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Modeling and Compensation for Efficient Human Robot Interaction

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MODELING AND COMPENSATION FOR EFFICIENT HUMAN ROBOT INTERACTION

by

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ABSTRACT

The purpose of this research is to first: identify the important human factors to performance when operating an assistive robotic manipulator, second: develop a predictive model that will be able to determine a user’s performance based on their known human factors, and third: develop compensators based on the determined important human factors that will help improve user performance and satisfaction. An extensive literature search led to the selection of ten potential human factors to be analyzed including reaction time, spatial abilities (orientation and visualization), working memory, visual perception, dexterity (gross and fine), depth perception, and visual acuity of both eyes (classified as strongest and weakest). 93 participants were recruited to perform six different pick-and-place and retrieval tasks using an assistive robotic device. During this time, a participants Time-on-Task, Number-of-Moves, and Number-of-Moves per minute were recorded. From this it was determined that all the human factors except visual perception were considered important to at least one aspect of a user’s performance. Predictive models were then developed using random forest, linear models, and polynomial models. To compensate for deficiencies in certain human factors, the GUI was redesigned based on a heuristic analysis and user feedback. Multimodal feedback as well as adjustments in the sensitivity of the input device and reduction in the robot’s speed of movement were also implemented. From a user study using 15 participants it was found that certain compensation did improve satisfaction of the users, particularly the multimodal feedback and sensitivity adjustment. The reduction of speed was met with mixed reviews from the participants.
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CHAPTER I: INTRODUCTION

1.1 Assistive Robotic Technologies

Many individuals experience physical and sensory limitations that reduce their abilities to interact with their surroundings. These individuals may include some with either a temporary (e.g., broken leg) or chronic condition (e.g., ALS, Spinal Cord Injury), frail elderly adults, and others suffering from conditions that limit the functional capability of their upper or lower limbs [1.1]. For one-third of these mobility-assisted users, receiving regular assistance completing everyday tasks (also called activities of daily living or ADLs) remains a critical need [1.2]. Furthermore, two-thirds of mobility device users have limitations in one or more Instrumental Activities of Daily Living (IADLs) – this includes activities such as grocery shopping, telephone use, meal preparation, light housework, etc. [1.3]. These findings directly underscore the need to implement solutions that improve users’ quality of life by decreasing their need to rely on caregivers for assistance. Over the past few years, an increasing variety of assistive robotic manipulators (under the broad category of personal service robots) have emerged to augment the functional capacity of the disabled individual.

Several of these wheelchair-mounted assistive robots (WMAR) are available on the market for purchase. The Jaco is a 6 degree-of-freedom (DOF) robotic arm produced by Kinova robotics and is controlled via a joystick/keypad interface. Similarly, the MANUS arm, which is also a 6-DOF robot that is manufactured by Exact Dynamics, is also controlled by either a joystick or a

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1 Parts of this chapter are comprised of sections of the paper “A Predictive Model of Human Factors vs Performance of Pick-and-Place/Retrieval Tasks for Users of an Assistive Robotic Manipulator” by N. Paperno, M. Rupp, J. Smither, E. Maboudou, and A. Behal.
keypad depending on the user’s preference and ability. The downside to these interfaces is that
they are difficult to learn given that for the joysticks you are using a 2-DOF device to control a
6-DOF robot and for the keypad you need to memorize the buttons for menu navigation as well
as those for controlling the robot. Given that the buttons are numbered this can be difficult and
time consuming given that there is no relation to what button is assigned what command.
Previous research done by [1.5] has sought to improve on the interface design for the MANUS
(the particular one has been named the UCF-MANUS) by developing one that intuitive and easy
to learn as well as easily utilized by people of varying levels of disability.

1.2 Problem Motivation

While the automated system of the UCF MANUS has been improved to make itself more
reliable and therefore more ideal to use [1.5], several users had expressed preference in
controlling the robot manually. In a previous study done by Kim et al [16], user satisfaction was
significantly better for those that manually controlled the robot. It was found that if mistakes
were made by the user there would be little change in the satisfaction of the experience. If,
however, the user was using the automated system and a mistake was made satisfaction would
significantly decrease. Since the previous research had sought to improve the automated system,
this research will seek to improve the experience using the manual system.

1.3 Goal
The goal of this research is to first: identify which human factors are important to performance
when using a robotic manipulator, second: develop a predictive model based on those important
human factors, and third: develop compensators that pertain to those determined important
human factors
1.4 Organization of Dissertation

The remainder of this dissertation is organized into five chapters. Chapter II relays the background research for this research. Chapter III analyzes the relationship between the human factors and performance as well as determines which human factors are suited to be used to develop predictive models. Chapter IV discusses the development of the various predictive models developed. Chapter V delves into the compensation that was developed to help improve the user experience and performance. Chapter VI summarizes and discusses the results from the research.

1.5 References


CHAPTER II: BACKGROUND RESEARCH

2.1 Introduction

This chapter introduces the reasoning behind the various methods and choices made throughout this research. The first section presents the research that has been done regarding the relations of human factors to performance with regards to teleoperation and remote control of robotic devices. The second section dwells into research that has been done regarding the development of predictive models based on prevalent human factors. The third section presents compensation techniques that have been developed in the hopes of improving user performance.

2.2 Chapter Objectives

- Review literature on human factors affecting performance
- Review literature on predictive models developed using human factors
- Review literature on compensation techniques for various human factors

2.3 Human Factors and Performance

Since the introduction of the remote control and the creation of teleoperation, researchers have been looking at various aspects of a person’s being (a.k.a human factors) to see which ones have an impact on performance. The majority of studies investigating human factors which affect performance look for ways to screen for potential adept operators and improve performance of others by identifying which factors are most important and then training individuals to improve those factors. Lathan and Tracy [2.1] found individuals with better spatial perception ability...
made fewer errors when controlling a teleoperated robotic system. Gomer and Pagano took it a step further and looked at the independent components of spatial abilities to determine how the performance relates not only to robotics but other fields as well [2.2-2.4]. Several studies have been done for NASA to determine how to screen for potential operators of the manipulators used on the shuttle [2.5, 2.6]. However, most of these studies only examine a select few factors, predominantly spatial abilities, and the analysis is typically limited to correlations. A study by Gomer et al. [2.3] that does look at factors other than spatial abilities does not report on the results for the other factors apart from mentioning that they were tested for.

2.4 Modeling Techniques

Prediction of a person’s performance based on spatial abilities for a rendezvous and docking task using a teleoperation system was reported by Wang et al. [2.7]. Further work recently completed by Liu et al. [2.8] developed logistic models that would predict an astronaut’s performance during teleoperation training based on their scores on various spatial abilities tests. However, the performance metrics used for each cannot be translated well to other fields, e.g., [2.8] used the astronauts’ training scores developed by NASA to evaluate their performance while [2.7] used metrics that are specific to the docking task such as docking accuracy and fuel consumption. Furthermore, as with other studies, these models only take into account the spatial abilities of the user and no other factors. Another issue with these studies is that they used a restricted population for their analysis, specifically astronauts, all of whom are kept to high standards of physical and mental conditioning. This makes it difficult to translate their results to a general population.
2.5 Compensation

The usability of the interface is a key factor that can affect a person’s performance when using a particular system. [2.9] suggested that an intuitive interface design would lower the effect of certain human factors on performance. [2.10] goes on to show that if a person suffers from increased frustration it can lead to shorter working memory, thereby affecting the user’s reaction time and performance. From this we can surmise that if the GUI is designed to be highly intuitive and easy to use, it will help improve performance and user satisfaction.

Research done regarding compensation for spatial abilities and visual abilities all suggest the same form of compensation: multimodal feedback. In [2.11], visual-audio and visual-haptic feedback is utilized to help improve the teleoperator’s perception of their surrounds which can be limited given the particular setup that is being utilized. [2.12] researched the effect multimodal feedback has on performance in HCI. They utilize both visual-audio, visual-haptic, and a tri-modal feedback using all three. From this it was found that the addition of feedback, especially the tri-modal, improved task performance. [2.9] looked to narrow the difference in performance of virtual environment navigation between the genders by implementing similar types of visual feedback that provide the user with more detail on their surroundings.

2.6 Discussion

This chapter has taken a look at the various human factors that have been previously determined to have a relation to a person’s performance during teleoperation and similar activities. It has also discussed the previous modeling techniques that have been used to predict a person’s
performance as well as different methods of compensation for those with deficits in certain physical and cognitive areas.

Spatial abilities have been well documented throughout several studies to have a relation with a person’s ability to perform well in teleoperation and virtual environment navigation. However, all the studies use specific populations for their analysis, specifically astronauts and military personnel, meaning that several factors were not considered for their testing due to the strict physical and mental conditions required for those populations.

The models that were developed performed well for their intended purposes, but due to the metrics that were being used for performance it is difficult to modify them to make them applicable to a different system. They also suffer from the same issue as the human factors research in that they use astronauts as their user population meaning that only a select few human factors were chosen to be utilized.

The compensation techniques used for spatial abilities and visual abilities are all multimodal. Additions of certain visual cues as well as audio and haptic feedback all helped to improve either performance or user satisfaction in some way. It can also be interpreted that if a GUI is designed to be intuitive and easy to use that it will decrease the cognitive load need and increase user performance and satisfaction.

2.7 References


CHAPTER III: IMPORTANT HUMAN FACTORS FOR PREDICTION

3.1 Introduction

Human factors are the innate abilities of a person that encompass both their physical and mental processes. These factors are what are utilized by a person to go about their daily lives and interact with the world around them. Several studies have been done that look into the relationship of various human factors to a person’s performance doing some sort of task, either with some type of technology or on their own. Based on these results, the human factors in question were chosen for further analysis to see if they can benefit in predicting a user’s performance when operating a robotic manipulator.

3.2 Chapter Objectives

- Go over chosen human factors
- Detail the experimental setup to obtain data
- Analyze importance of human factors when it comes to predictive properties

3.3 Choice of Human Factors for Consideration

Several human factors were identified for inclusion based on a task analysis and literature search [3.1-3.11]. The factors that were chosen to be analyzed are visual acuity, depth perception, spatial orientation, visualization, gross dexterity, fine dexterity, reaction time, working memory,

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3 This section is comprised of sections of the paper “A Predictive Model of Human Factors vs Performance of Pick-and-Place/Retrieval Tasks for Users of an Assistive Robotic Manipulator” by N.Paperno, M. Rupp, J. Smither, E. Maboudou, and A. Behal.
and visual memory. These physical and cognitive factors cover the relevant characteristics of a person that would be controlling a robotic device.

3.3.1 Visual and Biomechanical Ability

Manually completing a reaching, pointing, grasping, or other psychomotor task requires complex coordination between the biomechanical systems to move the effector to a spatial target and the cognitive systems to process sensory feedback and guide the effector to the target correcting for movement variability [3.12][3.13]. Pointing tasks are the simplest and are completed in two phases, an initial ballistic phase consisting of a gross motor movement to guide the effector near the target, and a secondary corrective phase that uses visual and proprioceptive feedback to improve the movements’ accuracy [3.14][3.15]. Successful performance of these tasks requires the balancing of the speed of the movement with accuracy to complete an efficient movement; thus movement time is thought to be the main performance criterion of these tasks [3.16]. Movement time has further been found to be constrained in two ways based on: (1) movement distance of the effector and (2) size of the target; this relationship is called Fitts law. These two parameters determine the movement’s difficulty called the Index of Difficulty (ID). This relationship predicts that movements to smaller targets that are farther away take longer than targets that are closer and larger [3.16][3.17]. Reaching and grasping tasks are more complex because they also must include the calculations of an optimal motor trajectory that will result in a stable grip (spatial location of the hand and optimal grip pressure) on the target object to be grasped, called a force-closure grasp [3.18]. Studies that removed visual feedback of the effector have showed the importance of vision for the performance of this task. One study showed that altering vision caused individuals to use suboptimal grip apertures [3.19]. Overall, these tasks are
much more difficult and take longer for older adults to complete due to both age related biomechanical declines (e.g., declines in dexterity) and cognitive changes such as decreases in spatial abilities and visual feedback processing ability \[3.20\][3.21] as well as decreases in cognitive processing speed \[3.22\]. These tasks may also be impossible for users with specific disabilities that impair the motor system, or users with decreased arm reach such as individuals in a wheelchair. Factors that are expected to predict performance during manual psychomotor tasks are also relevant for indirect psychomotor tasks such as using a keyboard and mouse (e.g., \[3.23\]) or controlling a robot to grasp an object. In fact, they may be more important to the successful execution of these tasks because during indirect tasks, a user is completing the task without direct visual or proprioceptive feedback of the effector and instead must rely on a surrogate such as a cursor on the screen or a view of the robotic arm \[63\]. This situation is also common in robotic teleoperation tasks where users may be controlling a robot from a great distance.

