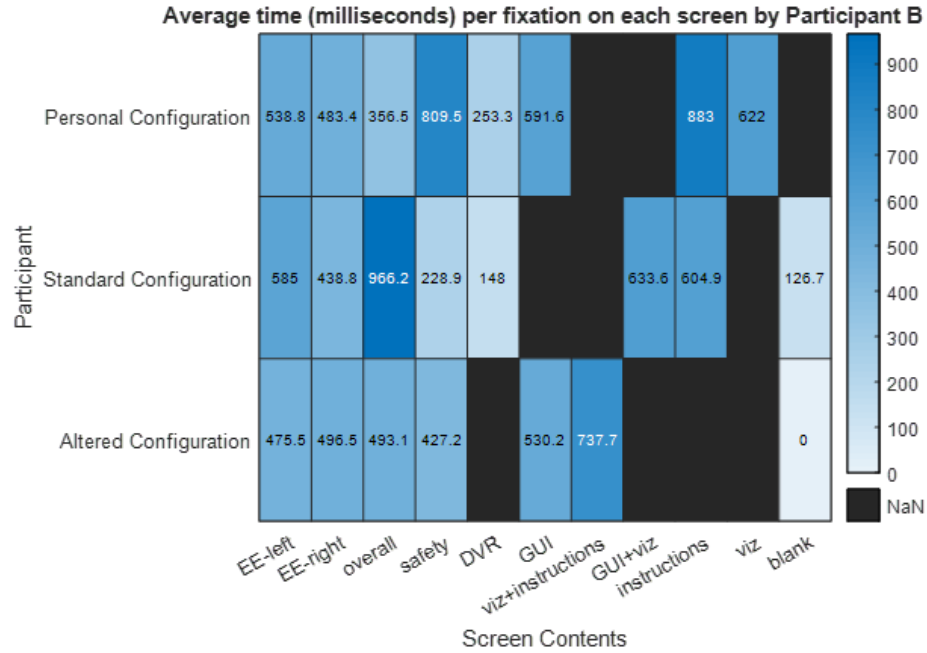


Figure E.7: Participant B time per fixation per AOI.

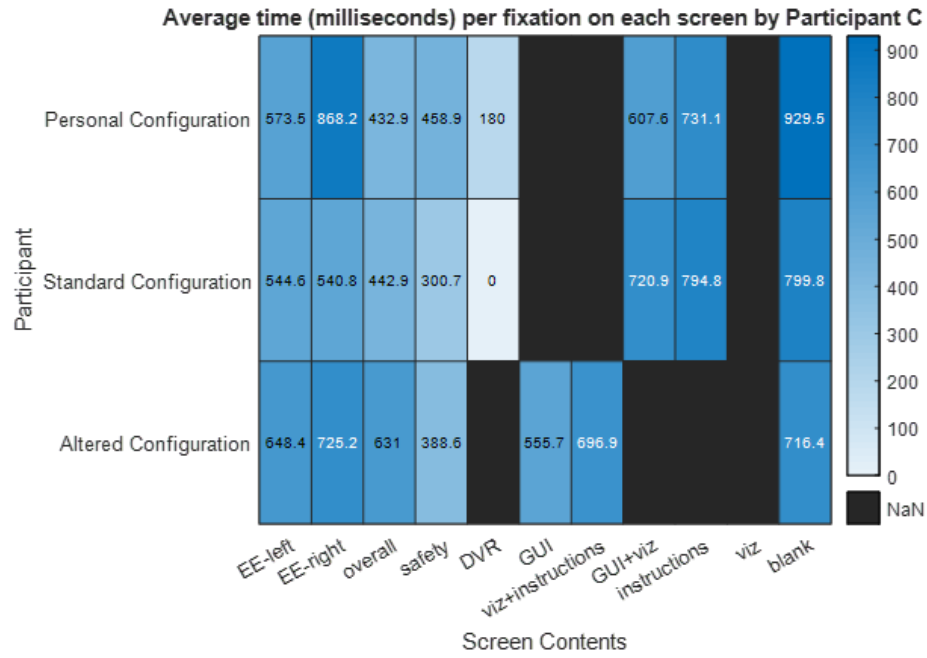


Figure E.8: Participant C time per fixation per AOI.

