Variations in Control and Display Gain in a First Control Order Compensatory Manual Tracking Task

Micah N. Morris

Embry-Riddle Aeronautical University - Daytona Beach

Follow this and additional works at: https://commons.erau.edu/db-theses

Part of the Ergonomics Commons

Scholarly Commons Citation
https://commons.erau.edu/db-theses/150

This thesis is brought to you for free and open access by Embry-Riddle Aeronautical University – Daytona Beach at ERAU Scholarly Commons. It has been accepted for inclusion in the Theses - Daytona Beach collection by an authorized administrator of ERAU Scholarly Commons. For more information, please contact commons@erau.edu.
Variations in Control and Display Gain in a First Control Order Compensatory Manual Tracking Task

by

MICAH NATHANAEL MORRIS

B.A., George Mason University, 2001

A Thesis Proposal Submitted to the
Department of Human Factors and Systems
in Partial Fulfillment of the Requirements for the Degree of
Master of Science in Human Factors and Systems

Embry-Riddle Aeronautical University
Daytona Beach, Florida
Fall 2003
Variations in Control and Display Gain in a First Control Order Compensatory Manual Tracking Task

by

Micah N. Morris

This thesis was prepared under the direction of the candidate’s thesis committee chair, Shawn Doherty, Ph.D., Department of Human Factors & Systems, and has been approved by the members of the thesis committee. It was submitted to the Department of Human Factors & Systems and has been accepted in partial fulfillment of the requirements for the degree of Master of Science in Human Factors & Systems.

THESIS COMMITTEE:

Shawn M. Doherty
Shawn Doherty, Ph.D., Chair

Steve Hall, Ph.D., Member

Kenneth Fleming, Ph.D., Member

MS HFS Program Coordinator

Department Chair, Department of Human Factors & Systems

Associate Chancellor of Academic Affairs
Acknowledgments

Special thanks should be given to Aage Rendalen, for his time spent in the considerate review of this document.
Abstract

There exist many factors that contribute to the optimal manual control of a system by a human operator (HO). Two such variables include control gain and display gain. Of particular interest to the following experiment is the contribution of these two variables to the manual tracking performance of any HO conducting a compensatory tracking task while using a first control-order tracking system. Since the optimal level of control gain required for maximal manual control of a tracking device is system dependent, it may be expected that the same holds true of display gain. Regardless, it is the purpose of the following proposed experiment to show that superior HO performance of the compensatory manual tracking system under study may be brought about by the combination of lower levels of control gain and higher levels of display gain in comparison to the combination of any other levels of these same variables. Tracking performance will be measured by the root mean squared error (RMSE) of tracking deviation as measured by the amount of distance that the element being controlled by participants under study deviated from the tracking device within a given time period.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Introduction</td>
<td>1</td>
</tr>
<tr>
<td>Control Theory</td>
<td>1</td>
</tr>
<tr>
<td>Sine Waves</td>
<td>4</td>
</tr>
<tr>
<td>Variables Affecting Sine Wave Output</td>
<td>5</td>
</tr>
<tr>
<td>Task Variables</td>
<td>6</td>
</tr>
<tr>
<td>Tracking</td>
<td>13</td>
</tr>
<tr>
<td>Hypotheses</td>
<td>18</td>
</tr>
<tr>
<td>Methods</td>
<td>20</td>
</tr>
<tr>
<td>Participants</td>
<td>20</td>
</tr>
<tr>
<td>Instrument/Apparatus</td>
<td>20</td>
</tr>
<tr>
<td>Design</td>
<td>21</td>
</tr>
<tr>
<td>Procedure</td>
<td>23</td>
</tr>
<tr>
<td>Pilot Study</td>
<td>23</td>
</tr>
<tr>
<td>Experiment</td>
<td>25</td>
</tr>
<tr>
<td>Data Analysis</td>
<td>25</td>
</tr>
<tr>
<td>Results</td>
<td>27</td>
</tr>
<tr>
<td>Control Gain</td>
<td>28</td>
</tr>
<tr>
<td>Display Gain</td>
<td>29</td>
</tr>
<tr>
<td>Interaction</td>
<td>31</td>
</tr>
<tr>
<td>Control/Display Gain Ratio</td>
<td>31</td>
</tr>
<tr>
<td>Discussion</td>
<td>34</td>
</tr>
<tr>
<td>Conclusions</td>
<td>39</td>
</tr>
</tbody>
</table>
## LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Closed-loop Model of Manual Control.</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>The Sine Wave.</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>Graph of Experimental Hypotheses.</td>
<td>19</td>
</tr>
<tr>
<td>4</td>
<td>Experimental Design.</td>
<td>23</td>
</tr>
<tr>
<td>5</td>
<td>Graph of estimated means of RMSE logs across the three levels of Control Gain.</td>
<td>29</td>
</tr>
<tr>
<td>6</td>
<td>Graph of estimated means of RMSE logs across the three levels of Display Gain.</td>
<td>30</td>
</tr>
<tr>
<td>7</td>
<td>Graph of estimated means of RMSE logs for the non-significant interaction of control gain X display gain.</td>
<td>31</td>
</tr>
<tr>
<td>8</td>
<td>Estimated mean RMSE log values as a function of Control Gain/Display gain ratios.</td>
<td>32</td>
</tr>
</tbody>
</table>
LIST OF TABLES