We, therefore, hypothesize that biomechanical ability, visual ability, and visual feedback processing will be essential to the successful performance using the robotic manipulator to grasp objects in three-dimensional (3-D) space and interacting with the computer interface to control the robot. To test our hypotheses, we plan to survey individuals’ biomechanical efficiency by testing their gross and fine dexterity, their visual ability by testing their visual acuity, and their ability to perceive depth (stereopsis). Since these abilities may be linked to feedback processing ability, we also plan to test their simple reaction time as a measure of overall cognitive processing as well as measure their specific memory for visual shapes. This will allow us to test whether specific visual feedback mechanisms account for more unique variance during the task than speed of processing in general and provide a more robust estimate of an individual’s ability.
3.3.2 Spatial Ability

In these situations, users often are required to view the robot from multiple camera angles and rotate their camera view during the task. These angles may lead to impoverished visual feedback and spatial transformations that lead the camera views to look drastically different than the task would look like as viewed in person [3.24]. For these tasks, spatial ability is a critical factor to successful performance. Spatial ability consists of two different oblique constructs [3.25]. The first is mental rotation also called spatial visualization. This facet consists of manipulation and completing spatial transformations of objects in one’s working memory. The second facet, spatial orientation which is also called perspective taking, involves one’s ability to take an egocentric view that is different from either one’s own view or an allocentric one, spatially transforming not an object but the environment. Previous research indicates that individuals with greater spatial skills were also more skilled at performing robotic navigation tasks [3.26-3.30]. Studies have shown that these individuals make fewer performance errors on robotic tasks [3.26] during both remote and direct line-of-sight navigation tasks [3.27]. Individuals with greater spatial abilities were also found, across several studies, to have greater attentional resources to engage in additional visual search tasks such as a threat detection task across several robot camera feeds [3.4][3.5], and a vehicle identification task [3.28] while maintaining a greater awareness of the situation [3.30]. Overall, we hypothesize that both mental rotation and perspective taking abilities will be critical during the robotic navigation task and our goal is to tease the several different types of spatial ability apart by using multiple measures of spatial abilities to predict performance.
3.3.3 Working Memory Capacity

While using the robot, individuals must interact with the interface and remember the commands needed to control the robot. They must also remember which object they wish to interact with and plan the best motor trajectory to allow the robot to achieve the goal. During manual grasping, this is all completed implicitly by an individual’s biomechanical and sensory systems. While controlling the robot however, individuals must keep their movement plan and the commands needed to enact the movements in their working memory during movement execution. Previous work has indicated that working memory capacity is a key predictor of performance during robotic teleoperation tasks (e.g., [3.32]). Individuals with fewer cognitive resources cannot hold as many pieces of information in memory at the same time; although this capacity is not well defined and can vary from person to person, it is thought to be roughly 7-10 items at a time (e.g., [3.33]). When individuals’ working memory reaches its capacity, they must use additional effort to maintain the same level of performance as someone who can chunk more information in working memory [3.34]. This working memory capacity is thought to determine performance and workload while working with the robotic manipulator. We therefore, hypothesize that working memory ability will be positively associated with performance with the robotic manipulator. We will also be able to test if overall working memory capacity is a better predictor of task performance than individuals’ specific capacity for visual stimuli since we are utilizing both a digit span test and a visual memory test. Previous work such as the Baddeley and Hitch [3.35] model of working memory and Wickens’ [3.36] Multiple Resource Theory posit that people may have separate memory stores for visual, auditory, and typographic or haptic information. This would lead to the hypothesis that while these two facets of working memory
may overlap in their predictive ability, they will provide a unique perspective in their prediction of task performance. On the other hand, both theories also posit that the multiple memory stores are still limited by the need to cognitively process this information in executive functioning. Further, previous research has hypothesized that working memory capacity may be task dependent [3.37] and vary with the difficulty or nature of the task. Therefore, we will need to measure both working memory and visual perception separately to determine the ability of each to predict task performance on this specific robotic task.

3.4 Experimental Methodology

3.4.1 Participants

We recruited 89 abled-bodied participants (45 Male, 44 Female) between the ages of 18–63 (M = 38:72; SD = 13:48) from UCF and the surrounding metropolitan areas using word of mouth, flyers, and the university’s subject pool. To be considered for this study, participants needed to not be considered part of one of the following vulnerable population as defined by the Internal Review Board: prisoners, disabled, cognitively impaired, elderly, or juvenile. This excluded people under 18 and over 65 years of age, those that were physically disabled, and those that were legally considered cognitively impaired. These restrictions kept the population as general as possible while not including individuals with disabilities.

3.4.2 Materials and Apparatus

3.4.2.1 Robotic Manipulator and Setup:
We used the A.R.M. assistive robotic manipulator (MANUS) developed by Exact Dynamics Inc. (Netherlands) which is a commercially available 6 degrees-of-freedom (6DOF) robotic arm with a maximum reach of 80cm and a maximum lifting capacity of 4.5 lbs. The end effector is outfitted with a two finger gripper with a maximal grip strength of 20N. More information
regarding the exact technical specifications of the robotic platform is available in our previous work [3.38][3.15][3.39][3.40]. Participants controlled the robot using a graphical user interface (GUI) which consisted of a view from the robot’s gripper mounted camera, a feedback panel and several buttons with their functions labeled. This software has previously been developed in the lab as an effective control method. All participants controlled the robotic manipulator manually using a mouse to click on desired functions on the screen. Users clicked and held the mouse button depressed to control the system. Once a function was clicked, the robot would perform the desired action after a brief delay and would continue to move until the user released their mouse click. The GUI was displayed on a 12x9in color desktop monitor and the software ran on a Windows computer. The experimental setup was designed to mimic the placement of a WMRA attached to the side of a user’s wheelchair. To achieve this, participants were required to sit in a chair positioned close to the robotic manipulator. A table and bookshelf were placed near the user. The table was placed in front of the robotic arm and the bookshelf was placed to the participants’ right side next to the table. The setup as a whole can be seen in Fig. 3-1.

Figure 3-1 Setup for experiment
3.4.2.2 Individual Differences Measurements:  

a) Measurements of Visual and Biomechanical Ability: We measured individuals’ vision and visual feedback processing efficacy in several ways. First, visual acuity for each eye was measured using a standard Snellen visual acuity chart [3.41]. Whichever eye was dominant (had the better score) was labeled as the strongest vision (SV) and the eye that performed worse was labeled as the weakest vision (WV). While the strongest eye will be predominantly used, the presence of a degraded visual receptor will have an effect on what visual cues are accurately recognized. Next, we measured individuals’ ability to perceive depth perception (DP) using the Randot Stereotest (see [3.42], [3.43]). Participants wore a polarized filter and viewed a set of vectorgraphics to present visual disparities to measure individuals’ stereo accuracy. Scores on the Snellen acuity and Randot test were normalized using a log scale transformation to linearize the data. We also measured individuals’ visual perception (VP) using the Motor-free Visual Perception Test [3.44] which has been shown as a reliable and valid method of testing for visuo-perceptual defects [3.45]. Performance was determined by the number of items correct and used to create a standardized score based on the manufacturer’s scoring instructions. Finally, speed of cognitive processing to perceptual stimuli was also administered using a simple reaction time test administered in MATLAB [3.46]. This test consisted of displaying a target stimuli and measuring participant’s reaction time in milliseconds by pressing a button. Finally, we also measured individuals’ biomechanical ability consisting of a measurement of their gross and fine dexterity using the Purdue Pegboard Test [3.47]. This test consists of a pegboard with four cups two filled with 25 pins each, another with 40 washers, and a final cup filled with 20 collars across the top and two vertical rows of 25 small holes down the middle of the board. Gross dexterity was determined summing the number of pins an individual was able to place using just
their right hand, just their left hand, and both hands at the same time while fine dexterity was individuals score on the assembly portion of the task. We used the default scoring and instructions for this task.

b) Measurements of Spatial Ability: We measured spatial ability using two measures. First spatial visualization (V) was measured using the Paper Folding Test (PFT) [3.48]. Second, spatial orientation (SO) was measured using the Cube Comparison test (CC) [3.49]. Both tests were administered and scored according to the manufacturer’s recommended instructions. The PFT showed a series of folded pieces of paper along with several unfolded sheets of paper with holes punched in them. Participants’ task was to mentally match the folded piece of paper to the potential unfolded ones and select the one that matched the hole-punch patterns in the folded piece of paper. The CC displayed two reference cubes and participants had to determine if both cubes were different or the same and displayed in a different orientation.

c) Measurements of Working Memory: Our final metric, working memory capacity, was measured using the NAB backward digit span test [3.50]. This test consisted of the auditory presentation of a series of numbers of various lengths. Participants were required to listen to the digits hold them in memory and write them down in the backwards order of how they were presented. For example, 1, 2, 3 would become 3, 2, 1 etc. This test was presented using a computer and each participant’s score was the highest numbered sequence that they could accurately remember.

d) Measurements of Performance Metrics: In accordance with previous research [3.3][3.4][3.6], we decided to measure user performance using the total time duration it took for the participant to complete the task once they began moving the robot (called Time-on-Task; ToT) and a measure of task efficiency which was determined to be the number of button presses required for
the user to complete the task (called Number-of-Moves; NoM). Number-of-Moves per minute (NoM/min) was measured by dividing Number-of-Moves by Time-on-Task (measured in minutes). The final score was determined by averaging these metrics across all tasks performed. This was done to obtain measurement of the user’s overall performance which serves two purposes: (a) mitigate the effect of a user’s state of being (are they stressed, distracted, etc.) during a task, and (b) obtain data that encompasses more of the gamut of moves and sequences that are involved in ADL tasks.

3.4.3 Choice of Tasks (Simulated ADLs)

Participants completed a total of six different tasks with the robotic manipulator. Tasks consisted of both find-and-fetch and pick-and-place tasks modeled after realistic ADLs where the user was required to pick up a standardized object (.81OZ travel sized cereal box) which was placed at standardized locations denoted by blue tape. Based on prior research by Stanger et al. [3.51] that found that both find-and-fetch and pick-and-place tasks were essential to ADLs that users would require help with, these tasks were designed to mimic those that would be encountered in day-to-day use of the robot. Each user was asked to operate the robot manually (i.e., using the white command buttons in the GUI seen in Fig. 3-2) to perform a standardized set of tasks that were randomized between participants. At the start of each task, the robot was reset to a predefined start position for the user. Specifically, the users were assigned the following six tasks:

T1: Retrieve an object from a tabletop and bring it the participant (Find and Fetch).

T2: Move object from one side of the table to the other (Pick and Place).

T3: Take object and move it from the top of the table to the bottom of the table (Pick and Place).

T4: Retrieve an object from the middle shelf on the bookcase and bring it to the participant (Find and Fetch).
T5: Take an object from the top of the bookshelf and move it to the middle shelf (Pick and Place).

T6: Take an object from the top of the bookshelf and move it to the tabletop (Pick and Place).

3.4.4 Procedure

Upon arrival to the laboratory, all participants completed the informed consent, followed by an assessment of all potential demographic variables: (1) vision screening (acuity & depth perception), (2) demographics, (4) reaction time test, (5) spatial ability testing (visualization & orientation), (6) dexterity (gross & fine), (7) backward digit span, and (8) visual perception tests. All tests were administered in a randomized order to prevent order effects and fatigue. The only exception was the reaction time test which was always performed first due to prevent the effect of fatigue from influencing the results.

Participants were then seated in a chair positioned in front of a desk which held the computer used to control the robotic manipulator. The WMRA was positioned to the right side of the participant’s chair similarly to its position if it were mounted on their wheelchair. Following this, the participants were then introduced to the robot. A demonstration of the interface was given by first showing how the pan and tilt commands work, followed by demonstrating the translational buttons (forward, backward, left, right, up, and down) that correspond to the base frame of the robot (±x, ±y, ±z respectively. This can be seen in Fig. 3-3). After that, the translational buttons (approach and retreat) that correspond to the z-axis in the camera frame were demonstrated and the difference between them and the previous group of buttons was explained. Following this, the predefined position buttons were demonstrated for the user. Once the demonstration was finished, the participants were allowed to freely use the robot as they wished in order to gain a
better understanding of the controls for up to ten minutes. Within this time, they were allowed to ask any questions they had regarding the robot and its operation. If the participants felt comfortable enough with their abilities before the ten minutes were up, they could state so and the experiment would continue on to the next phase. Out of the 89 participants, only one used the whole ten minutes before moving on to the next phase.

![Figure 3-2 Hybrid Interface for UCF-MANUS](image1)

![Figure 3-3 Coordinate system for robotic base frame and camera frame](image2)
Following practice, all participants completed a series of 6 experimental tasks. Each task was described and acknowledged by the participant before they began and participants were instructed to move both quickly and efficiently. The tasks were given in a random order to help mitigate any effects of learning and fatigue on the outcomes. Following all tasks, participants were told about the purpose of the study and given an opportunity to ask questions about the study.