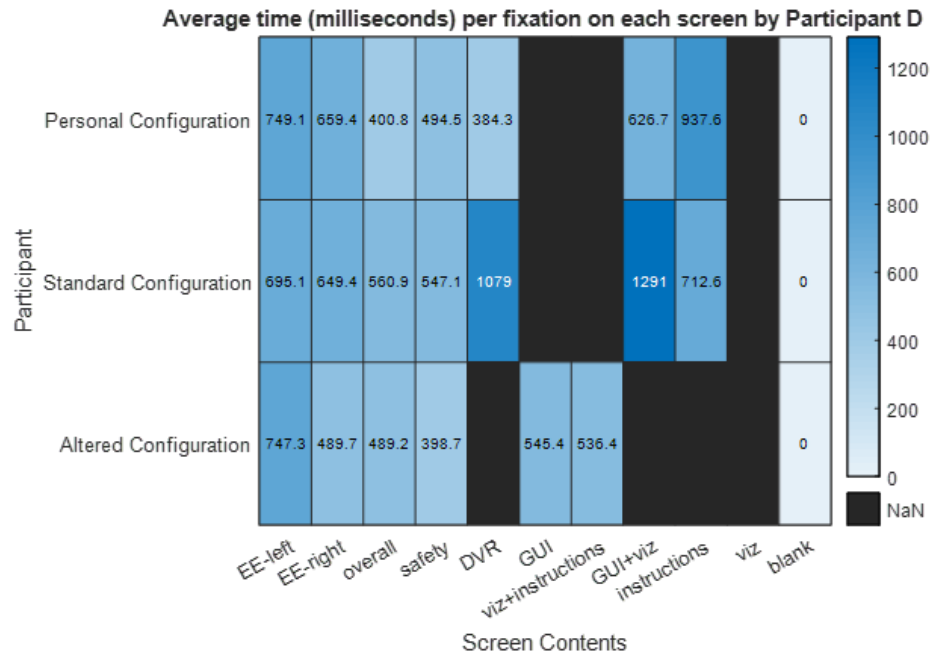


Figure E.9: Participant D time per fixation per AOI.

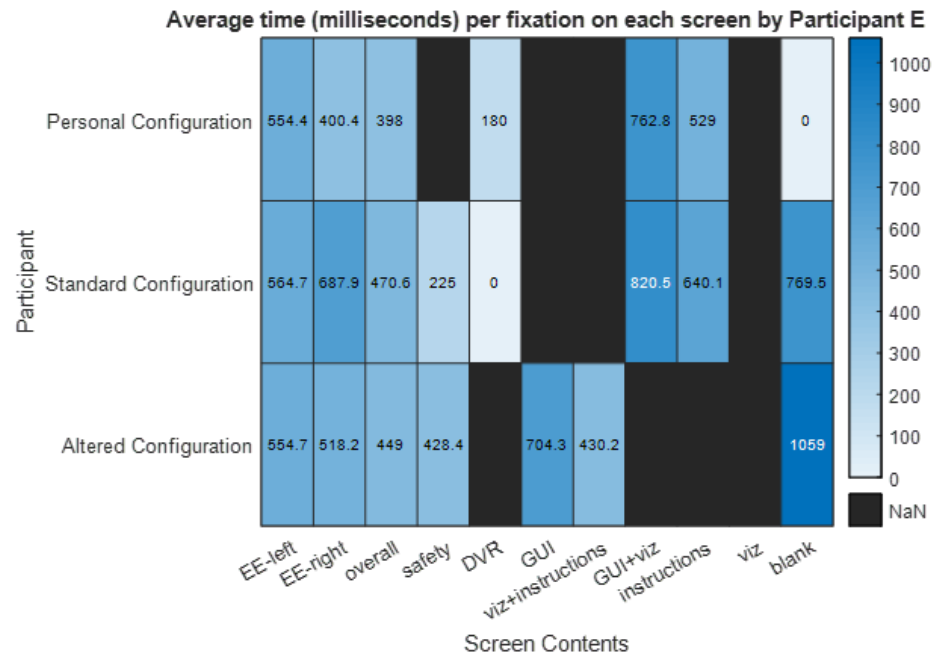


Figure E.10: Participant E time per fixation per AOI.

Appendix F: Institutional Review Board Paperwork

What follows are the documents submitted to the Institutional Review Board in order to obtain approval for the human subjects in this experiment.

F.1 IRB Initial Application - Part 1

University of Maryland College Park Institutional Review Board IRB Initial Application - Part 1

Last edited by: Casey Kracinovich

Last edited on: February 14, 2020

[\[click for checklist\]](#)

☐ Full
☒ Expedited
☐ Exempt

[1566449-1] Evaluation of a Space Robotics Control Console Using Eye Tracking Glasses

Answer all questions on this form completely, include attachments and obtain signatures of Co-Investigators and your department IRB Liaison prior to final submission on IRBNet.