Table 1: Mean RMSE log scores for the combination of control gain levels 1-3 with display gain levels 1-3. 27

Table 2: Source Table for ANOVA involving the main effects of control gain, display gain, participant sex, and the interaction of control gain with display gain. 28

Table 3: Bonferroni post hoc comparison of RMSE log means for control gain including 95% confidence intervals. 29

Table 4: Bonferroni post hoc comparison of RMSE log means for display gain including 95% confidence intervals. 31
Introduction

There is a relationship between the input of a system and its output, described as control-display gain (Gibbs, 1962), and is defined by the control-display ratio (McCormick, 1976). This ratio may be divided into two categories or fundamental system components that are characteristic of an optimal control model. The first of these components is the decision or control component. It consists of the amount of control movement provided by the Human Operator (HO) to the system. The other component is perceptual. This component is used by the HO to estimate the state of a system, and it is defined by the amount of movement perceptually occurring on a display when the display provides visual feedback from the control movements. In a manual tracking task, the perceptual component is used by the HO in order to provide feedback as to the state of the system in terms of tracking deviation. This feedback is then utilized by the HO in order to produce the proper control to maintain maximum performance of the task at hand. The relationship between control and display components is a factor that should be considered in operator-machine interfaces due to its ability to provide optimal manual control of the system to which it pertains (Jagacinski & Flach, 2003; Parng, 1988).

Control Theory

Control Theory (CT) is often used to analyze control process concepts for anyone performing a manual control task (Wickens & Hollands, 2000; Poulton, 1974). It argues that control tasks can be measured by the amount of error reduction between the desired state of a system and its actual state. This error reduction is brought about by the application of force through a controlled element such as a joystick or mouse. The theory takes into account the forces provided by the HO, those inherent in the actual system, and
the application of force through a controlled element such as a joystick or mouse. The theory takes into account the forces provided by the HO, those inherent in the actual system, and any outside forces that could affect manual control (Doherty & Wickens, 2000). The theory uses techniques that are well-suited to the analysis of all systems involving manual control, whether simple or highly complex. The theory argues that an optimal level of human-machine performance can be found, and that systems should thus be designed based on that assumption. This framework for investigation is very useful, because the real potential for human operator optimality is now becoming a factor that is given great consideration (Kleinman, Baron, & Levison, 1970). It is therefore important to understand the system elements that contribute to this optimality for the particular system at hand, and CT provides the framework for this understanding.

![Figure 1](image_url)

**Figure 1.** A closed-loop model of system control as adapted from Moray, 1981.

The model in figure 1 is considered a closed-loop model of system control because it describes system control as a repetitive, circular process. Stimuli are first perceived by the controller in the form of system error, or the difference between the desired state of the system and its actual state. Once this error is perceived, the human decides what response to execute in regard to the perceived stimuli. This response
decision is then physically executed by means of a controlled element, such as a joystick, yoke, or steering wheel. The response from the system being controlled (such as a car) to the control behavior of the human generates feedback as to the outcome of the action with the inclusion of the injected disturbances. This feedback is then received by the sensory receptors, and the cycle repeats (Moray, 1981).