3.4.5 Results

The raw statistics for the human factors tests can be found in Table 3-1. These results fall in line with the statistics given by the tests as representative of a general population. Raw statistics for performance metrics can be found in Table 3-2. From this collected data, we can now look to determine which factor are important.

<table>
<thead>
<tr>
<th>Human Factors</th>
<th>Min</th>
<th>Q1</th>
<th>Median</th>
<th>Q3</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reaction Time</td>
<td>207.8</td>
<td>273.6</td>
<td>306.7</td>
<td>363.4</td>
<td>667.2</td>
</tr>
<tr>
<td>Spatial Orientation</td>
<td>-10</td>
<td>1.75</td>
<td>11</td>
<td>19</td>
<td>38</td>
</tr>
<tr>
<td>Spatial Visualization</td>
<td>-18</td>
<td>-2</td>
<td>5</td>
<td>9</td>
<td>20</td>
</tr>
<tr>
<td>Visual Perception</td>
<td>55</td>
<td>86.5</td>
<td>100</td>
<td>112.5</td>
<td>145</td>
</tr>
<tr>
<td>Working Memory</td>
<td>3</td>
<td>4</td>
<td>6</td>
<td>7</td>
<td>9</td>
</tr>
<tr>
<td>Gross Dexterity</td>
<td>25</td>
<td>36</td>
<td>40</td>
<td>43</td>
<td>54</td>
</tr>
<tr>
<td>Fine Dexterity</td>
<td>13</td>
<td>32</td>
<td>38</td>
<td>42</td>
<td>52</td>
</tr>
<tr>
<td>Weakest Vision</td>
<td>-1</td>
<td>-0.1761</td>
<td>0</td>
<td>0.0312</td>
<td>0.3010</td>
</tr>
<tr>
<td>Strongest Vision</td>
<td>-0.3979</td>
<td>-0.0242</td>
<td>0</td>
<td>0.1249</td>
<td>0.6021</td>
</tr>
<tr>
<td>Depth Perception</td>
<td>1.301</td>
<td>1.477</td>
<td>1.6021</td>
<td>1.8451</td>
<td>2.699</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Performance Metrics</th>
<th>Min</th>
<th>Q1</th>
<th>Median</th>
<th>Q3</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time-on-Task</td>
<td>48</td>
<td>74.17</td>
<td>89</td>
<td>105.17</td>
<td>207</td>
</tr>
<tr>
<td>Number-of-Moves</td>
<td>16.17</td>
<td>29.17</td>
<td>34.83</td>
<td>44.83</td>
<td>103.17</td>
</tr>
<tr>
<td>Number-of-Moves per Minute</td>
<td>13.27</td>
<td>20.04</td>
<td>23.59</td>
<td>28.33</td>
<td>44.32</td>
</tr>
</tbody>
</table>
3.5 Analysis of Factors

A machine learning technique known as Random Forest [3.52] was used for the analysis of the factors. Random Forest originally started as a classification technique and has since moved to regression. The ensembles are useful for fitting a model to a set of data due to their robust nature that is derived from the multitude of decision trees that comprise them and their ability to self-validate during the training process. This technique works by taking a sample of the training set to grow decision trees and then using remainder of the set to validate the grown trees (known as out-of-bag). The results of the forest are the consensus of the various trees grown. One of the benefits of using a Random Forest model is the importance index that it generates which can be used to determine which human factors are relevant to which performance metrics. The importance index is created by analyzing the mean squared error (MSE) of the trees developed when used with a particular variable and a randomly permuted version of that variable. If the original variable performs better than its randomized counterpart, it will have a positive importance index. If it performs equally or worse than the randomized variable, it will be given zero or negative importance. This will be used as the basis for determining the important human factors. The global sensitivity analysis presented in Appendix A was used as a method for validating the importance index by other means. The importance indices of the human factors for each of the performance metrics are given in Table 3-3.

<table>
<thead>
<tr>
<th>Human Factors</th>
<th>Time-on-Task</th>
<th>Number-of-Moves</th>
<th>Number-of-Moves per Minute</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reaction Time</td>
<td>0.65</td>
<td>0.08</td>
<td>0.05</td>
</tr>
<tr>
<td>Spatial Orientation</td>
<td>0.18</td>
<td>-0.16</td>
<td>-0.06</td>
</tr>
<tr>
<td>Spatial Visualization</td>
<td>0.09</td>
<td>0.20</td>
<td>-0.10</td>
</tr>
<tr>
<td>Visual Perception</td>
<td>-0.15</td>
<td>-0.09</td>
<td>-0.02</td>
</tr>
<tr>
<td>Working Memory</td>
<td>0.19</td>
<td>-0.03</td>
<td>0.13</td>
</tr>
</tbody>
</table>
The human factors that are considered important for this interaction are the ones that will be used during model development in the sequel. From Table 3-3, it can be seen that all human factors are important for Time-on-Task except visual perception (VP) and depth perception (DP) which have negative importance. The important factors for Number-of-Moves per minute are working memory (WM), fine dexterity (FD), and depth perception (DP). For Number-of-Moves, the only important factors are reaction time (RT) and spatial visualization (V). From this, the predictive models for this interface can now be developed.

### 3.6 Age and Gender Differences

It has been observed in literature that there is a difference in performance between men and women as well as the young and old when it comes to teleoperation or similar computer/robot interaction tasks. The purpose of this section is to analyze the difference, if any, between the groups and see if this difference has any effect on the which human factors are considered important. For the gender analysis, the population was divided into male (46) and female (47) and for the age analysis the population was divided into young (those less than 40 years old) and old (those 40 years and older). This age was chosen due to it being the median age between 18 and 63 as well as the age that divides the population evenly (46 young, 47 old). The statistics for the performance metrics of each group can be seen in Table 3-4 below.
### Table 3-4 Statistics for Performance Metrics for Different Gender and Age Groups

<table>
<thead>
<tr>
<th></th>
<th>MALE</th>
<th>FEMALE</th>
<th>YOUNG</th>
<th>OLD</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Performance Metric</strong></td>
<td><strong>Min</strong></td>
<td><strong>Q1</strong></td>
<td><strong>Median</strong></td>
<td><strong>Q3</strong></td>
</tr>
<tr>
<td>Time-on-Task</td>
<td>48</td>
<td>71.67</td>
<td>80.25</td>
<td>97</td>
</tr>
<tr>
<td>Number-of-Moves</td>
<td>16.17</td>
<td>27.83</td>
<td>31.33</td>
<td>41.83</td>
</tr>
<tr>
<td>Number-of-Moves per minute</td>
<td>13.27</td>
<td>20.03</td>
<td>23.36</td>
<td>38.82</td>
</tr>
</tbody>
</table>

#### 3.6.1 Gender

Before determining what human factors are important for each group, we first need to see if there is in fact a difference in performance. The performance data was first checked for normality to determine which tests were suitable to use for the comparison. Using both multivariate and univariate techniques it was determined that both sample populations were not normal meaning that a nonparametric test is needed for the comparison. To compare the two populations, the Cramer-Von Mises T-test was used to determine if there is in fact a difference in performance using the cramer package in R by testing the Null Hypothesis $H_0$ that the two sample groups come from the same distribution [3.53]. The results of the Cramer test can be seen in Table 3-5 below.
From the table it can be seen that there is a difference in the Time-on-Task and Number-of-Moves for men and for women. From looking at the statistics it can be seen that men, on average, complete the task faster and with fewer moves than their female counterparts. This could be due to two things: 1) behavioral differences [3.54] and 2) strategic differences in completing the tasks [3.55][3.56]. This difference in performance also produces a difference in the important human factors as seen in Tables 3-6 and 3-7 below.

Table 3-6 Important Indices for Males

<table>
<thead>
<tr>
<th>MALE</th>
<th>Human Factors</th>
<th>Time-on-Task</th>
<th>Number-of-Moves</th>
<th>Number-of-Moves per Minute</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Reaction Time</td>
<td>0.41</td>
<td>0.17</td>
<td>-0.06</td>
</tr>
<tr>
<td></td>
<td>Spatial Orientation</td>
<td>0.38</td>
<td>0.01</td>
<td>0.13</td>
</tr>
<tr>
<td></td>
<td>Spatial Visualization</td>
<td>0.22</td>
<td>0.04</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>Visual Perception</td>
<td>0.00</td>
<td>-0.11</td>
<td>-0.09</td>
</tr>
<tr>
<td></td>
<td>Working Memory</td>
<td>0.25</td>
<td>-0.06</td>
<td>0.13</td>
</tr>
<tr>
<td></td>
<td>Gross Dexterity</td>
<td>0.07</td>
<td>0.00</td>
<td>-0.09</td>
</tr>
<tr>
<td></td>
<td>Fine Dexterity</td>
<td>0.15</td>
<td>-0.16</td>
<td>0.20</td>
</tr>
<tr>
<td></td>
<td>Weakest Vision</td>
<td>0.04</td>
<td>0.14</td>
<td>-0.02</td>
</tr>
<tr>
<td></td>
<td>Strongest Vision</td>
<td>0.06</td>
<td>-0.02</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td>Depth Perception</td>
<td>0.06</td>
<td>0.17</td>
<td>0.09</td>
</tr>
</tbody>
</table>

Table 3-7 Important Indices for Females

<table>
<thead>
<tr>
<th>FEMALE</th>
<th>Human Factors</th>
<th>Time-on-Task</th>
<th>Number-of-Moves</th>
<th>Number-of-Moves per Minute</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Reaction Time</td>
<td>0.37</td>
<td>0.00</td>
<td>0.21</td>
</tr>
</tbody>
</table>
From this it can be seen that for women, the physical factors are considered the most important for Time-on-Task while the cognitive factors are considered the most important for Number-of-Moves. This is evident by the fact that for Time-on-Task fine dexterity was given the most importance, even over reaction time. The other physical factors such as visual acuity and gross dexterity were also given a high importance. The two cognitive factors that were given importance, that being working memory and visual perception, were given considerable less importance than any of the physical factors. For Number-of-Moves, visual perception was given greatest importance followed by spatial visualization.

For men, the spatial abilities were the most prevalent human factor for performance. Even if they were not rated as the most important, either one or both were given importance for all the performance metrics. This is due to the fact that both spatial abilities have more significant correlations with the other human factors for men than they do for women (as seen in Table A-7 and A-8 in Appendix A). The visual abilities were also considered important for all the performance metrics as well. Given the importance of the spatial abilities, it would stand to reason that if the devices that provide the necessary information for the spatial abilities to operate
are poor that the overall performance will also suffer given that the perceived spatial manipulations needed are incorrect.

As stated earlier, these differences can be attributed to two things: 1) the behavioral differences between men and women and 2) the strategic differences in carrying out the tasks. Behaviorally women tend to be more cautious while men tend to be more aggressive. This cautiousness was observed in female participants when operating the robot in the use of several small successive movements to move in one direction. As an example, a participant would use five 10cm moves to move to their 50cm target location as opposed to on 50cm move to do the same. While some men did display this tendency, it was not as common and not done to the same extent (meaning that they would use excessive moves, but not as many).

The important human factors for each group indicate that there is a difference in strategy, that being that men tend to plan as they go while women will devise a plan beforehand and then alter it if the need arises. This is represented by the given importance of the physical factors for Time-on-Task and the cognitive factors for Number-of-Moves. For men, their more impulsive nature is shown by having a mixture of both the cognitive and physical human factors being given importance for both Time-on-Task and Number-of-Moves.

3.6.2 Age

As with gender, the performance was first analyzed to see if there were any distinct differences between the two groups. Given that the older population is non-normality of the older population the Cramer-Von Mises test was used for comparison. The results of the Cramer test can be seen in Table 3-8 below.
Table 3-8 Cramer T-test Results for Comparing Performance of Different Age Groups

<table>
<thead>
<tr>
<th>Performance Metric</th>
<th>p Value</th>
<th>Cramer Statistic</th>
<th>Critical Value</th>
<th>H₀</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time-on-Task</td>
<td>0</td>
<td>92.58</td>
<td>38.05</td>
<td>Reject</td>
</tr>
<tr>
<td>Number-of-Moves</td>
<td>0.589</td>
<td>4.99</td>
<td>19.55</td>
<td>Fail to Reject</td>
</tr>
<tr>
<td>Number-of-Moves per minute</td>
<td>0</td>
<td>33.0393</td>
<td>8.51</td>
<td>Reject</td>
</tr>
</tbody>
</table>

From this it can be seen that there is a difference in the Time-on-Task and Number-of-Moves per minute between the two groups. Looking at the statistics of each from Table 3-4 it can be seen that the younger population is faster on average and has a higher rate of input into the system over their older cohorts. This is supported by literature that show that older individuals tend to be slower and more cautious with their actions and think things through as opposed to their younger counterparts who tend to be more impulsive [3.57-3.59]. This difference also in performance also led to some differences in which human factors are considered important. Tables 3-9 and 3-10 below shows which human factors are considered important for each group.

