THE IMPACT OF VISUAL FEEDBACK AND CONTROL CONFIGURATIONS ON PILOT-AIRCRAFT INTERFACES USING HEAD TRACKING TECHNOLOGY

THESIS

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Abstract

Advances in human interface technology are required to improve pilot effectiveness in 5th generation fighters. Traditional control mechanisms provide a significant bottleneck to human input on the large displays in these aircraft. This research explored methods for enhancing pilot interaction with large, information dense, cockpit displays. Specifically, this research explored the effects of visual feedback and control button configuration when augmenting cursor control with head tracking technology. Previous studies demonstrated that head tracking can be combined with traditional cursor control to decrease selection times but can increase pilot mental and physical workload. Literature search and brainstorming produced alternate control and feedback configurations which may reduce these limitations. A human subject experiment was performed to evaluate two control button configurations and three visual feedback conditions to explore these alternatives. A Fitts' Law analysis was performed to create predictive models of selection time using each configuration. The models provided a poor fit to the observed data, indicating that Fitts' Law does not adequately describe human performance for these systems. A repeated measures analysis of variance revealed that there was no difference in performance between the two control configurations. Conditions without visual feedback were less accurate and slower than those with feedback. However, all configurations employing head tracking were faster than the current cursor control system and the results support the concept that conditions without visual feedback may impose lower physical workload than the other configurations.

Recommendations for future research and enhanced head tracking cursor control systems are discussed.

Acknowledgments

I would like to express my sincere appreciation to my faculty advisor, Dr. Michael Miller, for his continuous guidance throughout this process. Your feedback and insights helped me more than I can express. Thank you for lending your time and expertise to help me become a better researcher.

Thank you to my wife for your support and belief over the last 18 months. I hope I can continue to make you proud.

Christopher M. Arnold

Table of Contents

List of Figures

Page

List of Tables

THE IMPACT OF VISUAL FEEDBACK AND CONTROL CONFIGURATIONS ON PILOT-AIRCRAFT INTERFACES USING HEAD TRACKING TECHNOLOGY

I. Introduction

General Issue

Advances in sensor capabilities and the implementation of sensor fusion has drastically increased the amount of data available to display to pilots in the cockpit. While this data has the potential to improve the pilot's situation awareness and increase the speed and quality of decisions on the battlefield as targeted in the Air Force Science and Technology 2030 strategy (United States of America Department of the Air Force, 2019) , this vision will only be attained if the user interface permits this information to be readily perceived and acted upon.

Two methods for enhancing information display are to increase the display resolution, which increases the information density by making icons or other information smaller, or by increasing the size of the display. The resolution of the display is limited by the resolution of human vision in this dynamic environment where vibration, turbulence and other factors can significantly limit this resolution. The size of the display is restricted by the physical space limitation of the cockpit and the pilot's ability to rapidly select objects on the display using cursor controls on the throttle and stick. Thus, the use of larger displays can increase interaction time, counter to the objective of decreasing the time required for effective decision making.

It is well known that for a given input device, the time required for a user to select an object increases as the size of the object decreases and the distance required for cursor movement increases. This relationship, known as Fitts' Law, limits the speed of interaction for most input devices, particularly when the distance of cursor movement is proportional to the amount of time a cursor control is pressed or the distance that a cursor control device must be moved (MacKenzie, 1992). Input devices have not evolved to maintain rapid object selection as the size of displays have increased. A potential way to avoid the limits imposed by Fitts' Law is to adopt multiple input devices, where one input device provides rapid, although inaccurate movement when large movements in cursor control are required while the second, like the cursor slew switch on current aircraft controls, provides accurate but slower movement once the cursor is near its final target.

In the F-35, the primary display is nearly twice as tall and five times as wide as the displays in fourth generation aircraft. However, the cursor slew switch is the primary cursor control in all aircraft. Knowing that the increase in display size would increase selection time, the F-35 adopted a touchscreen as a potential alternative to the cursor slew switch. However, the touchscreen comes with additional drawbacks, such as requiring the pilot to remove their hands from the flight controls and diminished touch accuracy while the pilot is maneuvering or experiencing turbulence.

In addition to these cursor control devices, fighter aircraft have employed head tracking as part of the cueing system for decades. In these systems head tracking permits off boresight targeting, enhancing the lethality of these aircraft. Additionally, head tracking is used in the civilian sector for control of virtual reality displays and to aid physically disabled individuals in using computers. Thus, there may be an opportunity to pair head tracking with the traditional cursor control to improve the pilot's ability to select objects quickly and accurately on large heads down displays within the cockpit.

Problem Statement

In a recent experiment, head tracking was paired with the cursor slew switch within an aircraft cockpit and was shown to improve the speed of selection while maintaining accuracy (Harp et al., 2020). However, feedback from the test participants indicated that this new input method introduced increased physical and mental loads, resulting in undesirable levels of fatigue. Based on this feedback it was thought that the constantly visible cursor feedback for the head position was driving the participants to refine the cursor position as the pilots attempted to use precise head positioning when selecting targets rather than using the head movement only for large cursor movements and the cursor slew switch for fine tuning and final target selection. The researchers hypothesized that precise head positioning over an extended period of time drove increases in muscle and mental fatigue. Fatigue was also reported when the participants were required to repeatedly move their head from one edge of the display to the other. This fatigue likely results from the fact that users typically pair head and eye movements when shifting their gaze over large angles and therefore this system requires larger head movements than would occur naturally. The increased mental workload was hypothesized to come from the combination of the unconscious cursor refinement from the visual feedback and the decision to have the control mechanisms split across both hands, rather than activated with a single hand. Thus, there is a need to explore alternate implementations of the pairing between these devices which can provide the speed advantages observed in this experiment without the enhanced physical and mental fatigue.

Research Focus

This research focused on finding methods to reduce the physical and mental load induced by the combination of head tracking and traditional cursor slew systems. Specifically, this research studied the effects of visual cursor feedback on physical and mental workload. In addition, the effect of control layout on mental workload was studied.

Research Objectives/Questions/Hypotheses

This thesis attempts to address the hypotheses listed below:

1. Removing the visual feedback of the cursor during head movement will prevent the pilot from attempting to precisely position the cursor using head movements.
2. Removing the visual feedback of the head tracking cursor will have a negative effect on the accuracy of the cursor snap, which occurred in the previous research as the cursor is moved based upon current head orientation.
3. Using the cursor slew switch to relocate the display cursor, rather than a separate snap activation button, will decrease the perceived cognitive workload.
4. Visual feedback and control method will have a significant effect on selection time.

Methodology

Alternative control implementations were developed based on suggestions from previous experiments and additional analysis of existing data. Human subject tests were designed and performed to test the effects of visual feedback and control layout on selection time and physical and mental workload.

Assumptions/Limitations

The following assumptions and limitations apply to the current research:

1. This study is limited to lab experiments, and therefore are unable to measure the effects of g-forces or turbulence. It is assumed that g-forces or turbulence might negatively affect the accuracy of the pilot's performance using the head tracking system, but would not affect the traditional cursor slew switch system.
2. This study employed Air Force Institute of Technology (AFIT) students rather than operational pilots as participants. Therefore, it is assumed that the results of this research are generalizable and applicable to predict the effects of these interface changes for experienced pilots.
3. This study did not employ primary flight tasks along with the selection task. Therefore, it is assumed that the trials did not approach the participants maximum mental workload and that higher workload may change the way participants use the interface.

Implications

This study has potential impacts to the decision making and action cycle of fifth generation fighter pilots. As improved sensors and sensor fusion provide increased amounts of data to the pilots and the displays grow to present this data, more effective communication between the pilot and the aircraft is needed. One solution that achieves this is a more efficient method of navigating the display. This research analyzed the effects of visual feedback and control layouts on selection times and pilot workload. These impacts are important to the design and function of any future pilot-aircraft interface.

Preview

The first chapter covered the purpose, objectives, methods, limitations, and implications of this research. Chapter two is a review of literature relevant to human-computer interfaces and head tracking technology used for computer interfaces. Chapter three outlines the experimental design and data collection used for this research. Chapter four discusses the results from the data analysis. Finally, Chapter five, summarizes the meaning of the data analysis findings and suggests areas for future research.

II. Literature Review

Chapter Overview

This chapter provides the theoretical framework for the current research through a review of the relevant literature. The chapter begins by examining seven studies that sought to improve traditional cursor control. The first two are in the computer and virtual/augmented reality domain, while the following five are in the aviation domain. Next, the chapter discusses selection mechanisms used in gaze tracking systems. The chapter concludes with a brief discussion of the use of Fitts' Law to evaluate human-computer interfaces.

Alternative Cursor Control Methods

Outside of the aircraft cockpit, cursor control research using head or eye tracking primarily falls into two categories, helping users with disabilities use computers and improving the control of virtual or augmented reality systems. Sancheti et al. sought to find an inexpensive hands-free cursor control method to aid computer users with disabilities. The system used an accelerometer to measure head tilt to control cursor vertical position and a magnetometer to measure head rotation to control horizontal cursor position (Sancheti et al., 2019). Flex sensors were fixed to the users' cheeks to control the clicking action (Sancheti et al., 2019). Like the Harp et al study referenced in Chapter 1, the cursor was displayed continuously, and head motion was used to control the exact location of the cursor. The results of the study showed that the head tracking system was slower than a traditional optical mouse but was feasible as an adaptive technology for users unable to operate a mouse (Sancheti et al., 2019).

With the growing popularity of virtual and augmented reality systems, Qian and Teather performed a study to compare target selection performance using gaze tracking, head tracking, and both in combination. Gaze tracking only was found to be the slowest and least accurate, while head tracking was the fastest and most accurate (Qian & Teather, 2017). While the combined gaze and head tracking provided improvements over pure gaze tracking, its performance fell short of pure head tracking. In post experiment interviews it was revealed that some subjects experienced nausea when using the combined method, and many of the subjects experienced neck fatigue while using both the combined and head only methods.

As early as 1988, studies have been performed on the use of head tracking and other technologies within the cockpit to reduce pilot workloads. At that time, head tracking could be used for target designation, but Smyth and Dominessy sought to determine if the same technology could be used to interact with displays in a helicopter. Both head and gaze tracking were tested, along with a touchscreen. The study found that head tracking was faster than the gaze tracking implementations, but that the touchscreen was faster than both (Smyth & Dominessy, 1988). Additionally, the touchscreen interaction performance was twice as accurate as either head or gaze tracking methods (Smyth & Dominessy, 1988). It should be noted that this experiment was performed in a lab setting where the users were not subject to the effects of vibration or turbulence and may have been more willing to remove their hands from the flight controls than if they were in an aircraft.

Another study examined the use of touchscreens in commercial aviation to reduce flight crew workload during critical phases of flight (Rouwhorst et al., 2017). A touch screen interface was developed to change the speed, heading, altitude, flight level, and vertical speed of the aircraft and to aid the crew in handling a runway or airport change late in the landing phase (Rouwhorst et al., 2017). The findings from the study showed that the design of the interface was extremely important in determining how much the crew workload was affected (Rouwhorst et al., 2017). The team redesigned the interface between iterations of the test based on pilot feedback, ultimately the researchers determined that the touchscreen did not reduce workload when changing flight characteristics and the touchscreen input was prone to errors during turbulence. (Rouwhorst et al., 2017).

Two studies were performed to determine the performance of gaze tracking in controlling fighter aircraft multifunction displays. The first used subjects in a flight simulator who were directed to maintain altitude and heading while performing selection tasks on a heads down display (Rajesh & Biswas, 2018). The results showed that the mean selection time was approximately 0.5 second faster using the gaze tracking system than when using the traditional joystick selection. However the accuracy when using the gaze tracking system was half that of the joystick method (Rajesh & Biswas, 2018). The second study consisted of two parts of interest. Part one was a study of the accuracy of the gaze tracking system under various G-loads (Murthy et al., 2020). The team found that their gaze tracking system can track eye gaze within four degrees of visual angle up to three G’s, but accuracy was reduced to 9.5 degrees at 5 G’s (Murthy et al., 2020). Part two was a study that compared a combined head and gaze tracking system with traditional joystick selection (Murthy et al., 2020). The results showed that the head and gaze tracking system had an average selection time that was 1.5 seconds faster than the joystick for targets between two and three degrees of visual angle. However, the head and gaze tracking system was not compared to head or gaze tracking alone as in Qian & Teather, 2017.

The final study addressed the slow selection time on large displays by testing three alternative control mechanisms in flight test. When determining the alternatives, the team proposed that any new control method should meet four characteristics (Harp et al., 2020), including; 1) prioritizing hands on throttle and stick; 2) enabling rapid relocation of a cursor from one side of a large-format display to another; 3) allowing precise and accurate manipulation of densely-spaced data or symbols; and 4) imposing minimal cognitive and physical workload for use.