I. Principal Investigator

Name: Dave Akin **Status:** Faculty
Department: ENAE- Aerospace Engineering
Phone: 301.405.1138 **Email:** dakin@ssl.umd.edu
Address: 382 Technology Dr, College Park, MD 20742

II. Faculty Advisor

N/A ☒

Note: A faculty advisor is required if the PI is a student resident or fellow and the Faculty Advisor MUST sign this package through IRBNet.

Name:
Department:
Phone: **Email:**
Address:

III. Co-Investigators

N/A ☐

Note: All co-investigators MUST sign this package through IRBNet.

Name: Casey Kracinovich
Department: ENAE- Aerospace Engineering
Phone: 4127285085 **Email:** casey@ssl.umd.edu
Address: University of Maryland, Neutral Buoyancy Research Facility, 382 Technology Dr, College Park, MD 20742

IV. Funding Information

N/A ☐

Note: A copy of the awarded grant application (minus budgetary information) must be provided.

Status	Funding Type	Sponsor Name	ORAA #	COI
Awarded	Subcontract	Aviation Technical Services		No
Funding Title:				

V. Project Information

Lay Summary:

Manually teleoperating a robot arm requires the operator to split their attention between command dialogues, data streams, and video feeds. We seek to evaluate the human factors of the design of a robotics control console, using eye tracking glasses to gain insights into the ways in which operators interact with the various console elements. Using the data we gather, we will gain insights into how the various elements of a robot control console might ideally be arranged.

Requested Review Path:

- ☐ Full
☒ Expedited
☐ Exempt

Projected Completion Date: 09/30/2020

Research Category:

- ☐ Faculty or Staff Research
☒ Graduate Student Research
☐ Student/Faculty Collaboration
☐ Undergraduate Student Research
☐ Other:

Academic Committee Review:

- ☒ Yes - Masters committee
☐ Yes - Dissertation committee
☐ No additional academic review required

Participant Incentives:

- ☐ Cash
☐ Check
☐ Raffle/ Lottery:

☐ Extra Credit/ Course Credit:

☐ Gift:

- ☐ Food:
- ☐ Other:
- ☒ Not Applicable

VI. Performance Sites

Performance Sites Engaged in Human Subject Research:
(where the research will be conducted)

- ☐ UMCP - Campus:
- ☐ University of Maryland - Extension:
- ☐ Campus Health Center
- ☐ Universities at Shady Grove:
- ☐ Schools:
- ☐ Prison/Jail:
- ☒ Other:
- NASA Goddard

Is this an international study?

- ☐ Yes [complete Section 10 of Initial Application Part 2]
- ☒ No

If yes: International Sites:

VII. Subject Information

Targeted Populations:

- ☐ Normal adult/healthy persons
- ☐ Cognitively impaired persons
- ☐ Economically disadvantaged persons
- ☐ Educationally disadvantaged persons
- ☐ Elderly/aged persons
- ☐ Hospital patients or outpatients
- ☐ Illiterate persons
- ☐ Individuals with physical disabilities
- ☐ Minority group(s)
- ☐ Minors/children
[inclusion of anyone under 18 requires a Parental Consent Form]
- ☐ Non-English speakers

- ☐ Pregnant women
- ☐ Prisoners
- ☐ Students (non-minors)
- ☐ UMCP employees
- ☒ Other special characteristics and special populations:

Space robot operators

Informed Consent Process:

- ☒ Informed consent will be obtained from subjects and documented with a signed, written consent form
- ☐ Informed consent will be obtained from subjects, but no signed consent form will be used. This includes oral consent and implied consent (e.g., completing a survey).
[please see the Requesting a Waiver of Informed Consent Guidance]
- ☐ Fully informed consent will not be obtained from all subjects. This includes deception, withholding information, etc.
[please see the Requesting a Waiver of Informed Consent Guidance]

Will you be collecting health information from or as a HIPAA covered entity?

(See the [HIPAA section of the IRB website](#) for more information and additional resources.)

- ☒ No
- ☐ Yes, data are de-identified or constitute a limited data set.
- ☐ Yes, subject's authorization will be obtained or a waiver or alteration of authorization will be requested.
[complete IRB Form HIPAA]

VIII. Research Procedures

Research Procedures:

- ☐ Records review - retrospective
- ☐ Records review - prospective
- ☐ Education research
- ☒ Behavioral experiments
- ☒ Behavioral observation
- ☐ Questionnaires/surveys
- ☒ Interviews
- ☐ Audiotaping/videotaping
- ☐ The Internet
- ☐ Deception
[describe debriefing process in Section 7 of Initial Application Part 2]
- ☐ Cancer Interventions (health promotion, implementation, etc.)
- ☐ None of the above