Table 3-9 Important Indices for Young Age Group

<table>
<thead>
<tr>
<th>Human Factors</th>
<th>Time-on-Task</th>
<th>Number-of-Moves</th>
<th>Number-of-Moves per Minute</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reaction Time</td>
<td>0.48</td>
<td>0.01</td>
<td>-0.12</td>
</tr>
<tr>
<td>Spatial Orientation</td>
<td>0.03</td>
<td>-0.05</td>
<td>-0.14</td>
</tr>
<tr>
<td>Spatial Visualization</td>
<td>0.05</td>
<td>0.27</td>
<td>0.06</td>
</tr>
<tr>
<td>Visual Perception</td>
<td>-0.19</td>
<td>-0.21</td>
<td>-0.15</td>
</tr>
<tr>
<td>Working Memory</td>
<td>0.21</td>
<td>0.39</td>
<td>0.15</td>
</tr>
<tr>
<td>Gross Dexterity</td>
<td>-0.12</td>
<td>-0.03</td>
<td>-0.10</td>
</tr>
<tr>
<td>Fine Dexterity</td>
<td>0.05</td>
<td>0.01</td>
<td>-0.17</td>
</tr>
<tr>
<td>Weakest Vision</td>
<td>0.01</td>
<td>-0.02</td>
<td>-0.18</td>
</tr>
<tr>
<td>Strongest Vision</td>
<td>0.21</td>
<td>-0.01</td>
<td>-0.15</td>
</tr>
<tr>
<td>Depth Perception</td>
<td>-0.10</td>
<td>-0.15</td>
<td>-0.21</td>
</tr>
</tbody>
</table>
Table 3-10 Important Indices for Older Age Group

<table>
<thead>
<tr>
<th>Human Factors</th>
<th>OLD Time-on-Task</th>
<th>OLD Number-of-Moves</th>
<th>OLD Number-of-Moves per Minute</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reaction Time</td>
<td>0.36</td>
<td>0.08</td>
<td>-0.19</td>
</tr>
<tr>
<td>Spatial Orientation</td>
<td>0.11</td>
<td>-0.19</td>
<td>0.00</td>
</tr>
<tr>
<td>Spatial Visualization</td>
<td>0.26</td>
<td>0.22</td>
<td>-0.03</td>
</tr>
<tr>
<td>Visual Perception</td>
<td>0.13</td>
<td>0.01</td>
<td>-0.13</td>
</tr>
<tr>
<td>Working Memory</td>
<td>0.39</td>
<td>0.29</td>
<td>-0.12</td>
</tr>
<tr>
<td>Gross Dexterity</td>
<td>-0.08</td>
<td>0.01</td>
<td>-0.02</td>
</tr>
<tr>
<td>Fine Dexterity</td>
<td>0.18</td>
<td>0.08</td>
<td>0.02</td>
</tr>
<tr>
<td>Weakest Vision</td>
<td>0.03</td>
<td>-0.12</td>
<td>-0.02</td>
</tr>
<tr>
<td>Strongest Vision</td>
<td>-0.03</td>
<td>-0.03</td>
<td>0.05</td>
</tr>
<tr>
<td>Depth Perception</td>
<td>-0.15</td>
<td>-0.05</td>
<td>0.06</td>
</tr>
</tbody>
</table>

The main differences between the young and old age groups are the importance of information processing to older individuals (represented by the importance of reaction time, visual perception, and working memory) for Time-on-Task and Number-of-Moves. While both reaction time and working memory are both important to younger individuals as well, the addition of visual perception indicates that older adults are using more aspects of their information processing abilities to aid them. This supports the idea that the older users are thinking and being more diligent with their moves given that they are using all facets of their information processing ability as well as their spatial abilities as opposed to younger users only using their spatial abilities and some of their information processing ability.

The other noticeable difference comes with which factors were considered important for Number-of-Moves per minute. For the young age group, only visual perception and working memory were considered important while for the older age group fine dexterity, strongest vision and depth perception. This is most likely due to the familiarity that younger adults have with technology. Since the younger generation grew up with the current technology, their skill in
using it reduces the negative effects that their physical abilities would have on performance given that their use of the mouse as an input is second nature to them. This has the opposite effect with older adults. Since the technology is recent for most and was not commonplace until the late 1980s to early 1990s, older adults had to learn how to use this new technology later in their life giving them less experience. This would lead to the physical abilities playing a greater role and any detriment would have a greater effect.

### 3.7 References


[3.43] Randot Stereotests, Stereo Optical CO., Inc.


CHAPTER IV: MODELING

4.1 Introduction

Now that the important human factors have been determined, models can be developed to predict a user’s performance based on their determined important human factors. Previous research in the field have utilized logistic regression models to predict performance for astronauts by Lei et al. [4.1]. However, the metrics used to measure performance were more categorical in nature making this type of modeling more appropriate. Given that the quantification of the human factors and the performance metrics can be treated as continuous data, even though some would be more akin to being classified as discrete, standard regression methods can be utilized to develop the predictive models.

4.2 Chapter Objectives

- Select modeling techniques to be used
- Develop Random Forest Models
- Develop Linear Models
- Develop Polynomial Models
- Compare performance

---

4 This section is comprised of sections of the paper “A Predictive Model of Human Factors vs Performance of Pick- and-Place/Retrieval Tasks for Users of an Assistive Robotic Manipulator” by N.Paperno, M. Rupp, J. Smither, E. Maboudou, and A. Behal.
4.3 Model Selection

A variety of choices is available in terms of types of modeling techniques to use to develop a predictive model for user performance based on measurements of their physical and cognitive abilities. General Additive Models (GAMs) \[4.2\] are models that generalize a linear regression, say, \( y = Ax_1 + Bx_2 + Cx_3 + D \) to the form \( y = f_0 + f_1(x_1) + f_2(x_2) + f_3(x_3) \) where \( f_0 \) is the mean value of \( y \). These models provide more robust outputs than traditional regression techniques. For this study, three different bases for \( f_i(x_i) \) were chosen to be analyzed to see which would provide the best model for predicting performance: Boost, Splines, and Locally Weighted Scatterplot Smoother (LOESS). Random forest was also chosen as a potential model. These models are useful due to their robust nature that is derived from the multitude of decision trees that comprise them and their ability to self-validate during the training process. This technique works by taking a sample of the training set to grow decision trees and the remainder of the set to validate the grown trees. The results of the forest are the consensus of the various trees grown. Table 4-1 shows the results from using linear, GAM, and Random Forest based regression techniques using the ‘caret’ package in R. The root-mean-squared-error (RMSE) and adjusted \( R^2 \) were used to compare the models’ performance.

Table 4-1 Results of Model Comparison for Time-on-Task Number-of-Moves and Number-of-Moves per minute

<table>
<thead>
<tr>
<th>Method</th>
<th>Time-on-Task</th>
<th>Adjusted ( R^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear</td>
<td>23.79</td>
<td>0.31</td>
</tr>
<tr>
<td>Spline (GAM)</td>
<td>23.79</td>
<td>0.31</td>
</tr>
<tr>
<td>Boost (GAM)</td>
<td>22.28</td>
<td>0.42</td>
</tr>
<tr>
<td>LOESS (GAM)</td>
<td>20.73</td>
<td>0.48</td>
</tr>
<tr>
<td>Random Forest</td>
<td>13.30</td>
<td>0.88</td>
</tr>
</tbody>
</table>

36
As can be seen in the table, the random forest models significantly outperform the others in predicting each of the performance metrics. The adjusted $R^2$ is quite near one showing that they are an excellent fit and there is significant improvement in the RMSE over the rest of the tested models. The closest model in terms of performance to the random forest is the LOESS GAM for Time-on-Task and Number-of-Moves and the boost GAM for Number-of-Moves per minute with adjusted $R^2$ around 0.5 and slightly improved RMSEs over the rest of the models. Based on this analysis, the Random Forest technique was used to construct the initial models for our study.

### 4.4 Random Forest Models

Given that the random forest performed well during the model validation, it was used initially for the model development. The RMSE (RMSPE) for the random forest models are 16.81 (16.48%) for Time-on-Task (ToT), 10.66 (30.43%) for Number-of-Moves (NoM), and 4.15 (18.57%) for Number-of-Moves per minute (NoM/min) when used on the training set. The probability
distributions functions (pdfs) of the percent errors were generated using MATLAB’s ‘fitdist’ and ‘pd’ function with a Gaussian kernel and can be seen below in Fig.4-1.

These results appear to show at first glance that the random forest would serve well as our model, but it unfortunately does not pass muster when it is used to predict values for data outside of its training set. The resulting RMSE (RMSPE) for the random forests when used on the test data are 43.11 (35.87%) for ToT, 23.62 (41.77%) for NoM, and 9.93 (31.74%) for NoM/min. It is expected that the error values for the test set will be large than those from the training set, but the errors for predictions made by the random forest on the test set are nearly double those that were obtained on the training set.

4.5 Linear Models
4.5.1 Simple Linear Models

While Random Forests are excellent modeling tools, one of the drawbacks is their pseudo-black box nature that is inherent to their creation. This makes it difficult to discern what is truly happening within the model to obtain the results. It also presents an issue when trying to develop an inverse model based on the Random Forest. On the other hand, while GAMs do provide a more formulaic model compared to Random Forests, they can be just as difficult to decipher.
because the global component functions of GAMs are made up from several locally optimized functions. By reducing the number of local neighborhoods, these models can be smoothed out to a point where the component functions become lower order polynomials that can be more easily deciphered. However, if this is what is required for the model to be understood, then it makes more sense to use simpler regression techniques that will produce the same results. Even at the cost of higher adjusted $R^2$ values, a linear regression provides a simple and robust predictive model. More importantly, it provides a benchmark to compare the performance of other more sophisticated models. A linear regression was performed using only the important factors from Random Forest modeling to obtain a predictive model in the form of $Y = CX + b$, where $Y = [ToT \ NoM_{\min}^{NoM}]^T$ denotes a vector of performance metrics, while $X = [RT \ SO \ V \ WM \ GD \ FD \ WV \ SV \ DP]^T$ denotes human factors data normalized between 0 and 1.

The resulting C and b from this regression can be seen in Table 4-2

<table>
<thead>
<tr>
<th>Human Factor</th>
<th>Time-on-Task</th>
<th>Number-of-Moves</th>
<th>Number-of-Moves per minute</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reaction Time</td>
<td>12.40</td>
<td>-5.81</td>
<td>-7.04</td>
</tr>
<tr>
<td>Spatial Orientation</td>
<td>-34.53</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Spatial Visualization</td>
<td>-26.25</td>
<td>-21.4</td>
<td>0</td>
</tr>
<tr>
<td>Working Memory</td>
<td>0</td>
<td>0</td>
<td>4.47</td>
</tr>
<tr>
<td>Gross Dexterity</td>
<td>-28.86</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Fine Dexterity</td>
<td>-83.37</td>
<td>0</td>
<td>9.02</td>
</tr>
<tr>
<td>Weakest Vision</td>
<td>32.63</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Strongest Vision</td>
<td>-47.26</td>
<td>-19.24</td>
<td>0</td>
</tr>
<tr>
<td>Depth Perception</td>
<td>0</td>
<td>0</td>
<td>-3.37</td>
</tr>
<tr>
<td>b</td>
<td>187.09</td>
<td>64.4</td>
<td>20.88</td>
</tr>
</tbody>
</table>

The RMSE (RMSPE) for the training set are 22.54 (23.33%) for ToT, 12.58 (35.09%) for NoM, and 5.13 (21.72) for NoM/min. From these results it can be seen that these models do perform worse than their machine-learning counterparts, but the results for the test set will demonstrate as
to why the random forest was not chosen to be utilized for its predictive property. The resulting RMSE (RMSPE) for the test data set are 46.03 (38.86%) for ToT, 23.75 (44.62%) for NoM, and 9.69 (32.49%) for NoM/min. From this it can be seen that all the linear models perform comparably well on the test data set to the random forest models. The model for ToT does perform slightly worse than its random forest counterpart, but not enough to be considered useful. Despite Working Memory being given importance in the ToT model, it was left out of the linear model mainly due to its interaction with the other variables, predominantly reaction time and spatial abilities, which will be discussed more in the Polynomial Models section.