The traditional cursor slew switch met three of these four criteria, lacking the ability to provide rapid cursor relocation (Harp et al., 2020). Because of this, the new control methods were devised to supplement the cursor slew switch rather than replacing it as in previous implementations (Harp et al., 2020). In this research, both the head tracking and gaze tracking methods used a secondary cursor which was rapidly moved across the display based on the head or gaze tracking input data, then the pilot used an actuation on the flight controls to instantly move, i.e., snap, the traditional display-fixed cursor to the location of the secondary cursor (Harp et al., 2020). It is worth noting that this scheme of providing primary and secondary cursors provided the user with precise control to switch from the head or eye tracked mode to the cursor control mode. However, this control came at the cost of imposing an additional task in the middle of the well-learned motor control task that is typically used for cursor control. The study showed that gaze tracking was unreliable due to calibration drift and g-forces (Harp et al., 2020). When the calibration was accurate, gaze tracking was fast and the pilots enjoyed using it (Harp et al., 2020). But most of the time the pilots felt it was unusable due to inaccurate calibration (Harp et al., 2020). Head tracking was found to be faster than the traditional control method and just as accurate (Harp et al., 2020). However, the pilots noted that this accuracy came at the cost of increased mental and physical workload (Harp et al., 2020). Several pilots reported neck fatigue, presumably from the fine head control required to achieve the necessary accuracy (Harp et al., 2020). The researchers suggested that the added workload was caused by the pilots' desire to "direct designate" the target (Harp et al., 2020). Because the head tracking cursor was visible, the pilots would expend extra time and energy to achieve higher levels of precision than necessary, rather than switching to the cursor slew switch once the cursor was close (Harp et al., 2020). This behavior was observed despite the fact that the participants were instructed to use the combination of the head tracker and cursor slew switch. Instead, the pilots sought to position the head tracking cursor so that when the screen cursor was moved, the pilot could immediately select the target without cursor refinement with the cursor slew switch (Harp et al., 2020). The data showed that the pilots would often position the cursor close enough for designation within 0.8 seconds, but then refine cursor position through precise head movements for an additional two seconds before snapping the screen cursor (Harp et al., 2020). The team suggested that removing the cursor visual feedback might prevent the pilots from using head motion for excessive fine motor control and reduce physical fatigue (Harp et al., 2020).

Selection Mechanisms

The study by Hansen et al. compared cursor control using a mouse with cursor control using head and gaze tracking (Hansen et al., 2018). All three control methods were tested using both a button press selection and a 300 millisecond dwell time selection (Hansen et al., 2018). The study showed that the mouse was the fastest method, and that head and gaze tracking were equally fast, however gaze tracking was less accurate (Hansen et al., 2018). The dwell time selection was faster than the click selection for all control methods (Hansen et al., 2018). As expected from the discussion of Harp et al., feedback from the users indicated that the physical workload for gaze tracking was lower than for head tracking (Hansen et al., 2018). Esteves et al. compiled and compared methods of selection from several virtual and augmented reality headsets such as: tapping the headset, gestures using optical or wearable sensors, dwell time selection, handheld controllers, and voice control (Esteves et al., 2020). The handheld controllers and on-device button presses were found to provide the fastest selection methods, followed by dwell time selection, then gesture, and speech (Esteves et al., 2020). The dwell and speech mechanisms had the lowest error rate, followed by gesture, clicker, and on-device tapping (Esteves et al., 2020). The majority of users rated either the handheld controller or dwell mechanism as their preferred method, citing them as the fastest, easiest, most familiar (handheld), most comfortable, most accurate, and most satisfying (dwell) (Esteves et al., 2020). The on-device tapping, hand gestures, and voice control mechanisms were all found to be ill-suited to the aviation environment. The first two require the pilot to remove their hand(s) from the flight controls and voice control is error prone in a loud environment. The handheld controller is analogous to the button press on the flight controls in the Harp et al. study. Dwell time selection is a possibility but could be prone to error due to turbulence or flight maneuvers. During this study, cursor visual feedback was used, the potential effects of which were discussed in Harp et al., 2020.

Fitts' Law for Human-Computer Interaction

Fitts' Law is the application of information theory to human performance modeling, specifically to model movement times (MacKenzie, 1992). Using Fitts' Law, movement time for a task is predicted using a linear equation that is a function of the index of difficulty (ID) of the task (MacKenzie, 1992). The ID is a function of the distance of the movement and the width of the target where the movement terminates (MacKenzie, 1992). The index of difficulty was originally defined according to Equation 1.

$$\boldsymbol{ID = \log_2(\frac{2A}{W})} \qquad (1)$$

Where *A* is the *movement distance* and *W* is the *width of the target* (MacKenzie, 1992). Over time, several corrections to the calculation of the index of difficulty have been proposed. The most prominent correction is the Shannon Formulation shown in Equation 2 (MacKenzie, 1992).

$$\boldsymbol{ID = \log_2(\frac{A}{W} + 1)} \qquad (2)$$

The Shannon Formulation was created in part because of the increased use of Fitts' Law in two dimensions as the original method would provide a negative ID in some combinations of movement distance and target width (MacKenzie, 1992). Another challenge of two-dimensional tests was determining the target width. One dimensional

Fitts’ Law tests typically used rectangles or squares as the target, but in two dimensional tests the width of these targets vary based on the approach angle. Two solutions to this issue were found, calculate the apparent width of the target object based on the approach angle or use circular targets because they have the same width from every angle (MacKenzie, 1992). Another correction that has been used is to use normalized models that have a known and consistent error rate (MacKenzie, 1992). This is accomplished by calculating an “effective” target width based on the observed distribution of hits (MacKenzie, 1992). One other relevant modification to Fitts’ Law is to break complex movements or tasks into multiple phases and to create a prediction model for each phase to determine the total movement time (Deng et al., 2019). Deng et al. applied this concept to predict time to position an object in a virtual 3D environment (Deng et al., 2019). The complex motion was separated into three phases acceleration, deceleration, and correction (Deng et al., 2019). Each phase was analyzed separately to determine the driving factors and correct model to use (Deng et al., 2019).

Summary

Head tracking technology has been used throughout the years as an accessibility aid for disabled persons to use computers or more recently as control methods for virtual and augmented reality. Head tracking was also used to enable off boresight targeting in aircraft but has not been utilized as a pilot-computer interface. Harp et. al recognized the need to improve this interface and demonstrated that head tracking can provide the accuracy and speed required to reduce selection times on large displays. However, the decreased selection time came at the cost of increased mental and physical workload for the pilot. This research examines alternative head tracking implementations and the effects on selection speed, accuracy, and pilot workload.

III. Methodology

Chapter Overview

This chapter contains descriptions of the equipment, interface and data collection methods used for the experiment and outlines the data analysis procedure. For this research, an experiment was designed to measure the effects of cursor control methods augmented by head tracking technology. Then, the experiment was conducted using human participants and the results were analyzed to address the hypotheses.

Experimental Design

The experiment performed was a target selection task using seven cursor control conditions. For six of the conditions, two cursors were present. The primary display cursor was controlled using the cursor slew switch on the throttle and was represented as a crosshair icon. The head tracking cursor was controlled using the Polhemus head tracking system and represented as a small circle icon. The display cursor icon was chosen to be representative of the icon currently used, the icon for the head tracking cursor was chosen to be distinctly different and easily distinguishable from the display cursor icon. Both cursors are shown in Figure 1.

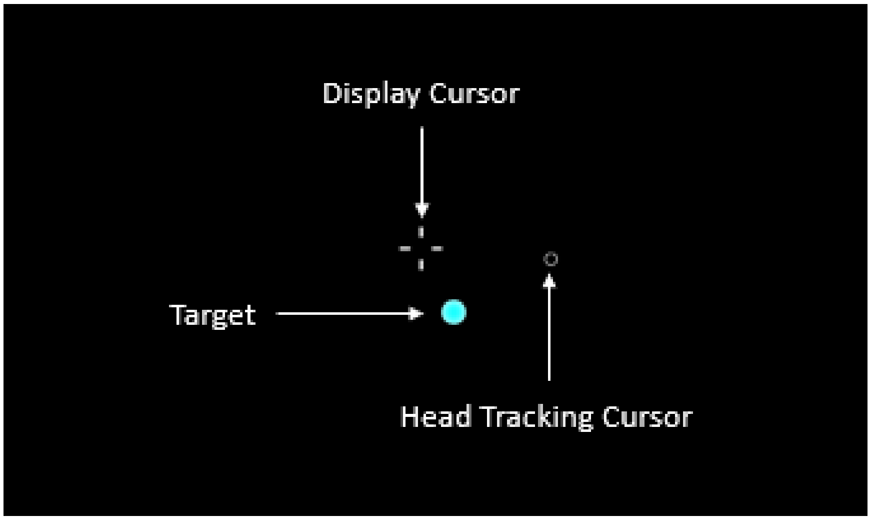


Figure 1--Experiment Interface with Dual Cursors and Target

As in the Harp experiments, the head tracking cursor could not be used to directly select the target. The head tracking cursor was only used to rapidly navigate across the display. To select a target, a participant had to first initiate the cursor snap to move the primary cursor to the location of the head tracking cursor, then press the target selection button. The experiment used two control layouts to activate the cursor snap and three levels of visual feedback for the head tracking cursor. These variables were used to create a within participants, full factorial experimental design, and are discussed in the next section. Additionally, participants completed the task using the cursor control switch only to provide a performance benchmark.

Independent Variables

The first independent variable was the method of activating the cursor snap and had two levels. The first method initiated the cursor "snap" by pressing the cursor slew switch in the z-axis direction. Both cursors were constantly visible throughout the trial. After using the head tracker to move the head tracking cursor near the target, the participant pressed the cursor slew switch in the z-axis direction, causing the display cursor to immediately move to the location of the head tracking cursor. Then the participant would use the cursor slew switch to refine the cursor aim by applying input in the x- and y- axis. The second method initiated the cursor "snap" when input was applied to the cursor slew switch in the x- or y- axis. In this case, the display cursor was not shown while the head tracking was active. When the participant applied x- or y- axis input to the cursor slew switch, the head tracking was disabled, the display cursor appeared at the location of the head tracking cursor, and the display cursor continued to move in the direction of the input. The participants were able to return to the head tracking mode by pressing a button on the throttle with their left thumb.

The second independent variable was the visual feedback of the head tracking cursor, which had three levels. First, the head tracking cursor was constantly visible throughout the trial. Second, the head tracking cursor was not visible at any point during the trial. Third, the head tracking cursor was displayed while it was in motion but was removed when movement did not exceed five pixels for 0.75 seconds. Table **1** shows a condition matrix of these first two variables. A trial consisted of a single combination of the cursor match activation method and the visual feedback condition. Participants selected 120 targets during each experimental trial.

Table 1-- Experimental Condition Matrix

Cursor Match Activation Method	Head Tracking Cursor Visual Feedback		
	Always Visible	Invisible	Remove after inactivity
Z-axis Press			
X/Y-axis input			
Cursor Slew Switch Only			

The third and fourth independent variables were each varied within each experimental trial. The third independent variable was target size. The targets were circular and had one of four diameters: 40, 60, 80, or 100 pixels. When viewed on the display these diameters ranged from approximately 0.25 inches to 0.61 inches. The visual angle was between 0.42 degrees and 1 degree. The distance between the display and seat position was fixed, however variations in participant posture could lead to minor variations in visual angle. At the viewing distance measured, small variations due to posture were negligible. The dimensions of each target level are shown in Table 2. Each trial consisted of 120 targets split evenly across the four sizes. Fourth was the initial distance between the target and the primary cursor. Each target was displayed at a random position on the screen. The initial distance was measured as the distance between the target and the display cursor at the time of target creation. Once a target was selected, the display cursor did not return to the center of the screen, but remained at the position of the last target selection until moved by the cursor slew switch or cursor “snap”.

Table 2--Dimensions of Targets

Target Size (pixels)	Target Size (inches)	Target Size (visual angle, degrees)
40	0.2458	0.4268
60	0.3688	0.6403
80	0.4917	0.8537
100	0.6146	1.0671

Dependent Variables

The dependent variables included selection time, time to cursor “snap” action, snap accuracy, perceived physical workload, and perceived mental workload. Selection time was defined as the amount of time required to select the target, measured as the difference between the time the target appeared and the time the participant selected the target. Time to cursor “snap” action was defined as the amount of time required to initiate the cursor “snap”, measured as the difference between the time of target appearance and the time of “snap” activation. Snap accuracy was defined and measured as the distance between the display cursor immediately after a “snap” and the center of the target. Perceived physical and mental workload were measured by participant feedback using NASA TLX questionnaires.

Experimental Apparatus

Head tracking was achieved using the Polhemus Fastrak system. The Polhemus Fastrak consisted of the system electronics unit (SEU), transmitter, and receiver. The SEU contains the connectors to allow the transmitter, receiver, and computer to communicate. The transmitter produces a near field, low frequency magnetic field that is sensed by the receiver. The signals sensed by the receiver are used to calculate the receiver's position and orientation relative to the transmitter.

Thrustmaster Warthog HOTAS throttle and stick were used to control the display cursor and initiate actions. The throttle contained the cursor slew switch, controlled by the middle finger of the left hand, and the button to re-activate head tracking for the X/Y-axis mode controlled by the left thumb. The joystick contained the select button activated by the right thumb.