Biomedical Procedures:

- ☐ Tissue banking
- ☐ Biopsy
- ☐ Blood draw:
- ☐ Use of pre-existing tissues
- ☐ Clinical tests
- ☐ Radiology
- ☐ Radiation/X-ray/DEXA
- ☐ fMRI
[use IRB fMRI templates]
- ☐ Pregnancy screening
- ☐ EKG
- ☐ EEG
- ☐ Genetic analysis
- ☒ None of the above

IX. Assurances and Signatures**Assurances**

This research, once approved, is subject to continuing review and approval by the IRB. The principal investigator will maintain records of this research according to IRB guidelines. If these conditions are not met, approval of this research could be suspended or terminated.

Electronic signatures certify that:

- The signatory agrees that he or she is aware of the policies on research involving participants of the University of Maryland College Park and will safeguard the rights, dignity, and privacy of all participants.
- The information provided in this application form is correct.
- The principal investigator will seek and obtain prior written approval from the IRB for any substantive modification in the proposal, including but not limited to changes in cooperating investigators/agencies as well as changes in procedures.
- Unexpected or otherwise significant adverse events in the course of this study which may affect the risks and benefits to participation will be reported to the IRB.
- The research will not be initiated and subjects cannot be recruited until final written approval is granted.

The following signatures are required for new project submissions:

- Principal Investigator
- Co-Investigator(s)
- IRB Liaison ([click here for list](#))

INSTRUCTIONS TO RESEARCHERS

[\[top\]](#)

Now that you have completed this document, check your work, attach all appropriate documents, electronically sign and submit your work. Based on your responses, the following additional documentation must be included with this package before submission. Upload additional documentation in the Designer.

Documents available in the IRBNet Forms and Templates Library:

- Consent Form (template and Completion Guide in Library)

Additional required documentation:

- Grant application for any awarded funding

If you have any questions, please refer to the guidelines in the IRBNet Forms and Templates Library or contact irb@umd.edu.

F.2 IRB Initial Application - Part 2



Institutional Review Board

1204 Marie Mount Hall • 7814 Regents Drive • College Park, MD 20742 • 301-405-4212 • irb@umd.edu

INITIAL APPLICATION PART 2

1. Abstract:

Manually teleoperating a robot arm requires the operator to split their attention between command dialogues, data streams, and video feeds. We seek to evaluate the human factors of the design of a robotics control console, using eye tracking glasses to gain insights into the ways in which operators interact with the various console elements. Using the data we gather, we will gain insights into how the various elements of a robot control console might ideally be arranged. This experiment is specifically in support of the Restore-L mission, a mission to robotically capture and refuel the Landsat-7 satellite while still on orbit. It will therefore involve trained Restore-L robot operators as subjects. No personally identifiable information for these robot operators will be published, as researchers will take care to protect their identity. There will be an identification key, kept in a secure location, which will link the subjects to their identities.

2. Subject Selection:

- a. **Recruitment:** The investigators will use contacts at NASA Goddard working on the Restore-L mission to recruit robot operators. We are already in contact with the lead robot operators, who can help us organize times to perform testing. We will recruit the participants via email. We will submit a letter from NASA Goddard granting us permission to conduct research at their site with their employees as an amendment. Note that the University of Maryland is currently under Severe Research Restrictions because of the COVID-19 outbreak. We will not begin enrolling participants for in-person procedures while these restrictions are still in place.
- b. **Eligibility Criteria:** Subjects will be trained robot operators at NASA Goddard, working on the Restore-L mission. Subjects must be at least 18 years of age to participate.
- c. **Rationale:** As this experiment is in support of the Restore-L mission, and the resulting console will ideally be used on the actual mission, we ideally should have trained robot operators, and ideally, robot operators trained to perform on the Restore-L mission.
- d. **Enrollment Numbers:** We expect to have 6 subjects.
- e. **Rationale for Enrollment Numbers:** There are 6 trained robot operators working on the Restore-L mission.

3. Procedures:

In the days or weeks leading up to the experiment, participants will be given a brief introductory interview, expected to take about 15 minutes, in which they will be introduced to the eye tracking glasses and asked a couple questions regarding their previous experience as a robot operator.

The procedures involve operating a robot through a basic training task three times, with the console in three different configurations, all while wearing eye tracking glasses. Each run is expected to take no more 30 minutes. If the operator indicates that they are inexperienced with the training task, they will be allowed to have a “dry run” without wearing eye tracking glasses before starting the planned data gathering runs. During all data gathering runs, a curtain will be drawn between the operator and the robot, such that they need to look at the camera views on the console instead of being able to directly look at the robot. After the second and third of the data gathering runs, they will be given a brief questionnaire, taking about 5 minutes, regarding their performance and feelings about the console configuration.