![Figure 4-2 Percent error pdfs for linear models](image)

While the linear models did perform as well as the random forest on the test set, they suffer from heteroscedasticity, evident by their QQ-plots seen in Fig. 4-3. This means that as the magnitude of the predicted value grows, so does the variance of the predicted error, making high value predictions highly unreliable. To counteract this, the performance metrics were converted using a log transformation (in this case the natural log was used). The results of the developed models can be found in the next section.
4.5.2 Linear Log Models

As stated in the previous section, when initially conducting the regression, it was noted that the linear models suffered from heteroscedasticity. To rectify this, the performance metrics were converted to a log scale. This removed the issue of heteroscedasticity as seen by the QQ-plots in Fig. 4-4. The resulting coefficients and constants for the log-linear models can be found in Table 4-3.

![Figure 4-3 QQ-plots for linear models](image1)

![Figure 4-4 QQ-plots for log linear models](image2)

**Table 4-3 Coefficients for and Constants 'b' for Log-linear Models**

<table>
<thead>
<tr>
<th>Human Factor</th>
<th>Time-on-Task</th>
<th>Number-of-Moves</th>
<th>Number-of-Moves per minute</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reaction Time</td>
<td>0.22</td>
<td>-0.19</td>
<td>-0.32</td>
</tr>
<tr>
<td>Spatial Orientation</td>
<td>-0.35</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Spatial Visualization</td>
<td>-0.17</td>
<td>-0.48</td>
<td>0</td>
</tr>
<tr>
<td>Human Factor</td>
<td>Time-on-Task</td>
<td>Number-of-Moves</td>
<td>Number-of-Moves per minute</td>
</tr>
<tr>
<td>-------------------</td>
<td>--------------</td>
<td>-----------------</td>
<td>-----------------------------</td>
</tr>
<tr>
<td>Working Memory</td>
<td>0</td>
<td>0</td>
<td>0.20</td>
</tr>
<tr>
<td>Gross Dexterity</td>
<td>-0.07</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Fine Dexterity</td>
<td>-0.93</td>
<td>0</td>
<td>0.41</td>
</tr>
<tr>
<td>Weakest Vision</td>
<td>0.35</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Strongest Vision</td>
<td>-0.57</td>
<td>-0.64</td>
<td>0</td>
</tr>
<tr>
<td>Depth Perception</td>
<td>0</td>
<td>0</td>
<td>-0.14</td>
</tr>
<tr>
<td>$b$</td>
<td>5.31</td>
<td>4.32</td>
<td>3.01</td>
</tr>
</tbody>
</table>

The RMSE (RMSPE) for the log models when used on the training set are $0.22 (4.74\%)$ for ToT, $0.31 (8.67\%)$ for NoM, and $0.21 (6.64\%)$ for NoM/min with $R^2$ of $0.49$, $0.31$, and $0.34$ respectively. From pdfs of the percent error in Fig. 4-5 and the resulting RMSPEs, it can be seen that there is a significant improvement in the predictability of the models given the improved normal shape of the curves.

![Percent error pdfs for log linear models (blue) and bi-linear models (red dashed)](image)

When used on the test data set the RMSE (RMSPE) for the models are $0.35 (7.41\%)$ for ToT, $0.48 (12.43\%)$ for NoM, and $0.36 (10.87\%)$ for NoM/min. These are slightly worse than those of the training set, but that is to be expected. The coefficients of the model do follow the expected relationships between the human factors and performance metrics. If a user’s spatial abilities are above average, it will result in more efficient movement (represented by the negative coefficients for NoM and ToT). The worse a person’s reaction time the worse their ToT and NoM. The
relation to ToT is obvious in that if a person is slow to react, they will in turn take more time completing a task. This slow reaction time also means that any response to an unexpected event will more often than not result in a situation that requires greater correction, further increasing the number of moves needed to complete a task. Given that the mouse was the input device used to operate the interface, it stands to reason that fine dexterity would have the relations expressed in the model. Greater expertise in operating the mouse will allow for quicker task completion as well as a more rapid pace of inputs to command the robot represented by the negative coefficient for ToT and the positive coefficient for NoM/min. This is also the reason for the coefficient for gross dexterity in ToT. Given that gross dexterity is not the main source of control, it stands to reason that it would contribute less than fine dexterity. The relation between weakest and strongest vision is also shown. If a person has weaker visual acuity in one eye, the other will compensate for it. This can be seen in the model with the opposing coefficients of the two. If a person has good visual acuity in both eyes, then it will have little effect on ToT, but if one is stronger than the other, the stronger eye will dominate and compensate for the deficit of the weaker eye.

4.6 Polynomial Models

The log-linear models performed adequately, but as noted in the choice of human factors section, there were interactions between the dependent variables that are not explained by using a linear model. To do this, bilinear and trilinear interaction terms in the form of \( x_1 \times x_2 \) and \( x_1 \times x_2 \times x_3 \) were added to the models. Initial analysis using a forward/backward step regression based on Akaike Information Criterion (AIC) was done to determine which of the interaction terms were significant to the model. The important interaction terms (\( p < 0.05 \)) were then added to the
regression model. The resulting equations can be found below. As seen from the equations, only ToT and NoM/min are modeled. This is due to the fact that the interaction terms for NoM were not considered significant.

\[
\ln(ToT) = rt(3.22so - 8.19gd + 5.13fd + 3.15sv - .004) + so(0.93v - 1.63wv + 0.45) + \\
wm(1.14 - 1.36rt - 1.63so - 0.95v + 2.62fd) + gd(2.53wv - 1.58sv + 1.98) + \\
fd(1.81sv - 3.32wv - 3.39) + 4.29
\] (1)

\[
\ln\left(\frac{NoM}{min}\right) = rt(0.07 - 0.67dp) + 0.39wm + 0.44fd - 0.13dp + 2.88
\] (2)

The RMSE (RMSPE) for these polynomial models are 0.18 (3.97\%) for ToT and 0.21 (6.61\%) for NoM/min. These models show some improvement over their log-linear counter parts which can be seen in the pdfs of the percent errors (red dashed lines) in Fig. 4-5. The results for the predictions on the test set are 0.4 (8.80\%) for ToT and 0.35 (10.39\%) for NoM/min. These results are better than those from the log-linear models. The main improvement of these models comes with the explanation of the relationships between all the human factors involved. From this, it can be seen that reaction time interacts with most of the other human factors. This is expected given it is correlated with most of the other variables. From this it can be seen that a poor reaction time can be compensated for with working memory. It can also be seen that a poor reaction time can inhibit any benefits of good visual acuity and fine dexterity. Having good cognitive abilities can also help to improve ToT. The interactions for working memory and the spatial abilities go to show that high performing cognitive functions will decrease a person’s time for completing tasks.
As stated in the previous section, working memory was left out of the linear model for a specific reason, that being its interaction with the other variables. By observing the scatterplot, it can be seen that working memory has a nonlinear relation with ToT, as seen in Fig. 4-6. If working memory is introduced and utilized in the linear model, it will have a positive coefficient of 0.25, the opposite of one would expect. This is not due solely to the nonlinear relation it holds with ToT given that if a linear model was developed with working memory alone its coefficient would be negative. The other part of this reason comes from working memory’s relationship with the spatial abilities, and fine dexterity. From Table A-4 in Appendix A, it can be seen that working memory has a high positive correlation with these variables. Whenever one of these human factors is introduced into the regression, working memory’s coefficient becomes positive. From the polynomial models it can be seen that in combination with the spatial abilities and reaction time, of which it has a strong negative correlation with, working memory affects ToT as expected, but to adhere to its nonlinear relationship with ToT, the singular working memory term has a positive coefficient. When reducing this to a linear model, the expected influence that working memory has on ToT is absorbed into the other human factor terms while its coefficient remains positive. Because of this, it has been left out of the linear model given that its non-intuitive coefficient would lead to misclassification of the user’s deficits.
4.7 Discussion

4.7.1 Summary

The statistical models themselves predicted well. Both the linear and polynomial models provide excellent predictive values for the performance metrics being examined. The main difference in the models comes from their explanations of the relationships between the human factors and the performance metrics. The linear model offers the most basic explanation and assumes that the human factors are all independent of each other. This, however, is known not to be true for some of the factors (e.g., spatial visualization and spatial orientation). The strength of the polynomial models comes from the fact that these relations are taken into account with the addition of the
interaction terms. This led to a decrease in the variance of the error of the models, both for TOT and NoM/min. Since it is known that performance on our dependent variables decreases as an individual’s age [4.2-4.8], we performed a two-step hierarchical linear regression analysis to confirm this. In the first step, we used participant age to predict each of the dependent variables (TOT, NoM, & NoM/min). We followed this up, in a second step, by calculating a linear model using our predictor variables (RT, SO, V, VP, WM, GD, FD, WV, SV, & DP) to predict the residuals of the first analysis using age. For TOT, age was found to be an important factor. However, none of the other variables were found to be important to the prediction of TOT after the variability associated with age was removed. Therefore, the model with age alone was found to be the simplest model accounting for the most variability in the data for the prediction of TOT. This has also been found in prior research as reaction time, working memory, spatial abilities and dexterity have all been found to decline with age [4.10][4.4] and older adults have been shown to take longer to complete manual reaching and pointing tasks [4.11]. For NoM/min, age was found to be an important predictor along with a couple of our human factors.

The resulting regression models had RMSEs (RMSPEs) of 0.25(5.48%) and 0.21(6.88%) respectively for the training set and 0.359(7.25%) and 0.27(8.10%) for the test set. These findings go to show that for TOT and NoM/min, age does have significance and models based on age can be developed given that the results are comparable to those obtained by the linear models based on important human factors. However, age is not a variable that can be directly compensated for. On the other hand, since our aforementioned human factors can be compensated for in an interface, models of performance versus human factors such as the ones in this paper are essential to understanding teleoperation and allowing even older individuals to
have a gainful relationship with assistive robots. Finally, age was not found to be an important factor for predicting NoM.

4.7.2 Limitations

As stated above, user performance metrics in our system are agnostic to the type of access method (i.e., input device) employed. However, the dependence of these metrics on human factors can be different between different access methods. As an example, in our study, fine dexterity was determined to be of greater importance than gross dexterity, most likely due to the use of a mouse as the input device. However, if a touch screen were used, it could have easily been gross dexterity that was considered the most important or if a speech-based interface were used, neither gross nor fine dexterity would have been considered important. The importance of visual acuity is another that can be affected by interface, e.g., if the robot is controlled via teleoperation, the binocular cues will not have an effect. Thus, our particular models may not be applicable to such setups. However, the methodology developed in this work to determine the important human factors and develop the predictive models is general enough to be applied to data collection and analysis for any setup.

Another limitation to this work is that the participants cannot definitively be considered trained in the sense of a learning plateau having been reached. The models were developed using individuals who had a limited amount of time working with the robot beforehand. This implies that many of them may still have been in the process of learning the system, which would have been impacted by the participant’s human factors. This could mean that the detriments to performance caused by the human factors could be magnified if the model were used to predict the performance of someone who was an expert at using the machine.
The last limitation relates to the performance metrics. As stated earlier, Time-on-Task and Number-of-Moves are task specific. Since the models are based on an average of these metrics across several tasks, they can be affected by the types of tasks that are being performed. If a person chooses to use the robotic arm for just complex tasks that would require a longer amount of time and significantly more moves, the average would be greater than if they chose to use the robot for just simpler tasks. This in turn would affect the error in the predictions of the models.

As an alternative to Number-of-Moves (NoM), Number-of-Moves per minute (NoM/min) was developed to help combat this given that it is consistent from task to task. An alternative metric similar to NoM/min could also be developed in place of Time-on-Task, e.g., by normalizing the individual tasks depending on type or complexity before averaging to ensure homogeneity of the data regardless of task.

4.8 References


CHAPTER V: COMPENSATORS

5.1 Introduction

Since the important human factors have been determined, appropriate compensation can now be developed. It is known that deficits in these particular factors can have adverse effects on performance, especially the spatial abilities. To lessen the effects of these deficits and help increase user performance and satisfaction, appropriate compensators need to be implemented to assist the user.

5.2 Chapter Objective

- Describe purpose and development of new GUI
- Describe choice of compensators for each important human factor
- Discuss results of usability experiments for model-based compensation

5.3 Improved GUI Compensator

An initial heuristic evaluation found several aspects of the original GUI lacking. The first item was a lack of context for certain buttons on the interface as well as a lack of explanation on the main menu. The second was a lack of help functionality or documentation that a user could access if needed. The third was the absence of a defined abort button in the automated mode and the hybrid mode, both of which utilize the automated grasping program of the UCF-MANUS [5.1]. The initial GUI design based on these findings can be seen in Fig. 5-1 below.
The GUI was then tested using ten participants to see if the usability could be improved. The experimental design is described in detail in the next section.