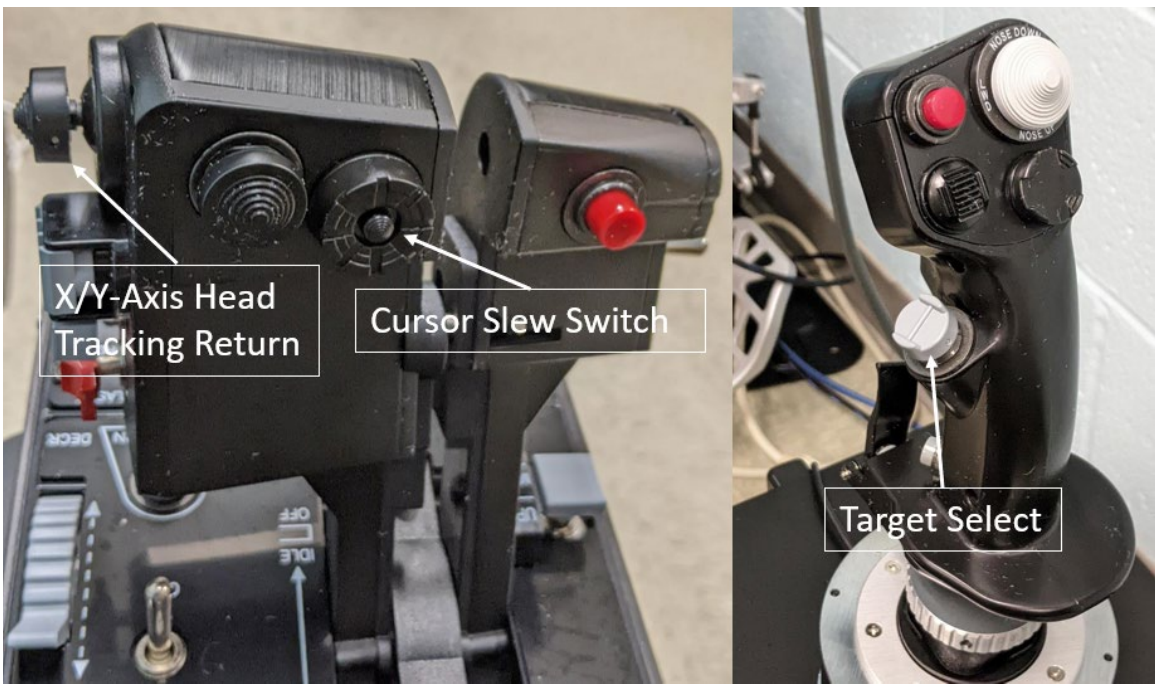


Figure 2--Control Layout of Throttle (left) and Joystick (right)

The display was a 27-inch LED Ultra High Definition screen produced by Tech Global Inc. The model number was EVO275-UHD. This display had a resolution of 3840x2160 pixels, with a pixel size of 0.00615 inches. The visual angle of this display was 22.8 degrees in the vertical direction and 39.4 degrees horizontally.

The interface was designed and programmed using Unity. The interface allows the experimenter to change cursor slew speed, transparency of the head tracking cursor, target size, mapping of the buttons for target select, and cursor “snap” activation. The application uses the experimenter inputs and controls the randomization of target size and location through each trial. The interface was designed to operate in the same way as the interface used by Harp et al (2020). The participants were unable to select a target with the head tracking cursor directly. They were required to use the cursor “snap” to relocate the display cursor before selecting the target. This decision preserves the selection accuracy during maneuvers or turbulence over head tracking direct selection.

Participants

Six participants were recruited from within the Air Force Institute of Technology. All participants were volunteers recruited through email within the Air Force Institute of Technology Department of Systems Engineering and Management. An institutional review board waiver was received with protocol number REN2021017R. Six participants (2 females, 4 males) volunteered to perform the experiment. Participants were all between 21 and 30 years of age and all reported normal or corrected to normal vision. One participant reported near-sighted vision and was wearing corrective lenses. Five participants reported right hand dominance and one left hand dominance. All responses to the participant survey can be found in Appendix C.

Procedure

Each trial consisted of 120 targets to be selected. Each of the target sizes was displayed 30 times for each trial. The participant began each trial by calibrating the head tracking system. This was accomplished by orienting their head toward a target at the center of the screen and pressing the “snap” activation button. Then they followed the same procedure for targets in each of corner of the display beginning at the top right corner and proceeding clockwise. Throughout the trial, the participant was required to locate the target and navigate the primary cursor to the target using the designated mode and press the target selection button. Participants were able to select the target as long as the center of the crosshair icon was within the boundary of the target.

For the cursor slew only mode, the participant was required to use the cursor slew switch to move the primary cursor to the target. Once the cursor was over the target, the target select button was pressed and the next target was displayed.

For the head tracking augmented scenarios, the participant was required to use the head tracking system to move the secondary cursor onto or near the target, then initiate the cursor “snap”. Then the participant used the cursor slew switch to move the primary cursor onto the target if required. Once the participant selected the target, the next target was displayed.

Output Data Analysis

The application recorded control inputs and position of display and head tracking cursors at 60 hertz. The resulting output provided timestamped data for the display of each target, target selection, snap activation, cursor slew switch input, and positions of both cursors. These data were used to calculate the dependent variables, which were then used for a regression analysis and a within-subjects analysis of variance was applied to determine the effects of the independent variables. MATLAB was used to perform the linear regression analysis to find a predictive model for selection time. SPSS was used to perform a repeated measures analysis of variance and Bonferroni pairwise comparisons to determine the differences in selection time, accuracy of cursor snap, and time to initiate cursor snap for each combination of visual feedback and snap method. The results are presented below. Results for the participant surveys are shown in Appendix C.

IV. Analysis and Results

Chapter Overview

This chapter details the analysis and results of the experiment performed in the study. First the results of the Fitts' Law regression analysis will be discussed, followed by the ANOVA analyses for selection time, time to initiate cursor snap, cursor snap accuracy, and NASA TLX survey results.

Time to Select Target

Fitts' Law Model

Fitts' Law was used to perform a linear regression to create a predictive model for the target selection time for each selection condition. The Shannon formulation was used to calculate the index of difficulty. The use of circular targets ensured that the index of difficulty was the same regardless of angle of approach. A two-part model, which included a first part that accounted for head movement and a second part which accounted for cursor control was applied. The generic model used follows Equation 3.

$$Selection\ Time = [a + b * ID_{head}] + [c + d * ID_{slew}] \quad (3)$$

Where ID_{head} was defined as the index of difficulty for the motion controlled by the head tracking system from the time of target appearance to the time of cursor snap initiation and ID_{slew} was defined as the index of difficulty for the component of motion controlled by the cursor slew switch from the time of cursor snap initiation to target selection. The distance used to calculate ID_{head} was defined as the distance between the display cursor at the time of target appearance and the center of the target. The distance used to calculate ID_{slew} was defined as the distance between the display cursor immediately following the cursor snap and the center of the target. In both instances the diameter of the target was used to calculate the index of difficulty. The slew only condition ignored the head motion component of Equation 3 and used the starting distance between the display cursor and center of the target to calculate the ID_{slew}.

Table 3 summarizes the model coefficients and the goodness of fit for each model. Although the model fit for the cursor control only condition was reasonable, the models which include a head tracking component represent a poor fit to the observed data. As such, it would appear that Fitts' Law does not adequately describe human performance when the head tracking systems are applied. Plots of the data and fit line for each condition are provided in Appendix A. A second regression was performed using the distribution of cursor locations following the cursor snap to calculate an effective target size for the head tracking model. The effective target size was determined by finding the circular area containing 95% of all cursor snaps for each selection condition and target size. The 95% circular area was calculated as CEP = 3.92σ, where σ is the standard deviation of the display cursor distance from the center of the target after cursor snap. Table 4 summarizes the effective target size calculated for each condition. This effective target size was then used in the Shannon formulation to calculate an effective index of difficulty. Using the effective index of difficulty did not improve model fit. Table 5 lists the original model coefficients on the left and the coefficients calculated using the effective index of difficulty on the right. The slew portion of the model was unaffected and so was omitted from this table. A final regression analysis was performed after using a linear calculation of the index of difficulty, $ID = \frac{Distance}{Target\ Size}$ rather than the logarithmic calculation. The linear index of difficulty did not increase model fit, as shown in the right side of Table 6.

Table 3--Linear Regression Coefficients

General Model-- $[a + b*ID_{head}] + [c + d*ID_{slew}]$										
	Head Tracking Model-- $a + b*ID_{head}$					Slew Model-- $c + d*ID_{slew}$				
Selection Condition	**a**	**95% CI**	**b**	**95% CI**	**R^2**	**c**	**95% CI**	**d**	**95% CI**	**R^2**
Slew Only						-1.250	(-1.625, -0.8748)	1.237	(1.154, 1.32)	0.473
Z-Axis, Visible	0.865	(0.7405, 0.989)	0.090	(0.06232, 0.1172)	0.042	0.619	(0.5495, 0.6887)	0.569	(0.5063, 0.6318)	0.250
Z-Axis, Invisible	0.842	(0.687, 0.9971)	0.004	(-0.03038, 0.03763)	0.000	0.499	(0.382, 0.6159)	0.572	(0.5264, 0.6173)	0.404
Z-Axis, Disappearing	0.792	(0.666, 0.9172)	0.094	(0.06674, 0.1216)	0.046	0.505	(0.443, 0.5666)	0.568	(0.5179, 0.6181)	0.344
X/Y-Axis, Visible	0.722	(0.5556, 0.8877)	0.140	(0.1034, 0.1772)	0.055	0.559	(0.4739, 0.6447)	0.462	(0.4051, 0.5187)	0.210
X/Y-Axis, Invisible	0.603	(0.4599, 0.746)	0.103	(0.07118, 0.1338)	0.043	0.594	(0.4354, 0.7533)	0.564	(0.5042, 0.6238)	0.270
X/Y-Axis, Disappearing	0.808	(0.6527, 0.9641)	0.118	(0.08354, 0.1518)	0.046	0.535	(0.4567, 0.6122)	0.442	(0.3893, 0.4937)	0.225

Table 4--Calculated Effective Target Size at Snap

Starting Size (pixels)	Effective Target Size (pixels)					
	Z-Axis, Visible	Z-Axis, Invisible	Z-Axis, Disappearing	X/Y-Axis Visible	X/Y-Axis, Invisible	X/Y-Axis, Disappearing
40	242.92	705.12	324.71	400.59	851.24	391.65
60	235.28	717.41	259.93	391.35	848.69	476.75
80	280.02	779.15	306.02	389.05	943.54	426.51
100	283.63	388.61	349.55	433.61	828.89	356.69

Table 5--Head Tracking Model Coefficients Determined Using Original and Effective Index of Difficulty

General Model-- $[a + b*ID_{head}] + [c + d*ID_{slew}]$										
	Original Head Tracking Model-- $a + b*ID_{head}$					Effective ID Head Tracking Model-- $a + b*ID_{effective}$				
Selection Condition	a	95% CI	b	95% CI	R^2	a	95% CI	b	95% CI	R^2
Z-Axis, Visible	0.865	(0.7405, 0.989)	0.090	(0.06232, 0.1172)	0.042	0.968	(0.8662, 1.07)	0.110	(0.07312, 0.1471)	0.035
Z-Axis, Invisible	0.842	(0.687, 0.9971)	0.004	(-0.03038, 0.03763)	0.000	0.839	(0.7387, 0.9386)	0.012	(-0.0475, 0.07202)	0.000
Z-Axis, Disappearing	0.792	(0.666, 0.9172)	0.094	(0.06674, 0.1216)	0.046	0.906	(0.8043, 1.007)	0.123	(0.08377, 0.1619)	0.039
X/Y-Axis, Visible	0.722	(0.5556, 0.8877)	0.140	(0.1034, 0.1772)	0.055	0.927	(0.8034, 1.051)	0.192	(0.1367, 0.2477)	0.046
X/Y-Axis, Invisible	0.603	(0.4599, 0.746)	0.103	(0.07118, 0.1338)	0.043	0.728	(0.6349, 0.8207)	0.232	(0.171, 0.2938)	0.056
X/Y-Axis, Disappearing	0.808	(0.6527, 0.9641)	0.118	(0.08354, 0.1518)	0.046	0.945	(0.8291, 1.061)	0.179	(0.1275, 0.2296)	0.047

Table 6--Head Tracking Model Coefficients Determined Using Original and Linear Index of Difficulty

General Model-- $[a + b*ID_{head}] + [c + d*ID_{slew}]$										
	Original Head Tracking Model-- $a + b*ID_{head}$					Linear ID Head Tracking Model-- $a + b*ID_{linear}$				
Selection Condition	a	95% CI	b	95% CI	R^2	a	95% CI	b	95% CI	R^2
Z-Axis, Visible	0.865	(0.7405, 0.989)	0.090	(0.06232, 0.1172)	0.042	1.138	(1.09, 1.187)	0.004875	(0.003274, 0.006476)	0.0363
Z-Axis, Invisible	0.842	(0.687, 0.9971)	0.004	(-0.03038, 0.03763)	0.000	0.8542	(0.7993, 0.9092)	0.0001585	(-0.001667, 0.001984)	3.22E-05
Z-Axis, Disappearing	0.792	(0.666, 0.9172)	0.094	(0.06674, 0.1216)	0.046	1.081	(1.033, 1.129)	0.005082	(0.003524, 0.006641)	0.0416
X/Y-Axis, Visible	0.722	(0.5556, 0.8877)	0.140	(0.1034, 0.1772)	0.055	1.156	(1.091, 1.221)	0.007408	(0.005186, 0.009631)	0.0428
X/Y-Axis, Invisible	0.603	(0.4599, 0.746)	0.103	(0.07118, 0.1338)	0.043	0.9317	(0.8756, 0.9879)	0.004965	(0.003146, 0.006784)	0.03
X/Y-Axis, Disappearing	0.808	(0.6527, 0.9641)	0.118	(0.08354, 0.1518)	0.046	1.172	(1.11, 1.234)	0.006272	(0.004231, 0.008313)	0.0368

Repeated Measures ANOVA

Selection times were analyzed using a two-way, within-subjects analysis of variance with selection condition, which was the combination of snap activation method (Z-Axis, or X/Y-axis), visual feedback (visible, invisible, or disappearing) and target size (40, 60, 80, or 100 pixels). The data passed Mauchly's test of sphericity and therefore sphericity is assumed. Both main effects were found to be significant with selection condition [$F(6,30) = 68.6, MSE = 10.792, p = 0.000, \eta_p^2 = 0.932$] and target size [$F(3,15) = 318.499, MSE = 63452, p = 0.000, \eta_p^2 = 0.985$]. The interaction selection condition*target size was also found to be significant [$F(18,90) = 5.279, MSE = 0.124, p = 0.000, \eta_p^2 = 0.514$]. The ANOVA table is shown below.