Note that the University of Maryland is currently under Severe Research Restrictions because of the COVID-19 outbreak. We will not perform in-person procedures while these restrictions are still in place.

4. Risks:

The only risks from participating in this research study are the risks normally associated with operating a robot in the subjects’ normal work; the worst of which being possible physical harm to a person who might interfere with the robot, or permanent damage to expensive hardware. Given the safety measures already in place (e.g. gated robotic workcell to keep people from interfering and trained emergency stopper present for all robot operations) as well as their status as a trained robot operator, these risks are assumed to be extremely unlikely.

There may be a mild discomfort from using a somewhat different console configuration, though we expect that this will be easily mitigated if the subjects perform the tasks at their own pace, so as to gradually grow accustomed to the new configuration. We will emphasize in the opening interview that this is not a time-based evaluation and that the subjects should take all the time they need.

The eye tracking glasses to be used are very light and unobtrusive, but may cause mild discomfort as well. To mitigate this, in the opening interview, subjects will try on the glasses and be asked if they find them to be at all uncomfortable; if they indicate a significant level of discomfort, minor alterations, such as changing out the nosepiece of the glasses, can be made. For any potential sources of discomfort, if a subject complains or visibly seems uncomfortable during the experiment, they will be allowed to stop to take a break, or stop altogether if necessary.

5. Benefits:

There are no direct benefits for participants. Possible benefits include data that may help design an improved, more ergonomic, robotic control console for the robot operator subjects. We hope that, in the future, other people might benefit from this study through improved understanding of robotic user interface design.

6. Confidentiality:

The identifiable data collected will be the subjects’ answers to the initial interview questions regarding their history as a robot operator. Additionally, video data will be recorded with the eye tracking glasses. It is unclear if this will be identifiable, as the video will be taken from the perspective of the subject, but it is at least worth mentioning. Any potential loss of confidentiality will be minimized by storing data in a locked office,

on a password protected computer or locked cabinets. Only the researchers conducting this experiment will have access to identifiable data.

Participants' names will not be included on any of the collected data. A code will be placed on the data. Through the use of an identification key, the research will be able to link data to identities. Only the researchers will have access to the identification key. Any identifiable data will be retained for seven years before being deleted or shredded.

7. Consent Process:

Researchers will obtain consent with a written consent form. One researcher will explain the research project and explain the consent form to each potential participant. The consent process will be conducted privately in a secured lab space. Participants will read and sign the consent form before participating in any experiment or filling out any surveys.

No part of this study involves deception.

All research participants will receive a copy of the consent form for their records.

8. Conflict of Interest:

Not applicable.

9. HIPAA Compliance:

Not applicable.

10. Research Outside of the United States:

Not applicable.

11. Research Involving Prisoners:

Not applicable.

12. SUPPORTING DOCUMENTS

Your Initial Application must include a **completed Initial Application Part 1 (On-Line Document)**, the information required in items 1-11 above, and all relevant supporting documents including: consent forms, letters sent to recruit participants, questionnaires completed by participants, and any other material that will be presented, viewed or read to human subject participants.

The consent forms in your approved IRBNet PACKAGE must be used. When creating or editing your consent form, please provide the most recent IRBNet package number at the bottom, right corner of the consent form. This ensures you are using the most "up-to-date" version of the form.

To find your IRBNet package number, go to the MY PROJECTS tab and click on the title of your project. In the PROJECT OVERVIEW page, your IRBNet package number will be listed at the top, next to your project title.

F.3 Recruitment Material

The following message, or a variation of it, is to be a recruitment email for the 6 robot operators at NASA Goddard. Note that "ROBO" is a term used at NASA meaning Robot Operator and "ROC" is an acronym for Robot Operations Center.

Hi ROBOs!

I'm emailing to ask you to participate in an experiment in which you wear eye tracking glasses while performing a simple training task involving operating the MH250 robot. What follows is a brief description of the experiment:

The procedures involve operating a robot through a basic training task three times, with the console in three different configurations, all while wearing eye tracking glasses. Each run is expected to take no more 30 minutes. If you indicate that you are inexperienced with the training task, you will be allowed to have a "dry run" without wearing eye tracking glasses before starting the planned data gathering runs. During all data gathering runs, a curtain will be drawn between you and the robot, such that you need to look at the camera views on the console instead of being able to directly look at the robot. After the second and third of the data gathering runs, you will be given a brief questionnaire, taking about 5 minutes, regarding your performance and feelings about the console configuration.