5.3.1 Experimental Setup

The experimental setup is similar to that of the Important Human Factor experimental design. The setup was identical to Fig. 3-1 where the user was placed to the left of the UCF-MANUS as if it were attached to a wheelchair. The same six tasks were also used with the addition of the tasks being completed with the participant using a specific mode of operation. The modes of operation for the tasks are as follows:

T1: Auto

T2: Manual
5.3.1.1 Participants
Ten participants (6 males, 4 females) were recruited for this study using the UCF Psychology departments SONA system.

5.3.1.2 Surveys
Before the tasks the participants were asked to complete several surveys that included the NARS (Negative Attitudes Towards Robots) [5.2], ITQ (Interpersonal Trust Questionnaire) [5.3], and the Mini-IPIP (International Personality Item Pool) [5.4]. Trust was measured using the Human-Robot Trust Scale [5.5] and a modified version of the Trust in Automation Scale. Both trust scales were given to the participants before and after completing the tasks.

5.3.1.3 Procedure
When the participants first entered the lab they were seated at the computer used to control the robot. They were first asked to complete the given surveys and indicate to the examiner when they have finished. Once the initial surveys were completed, the participants were then introduced to the robot and its interface. They were taken through the various modes of operation and shown how to control the robot in the various modes. They were then given ten minutes to use the robot however they saw fit to better acclimate themselves to the interface. Once the ten minutes passed or the participant indicated that they were ready, they were then asked to
complete the six given tasks using the mode specified for each task. Once complete the participant was then asked to fill out the post-test surveys.

5.3.2 Results

From the feedback of the participants two main improvements were need for the GUI. First there were no relative left and right commands that move the robot relative to the end-effector. The fixation of the manual commands to the base-frame as opposed to the end-effect led to confusion for several of the participants. The second was the lack of clarity of the function of the preset location buttons. For the initial GUI the buttons were numbered (1,2,3,4), but this gives little context into the function unless the participant has memorized the functionality of each. To correct this the GUI has been modified so that all the commands are relative to the end-effector and the preset locations are pictorially represented as opposed to by numbers. The redesigned GUI can be found in Fig. 5-2 below.
5.4 Model-based Compensators

From our models and initial analysis of the important human factors, compensators can be developed to help mitigate the effects that the detriments in certain human factors will have. A literature search will show that methods for compensating for certain human factors have been developed and tested for similar technologies such as teleoperation and navigation in a virtual environment [5.7-5.9]. The specific compensation that is developed for each of the human factors will be explained in more detail in the following sections.
5.4.1 Spatial Abilities and Visual Abilities

The concepts described in the literature search show that multimodal feedback was useful when assisting users with poor spatial or visual abilities [5.7-5.9]. These concepts were taken and utilized to develop similar multimodal feedback for the operation of the UCF-MANUS. In Fig. 5-3 below, the visual changes that were added can be seen. Depth information as well as cues that indicate whether or not the object is in within the gripper are given above the camera feed in the GUI. Auditory feedback is also given in the form of messages when the object first enters the gripper, when the object is fully within the gripper, and when the object is grasp with significant enough force. The messages are as follows for the events:

1. “The object has entered the grippers.”

2. “The object can be grabbed successfully.”

3. “The object has been grabbed.”
If a user has poor enough visual or spatial abilities, a highlight of a potential object in scene can be given as opposed to the target reticle that is initially given. This is implemented by using the SURF feature extractor that is a part of the OpenCV library. An example can be seen in Fig. 5-4 where the French’s can that is in view of the camera is highlighted.
These compensators reflect those that have been suggested in prior research for other systems. Haptic feedback was the only type that was not added due to an inability to implement it given the input mouse being used did not support that functionality.

5.4.2 Reaction Time and Dexterity

Reaction Time and Dexterity are the simplest human factors to compensate for. The compensation for reaction time comes from Fitts law, which is the faster a person is moving (or in this case the robot) the less accurate they will be. The previous section concerning the determination of important human factors showed that this can be extended to operating a robotic
manipulator. Given that those with poor reaction time will fail to respond to unforeseen events, the speed of the robot needs to be adjusted to ensure that the user can react in time. This adjustment is what will be used to compensate for reaction time.

Dexterity in this dissertation concerns how efficiently the user can operate the mouse which is being used as the primary input device. Given that the goal of this research is to provide the interface with a way to compensate for the user given the particular hardware, the only action that can be taken to help improve performance using the mouse is to adjust the sensitivity of input. This means adjusting the distance that the pointer on screen travels in relation to the physical distance that the mouse itself is moved. This is the only means for the interface to compensate for poor dexterity without outside assistance or alteration (changing of input method or upgrading the current device to an improved version).

5.4.3 Experimental Setup

The experimental setup is similar to that of the Important Human Factors experiment outlined in section 3.4. The same materials were used and the equipment was set up in a similar fashion. All human factors and performance metrics were recorded identically as in the previous experiment. The location of the experiments took place in a different room, but the setup of the robot in relation to the participants remained the same as seen in Fig. 5-5 below.
5.4.3.1 Participants
15 participants between the ages of 19-30 were recruited to take part in the study. The participants were comprised members of the university’s student population as well as faculty and staff. For a participant to be considered eligible they needed to be abled-bodied and not a part of any vulnerable populations as defined by the Internal Review Board.

5.4.3.2 Chosen Tasks
Participants completed three sets of two different. The goals of the tasks remained the same, but the initial and final locations were varied from set to set. This provides enough similarity that performance can be measured but also enough difference to where the participant is not improving due to repetition of the same tasks. The robot was set to a predefined start position at the beginning of each task for the participant. The two tasks used for this experiment were

T1: Pick up an object from the floor and place it on the top of a bookshelf.
T2: Move an object from the bookshelf to the bottom of the table.

5.4.3.3 Surveys
For this study the SUS survey was used to determine the usability of the robot. The SUS provides a quick and easy measurement of the usability of the system being observed [5.10]. A survey of open-ended questions was also developed to obtain feedback on the usefulness of the developed compensators and provide any suggestions of improvements that could be made to the system. The open-ended questions can be found in Appendix B.

5.4.3.4 Procedure
When the participants first arrive they are seated and given the informed consent document to read. After they have consented, they are given a demographic survey to fill out. The participants then complete the necessary human factors test for (1) reaction time, (2) spatial abilities (orientation and visualization), (3) visual abilities (acuity and depth perception), (4) dexterity
(gross and fine), and (5) working memory. The tests were given in a random order to mitigate any effect that fatigue would have on the results with the exception of the reaction time test that was given first to ensure that the participant was at their best when performing it.

Participants were then seated in front of a desk which the computer used to control the robot was held. The WMRA was positioned to the right of the participant similar to its placement to a user in a wheelchair. The participants were then shown the functionality of the manual controls of the robot followed by the various error states that can occur when operating the robot. Following this the participants were then asked to demonstrate whether or not they understood what each of the buttons on the interface did by performing simple maneuvers using each of the buttons. Directions were given as to what movement to do and when. Once they completed this, they were asked if they understood what all the controls did and whether or not they needed any further explanation on their functionality. If the participant indicated that they understood the controls, the next phase of the experiment was started.

After the training, the participants were asked to complete a set of six tasks. For this first set, no compensators were utilized. Each task was described to the participant and they then acknowledged that they understood.

5.4.3.5 Results
For this study 15 participants (6 males, 8 females) between the ages of 18 and 26 were recruited. The statistics for the human factors and the mean values for performance and usability scores can be found in the tables below.

<table>
<thead>
<tr>
<th>Human Factors</th>
<th>Min</th>
<th>Q1</th>
<th>Median</th>
<th>Q3</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reaction Time</td>
<td>248.78</td>
<td>270.72</td>
<td>290.88</td>
<td>331.88</td>
<td>393.31</td>
</tr>
<tr>
<td>Spatial Orientation</td>
<td>-2</td>
<td>3.25</td>
<td>12</td>
<td>24.25</td>
<td>36</td>
</tr>
<tr>
<td>Spatial Visualization</td>
<td>-10</td>
<td>-1</td>
<td>6</td>
<td>12</td>
<td>13</td>
</tr>
</tbody>
</table>
Table 5-2 Mean values of Performance Metrics and SUS scores for each of the task sets

<table>
<thead>
<tr>
<th>Performance Metric</th>
<th>Set 1</th>
<th>Set 2</th>
<th>Set 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time-on-Task</td>
<td>157.77</td>
<td>163.6</td>
<td>135.63</td>
</tr>
<tr>
<td>Number-of-Moves</td>
<td>85.53</td>
<td>84.1</td>
<td>74.07</td>
</tr>
<tr>
<td>Errors</td>
<td>2.37</td>
<td>2</td>
<td>1.77</td>
</tr>
<tr>
<td>SUS</td>
<td>70.67</td>
<td>69.17</td>
<td>77.17</td>
</tr>
</tbody>
</table>

Given the non-normality of the first set of data, the Friedman test was used for analysis. This is a non-parametric test similar to a repeated measures ANOVA. This test was conducted in R using the function found at [5.11]. This function also provides a post hoc analysis using if a difference is detected and the Null Hypothesis is rejected. The results for the comparisons can be found in Table 5-3 below.

Table 5-3 Friedman Test Results for Comparing Performance and Usability from Set 1 to Set 2 and 3

<table>
<thead>
<tr>
<th>Performance Metric</th>
<th>p Value</th>
<th>Friedman Statistic</th>
<th>H₀</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time-on-Task</td>
<td>0.23</td>
<td>1.4606</td>
<td>Fail to Reject</td>
</tr>
<tr>
<td>Number-of-Moves</td>
<td>0.55</td>
<td>1.278</td>
<td>Fail to Reject</td>
</tr>
<tr>
<td>Number-of-Moves per minute</td>
<td>0.67</td>
<td>0.4683</td>
<td>Fail to Reject</td>
</tr>
<tr>
<td>SUS</td>
<td>0.94</td>
<td>3.6566</td>
<td>Reject</td>
</tr>
</tbody>
</table>

From this it can be seen that there is no difference in performance across all sets of tasks. This means that the compensators did not have any effect on a user’s performance. The usability, however, is considered different across the different task sets. From the post hoc results, it is
revealed that the reason for the rejection of $H_0$ is due to a difference in the usability of the first set and the last set ($p = .00073$). From the parallel coordinates chart in Fig. 5-7 below it can be seen that on average, the usability increases as time increases. There were three cases where the usability of the system increased with the addition of the compensators and then decreased again when they were removed. There were also four cases where the usability decreased with the introduction of the compensators and then increased when they were removed. For the rest of the eight participants however, the usability increased as time went on. As the participants became more comfortable with the system their opinions of it improved.

![Parallel coordinates plot of SUS scores](image)

*Figure 5-7 Parallel coordinates plot of SUS scores*

5.4.4 Compensator Performance

While there was no change in performance, it does not mean that the compensators did not improve the user’s experience. The results from the open-ended questions survey revealed the
usefulness of each of the compensation methods. The sections below will detail the results for each compensator of how useful the participants found them to be.

5.4.4.1 Audio Feedback

For the audio feedback, 53% of the participants found it helpful, 13% found it benign, and 33% found it unhelpful. Those that found it helpful cited that it was helpful when grabbing an object, some noting that it was specifically when the object was out of view or obscured when it was the most beneficial. Those that cited it as benign simply stated that it was not useful to them since they were capable of making judgements based on their own vision. Those that cited it as unhelpful stated that it was distracting, or that it did not say much. There were two cases where the robot had malfunctioned causing the audio messages to either not play or to play repeatedly which affected their score on the survey. One even stated that if the feedback was working properly it would have been more of an asset instead of an annoyance.

Of the participants that were tested, seven showed deficits in one or more of the spatial abilities. 57% of those participants rated the audio feedback as helpful, 14% as benign, and 28% as unhelpful. One of the main criticisms from both those that rate it as helpful and unhelpful stated that the commands were only given when the robot was going to grab the object, indicating that if there were additional commands to help aid the user in the task it, may have been looked upon more favorably by the participants.

5.4.4.2 Visual Feedback

The visual feedback was rated as helpful by 40% of the participants, benign by 53%, and unhelpful by 7%. Those citing it as benign or unhelpful stated that the feedback was not
necessary or that they did not need to use it. This is understandable given that the majority of the participants and 20/20 vision and average or better than average depth perception.

The majority of the participants that did rate it as helpful had a deficit either in their visual acuity or depth perception, with three of them also having deficits in one or both of the spatial abilities. It can be concluded from this that the visual feedback was beneficial to those that suffered from poor visual abilities and unnecessary for those that did not have any deficits in these areas.

5.4.4.3 Sensitivity Adjustment

The sensitivity adjustment was the helpful by the majority of the participants with 67% rating it as helpful and 33% rating it as benign. It was the only compensator that did not receive a negative rating. The most common reason for this has to do with the prevalence of mouse sensitivity adjustment in other activities. Those that rated it favorably cited that they had dealt with high mouse sensitivity in other areas of their lives, predominantly through work or playing video games. The majority of these participants also stated in the demographic survey that they have either a fair amount or a lot of experience with video games or similar electronic input devices.