Table 7--Selection Time ANOVA Results

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Condition	Sphericity Assumed	64.751	6	10.792	68.6	0.000	0.932
Error (Condition)	Sphericity Assumed	4.719	30	0.157			
Target Size	Sphericity Assumed	19.355	3	6.452	318.499	0.000	0.985
Error (Target Size)	Sphericity Assumed	0.304	15	0.02			
Condition * Target Size	Sphericity Assumed	2.224	18	0.124	5.279	0.000	0.514
Error (Condition* Target Size)	Sphericity Assumed	2.106	90	0.023			

The interaction plot for selection condition*target size is shown in Figure 3. Conditions 1-7 in Figure 3 are slew only, z-axis visible, z-axis invisible, z-axis, disappearing, x/y-axis visible, x/y-axis invisible, and x/y-axis disappearing respectively. Target size 1-4 correspond with 40, 60, 80 and 100 pixels respectively. A repeated measures ANOVA was performed holding each selection condition constant and varying the target size. Inspection of the change in mean time between each target revealed that the slew only condition had larger changes in selection time for changes in target size than the head tracking conditions. This was caused by a difference in display cursor movement speed between the slew only condition and the conditions using head tracking. The display cursor moved at a rate of 640 pixels per second in the slew only condition and was reduced to 400 pixels per second for all head tracking conditions. The difference in selection time between the smallest target and largest target for the slew only condition was twice as large as for the head tracking conditions. The faster cursor motion made precise aiming more difficult and drove selection times disproportionately higher than for the slower cursor speed. This was verified by performing another within subjects ANOVA without the slew only case. When only the head tracking conditions were considered the interaction effect was non-significant [$F(15,75) = 0.746$, $p = 0.730$, $MSE = 0.013$, $\eta_p^2 = 0.130$]. Because this interaction effect is weak, the main effects will be discussed below.

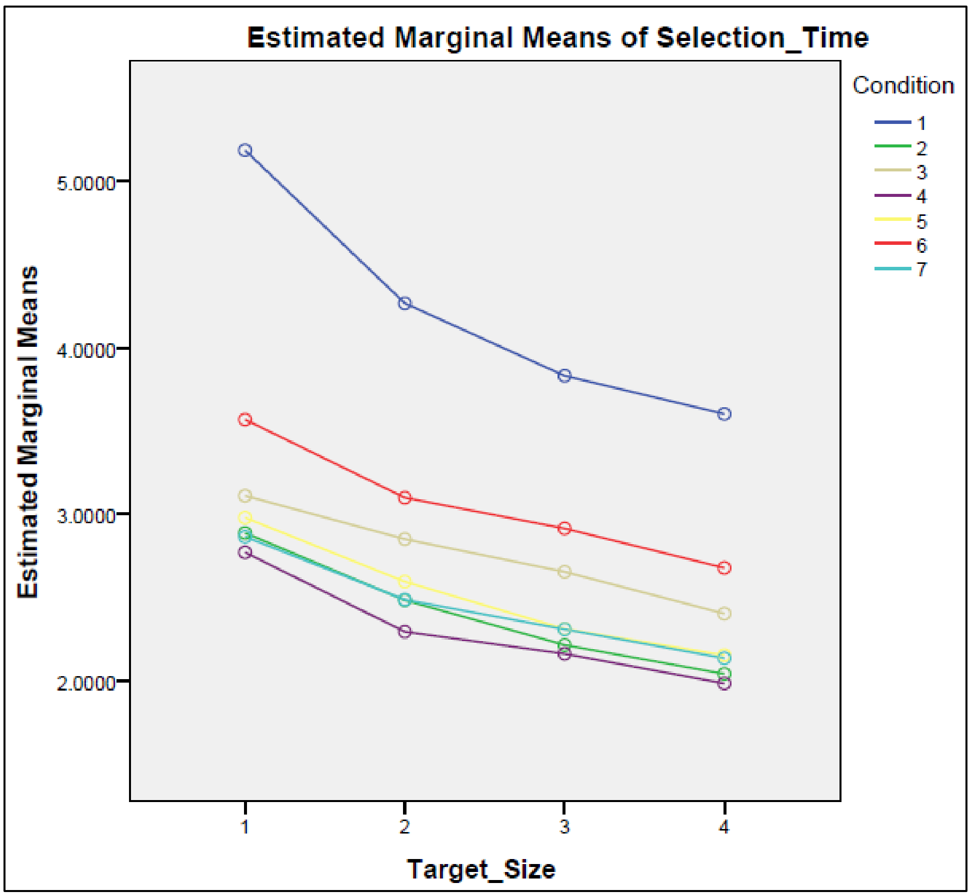


Figure 3--Selection Condition*Target Size Interaction Effect on Mean Selection Time

A Bonferroni pairwise comparison was performed to compare the mean selection times of the selection conditions. The mean selection times are summarized below in Figure 4. Table 8 summarizes the results of the pairwise comparisons the green cells indicate the pairs that are statistically different, and the red cells are pairs that are not statistically different. Time to select was greatest for the slew only condition followed by the X/Y-Axis, Invisible condition. The Z-Axis, Invisible condition was statistically different from some but not all conditions with visible feedback. And nearly all visible feedback conditions were not statistically different from one another.

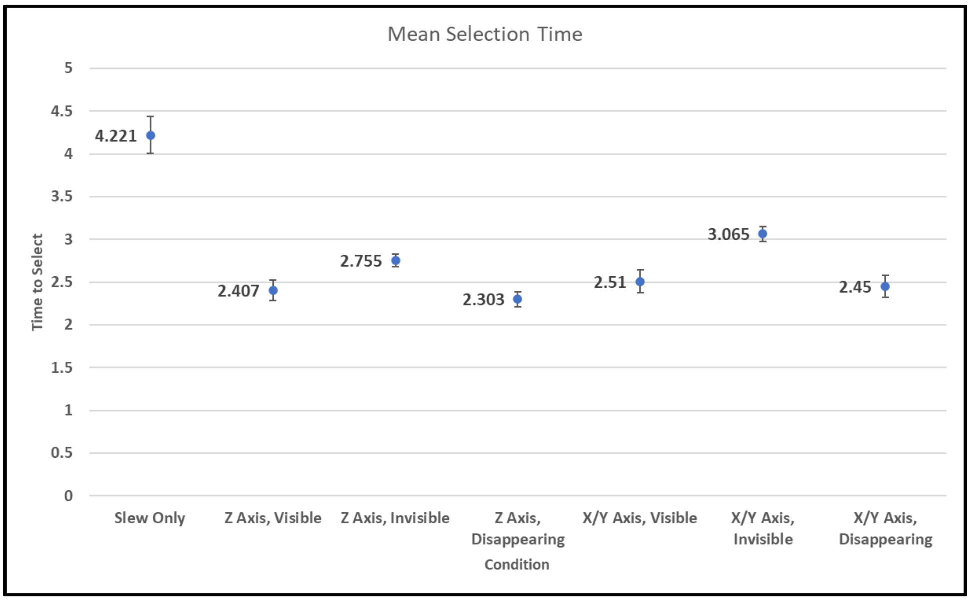


Figure 4--Mean Selection Time by Selection Condition with Standard Error

Table 8--Bonferroni Pairwise Control Comparison of Selection Condition

	Slew Only	Z-Axis, Visible	Z-Axis, Invisible	Z-Axis, Disappearing	X/Y-Axis, Visible	X/Y-Axis, Invisible	X/Y-Axis, Disappearing
Slew Only		0.002	0.006	0.003	0.002	0.023	0.005
Z-Axis, Visible			0.070	1.000	0.251	0.004	1.000
Z-Axis, Invisible				0.001	0.444	0.119	0.622
Z-Axis, Disappearing					0.672	0.002	1.000
X/Y-Axis, Visible						0.026	1.000
X/Y-Axis, Invisible							0.017
X/Y-Axis, Disappearing							

A Bonferroni pairwise comparison was performed to compare the mean selection times for each target size. The mean selection times for each target size are summarized below in Figure 5. Table 9 summarizes the results of the pairwise comparison, with green cells indicating statistically different pairs. All pairs of target size were statistically different from one another.

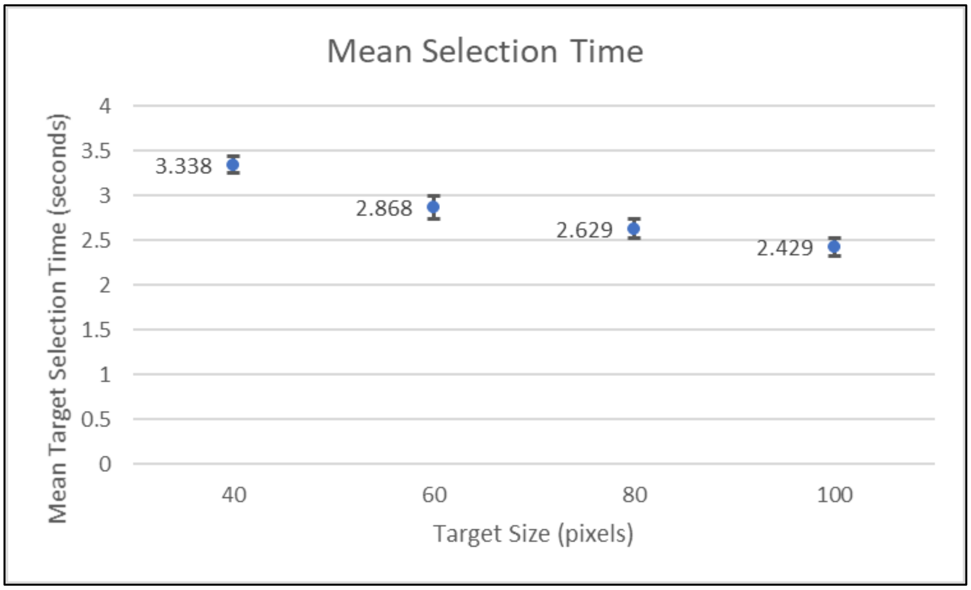


Figure 5--Mean Target Selection Time by Target Size with Standard Error

Table 9--Bonferroni Pairwise Comparison of Target Size

Target Size (pixels)	40	60	80	100
40		0.000	0.000	0.000
60			0.007	0.001
80				0.005
100				

Time to Initiate Cursor Snap

The time taken to initiate the cursor snap was analyzed using a two-way, within-subjects analysis of variance with selection condition, which was the combination of snap activation method (Z-Axis, or X/Y-axis) and visual feedback (visible, invisible, or disappearing) and target size (40, 60, 80, or 100 pixels). The data for the selection condition term failed Mauchly's test of sphericity and therefore a Greenhouse-Geisser correction is applied. Both the target size and selection condition*target size interaction terms passed Mauchly's test of sphericity. Both main effects were found to be significant with selection condition [$F(1.7,8.7) = 7.889$, $MSE = 2.38$, $p = 0.013$, $\eta_p^2 = 0.612$] and target size [$F(3,15) = 5.225$, $MSE = 0.043$, $p = 0.011$, $\eta_p^2 = 0.511$]. The interaction selection condition*target size was not found to be significant [$F(15,75) = 1.098$, $MSE = 0.007$, $p = 0.373$, $\eta_p^2 = 0.18$]. The ANOVA table is shown below with the Greenhouse-Geisser correction for the condition term.

Table 10--Time to Snap Initiation ANOVA Results

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Condition	Sphericity Assumed	4.161	5.000	0.832	7.889	0.000	0.612
	Greenhouse-Geisser	4.161	1.748	2.380	7.889	0.013	0.612
Error (Condition)	Sphericity Assumed	2.637	25.000	0.105			
	Greenhouse-Geisser	2.637	8.739	0.302			
Target Size	Sphericity Assumed	0.128	3.000	0.043	5.225	0.011	0.511
Error (Target Size)	Sphericity Assumed	0.122	15.000	0.008			
Condition * Target Size	Sphericity Assumed	0.098	15.000	0.007	1.098	0.373	0.180
Error (Condition* Target Size)	Sphericity Assumed	0.446	75.000	0.006			

A Bonferroni pairwise comparison was performed to compare the mean time to initiate cursor snap of the selection conditions. The mean time to initiate cursor snap are summarized below in Figure 6. Table 11 summarizes the results of the pairwise comparisons the green cells indicate the pairs that are statistically different, and the red cells are pairs that are not statistically different. The Z-Axis, Invisible condition was significantly faster to cursor snap than the two X/Y-Axis conditions with visible feedback. All other pairs were not significantly different from one another.