As control theory includes an account of the forces provided by the human operator, it asserts that optimal feedback control of a closed-loop system is achieved by the human’s capability of adjusting or equalizing their behavior to account for dynamics and disturbances in the system. The HO becomes a serial element due to their responsibility to act on any displayed error that exists between a desired input and the output of the system’s state, which results in a control action. The role of the human is described as “serial” because their action must be completed before the next step in the closed-loop cycle can commence.

Humans tend to show differences in system control abilities from their first exposure to the system to the point at which they have become familiar with it. The HO undergoes an adaptive process when attempting to control a system. When measuring human system control performance, it is important to distinguish between control that involves adaptation or learning, and control that involves a HO that is fully adapted to the dynamics of the system. By differentiating the two sources of performance scores, one can get a firm grasp of what human performance will look like for the system after HO adaptation. The adaptive process first involves the development of a desired level of mastery between the command by the controller and the response elicited by the controlled element. Next, the controller can suppress any inputs and disturbances that are
not desired. The controller then minimizes the effects that uncertainties and variations
existing in the control loop’s components may have. Finally, the controller attempts to
maintain the stability of the control they have over the system (McRuer & Jex, 1967).

The control behavior of the human, which typically involves a reduction in error
between the desired state of the system and its actual state, is a major component of
system output. Output is essentially comprised of the behavior of the operator, any
disturbances injected into the system, and the response elicited by the system to these two
factors. Output in a manual tracking task is characterized by the amount of error between
the position of a controlled element and a target. This output may be described by a sine
wave.

*Sine Waves.* Sine waves, also called sinusoids, are characterized by spatio-temporal
patterns pertaining to rhythmic phenomena, such as movements. Any sinusoid is made
up of a certain shape, which is defined by three factors: amplitude, frequency, and phase.
A wave’s amplitude is a measure of its magnitude. It defines the wave’s maxima and
minima. In manual control tasks, the amplitude of the sine wave provides a description
of the distance between the desired state of the system and its actual state. The frequency
of a wave is a measure of the number of times the wave’s pattern repeats within a given
time period. Higher frequency manual control systems are characterized by many
oscillations or deviations from the system’s desired state and its actual state within a
given time period. Lower frequency systems are characterized by fewer oscillations.
Frequencies are typically measured by cycles per second, and are reported in Hertz (Hz).
The phase of a wave is simply a description of the amplitude and frequency of the wave
cycle that is occurring at a particular time. Thus, the comparison of the phase of a system’s output to its desired phase describes how much deviation between the actual state of the system and its desired state is occurring at any given time.

Figure 2. The sine wave as adapted from Jagacinski & Flach, 2003.

The graphs in figure 2 illustrate the three aspects of a sine wave. The top graph shows two waves of different amplitudes. The middle graph contains two waves with different frequencies, and the bottom graph has waves of different phases.

Variables Affecting System Sine Wave Output

The ability of the human to minimize sine wave oscillations in terms of both amplitude and frequency, and thus reduce system error, depends heavily on the amount of control provided either by the human, or by the dynamics inherent in the mechanics of the system (Jagacinski & Flach, 2003). Both the human and machine components of the system as they apply to manual control may be divided into five classes of variables, all
of which affect overall system sine wave output. These variable classes include task, environmental, operator-centered, procedure, and remnant variables. Of particular relevance to the following study are task variables. For this reason, they will receive further discussion.

Task Variables. Task variables constitute one of the factors that increase variability in HO control of a system. They are the control elements of the system that are external to the controller. They impose on the HO's task of control directly and explicitly, and many of them have a major effect on the HO's dynamics (McRuer & Jex, 1967). They have a direct effect on the control actions of the HO because of the variability of the system's complexity that they provide (McCormick & Sanders, 1982). The task variables having the most impact on the task performance of the HO include the manipulator or control element, forcing function, display, and controlled element dynamics (McRuer & Jex, 1967).