5.4.4.4 Speed Adjustment

The reactions to the speed adjustment were mixed with 47% of the participants rating the compensator as helpful, 33% rating it as benign, 13% rating it as unhelpful, and 7% not rating it at all. Those that rated as helpful stated that the slower speed made the robot easier to maneuver and allowed for better accuracy and increased efficiency. Those that rated it as benign did not notice any difference between the two speeds. Those that rated it as unhelpful stated that the reduced speed made it more frustrating and increased the time it took to complete a task.
5.4 Discussion

The improvements made to the GUI interface greatly increased the intuitiveness of the design and made it easier for participants to use. It was found through testing of the compensators and testing of the revised GUI design that the users were associating the translational commands to the yaw angle of the end-effector, or in other terms, how far they panned left or right. This led to an adjustment of the relative commands to be relative only to the yaw angle of the end-effector. The exception to this is when the gripper is tilted down towards the floor when the pan and roll commands essentially become the same movement. In this case the commands will then become relative to the roll angle as well as the pan.

While the model-based compensators did not help to improve performance, they help to improve the satisfaction for several users. The multimodal feedback in particular was rated highly by those with deficits in spatial abilities and visual abilities. Those that did not have deficits in these areas overall found the feedback to be benign or annoying and unwanted in the case of the audio feedback.

The sensitivity adjustment was considered helpful by the majority of the participants due to its use in other areas. This familiarity with mouse sensitivity seems to have improved the satisfaction of the users given that they are already comfortable with this particular function.

The speed adjustment while helpful to some, was also unnoticed by others or seen as a source of frustration. Given that none of the participants had below average reaction time, it cannot be determined based on this data whether or not the speed adjustment is an appropriate compensator for reaction time. The same is also true for the sensitivity adjustment. None of the participants
had below average dexterity making the rating of whether or not they were helpful a
determination based off of personal preference as opposed to actual need.

5.5 References


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[5.5] R. E. Yagoda and D. J. Gillan, "You want me to trust a ROBOT? The development of a


with Norma and Impaired Vision”, User Interfaces for All, pp. 3 -22, 2003


[5.10] John Brooke, "SUS-A quick and dirty usability scale." Usability evaluation in industry
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CHAPTER VI: CONCLUSION AND FUTURE RESEARCH

6.1 Introduction

The purpose of this research was to determine what human factors were considered important to performance when operating a robot manipulator. From these important human factors, models were developed that could predict a user’s performance based on their given human factors. Compensators were also developed to help mitigate any negative effects that would occur due to detriments in particular human factors.

6.2 Chapter Objectives

- Summarize results of studies conducted
- Discuss future research to further improve the models and compensators

6.3 Summary of Research

6.3.1 Important Human Factors

The important human factors for performance were determined using the importance index from the random forest as well as through the use of various global sensitivity analysis techniques. For a general population it was found that the important human factors for operation an assistive robotic device were reaction time, spatial abilities, working memory, visual acuity, dexterity, and depth perception. The only factor that was not considered important to any aspect of performance was visual perception, most likely due to the presence of the spatial abilities which represents the more sophisticated visual cognitive functions that a person possesses.

For the performance metric Time-on-Task, all human factors were considered important with the exception of depth perception and visual perception. Reaction time was given the greatest
importance followed by spatial orientation, working memory, fine dexterity and strongest vision. Reaction time’s importance is obvious given that the faster a person can react to a situation, the faster their task is complete. The visual factors can affect time if the feedback of the environment they are given is incomplete or compromised. Poor or degraded visual acuity can lead to several visual cues that are necessary for proper interpretation of the environment being incorrect or missing depending on the severity. This can lead to improper movement of the robot which would then need to be followed by a correction for the mistake. The same is true for the spatial abilities. If a person’s manipulation due to their interpretation of what should be done is incorrect, it will lead to mistakes that then need to be corrected for, which will cost more time.

For Number-of-Moves, the important human factors were spatial visualization, reaction time, and strongest vision with spatial visualization being given the most important. This gives insight into how a person is formulating their plan by giving the greatest importance to the mental ability that manipulates objects in space. If a person cannot react quick enough to an unexpected event or their perception of the environment is flawed, this can have an impact on how many moves it will take to complete the task given that there will be errors that will need to be accounted for.

For Number-of-Moves per minute the important human factors were working memory, reaction time, fine dexterity and depth perception with working memory being given the greatest importance. Working memory and reaction time are both facets of the information processing construct and are integral to how fast a person can remember and execute a plan. Given that the input device used in the experiments was a mouse, fine dexterity was given importance given that it is the main form of control of the mouse and is therefore integral to the speed at which the user inputs their commands into the system.
6.3.2 Predictive Models

Several modeling techniques were examined to see which ones would be beneficial for predicting performance. From the initially selected techniques, random forest and simple linear models were chosen to be developed. The random forest performed well on the training set of data, but did poorly on the test set. This is due to random forest overfitting the model to the data as well as not being able to handle sparse or missing data well. Its results were similar enough to the linear models that it would not be considered for further use. While random forest models can provide insight into the relationships of the variables, it is not suitable for use in prediction.

As stated in the previous paragraph, the linear models performed as well as the random forest models when it came to predicting performance. One issue that the models had was that of heteroscedasticity. This means that as the magnitude of the predicted value increased, so did the variance of the error, making these high value predictions significantly more unreliable. To rectify this, the performance metrics were converted to a log-scale which solved this issue.

From the log-linear models, polynomial models were developed using bilinear and trilinear interaction terms. The terms that were added to the model were determined by using a forward-backward stepwise regression with the AIC used as the best-fit criteria. Those chosen terms were then added to the models. Number-of-Moves was the only model in which no interaction term was given any importance. The new polynomial models were then tested and compared to their linear counterparts. They performed as well as the linear models with only a slight improvement in predictive performance for Number-of-Moves per minute. While they do offer better insight into how the human factors interact with each other, they do not offer enough in the way of predictive performance to be used.
6.3.3 Compensator and Interface Design

The first method of compensation was an intuitive redesign of the UCF-MANUS GUI. A heuristic evaluation was initially performed and the first designs for the new GUI were developed. These designs were then subjected to user testing and the GUI was then updated based on the feedback that was received. The main changes that were made to the GUI were the addition of help buttons to each menu as well as the addition of designated abort buttons to the Auto and Hybrid menus. The translational controls were also adjusted to be relative to the end-effector frame as opposed to the base frame of the robot. It was found through later testing that the users were assuming that the translational commands were relative the yaw angle of the end effector as opposed to the yaw, pitch, and roll. The translational commands were then updated to adhere to this new control scheme.

Model based compensators were also developed and tested. Audio and visual feedback were added to help compensate for poor spatial abilities and poor visual abilities while the mouse sensitivity was adjusted to compensate for poor dexterity and the speed was adjusted to compensate for poor reaction time. To test the effectiveness of these compensators, 15 participants were asked to complete tasks first with no compensation, then with compensation, and then again without compensation. It was found that there was no quantitative difference in a user’s performance when the compensators were present. While the compensators did not have any effect on performance, there was a change in user satisfaction.

The audio and visual feedback were found to be useful by those who had a deficit in either spatial ability or visual ability. These were the only compensators tested that showed in increase in satisfaction from those that would need to use it. While the sensitivity adjustment was rated
favorably be the majority of the participants, its rating was due to the comfortable familiarity the participants had with mouse sensitivity from other activities, such as video games. The speed adjustment was met with mixed opinions and its ratings were more due to personal preference as opposed to actual need.

6.4 Scope of Future Research

The research presented in this dissertation has laid the groundwork for further development in the usability of the UCF-MANUS system. Several factors have been determined and will utilized for developing improved modeling as well as compensation. Future research for the further improvement of the UCF-MANUS system will include:

- The development of an inverse model based on the important human factors as well as the parameterization of the desired behavior of the robot for the given task.

- Improvement and redesign of the GUI interface for a tablet device.

- Improvement of the compensators derived from new sensory inputs into the system.
APPENDIX A: GLOBAL SENSITIVITY ANALYSIS AND STATISTICAL DATA
The analysis presented in this section come from the methods used in [A1] and [A2]. The main methods used were the correlation coefficients, both Pearson and rank as well as partial. Correlation data for the general population as well as for the separate age and gender groups presented in Chapter III are also present.

**Table A-1 Correlation and Sensitivity of Human Factors for Performance Metrics for ToT**

<table>
<thead>
<tr>
<th>Human Factor</th>
<th>Pearson</th>
<th>Spearman</th>
<th>Kendall</th>
<th>Partial</th>
<th>Partial Rank</th>
<th>Sp</th>
<th>SpA</th>
<th>SpB</th>
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</thead>
<tbody>
<tr>
<td>Reaction Time</td>
<td>0.48</td>
<td>0.51</td>
<td>0.36</td>
<td>0.34</td>
<td>0.34</td>
<td>0.28</td>
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<td>-0.39</td>
<td>-0.28</td>
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<td>-0.08</td>
<td>0.18</td>
<td>0.22</td>
<td>-0.04</td>
</tr>
<tr>
<td>Visual Perception</td>
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<td>-0.16</td>
<td>-0.12</td>
<td>0.09</td>
<td>0.20</td>
<td>-0.01</td>
<td>0.09</td>
<td>-0.10</td>
</tr>
<tr>
<td>Working Memory</td>
<td>-0.24</td>
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<td>-0.17</td>
<td>-0.00</td>
<td>0.08</td>
<td>0.09</td>
<td>0.08</td>
<td>0.00</td>
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<tr>
<td>Gross Dexterity</td>
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<td>-0.17</td>
<td>-0.11</td>
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<td>0.14</td>
<td>0.02</td>
<td>0.07</td>
<td>-0.05</td>
</tr>
<tr>
<td>Fine Dexterity</td>
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<td>-0.36</td>
<td>-0.25</td>
<td>-0.21</td>
<td>-0.28</td>
<td>0.08</td>
<td>0.11</td>
<td>-0.04</td>
</tr>
<tr>
<td>Weakest Vision</td>
<td>-0.12</td>
<td>-0.23</td>
<td>-0.17</td>
<td>0.13</td>
<td>0.01</td>
<td>0.04</td>
<td>0.08</td>
<td>-0.04</td>
</tr>
<tr>
<td>Strongest Vision</td>
<td>-0.18</td>
<td>-0.29</td>
<td>-0.21</td>
<td>-0.17</td>
<td>-0.16</td>
<td>0.12</td>
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<td>-0.13</td>
</tr>
<tr>
<td>Depth Perception</td>
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<td>0.07</td>
<td>0.05</td>
<td>-0.04</td>
<td>-0.14</td>
<td>0.02</td>
<td>0.12</td>
<td>-0.10</td>
</tr>
</tbody>
</table>

**Table A-2 Correlation of Human Factors to Performance Metrics for NoM**

<table>
<thead>
<tr>
<th>Human Factor</th>
<th>Pearson</th>
<th>Spearman</th>
<th>Kendall</th>
<th>Partial</th>
<th>Partial Rank</th>
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<tbody>
<tr>
<td>Reaction Time</td>
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<td>0.21</td>
<td>0.15</td>
<td>0.16</td>
<td>0.12</td>
</tr>
<tr>
<td>Spatial Orientation</td>
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<td>-0.13</td>
<td>-0.10</td>
<td>0.02</td>
<td>-0.05</td>
</tr>
<tr>
<td>Spatial Visualization</td>
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<td>-0.15</td>
<td>-0.21</td>
<td>-0.19</td>
</tr>
<tr>
<td>Visual Perception</td>
<td>-0.22</td>
<td>-0.07</td>
<td>-0.05</td>
<td>0.02</td>
<td>0.08</td>
</tr>
<tr>
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<td>0.03</td>
<td>0.03</td>
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<td>-0.05</td>
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Table A-3 Correlation of Human Factors to Performance Metrics for NoM/min

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<td>0.02</td>
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<td>-0.09</td>
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<tr>
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<td>0.23</td>
<td>0.17</td>
<td>0.24</td>
<td>0.16</td>
</tr>
<tr>
<td>Gross Dexterity</td>
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<td>0.09</td>
<td>0.07</td>
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<td>-0.09</td>
</tr>
<tr>
<td>Fine Dexterity</td>
<td>0.17</td>
<td>0.23</td>
<td>0.16</td>
<td>0.11</td>
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<td>Weakest Vision</td>
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<td>Depth Perception</td>
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Table A-4 Correlation Matrix for Human Factors