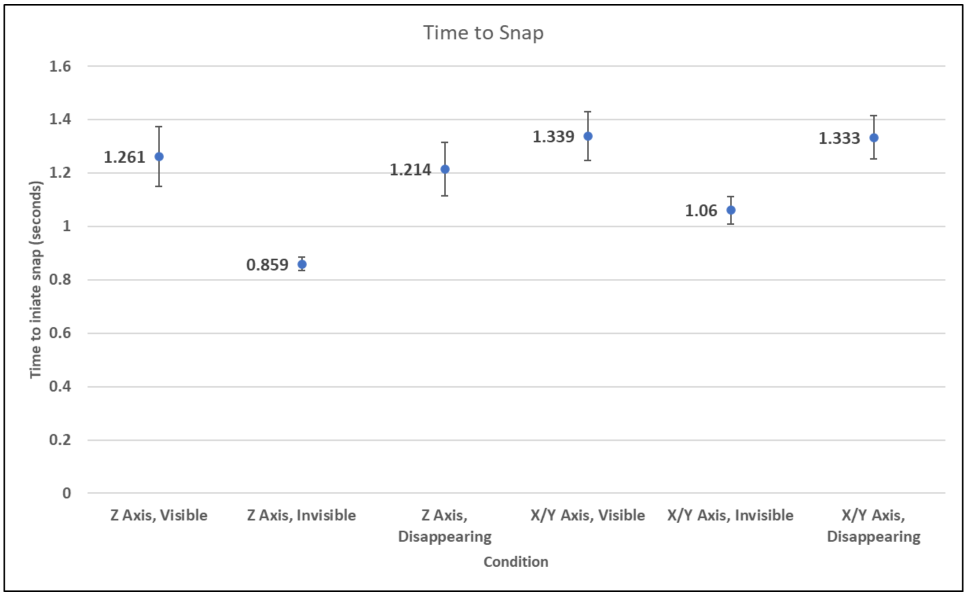


Figure 6--Time to Initiate Cursor Snap by Selection Condition with Standard Error

Table 11--Bonferroni Pairwise Comparison of Time to Initiate Cursor Snap

Selection Condition	Z-Axis, Visible	Z-Axis, Invisible	Z-Axis, Disappearing	X/Y-Axis, Visible	X/Y-Axis, Invisible	X/Y-Axis Disappearing
Z-Axis, Visible		0.141	1.000	1.000	1.000	1.000
Z-Axis, Invisible			0.166	0.040	0.295	0.044
Z-Axis, Disappearing				0.525	1.000	1.000
X/Y-Axis, Visible					0.807	1.000
X/Y-Axis, Invisible						0.247
X/Y-Axis Disappearing						

A Bonferroni pairwise comparison was performed to compare the mean time to initiate cursor snap by cursor size. The mean time to initiate cursor snap are summarized below in Figure 7. Table 12 summarizes the results of the pairwise comparisons the green cells indicate the pairs that are statistically different. As shown, the times are different between all target size pairs with larger targets requiring less time for selection.

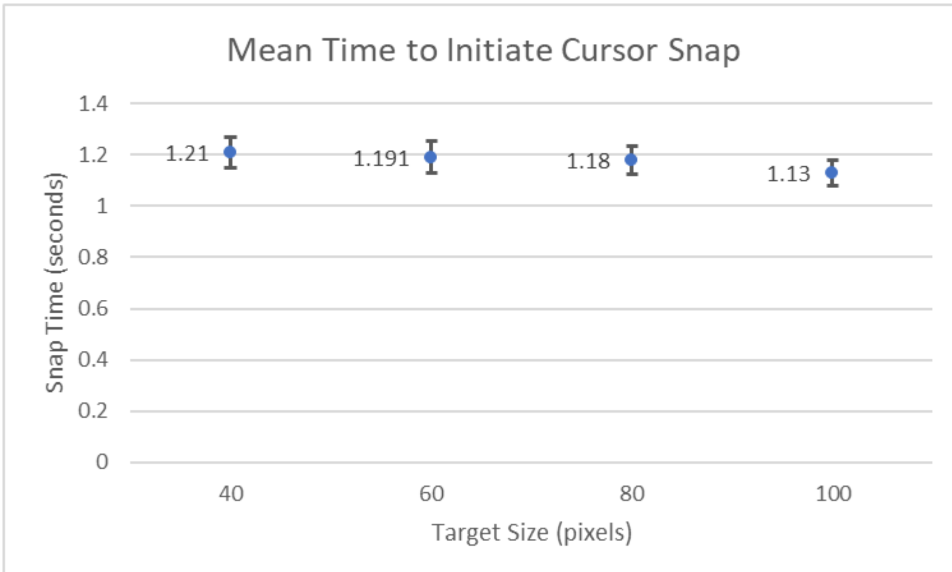


Figure 7--Time to Initiate Cursor Snap by Target Size with Standard Error

Table 12--Bonferroni Pairwise Comparison of Time to Cursor Snap by Target Size

Target Size (pixels)	40	60	80	100
40		0.030	0.019	0.021
60			0.023	0.020
80				0.010
100				

Accuracy of Cursor Snap

The accuracy of the cursor snap was analyzed using a two-way, within-subjects analysis of variance with selection condition, which was the combination of snap activation method (Z-Axis, or X/Y-axis) and visual feedback (visible, invisible, or disappearing) and target size (40, 60, 80, or 100 pixels). The data passed Mauchly's test of sphericity and therefore sphericity is assumed. The selection condition main effect [$F(5,25) = 86.493$, $MSE = 409169.199$, $p = 0.000$, $\eta_p^2 = 0.945$] and interaction effect selection condition*target size [$F(15,75) = 2.003$, $MSE = 828.116$, $p = 0.026$, $\eta_p^2 = 0.286$] were found to be significant. Target size [$F(3,15) = 2.949$, $MSE = 808.662$, $p = 0.067$, $\eta_p^2 = 0.371$] was found not to be significant. The ANOVA table is shown below in Table 13.

Table 13--Cursor Snap Accuracy ANOVA Results

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Condition	Sphericity Assumed	2045845.966	5.000	409169.199	86.493	0.000	0.945
Error (Condition)	Sphericity Assumed	118266.618	25.000	4730.665			
Target Size	Sphericity Assumed	2425.985	3.000	808.662	2.949	0.067	0.371
Error (Target Size)	Sphericity Assumed	4113.858	15.000	275.257			
Condition * Target Size	Sphericity Assumed	12421.745	15.000	828.116	2.003	0.026	0.286
Error (Condition* Target Size)	Sphericity Assumed	31001.980	75.000	413.360			

A Bonferroni pairwise comparison was performed to compare the mean cursor snap accuracy of the selection conditions. The mean cursor snap accuracies are summarized below in Figure 8. Table 14 summarizes the results of the pairwise comparisons the green cells indicate the pairs that are statistically different, and the red cells are pairs that are not statistically different. Each of the conditions without visible feedback were significantly less accurate than the conditions with visible feedback. None of the visible feedback conditions were significantly different from one another.

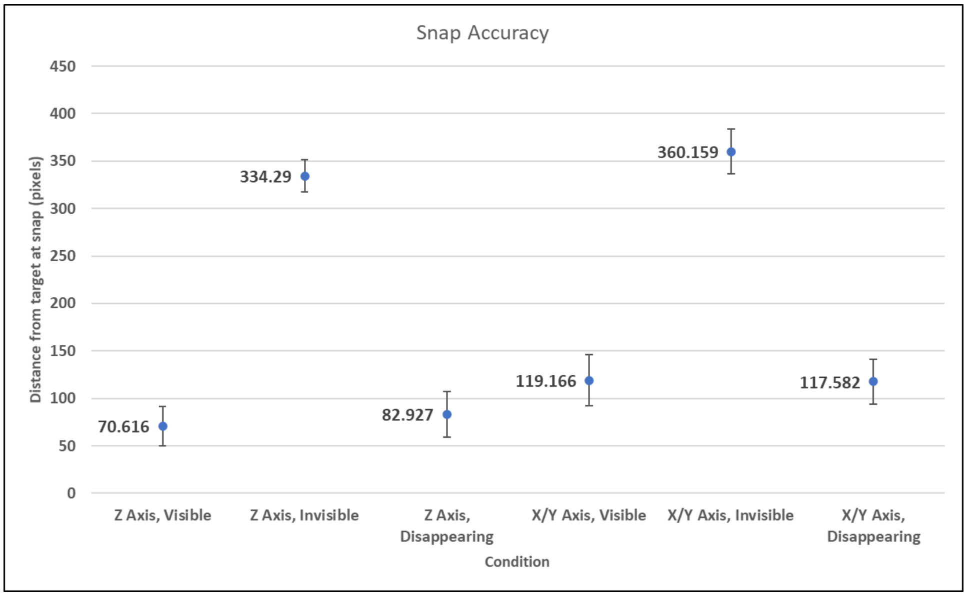


Figure 8--Mean Cursor Snap Accuracy by Selection Condition with Standard Error

Table 14--Bonferroni Pairwise Comparison of Cursor Snap Accuracy by Selection Condition

Selection Condition	Z-Axis, Visible	Z-Axis, Invisible	Z-Axis, Disappearing	X/Y-Axis, Visible	X/Y-Axis, Invisible	X/Y-Axis Disappearing
Z-Axis, Visible		0.000	1.000	0.453	0.004	0.421
Z-Axis, Invisible			0.000	0.001	1.000	0.001
Z-Axis, Disappearing				0.940	0.006	0.902
X/Y-Axis, Visible					0.003	1.000
X/Y-Axis, Invisible						0.002
X/Y-Axis Disappearing						

A repeated measures ANOVA was performed holding selection condition constant and analyzing target size effect to determine the cause of the interaction effect. Three conditions returned a significant target size effect; Z-Axis, Visible [$F(3,15) = 4.741$, $MSE = 228.956$, $p = 0.016$, $\eta_p^2 = 0.487$], Z-Axis, Invisible [$F(3,15) = 4.485$, MSE

$= 3143.715, p = 0.019, \eta_p^2 = 0.473$] and, X/Y-Axis, Visible [$F(3,15) = 5.339, MSE = 453.114, p = 0.011, \eta_p^2 = 0.516$]. However, a Bonferroni pairwise comparison showed no significant differences across target size. This is potentially due to the loss of sensitivity with the pairwise comparisons. Figure 9, shows the mean snap accuracy of each condition based on target size. Conditions 1-6 in Figure 9 are z-axis visible, z-axis invisible, z-axis, disappearing, x/y-axis visible, x/y-axis invisible, and x/y-axis disappearing respectively. Target sizes 1-4 correspond with 40, 60, 80 and 100 pixels respectively. A close look at the change in mean accuracy across target size for the Z-Axis, Visible condition (Condition 1 in Figure 9) showed a minor rise in distance from the center of the target with an increase in target size. This result is expected, as the size of the target increases the cursor can be further from the center of the target but still be within the border of the target. The significant interaction result may be due to the X/Y-Axis, Invisible condition (Condition 5 in Figure 9) showing the opposite relationship. However, these results are not conclusive due to the non-significant results of the ANOVA analysis of the X/Y-Axis, Invisible condition and the non-significant results of all pairwise comparisons. Finally, a repeated measures ANOVA was performed to determine if the interaction was due to a speed-accuracy trade off. A term, the efficiency score, was created to capture the inverse effect of speed on accuracy. The efficiency score was used so that participants that prioritized speed but were less accurate could be more directly compared to participants that were slower but more accurate. This was done by multiplying the time to initiate cursor snap by selection accuracy so that high times and smaller distances would be approximately equal to low times and larger distances. The results of this analysis showed no significant effect of the interaction between selection condition and target size [$F(15,75) = 1.448, MSE = 1018.594, p = 0.148, \eta_p^2 = 0.225$].