I know that you're all over 18, but for IRB reasons, I'm required to mention in this email that you must be at least 18 years of age to participate in this experiment. So if you're interested and over 18, please let me know.

If you agree to participate, I'd like to meet with each of you individually in the ROC for about 15 minutes each to ask some questions regarding your previous experience as a robot operator and introduce you to the eye tracking glasses. If possible, I'd like to meet at some point in the next couple days. Please let me know if you have 15 minutes free sometime soon.

Also, please respond to both my NASA email and my school email (cc'd; casey@ssl.umd.edu), as I am not reliably onsite, and don't have remote email access.

Thank you
Casey Kracinovich

F.4 Introductory Questions

Introductory Questions

These are eye tracking glasses; they will track your eyes.

Do you wear contacts? Would you describe them as a strong or light prescription?

Answer:

Have subject put on glasses and attempt calibration

Success/failure:

Experiment with different glasses nosepieces and decide which fits the subject's nose best

Best nosepiece:

Do you think the glasses will impact your performance at all? Are they at all uncomfortable?

Answer:

How long have you been a robot operator and what is your previous experience operating robots?

Answer:

Briefly describe task to be performed

Have you done this task before? How many times/how recently?

Answer:

Show the subject a picture of the "standard" screen configuration

Have you used this screen and camera view configuration before?

Answer:

Show the subject a screenshot of the "standard" GUI configuration
Have you used this GUI configuration before?
Answer:

Some final notes and reminders:
Data published will not be attributable to you-
We will not publish your identity and any results that involved data from specific participants will call you participant A, B, etc.
Also: when performing this task, don't rush, go at your own pace, go as you normally would. I may be timing you, but I am not evaluating you on how fast you go; it'll just be so I can record timestamps of when you get to certain milestones.

F.5 Post-Task Questions

Post-Task Questions

So far, have you noticed that the eye tracking glasses have had any impact on your performance? Have they been uncomfortable at all?

Answer:

Has performing this task multiple times in a row had any impact on how easy/difficult it was for you?

Answer:

Has this alternative screen/GUI configuration had any impact on how well you performed the task? What is that impact?

Answer:

F.6 Consent Form



Initials: _____ Date: _____

Institutional Review Board

1204 Marie Mount Hall • 7814 Regents Drive • College Park, MD 20742 • 301-405-4212 • irb@umd.edu

CONSENT TO PARTICIPATE

Project Title	<i>Evaluation of a Space Robotics Control Console Using Eye Tracking Glasses</i>
Purpose of the Study	<p><i>This research is being conducted by Dr. David Akin at NASA's Goddard Space Flight Center. We are inviting you to participate in this research project because you are a trained robot operator.</i></p> <p><i>The purpose of this research project is to evaluate the human factors of the design of a robotics control console, using eye tracking glasses to gain insights into the ways in which operators interact with the various console elements. Using the data we gather, we will gain insights into how the various elements of a robot control console might ideally be arranged.</i></p>
Procedures	<p><i>In the days or weeks leading up to the experiment, you will be given a brief introductory interview, expected to take about 15 minutes, in which you will be introduced to the eye tracking glasses and asked a couple questions regarding your previous experience as a robot operator.</i></p> <p><i>The procedures involve operating a robot through a basic training task three times, with the console in three different configurations, all while wearing eye tracking glasses. Each run is expected to take no more 30 minutes. If you indicate that you are inexperienced with the training task, you will be allowed to have a "dry run" without wearing eye tracking glasses before starting the planned data gathering runs. During all data gathering runs, a curtain will be drawn between you and the robot, such that you need to look at the camera views on the console instead of being able to directly look at the robot. After the second and third of the data gathering runs, you will be given a brief questionnaire, taking about 5 minutes, regarding your performance and feelings about the console configuration.</i></p>
Potential Risks and Discomforts	<p><i>The only risks from participating in this research study are the risks normally associated with operating a robot in your usual work; the worst of which being possible physical harm to a person who might interfere with the robot, or permanent damage to expensive hardware. Given the safety measures already in place (e.g. gated robotic workcell to keep people from interfering and trained emergency stopper present for all robot operations) as well as your status as a trained robot operator, these risks are assumed to be extremely unlikely.</i></p> <p><i>There may be a mild discomfort from using a somewhat different console configuration, though we expect that this will be easily</i></p>