Since variability in controller ability can be observed as a function of the type of control device used, various control devices have been incorporated in prior research involving manual control systems. Control devices used include control knobs, joysticks, and a mouse (Jenkins & Connor, 1949). It has been discovered that joysticks enhance the impact that mechanical properties have on the controller output (Doeringer & Hogan, 1988, Poulton, 1974). Research in tracking tasks that incorporate various levels of control order indicate that velocity systems are controlled best when using a spring-centered joystick or force stick. When the system involves position control such as moving a cursor to a new position on a screen, a mouse provides optimal control
In addition, control of visual targets are more accurate if the participant's hands remain visible (Woodworth, 1899). If the hand is moved out of view after a long training period during which it is visible, large increases in spatial errors result (Khan & Franks, 2000; Khan, Franks, & Goodman, 1998; Proteau, 1992, 1995).

A forcing function is a force or disturbance imposed upon the control exerted by the HO using a controlled element. It is deliberately put into the system for the purpose of testing its control abilities. For instance, in a manual control task, some initial input function must be exerted upon the system element that is to be controlled by the HO. The forcing function is used to initiate movement, which translates to sine wave oscillations that must be controlled. A primary example is in the control of an automobile. A forcing function may be provided by curves in the road, or inclines and declines. The HO must control the vehicle to match the road. The controller will not attempt to correct any system state errors unless this force is first placed upon the controlled element. Without any curve in the road, there is no forcing function and the driver will not make any corrective movements. Another form of a forcing function may come from wind gusts. In this case, each gust of wind would be considered to be a disturbance on the system. The driver will have to correct the vehicle in response to these disturbances.

In a compensatory manual tracking task, the forcing function of a moving target cannot be observed because the target is stationary. Therefore, the forcing function must come from disturbances. If the object under control by the human is being pushed away from the target by some external force other than the human, the system is experiencing the forcing function of a disturbance.
The display being used involves several task variables that affect controller output. One component of the display that has such an impact is the level of display gain inherent in the display. Essentially, display gain is a perceptual phenomenon involving the ratio of change provided by a display with reference to a real-world movement (Wickens & Hollands, 2000). A high amount of display gain can be observed by a large change in the display in response to a small amount of real-world change. Conversely, a low amount of display gain is associated with a small change in the display in response to the same amount of real-world change (Doherty & Wickens, 2000). For example, there is more movement or change in display when a movie is viewed at a theater in comparison to the amount of display change when the same movie is viewed at the same seating distance at home on a 26' television. The movie theater, in this example, has more display gain than the television, for the same image. Thus, display gain levels can be manipulated by adjusting the size of the display. This is due to the fact that movements become larger, and greater movements in the display are provided, as the display increases in size and the “real-world” movement remains the same. Because movements are observed over a greater distance, a display with higher gain allows the controller to predict the future state of the system with greater accuracy.

As McRuer & Krendel (1959) indicate, more aggressive control actions are observed when displays with higher gain are used in a tracking task. This is due to the fact that higher display gain results in a greater amount of error displayed. It may be assumed that the HO is more likely to perceive displayed errors when they are larger, and it is for this reason that tracking performance increases with higher levels of display gain. This claim is consistent with the findings of Doherty and Wickens (2000), who observed
fewer participant tracking errors with a higher-display gain system than with a lower-display gain system. Based on these findings, it is evident that HO control abilities of a system are affected in part by the display gain of the system. It is therefore important that an optimal level of this factor should be discovered for the system under investigation.

A task variable that impacts the output of the overall system is the concept of control gain. Control gain is the ratio of the amount of control provided to the device used by the human compared to the actual control of the system as indicated by its output. In a real-world application, control gain is experienced in driving a car or operating a drill (Buck, 1980). Automobiles vary in the amount of control output they provide in response to the control input by the driver. Vehicles with large changes in steering system output for small variations in control input are high control gain systems and make sharp turns in response to a small amount of steering. This is often the case with sports cars, as they are typically designed with high control gain, providing the vehicle with the capability of making quick turns in response to a small amount of input from the driver. On the other hand, a steering wheel requiring multiple turns in order to achieve the same amount of turn as the high gain vehicle is considered to have lower control gain. Sports utility vehicles are often equipped with lower levels of control gain due to the high roll-over rate that result when a vehicle with such a high center of gravity makes a turn too quickly. In the example of a power drill, a high control gain drill produces many revolutions in a short period of time in response to a given amount of input, whereas a drill with lower control gain makes fewer revolutions for the same amount of input.