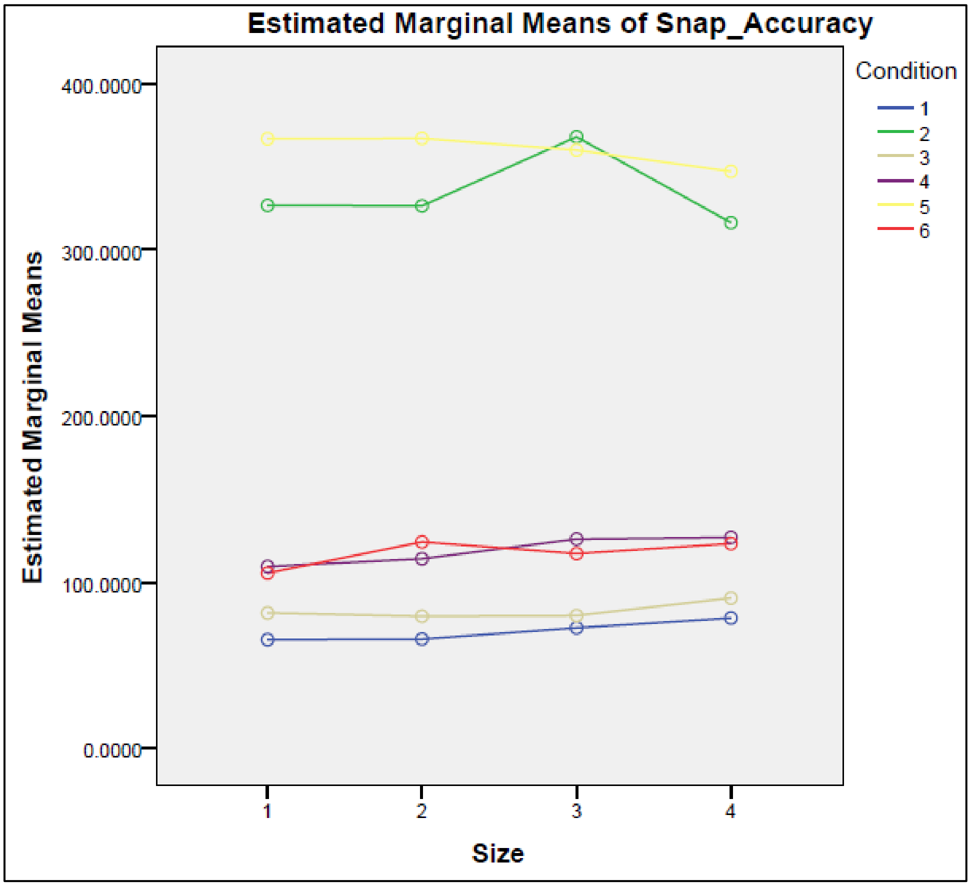


Figure 9--Interaction Plot for Cursor Snap Accuracy

User Perceived Workload

A repeated measures ANOVA was performed on the results of the NASA TLX survey to determine differences in the perceived workload between each condition. The effect of condition on the weighted TLX core was non-significant [$F(6,30) = 2.033, MSE = 492.699, p = 0.092, \eta_p^2 = 0.289$]. Additionally, there was no difference in the mental workload component [$F(6,30) = 1.859, MSE = 25552.579, p = 0.121, \eta_p^2 = 0.271$] or the physical workload component [$F(6,30) = 0.881, MSE = 4899.206, p = 0.521, \eta_p^2 =$

0.150] between conditions. The full survey results for each condition, including scores and weightings, can be found in Appendix C.

Summary

The Fitts' Law analysis resulted in no significant models. The lack of model fit to the collected data means Fitts' Law cannot be used to predict human performance using these human-cockpit interaction methods. Results of the ANOVA analyses indicated that all conditions using head tracking were faster in selecting the target than the slew only condition. Additionally, the conditions without visible feedback were slower than those with visible feedback. As expected, the conditions without visual feedback were significantly less accurate at the time of cursor snap, leading to the increased selection times. However, the removal of visual feedback decreased the time required to initiate the cursor snap. Selection condition did not change the workload perceived by the participants.

V. Conclusions and Recommendations

Discussion

Removal of the visual feedback of the cursor during head movement was shown to prevent the pilot from attempting to precisely position the cursor using head movements in the Z-Axis, Invisible condition. The mean time to snap activation for this method was approximately 1.25 seconds faster than the X/Y-Axis, Visible and X/Y-Axis, Disappearing conditions. Removal of the visual feedback of the head tracking cursor had a negative effect on the accuracy of the cursor snap. The invisible feedback conditions were more than three times less accurate than all of the visible feedback conditions. Snap activation method had no significant effect on participant cognitive workload. The NASA TLX survey did not show any significant difference in total workload rating, physical workload rating, or mental workload rating between any conditions. Snap activation method did not have a significant effect on selection time performance. All head tracking conditions performed faster than the slew only condition, but there was no performance difference between Z-Axis of X/Y-Axis conditions. Visual feedback did have a significant effect on selection time. The conditions without visual feedback were significantly slower than the conditions with visual feedback.

Fitts' Law was found to be a poor predictor of performance for the head tracking cursor control systems. Additionally, the model fit for the slew only case was lower than is typically seen for Fitts' Law studies. It is possible this is due to the cursor slew speeds chosen for the experiment. The slew speed was balanced between the need to navigate the display quickly while retaining the ability to precisely aim at small targets. However, the slew speed may not have been fast enough to be represented by Fitts' Law, which is most suited to ballistic movements.

The series of ANOVA analyses revealed that the two conditions without visual feedback had significantly faster selection times than the slew only condition. Additionally, the four conditions with visual feedback were significantly faster than the conditions without. The difference between the visible and invisible feedback conditions was approximately 0.76 seconds. This difference was likely due to the decreased snap accuracy of the invisible cursor conditions. After the cursor snap was initiated, the display cursor was more than twice as far from the center of the target when there was no visual feedback. This increased distance required additional aim refinement using the cursor slew switch, adding time to the selection task. However, some of this additional time was offset by reduced time to initiate cursor snap. Both invisible feedback conditions had lower mean time to initiate cursor snap, but only the z-axis snap activation method without feedback was statistically different. This condition was up to 1.25 seconds faster in relocating the display cursor. It is expected that this reduction is associated with a reduction in aim refinement prior to the cursor snap. The presence of visual feedback caused the participants to spend extra time refining cursor aim to minimize refinement needed using the cursor slew switch. This reduction of aim using the neck muscles has the potential to reduce the fatigue experienced by users as reported by Harp et. al. Ultimately the increase in selection time between visible and invisible feedback, while statistically meaningful, may not be operationally relevant. It is worth considering a 0.75 second increase in selection time if the pilot can use the system for longer without experiencing fatigue.

Recommendations for Acquisitions & Operators

It is important to recognize that design decisions of pilot-aircraft interfaces affect more than the selection time metric. The control layout has the potential to increase mental workload of the pilot. Or as this research shows, visual feedback can alter the amount of time until the pilot takes their first action. In conditions when increased speed is the only consideration then an interface with visual feedback may be appropriate. However, when considering prolonged use for a long duration mission, the tendency to use fine motor control to refine aim can become detrimental. In this situation a slight, and likely operationally irrelevant, decrease in selection time when the head cursor is not shown may improve pilot comfort and endurance when using this system.

Recommendations for Future Research

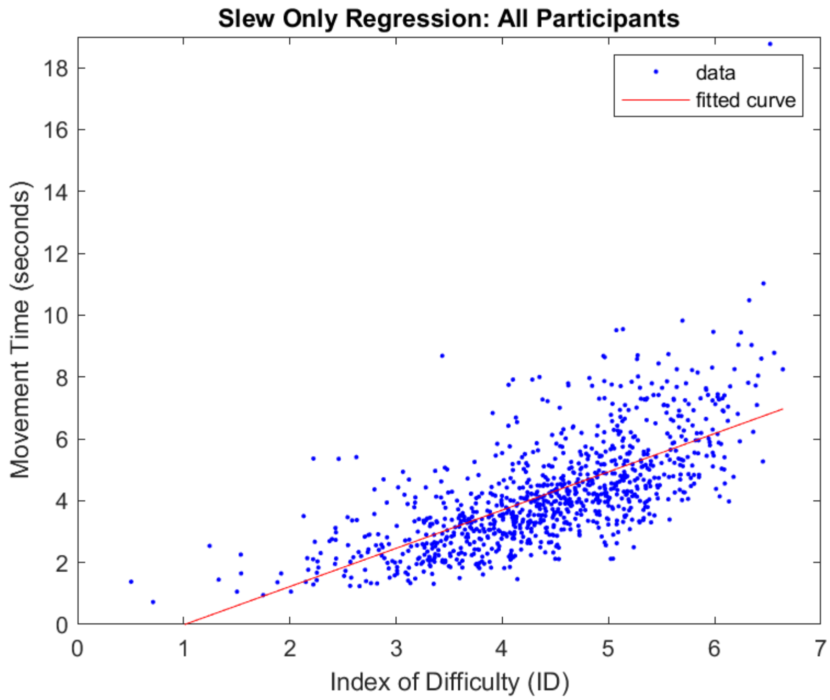
The recommendations for future research primarily focus on the search for better head tracking interfaces than those tested or improving the interfaces above. This research focused on two control configurations and three types of visual feedback in a laboratory setting. The next step to analyzing the performance of these implementations would to be to test accuracy and selection time under adverse conditions. The best performing conditions could be tested using a vibration table to simulate turbulence.

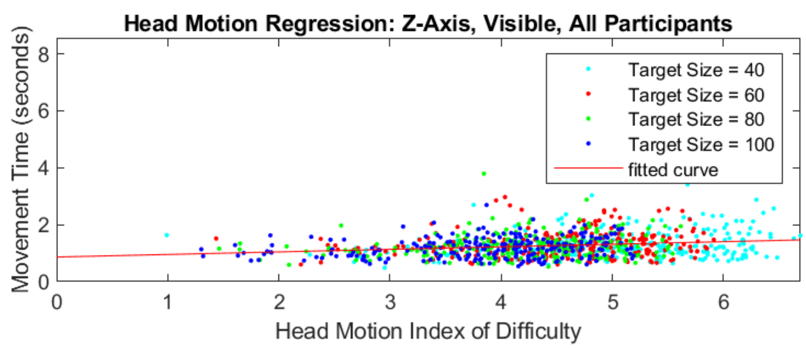
A similar experiment could be performed with the addition of performing primary flight tasks. Or by performing more complex target selection tasks such as data entry or selection in a cluttered environment. This would determine if overall pilot workload changes the performance of any of the tested implementations.

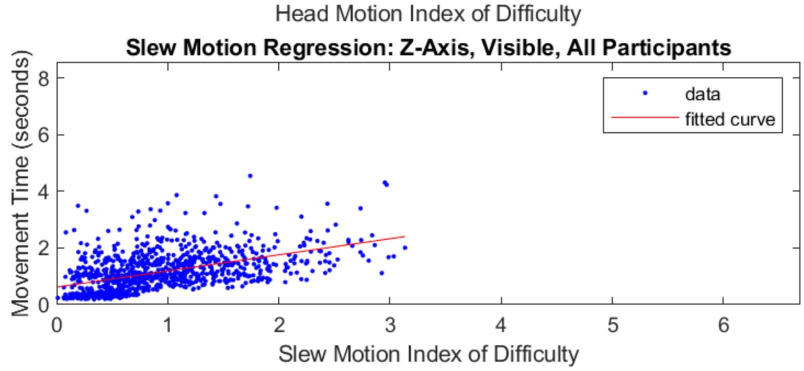
Alternatively, the fatigue factor can be explored more fully. This study did not account for the weight of the flight helmet that would be present in an operational mission. This added weight would put additional stress on the neck muscles when aiming at a target. Additionally, the trial duration for each condition was approximately ten minutes or less. Therefore, a study could be performed to assess the impact of adding the flight helmet and increased duration of select conditions. Especially the difference in impact between visible and invisible feedback conditions.

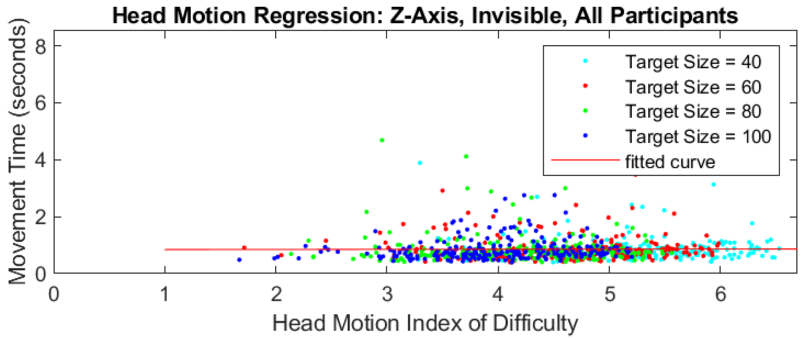
A gaze tracking system could be added to analyze the movement of the users eyes relative to their head motion, especially without visual feedback. This could allow for changes in cursor motion based on relative head motion. For example, requiring smaller head motions to move the cursor larger distances thus potentially reducing fatigue further.