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<th>V</th>
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<td>0.16</td>
</tr>
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<td>0.56</td>
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<td>0.30</td>
<td>0.09</td>
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<td>-0.35</td>
</tr>
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<td>1.00</td>
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<td>-0.13</td>
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<tr>
<td>Weakest Vision</td>
<td>-0.36</td>
<td>0.09</td>
<td>0.04</td>
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<tr>
<td>Strongest Vision</td>
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<tr>
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<td>-0.29</td>
<td>-0.07</td>
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</tbody>
</table>

Table A-5 Correlation of Human Factors to Performance Metrics for Males

<table>
<thead>
<tr>
<th>Human Factor</th>
<th>Time-on-Task</th>
<th>Number-of-Moves</th>
<th>Number-of-Moves per minute</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reaction Time</td>
<td>0.50</td>
<td>0.22</td>
<td>-0.23</td>
</tr>
<tr>
<td>Spatial Orientation</td>
<td>-0.47</td>
<td>-0.21</td>
<td>0.25</td>
</tr>
<tr>
<td>Spatial Visualization</td>
<td>-0.48</td>
<td>-0.26</td>
<td>0.19</td>
</tr>
<tr>
<td>Visual Perception</td>
<td>-0.30</td>
<td>-0.08</td>
<td>0.20</td>
</tr>
<tr>
<td>Working Memory</td>
<td>-0.38</td>
<td>-0.09</td>
<td>0.34</td>
</tr>
<tr>
<td>Gross Dexterity</td>
<td>-0.23</td>
<td>-0.07</td>
<td>0.12</td>
</tr>
<tr>
<td>Fine Dexterity</td>
<td>-0.41</td>
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<td>0.16</td>
</tr>
<tr>
<td>Weakest Vision</td>
<td>0.07</td>
<td>-0.13</td>
<td>-0.28</td>
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<td>Strongest Vision</td>
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<td>0.03</td>
<td>-0.14</td>
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### Table A-6 Correlation of Human Factors to Performance for Females

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<th>Human Factor</th>
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<th>Number-of-Moves</th>
<th>Number-of-Moves per minute</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reaction Time</td>
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<td>-0.29</td>
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<td>0.03</td>
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<td>-0.22</td>
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<td>Visual Perception</td>
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<td>-0.20</td>
</tr>
<tr>
<td>Working Memory</td>
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<td>-0.04</td>
<td>0.21</td>
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<td>0.27</td>
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<td>-0.14</td>
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<tr>
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### Table A-7 Correlation Matrix for Male Human Factors

<table>
<thead>
<tr>
<th>Human Factor</th>
<th>RT</th>
<th>SO</th>
<th>V</th>
<th>VP</th>
<th>WM</th>
<th>GD</th>
<th>FD</th>
<th>WV</th>
<th>SV</th>
<th>DP</th>
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</thead>
<tbody>
<tr>
<td>Reaction Time</td>
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<td>-0.61</td>
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<td>0.16</td>
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<td>0.74</td>
<td>0.57</td>
<td>0.56</td>
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<td>0.39</td>
<td>0.09</td>
<td>0.03</td>
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<tr>
<td>Visual Perception</td>
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<td>0.43</td>
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<tr>
<td>Working Memory</td>
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<td>1.00</td>
<td>0.25</td>
<td>0.39</td>
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<tr>
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<td>-0.30</td>
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<tr>
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<tr>
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<td>0.11</td>
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<td>0.05</td>
<td>0.74</td>
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<tr>
<td>Depth Perception</td>
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<td>-0.34</td>
<td>-0.17</td>
<td>-0.21</td>
<td>-0.19</td>
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### Table A-8 Correlation Matrix for Female Human Factors

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<th>Human Factor</th>
<th>RT</th>
<th>SO</th>
<th>V</th>
<th>VP</th>
<th>WM</th>
<th>GD</th>
<th>FD</th>
<th>WV</th>
<th>SV</th>
<th>DP</th>
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</thead>
<tbody>
<tr>
<td>Reaction Time</td>
<td>1.00</td>
<td>-0.34</td>
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<td>-0.19</td>
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</tr>
<tr>
<td>Spatial Orientation</td>
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<td>0.56</td>
<td>0.09</td>
<td>0.33</td>
<td>0.26</td>
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</tr>
<tr>
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<td>-0.02</td>
<td>-0.04</td>
<td>-0.14</td>
</tr>
<tr>
<td>Visual Perception</td>
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<td>0.56</td>
<td>0.57</td>
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<td>0.08</td>
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<td>0.31</td>
<td>0.19</td>
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<td>-0.19</td>
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<tr>
<td>Working Memory</td>
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<td>0.13</td>
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<td>0.00</td>
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</tr>
<tr>
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</tr>
<tr>
<td>Fine Dexterity</td>
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<td>-0.17</td>
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APPENDIX B: SURVEYS
1. Was the audio feedback helpful?

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<th>Extremely Not Helpful</th>
<th>Very Not Helpful</th>
<th>Slightly Not Helpful</th>
<th>Benign</th>
<th>Slightly Helpful</th>
<th>Very Helpful</th>
<th>Extremely Helpful</th>
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</thead>
<tbody>
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<td>7</td>
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</tbody>
</table>

Why do you think this?
_____________________________________________________________________________________
_____________________________________________________________________________________
_____________________________________________________________________________________
_____________________________________________________________________________________

2. Was the highlighting of the object on screen helpful?

<table>
<thead>
<tr>
<th>Extremely Not Helpful</th>
<th>Very Not Helpful</th>
<th>Slightly Not Helpful</th>
<th>Benign</th>
<th>Slightly Helpful</th>
<th>Very Helpful</th>
<th>Extremely Helpful</th>
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</thead>
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<td>3</td>
<td>4</td>
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<td>7</td>
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</tbody>
</table>

Why do you think this?
_____________________________________________________________________________________
_____________________________________________________________________________________
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_____________________________________________________________________________________

3. Was the change in mouse sensitivity helpful?

<table>
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<tr>
<th>Extremely Not Helpful</th>
<th>Very Not Helpful</th>
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<th>Benign</th>
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<tbody>
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<td>3</td>
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<td>7</td>
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</tbody>
</table>

Why do you think this?
_____________________________________________________________________________________
_____________________________________________________________________________________
_____________________________________________________________________________________
_____________________________________________________________________________________
4. Was the change in speed helpful?

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<th>6</th>
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<tr>
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<td></td>
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<td></td>
<td></td>
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</tr>
<tr>
<td>Very Not Helpful</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slightly Not Helpful</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Benign</td>
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<tr>
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<td></td>
</tr>
</tbody>
</table>

Why do you think this?

_____________________________________________________________________________________
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5. Was there anything confusing about the interface?

_____________________________________________________________________________________
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6. What do you think can be done to improve the system?

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APPENDIX C: IRB APPROVAL LETTERS FOR STUDIES
Approval of Human Research

From: UCF Institutional Review Board #1
FWA00006381, IRB00001138

To: Nicholas Paperno

Date: March 19, 2015

Dear Researcher:

On 3/19/2015, the IRB approved the following human participant research until 03/18/2016 inclusive:

Type of Review: IRB Continuing Review Application Form
Project Title: Evaluation of Human Factors Using Global Sensitivity Analysis to Determine which Have a Greater Impact on Performance when Operating a Robotic Manipulator
Investigator: Nicholas Paperno
IRB Number: SBE-14-10250
Funding Agency: National Institute on Disability and Rehabilitation Research (NIDRR)
Grant Title: N/A
Research ID: N/A

The scientific merit of the research was considered during the IRB review. The Continuing Review Application must be submitted 30 days prior to the expiration date for studies that were previously expedited, and 60 days prior to the expiration date for research that was previously reviewed at a convened meeting. Do not make changes to the study (i.e., protocol, methodology, consent form, personnel, site, etc.) before obtaining IRB approval. A Modification Form cannot be used to extend the approval period of a study. All forms may be completed and submitted online at https://iris.research.ucf.edu.

If continuing review approval is not granted before the expiration date of 03/18/2016, approval of this research expires on that date. When you have completed your research, please submit a Study Closure request in IRIS so that IRB records will be accurate.

Use of the approved, stamped consent document(s) is required. The new form supersedes all previous versions, which are now invalid for further use. Only approved investigators (or other approved key study personnel) may solicit consent for research participation. Participants and their representatives must receive a copy of the consent form(s).

All data, including signed consent forms if applicable, must be retained and secured per protocol for a minimum of five years (six if HIPAA applies) past the completion of this research. Any links to the identification of participants should be maintained and secured per protocol. Additional requirements may be imposed by your funding agency, your department, or other entities. Access to data is limited to authorized individuals listed as key study personnel.

In the conduct of this research, you are responsible to follow the requirements of the Investigator Manual.

On behalf of Sophie Dziegielewski, Ph.D., L.C.S.W., UCF IRB Chair, this letter is signed by:

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Approval of Human Research

From: UCF Institutional Review Board
FWA0000351, IRB00001138

To: Nicholas Paperno and Co-PI: Tracy Sanders

Date: March 18, 2015

Dear Researcher:

On 3/18/2015, the IRB approved the following human participant research until 03/17/2016 inclusive:

Type of Review: UCF Initial Review Submission Form
Project Title: Evaluation of UCF MANUS Interface Design
Investigator: Nicholas Paperno
IRB Number: SBE-15-11114
Funding Agency: Grant Title: Research ID: N/A

The scientific merit of the research was considered during the IRB review. The Continuing Review Application must be submitted 30 days prior to the expiration date for studies that were previously expedited, and 60 days prior to the expiration date for research that was previously reviewed at a convened meeting. Do not make changes to the study (i.e., protocol, methodology, consent form, personnel, site, etc.) before obtaining IRB approval. A Modification Form cannot be used to extend the approval period of a study. All forms may be completed and submitted online at https://iris.research.ucf.edu.

If continuing review approval is not granted before the expiration date of 03/17/2016, approval of this research expires on that date. When you have completed your research, please submit a Study Closure request in IRIS so that IRB records will be accurate.

Use of the approved, stamped consent document(s) is required. The new form supersedes all previous versions, which are now invalid for further use. Only approved investigators (or other approved key study personnel) may solicit consent for research participation. Participants or their representatives must receive a copy of the consent form(s).

All data, including signed consent forms if applicable, must be retained and secured per protocol for a minimum of five years (six if HIPAA applies) past the completion of this research. Any links to the identification of participants should be maintained and secured per protocol. Additional requirements may be imposed by your funding agency, your department, or other entities. Access to data is limited to authorized individuals listed as key study personnel.

In the conduct of this research, you are responsible to follow the requirements of the Investigator Manual.

On behalf of Sophia Dziegielewski, Ph.D., L.C.S.W., UCF IRB Chair, this letter is signed by:

[Signature]

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Approval of Human Research

From: UCF Institutional Review Board #1
FWA00000351, IRB00001133

To: Nicholas Paperno and Co-PIs: Janan A. Smith, Michael A. Rupp

Date: March 16, 2016

Dear Researchers,

On 03/16/2016, the IRB approved the following human participant research until 03/15/2017 inclusive:

- Type of Review: UCF Initial Review Submission Form
- Project Title: Testing of Compensator for Performance using an Assistive Robotic Manipulator
- Investigator: Nicholas Paperno
- IRB Number: SBE-16-12126
- Funding Agency: National Science Foundation
- Grant Title: CHS: SMALL: EMPOWERMENT OF DISABLED INDIVIDUALS VIA AN ADAPTIVE FRAMEWORK FOR INDIRECT HUMAN ROBOT INTERACTION
- Research ID: 1058430

The scientific merit of the research was considered during the IRB review. The Continuing Review Application must be submitted 30 days prior to the expiration date for studies that were previously expedited, and 60 days prior to the expiration date for research that was previously reviewed at a convened meeting. Do not make changes to the study (i.e., protocol, methodology, consent form, personnel, site, etc.) before obtaining IRB approval. A Modification Form cannot be used to extend the approval period of a study. All forms may be completed and submitted online at https://iris.research.ucf.edu.

If continuing review approval is not granted before the expiration date of 03/15/2017, approval of this research expires on that date. When you have completed your research, please submit a Study Closure request in iRIS so that IRB records will be accurate.

Use of the approved, stamped consent document(s) is required. The new form supersedes all previous versions, which are now invalid for further use. Only approved investigators (or other approved key study personnel) may solicit consent for research participation. Participants or their representatives must receive a copy of the consent form(s).

All data, including signed consent forms if applicable, must be retained and secured per protocol for a minimum of five years (six if HIPAA applies) past the completion of this research. Any links to the identification of participants should be maintained and secured per protocol. Additional requirements may be imposed by your funding agency, your department, or other entities. Access to data is limited to authorized individuals listed as key study personnel.

In the conduct of this research, you are responsible to follow the requirements of the Investigator Manual.

On behalf of Sophia Dziubaslawski, Ph.D., L.C.S.W., UCF IRB Chair, this letter is signed by:

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