Initials: _____ Date: _____

	<p>mitigated if you perform the tasks at your own pace, so as to gradually grow accustomed to the new configuration. We will emphasize in the opening interview that this is not a time-based evaluation and that you should take all the time they need. The eye tracking glasses to be used are very light and unobtrusive, but may cause mild discomfort as well. To mitigate this, in the opening interview, you will try on the glasses and be asked if you find them to be at all uncomfortable; if you indicate a significant level of discomfort, minor alterations, such as changing out the nosepiece of the glasses, can be made. For any potential sources of discomfort, if you indicate that you are uncomfortable you will be allowed to stop to take a break, or stop altogether if necessary.</p>
Potential Benefits	<p>Possible benefits include data that may help design an improved, more ergonomic, robotic control console. We hope that, in the future, other people might benefit from this study through improved understanding of robotic user interface design.</p>
Confidentiality	<p>The identifiable data collected will be your answers to the initial interview questions regarding your history as a robot operator. Additionally, video data will be recorded with the eye tracking glasses. It is unclear if this will be identifiable, as the video will be taken from your perspective, but it will be treated as identifiable data regardless. Any potential loss of confidentiality will be minimized by storing data in a locked office, on a password protected computer or locked cabinets. Only the researchers conducting this experiment will have access to identifiable data.</p> <p>If we write a report or article about this research project, your identity will be protected to the maximum extent possible. Your information may be shared with representatives of the University of Maryland, College Park or governmental authorities if you or someone else is in danger or if we are required to do so by law.</p>
Right to Withdraw and Questions	<p>Your participation in this research is completely voluntary. You may choose not to take part at all. If you decide to participate in this research, you may stop participating at any time. If you decide not to participate in this study or if you stop participating at any time, you will not be penalized or lose any benefits to which you otherwise qualify. Your decision to participate or not participate will not have a negative or positive impact on your employability status or relationship with the NASA Goddard Space Flight Center.</p> <p>If you decide to stop taking part in the study, if you have questions, concerns, or complaints, or if you need to report an injury related to the research, please contact the investigator:</p> <p>Dr. David Akin Building 382 Technology Dr., Room 2100D College Park, MD 20742 301-405-1138 dakin@ssl.umd.edu</p>

Initials: _____ Date: _____

Participant Rights	<p><i>If you have questions about your rights as a research participant or wish to report a research-related injury, please contact:</i></p> <p style="text-align: center;">University of Maryland College Park Institutional Review Board Office 1204 Marie Mount Hall College Park, Maryland, 20742 E-mail: irb@umd.edu Telephone: 301-405-0678</p> <p><i>For more information regarding participant rights, please visit:</i> https://research.umd.edu/irb-research-participants</p> <p><i>This research has been reviewed according to the University of Maryland, College Park IRB procedures for research involving human subjects.</i></p>	
Statement of Consent	<p><i>Your signature indicates that you are at least 18 years of age; you have read this consent form or have had it read to you; your questions have been answered to your satisfaction and you voluntarily agree to participate in this research study. You will receive a copy of this signed consent form.</i></p> <p><i>If you agree to participate, please sign your name below.</i></p>	
Signature and Date	NAME OF PARTICIPANT [Please Print]	
	SIGNATURE OF PARTICIPANT	
	DATE	

Bibliography

- [1] Jennifer Romano Bergstrom and Andrew Schall. *Eye Tracking in User Experience Design*. Google-Books-ID: 5Hp0AgAAQBAJ. Elsevier, Mar. 12, 2014. 395 pp. ISBN: 978-0-12-416709-4.
- [2] Tanja Blascheck et al. “AOI hierarchies for visual exploration of fixation sequences”. In: *Proceedings of the Ninth Biennial ACM Symposium on Eye Tracking Research & Applications - ETRA '16*. the Ninth Biennial ACM Symposium. Charleston, South Carolina: ACM Press, 2016, pp. 111–118. ISBN: 978-1-4503-4125-7. DOI: 10.1145/2857491.2857524. URL: <http://dl.acm.org/citation.cfm?doid=2857491.2857524> (visited on 08/10/2020).
- [3] Agnieszka (Aga) Bojko. “Informative or Misleading? Heatmaps Deconstructed”. In: *Human-Computer Interaction. New Trends*. Ed. by Julie A. Jacko. Lecture Notes in Computer Science. Berlin, Heidelberg: Springer, 2009, pp. 30–39. ISBN: 978-3-642-02574-7. DOI: 10.1007/978-3-642-02574-7_4.
- [4] Ricardo Buettner. “Cognitive Workload of Humans Using Artificial Intelligence Systems: Towards Objective Measurement Applying Eye-Tracking Technology”. In: *KI 2013: Advances in Artificial Intelligence*. Ed. by Ingo J. Timm and Matthias Thimm. Lecture Notes in Computer Science. Springer Berlin Heidelberg, 2013, pp. 37–48. ISBN: 978-3-642-40942-4.
- [5] Nancy J. Currie and Brian Peacock. “International Space Station Robotic Systems Operations - a Human Factors Perspective”. In: *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* 46.1 (Sept. 1, 2002), pp. 26–30. ISSN: 2169-5067. DOI: 10.1177/154193120204600106. URL: <https://doi.org/10.1177/154193120204600106> (visited on 08/01/2019).
- [6] Robert C. Dempsey. *The International Space Station: Operating an Outpost in the New Frontier*. Google-Books-ID: 9mseNE1wkLMC. Government Printing Office, 2017. 440 pp. ISBN: 978-0-16-094389-8.
- [7] Andrew T. Duchowski. “Eye Tracking Methodology - Theory and Practice, Third Edition”. In: 2017. DOI: 10.1007/978-3-319-57883-5.
- [8] Andrew T. Duchowski et al. “Using Microsaccades to Estimate Task Difficulty During Visual Search of Layered Surfaces”. In: *IEEE Transactions on Visualization and Computer Graphics* 26.9 (Sept. 2020). Conference Name: IEEE Transactions on Visualization and Computer Graphics, pp. 2904–2918. ISSN: 1941-0506. DOI: 10.1109/TVCG.2019.2901881.