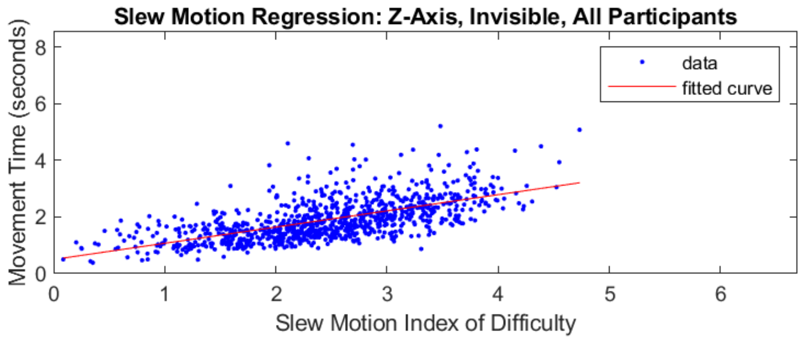
Appendix A. Fitts' Law Regression Plots

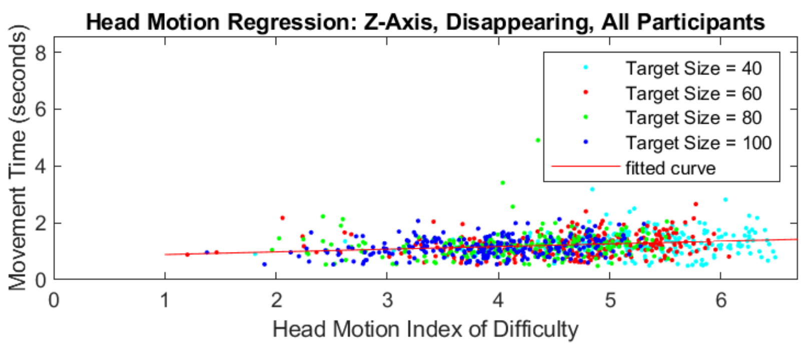


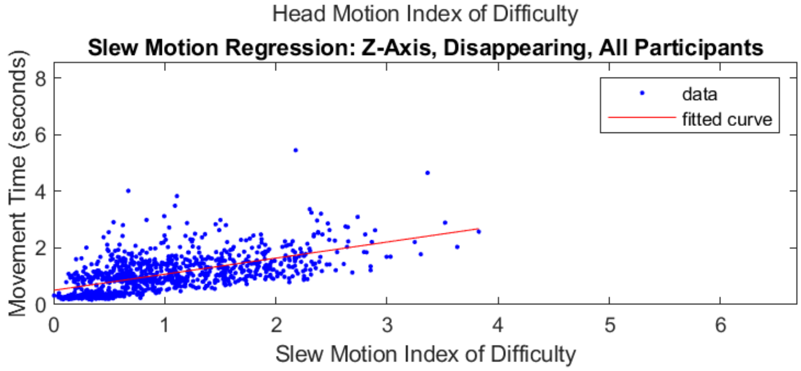


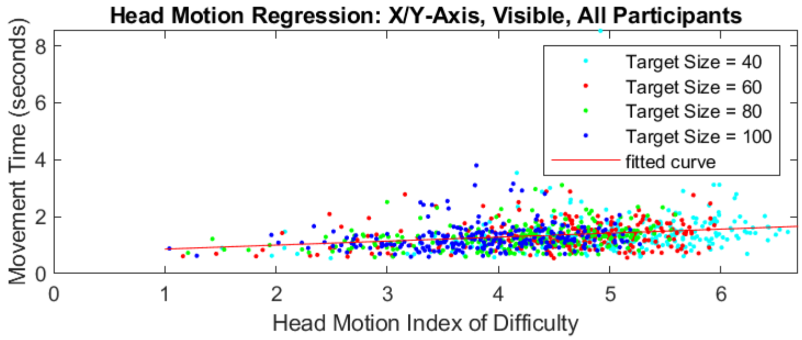


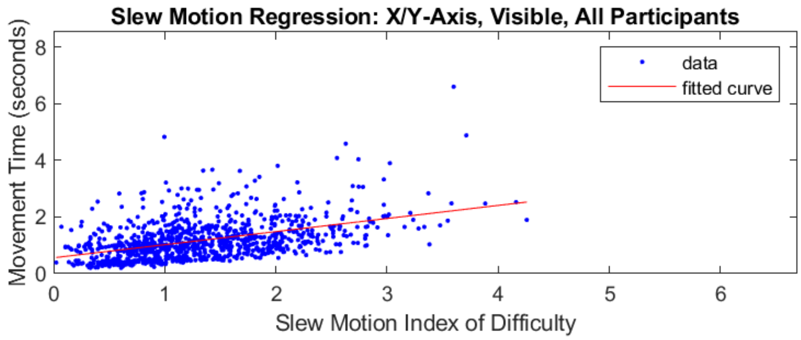

Head Motion Regression: Z-Axis, Invisible, All Participants
Movement Time (seconds)
Head Motion Index of Difficulty
Target Size = 40
Target Size = 60
Target Size = 80
Target Size = 100
fitted curve

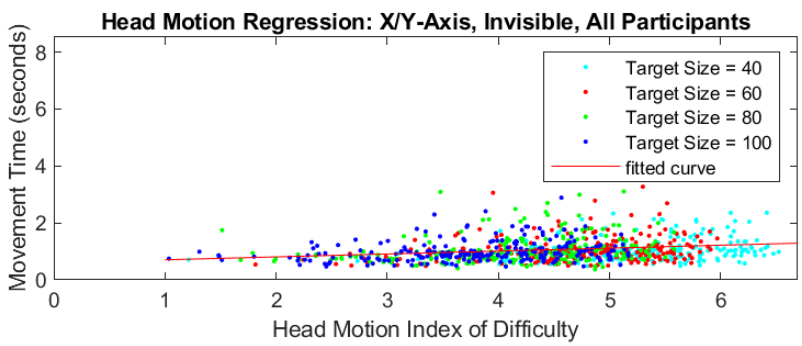

Slew Motion Regression: Z-Axis, Invisible, All Participants
Movement Time (seconds)
Slew Motion Index of Difficulty
data
fitted curve

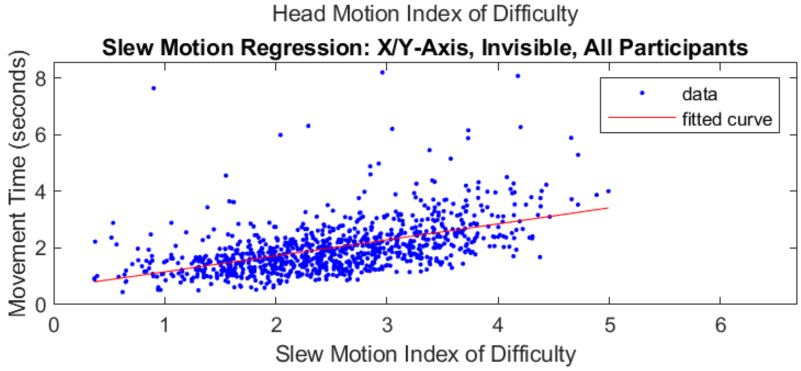

Head Motion Regression: Z-Axis, Disappearing, All Participants
Movement Time (seconds)
Head Motion Index of Difficulty
Target Size = 40
Target Size = 60
Target Size = 80
Target Size = 100
fitted curve

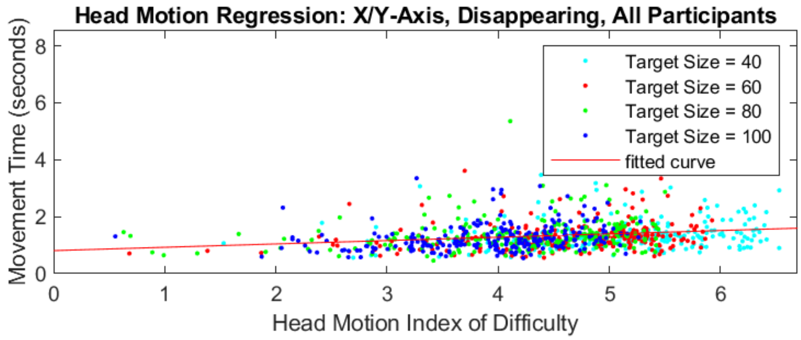

Slew Motion Regression: Z-Axis, Disappearing, All Participants
Movement Time (seconds)
Slew Motion Index of Difficulty
data
fitted curve

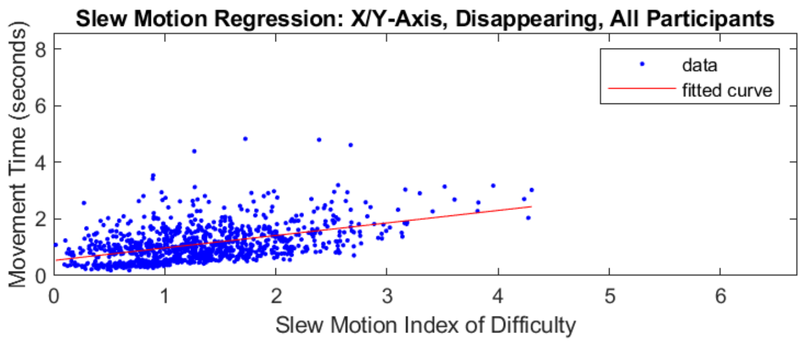

Head Motion Regression: X/Y-Axis, Visible, All Participants
Movement Time (seconds)
Head Motion Index of Difficulty
Target Size = 40
Target Size = 60
Target Size = 80
Target Size = 100
fitted curve
0
2
4
6
8
0
1
2
3
4
5
6


Slew Motion Regression: X/Y-Axis, Visible, All Participants
Movement Time (seconds)
Slew Motion Index of Difficulty
data
fitted curve
0
2
4
6
8
0
1
2
3
4
5
6


Head Motion Regression: X/Y-Axis, Invisible, All Participants
Movement Time (seconds)
Head Motion Index of Difficulty
Target Size = 40
Target Size = 60
Target Size = 80
Target Size = 100
fitted curve
0
2
4
6
8
0
1
2
3
4
5
6


Slew Motion Regression: X/Y-Axis, Invisible, All Participants
Movement Time (seconds)
Slew Motion Index of Difficulty
data
fitted curve
0
2
4
6
8
0
1
2
3
4
5
6


Head Motion Regression: X/Y-Axis, Disappearing, All Participants
Target Size = 40
Target Size = 60
Target Size = 80
Target Size = 100
fitted curve
Movement Time (seconds)
Head Motion Index of Difficulty


Slew Motion Regression: X/Y-Axis, Disappearing, All Participants
data
fitted curve
Movement Time (seconds)
Slew Motion Index of Difficulty

Appendix B. Participant Survey

Age: 20 and under 21-30 31-40 41-50 51-60+ Prefer not to answer

Are you male or female? Male Female Prefer not to answer

Have you had pilot training or have flight experience? Yes or No

If yes: What training?

Do you have experience with input methods other than mouse and keyboard such as head tracking, eye tracking, or HOTAS cursor slew switch?

If yes: What experience?

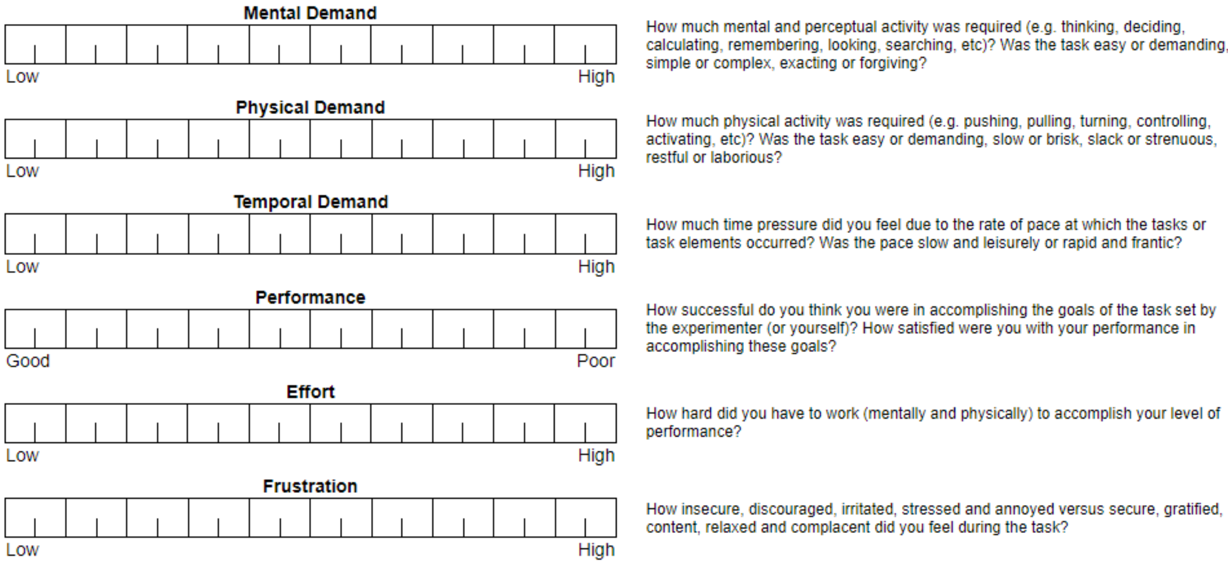
Are you predominately left or right handed? Left or Right

Do you have corrected vision? Yes (circle: glasses or contacts) or No

If yes: Are you near or far-sighted? Near Far Neither

If yes: Are you wearing them now? Yes No

NASA TLX



For each of the following pairs, select the scale title that represents the more important contributor to workload for the task:

Mental Demand or Physical Demand

Effort or Frustration

Effort or Physical Demand

Effort or Mental Demand

Physical Demand or Temporal Demand

Temporal Demand or Effort

Frustration of Mental Demand

Performance or Effort

Temporal Demand or Performance

Mental Demand or Temporal Demand

Performance or Frustration

Temporal Demand or Frustration

Mental Demand or Performance

Frustration or Physical Demand

Physical Demand or Performance

Comments:

Appendix C. Survey Results

Participant	Age	Gender	Pilot Training	Exp.	Head/Eye Tracking or HOTAS Experience	Handedness	Corrected Vision	Near/Far Sighted	Wearing corrective lenses
1	21-30	M	No	N/A	No	Right	No	N/A	N/A
2	21-30	M	Yes	Several hours of powered GA flight	No	Right	No	N/A	N/A
3	21-30	F	No	N/A	No	Left	No	N/A	N/A
4	21-30	M	No	N/A	No	Right	Yes	Near	Yes
5	21-30	M	Yes	Around 25 instructional hours in a Cessna 172. Father is a pilot, I have flown with him numerous times.	No	Right	No	N/A	N/A
6	21-30	F	No	N/A	No	Right	No	N/A	N/A

Selection Condition	Overall	Mental	Physical	Temporal	Performance	Effort	Frustration
Slew Only	53.54	117.5	112.5	193.75	126	187.5	211
Z-Axis, Visible	41.44	191.67	91	97.5	125	104.2	120
Z-Axis, Invisible	48.5	242.5	147	86	98.75	173.3	77.5
Z-Axis, Disappearing	33.98	135.83	106	60.83	101.67	108.3	60
X/Y-Axis, Visible	44.82	167.5	88.33	103.33	151.67	107.5	178.33
X/Y-Axis, Invisible	55.83	260.83	126.67	167.5	96	155	166.25
X/Y-Axis, Disappearing	32.22	82.5	178.75	102.5	110	60.83	25

Slew Only Condition																																				
	User Ratings						User Weightings																													
Participant	Mental	Physical	Temporal	Performance	Effort	Frustration	Mental Demand	Physical Demand	Temporal Demand	Performance	Effort	Frustration	Mental Demand	Temporal Demand	Effort	Physical Demand	Performance	Frustration	Effort	Mental Demand	Temporal Demand	Frustration	Physical Demand	Temporal Demand	Mental Demand	Performance	Temporal Demand	Effort	Frustration	Physical Demand	Frustration	Mental Demand	Physical Demand	Performance	Performance	Effort
1	80	20	70	80	85	60	1			1	1		1		1		1			1	1			1	1			1	1			1		1		
2	35	25	20	35	75	60	1			1	1		1		1		1		1			1	1			1		1	1			1		1		1
3	15	35	15	85	45	15		1	1		1			1	1		1		1		1			1		1	1			1		1	1			1
4	55	60	65	75	75	65		1	1			1		1	1			1	1			1		1	1		1		1		1		1			1
5	40	30	60	20	35	50	1		1			1		1	1			1		1	1			1	1		1		1		1			1		1
6	10	50	10	20	10	70		1		1		1	1			1		1	1			1	1			1		1	1		1		1		1	
Comments:	Likely would have been significantly more difficult and demand more mental and physical effort to perform as well																																			
	It took longer to get the cursor where I wanted, but was not mentally taxing.																																			
	Trying to hit the smallest dots was very difficult and led to a lot of circling around to hit it.																																			
	Hardest and most frustrating method out of all of them.																																			

X/Y-Axis, Disappearing																																				
	User Ratings						User Weightings																													
Participant	Mental	Physical	Temporal	Performance	Effort	Frustration	Mental Demand	Physical Demand	Temporal Demand	Performance	Effort	Frustration	Mental Demand	Temporal Demand	Effort	Physical Demand	Performance	Frustration	Effort	Mental Demand	Temporal Demand	Frustration	Physical Demand	Temporal Demand	Mental Demand	Performance	Temporal Demand	Effort	Frustration	Physical Demand	Frustration	Mental Demand	Physical Demand	Performance	Performance	Effort
1	20	30	10	10	10	10	1			1	1			1	1		1			1	1			1		1	1		1			1		1	1	
2	40	55	35	30	45	30		1		1	1		1			1	1		1		1		1			1		1		1		1		1	1	
3	45	35	65	15	25	15	1		1		1			1		1	1			1	1			1		1	1			1		1		1	1	
4	25	45	20	20	25	15		1		1	1		1			1	1			1	1		1		1			1		1		1	1			1
5	20	10	15	10	15	10	1		1			1		1	1			1		1	1			1	1		1		1		1			1		1
6	30	50	60	70	40	20		1		1	1			1		1	1			1	1		1			1		1		1		1		1	1	
Comments:	I thought this was the least distracting option and it was the easiest for me to pick up on.																																			
	This method worked the smoothest and I felt the most confident about being accurate with it.																																			
	I couldn’t tell much of a difference at all between this test and the previous one. [XY, Visible]																																			

X/Y-Axis, Invisible Cursor																																						
	User Ratings						User Weightings																														
Participant	Mental	Physical	Temporal	Performance	Effort	Frustration	User #	Mental Demand	Physical Demand	Temporal Demand	Performance	Effort	Frustration	Mental Demand	Temporal Demand	Effort	Physical Demand	Performance	Frustration	Effort	Mental Demand	Temporal Demand	Frustration	Physical Demand	Temporal Demand	Mental Demand	Performance	Temporal Demand	Effort	Frustration	Physical Demand	Frustration	Mental Demand	Physical Demand	Performance	Performance	Effort
1	30	30	10	10	10	10	1	1			1		1	1		1		1			1	1			1		1	1		1		1			1	1	
2	55	40	35	60	50	50	2	1			1	1		1			1	1			1	1		1		1			1		1		1		1	1	
3	85	35	65	55	95	85	3	1		1			1	1		1			1	1		1			1	1			1	1			1		1		1
4	90	80	90	60	80	80	4	1		1			1	1		1			1		1	1			1	1		1		1			1	1			1
5	30	15	35	35	35	35	5	1		1			1		1	1			1		1	1			1	1		1		1		1			1		1
6	80	60	70	50	70	50	6	1		1		1		1		1		1		1		1		1		1		1			1		1	1		1	

Comments:
- I found it was difficult to prevent myself from engaging the cursor by accident when I couldn't see it.
- This one was really frustrating for me. It was difficult to figure out where the cursor was going to be.
- This method was difficult to use as I had no idea where the crosshair would show up. Most of my time was spent correcting where it was after it showed up to where I wanted it to be.
- Easier than the cursor only but harder than the rest

X/Y-Axis, Visible Cursor																																				
	User Ratings						User Weightings																													
Participant	Mental	Physical	Temporal	Performance	Effort	Frustration	Mental Demand	Physical Demand	Temporal Demand	Performance	Effort	Frustration	Mental Demand	Temporal Demand	Effort	Physical Demand	Performance	Frustration	Effort	Mental Demand	Temporal Demand	Frustration	Physical Demand	Temporal Demand	Mental Demand	Performance	Temporal Demand	Effort	Frustration	Physical Demand	Frustration	Mental Demand	Physical Demand	Performance	Performance	Effort
1	20	30	10	10	10	10	1			1		1	1		1		1			1	1			1		1	1		1			1		1	1	
2	65	40	45	35	45	35	1			1	1		1		1		1		1		1		1			1		1		1		1		1	1	
3	65	35	75	25	55	25	1		1		1			1	1		1			1	1			1	1		1			1		1		1	1	
4	85	70	75	75	85	95	1			1		1	1		1			1		1		1		1	1			1	1		1			1		1
5	20	10	15	10	15	10	1		1			1		1	1			1		1	1			1	1		1		1		1			1		1
6	35	50	20	90	20	10		1		1	1		1			1	1		1		1		1			1		1				1		1	1	

Comments:
- This was slightly confusing at first until I figured out how to track the two cursors separately, after that I felt it was the one I performed best on. It also seemed to me like if I had multiple tasks to complete at once, I could shift the head cursor to the next target while using the slew switch to engage the current target.
- This one became very confusing have two moving cursors on the screen at once. The head tracker didn't always stop upon switching to crosshairs and I would get them mixed up and move the cross hair away from the target.
- I thought my performance on this one was much higher and that I could select things much quicker.

Z-Axis, Disappearing Cursor																																				
	User Ratings						User Weightings																													
Participant	Mental	Physical	Temporal	Performance	Effort	Frustration	Mental Demand	Physical Demand	Temporal Demand	Performance	Effort	Frustration	Mental Demand	Temporal Demand	Effort	Physical Demand	Performance	Frustration	Effort	Mental Demand	Temporal Demand	Frustration	Physical Demand	Temporal Demand	Mental Demand	Performance	Temporal Demand	Effort	Frustration	Physical Demand	Frustration	Mental Demand	Physical Demand	Performance	Performance	Effort
1	10	30	10	10	10	10		1		1	1		1			1	1		1		1			1		1		1		1		1		1	1	
2	55	40	35	25	40	30	1			1	1		1		1		1			1	1		1		1			1		1		1	1		1	
3	65	55	55	15	75	35	1		1		1		1		1		1			1	1		1		1			1		1		1		1		1
4	30	30	30	10	30	10			1		1			1	1		1			1	1		1		1			1		1		1	1			1
5	25	15	20	20	20	15	1		1			1		1	1			1		1	1			1	1		1		1		1			1		1
6	10	30	10	85	20	0		1		1	1		1			1	1			1	1		1			1		1		1		1		1	1	

Comments:
- This one was more mentally taxing, but went at a quicker pace.
- This method was much easier due to only needing two buttons to complete the task. Flowed very smoothly.

Z-Axis, Invisible Cursor																																				
	User Ratings						User Weightings																													
Participant	Mental	Physical	Temporal	Performance	Effort	Frustration	Mental Demand	Physical Demand	Temporal Demand	Performance	Effort	Frustration	Mental Demand	Temporal Demand	Effort	Physical Demand	Performance	Frustration	Effort	Mental Demand	Temporal Demand	Frustration	Physical Demand	Temporal Demand	Mental Demand	Performance	Temporal Demand	Effort	Frustration	Physical Demand	Frustration	Mental Demand	Physical Demand	Performance	Performance	Effort
1	30	30	20	20	20	20		1		1	1		1		1		1		1		1			1		1		1		1		1		1	1	
2	70	50	35	30	45	50	1			1	1		1		1		1			1	1			1	1			1		1		1		1	1	
3	85	85	45	45	85	65		1	1		1		1			1		1		1	1		1		1			1		1	1		1			1
4	60	40	30	50	50	30	1			1	1		1		1		1			1		1	1		1			1		1		1		1		1
5	30	15	30	25	25	25	1		1			1		1	1			1		1	1			1	1		1		1		1			1		1
6	80	40	40	40	80	50	1		1		1		1		1			1		1	1		1		1			1		1		1	1			1
Comments:	The cursor didn't snap exactly where I thought it would, so I had to be quick about snapping it to somewhere close and then using the slew to get it all the way there.																																			
	This method was difficult to grasp at first but ran more smoothly and I got practice. It is not my preferred way but could still get the job done.																																			

Z-Axis, Visible Cursor																																				
	User Ratings						User Weightings																													
Participant	Mental	Physical	Temporal	Performance	Effort	Frustration	Mental Demand	Physical Demand	Temporal Demand	Performance	Effort	Frustration	Mental Demand	Temporal Demand	Effort	Physical Demand	Performance	Frustration	Effort	Mental Demand	Temporal Demand	Frustration	Physical Demand	Temporal Demand	Mental Demand	Performance	Temporal Demand	Effort	Frustration	Physical Demand	Frustration	Mental Demand	Physical Demand	Performance	Performance	Effort
1	20	30	30	10	10	10		1		1	1		1			1	1		1		1			1		1		1		1		1		1	1	
2	50	35	30	20	40	20	1			1	1		1			1	1		1			1	1		1			1		1		1	1		1	
3	75	55	55	25	75	65	1		1		1		1		1		1			1	1			1	1		1			1		1		1		1
4	80	30	30	60	60	70	1			1		1	1		1			1		1		1	1		1			1	1			1		1		1
5	25	15	20	20	20	15	1		1			1		1	1			1		1	1			1	1		1		1		1			1		1
6	20	35	10	90	15	5		1		1	1		1			1	1			1	1		1			1		1		1		1		1	1	
Comments:	Really helpful in reducing downtime as cursor was moving, because I could snap it to where I was looking I was able to think and react quicker, and I performed better as I put in more effort compared to the slew only method. Mental workload went up, but performance also did.																																			
	I got confused sometimes on which cursor was the one I select with.																																			
	Once again, this one is confusing because of the two icons always seeming to move at the same time in different directions. I would get them confused and try to correct the wrong one.																																			

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14. ABSTRACT
Traditional control mechanisms restrict human input on the displays in 5th generation aircraft. This research explored methods for enhancing pilot interaction with large, information dense cockpit displays; specifically, the effects of visual feedback and control button configuration when augmenting cursor control with head tracking technology. Previous studies demonstrated that head tracking can be combined with traditional cursor control to decrease selection times but can increase pilot mental and physical workload. A human subject experiment was performed to evaluate two control button configurations and three visual feedback conditions. A Fitts' Law analysis was performed to create predictive models of selection time using each configuration. The models provided a poor fit to the observed data, indicating that Fitts' Law does not adequately describe human performance for these systems. A repeated measures analysis of variance revealed that there was no difference in performance between the two control configurations. Conditions without visual feedback were less accurate and slower than those with feedback. However, all configurations employing head tracking were faster than the current cursor control system and conditions without visual feedback will likely impose lower physical workload than the other configurations. Recommendations for future research and enhanced head tracking cursor control systems are discussed.

15. SUBJECT TERMS
Head Tracking, Human-Computer Interface, Cockpit Interface

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