- [9] Paul M. Fitts, Richard E. Jones, and John L. Milton. *Eye Fixations of Aircraft Pilots. III. Frequency, Duration, and Sequence Fixations When Flying Air Force Ground-Controlled Approach System (GCA)*. Section: Technical Reports. AIR MATERIEL COMMAND WRIGHT-PATTERSON AFB OH, Nov. 1, 1949. URL: <https://apps.dtic.mil/sti/citations/ADA329371> (visited on 08/16/2020).
- [10] Terrence Fong et al. "Space Telerobotics: Unique Challenges to Human-Robot Collaboration in Space". In: *Reviews of Human Factors and Ergonomics* 9.1 (Nov. 2013), pp. 6–56. ISSN: 1557-234X, 2163-3134. DOI: 10.1177/1557234X13510679. URL: <http://journals.sagepub.com/doi/10.1177/1557234X13510679> (visited on 04/16/2020).
- [11] *Glasses, lenses and eye surgery*. Tobii Eye Tracking Support. Library Catalog: help.tobii.com. URL: <http://help.tobii.com/hc/en-us/articles/210249865> (visited on 04/17/2020).
- [12] D. H. Jones. "An error-dependent model of instrument-scanning behavior in commercial airline pilots. Ph.D. Thesis - May 1983". PhD thesis. July 1, 1985. URL: <https://ntrs.nasa.gov/search.jsp?R=19850024452> (visited on 04/30/2020).
- [13] Krzysztof Krejtz et al. "Eye tracking cognitive load using pupil diameter and microsaccades with fixed gaze". In: *PLOS ONE* 13.9 (Sept. 14, 2018), e0203629. ISSN: 1932-6203. DOI: 10.1371/journal.pone.0203629. URL: <https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0203629> (visited on 08/01/2019).
- [14] Marcus Nyström and Kenneth Holmqvist. "An adaptive algorithm for fixation, saccade, and glissade detection in eyetracking data". In: *Behavior Research Methods* 42.1 (Feb. 2010), pp. 188–204. ISSN: 1554-351X, 1554-3528. DOI: 10.3758/BRM.42.1.188. URL: <http://link.springer.com/10.3758/BRM.42.1.188> (visited on 08/09/2020).
- [15] Anneli Olsen. "The Tobii I-VT Fixation Filter". In: (2012), p. 21.
- [16] A Poole and Linden Ball. "Eye tracking in human-computer interaction and usability research: Current status and future prospects". In: *Encyclopedia of Human Computer Interaction*. Jan. 1, 2006, pp. 211–219.
- [17] *Tobii Pro Glasses 2 wearable eye tracker*. June 25, 2015. URL: <https://www.tobiipro.com/product-listing/tobii-pro-glasses-2/> (visited on 08/16/2020).
- [18] Rebecca (Contractor) Toman. "Eye tracking in the cockpit: a review of the relationships between eye movements and the aviator's cognitive state." In: (2014), p. 58.

- [19] Michel Wedel and Rik Pieters. “Eye Tracking for Visual Marketing”. In: *Foundations and Trends® in Marketing* 1.4 (Aug. 19, 2008). Publisher: Now Publishers, Inc., pp. 231–320. ISSN: 1555-0753, 1555-0761. DOI: 10.1561/17000000011. URL: <https://www.nowpublishers.com/article/Details/MKT-011> (visited on 03/06/2020).