Previous research on the effects of control gain indicates that the type of movements required of the system determines the optimal level of control gain. High
control gain has been associated with a reduction in the time required to move within the range of a target (Buck, 1980). Further support for the use of high control gain is provided by McRuer & Jex (1967), who note that increases in control gain tend to reduce overall system output errors for pilot vehicle systems. On the other hand, low control gain has shown to be beneficial in making final corrective movements onto a target. An optimal ratio of human input to system output for the system under observation balances the advantages of high control gain with the advantages of low control gain. Since the current study attempts to establish the optimal level of control gain needed to achieve minimal system state deviations, it is important to keep the aforementioned findings in mind.

Another task variable involving the control dynamics of the system is the control order of the system. The state of the system is determined as a function of the order of control inherent in the system. System control involves zero- through third and higher-order control systems. The level of control order inherent in the system has a profound impact on the input required by the HO in order to generate the desired output.

A zero-order system is also called a “null position” system. When the HO sends a signal to the system via a controlled element to move, the system moves at a distance proportionate to the HO input. Once the HO stops sending the command signal, the system stops moving. For example, the mouse cursor used on the display of most personal computers involves a zero-order system. The cursor starts moving once the mouse has been moved by the HO, and it stops moving once the HO stops moving the mouse.
First control-order systems are also called velocity (Roscoe, Eisele, & Bergman, 1980) or rate (Poulton, 1974) systems. The major difference between zero- and first-order systems is that a first-order system continues to change at a constant velocity once initiated until commanded by the HO to do otherwise. The first-order system will therefore continue to move if no signal is sent to change its movement. Because of this, one must know the initial position of the system, in addition to the amount of input, in order to determine the system’s output. One advantage of a first-order system over a zero-order system is its reduction in the amount of input force required by the human to make the system reach a certain state. This is particularly advantageous in circumstances in which the HO’s range of motion is limited. For instance, the first control-order mouse of a personal computer would allow a person to scroll through a limitless amount of displayed information without using the mouse once the initial movement has been made.

First-order systems are used in space travel. Space flight without gravitational pull involves the movement of a shuttle at a constant velocity through space. Once the velocity of the shuttle has been initiated, there is no longer the need for any more control input in order to keep it moving. Input is required, however, when the pilot of the shuttle needs to change its direction in order to adhere to a designated path.

Second-order systems are also called “acceleration” systems. In order to control or determine the output of second-order systems, one must know the initial position and velocity of the system, as well as any future input required to control the system. Essentially, second-order systems will continue to accelerate in response to an input, until controlled to change position. Second order systems are more difficult to control than
first-order systems due to the fact that more system state knowledge is required. It is very
difficult to determine where the state of the system will be in the distant future.

When a space shuttle is experiencing the gravitational pull of some source, it
becomes a second control-order system. It will continue to accelerate once it starts
moving in the direction of the pull at a specific rate unless controlled to do otherwise
until it reaches a terminal velocity. Because careful calculations must be made, based on
knowledge of the gravitational pull, as well as the initial speed of the shuttle, it is very
difficult to determine the future state of the shuttle mathematically. Humans, however,
are equipped with the ability to predict this future state in such cases, particularly when
they have received practice with such a task. Regardless, it is more difficult to predict the
behavior of second-order systems than first-order systems because of the increased
amount of system state knowledge required. This is true of third control-order and higher
systems as well. It is possible for a skilled controller to achieve proficiency in the control
of these systems with proper training and proper display of control feedback, but it
becomes increasingly difficult with higher control-order systems (Jagacinski & Flach,
2003). In order to predict optimal system control for a system which has control order of
these levels, one would have to account for and be able to manipulate many dynamics
inherent in the system. While this may be done experimentally, the current study will
focus on a system of first control order, requiring fewer manipulations.

Another system dynamic that impacts controller output is signal degradation.
There are various ways in which a signal may be degraded which impacts human
performance in system control. Lag, or transport delay, is a common source of signal
degradation. Essentially, lag is defined by the amount of time offset between a HO’s input command to the response by the system.

The notion of lag has been widely studied, particularly as it pertains to human performance in real-time interactive computer graphics applications. Sources of lag in a typical computer system are numerous. There may be delays in the tracker signal. There may also be communication delays existing between the human tracker and the computer system. Lag may also result from computation delays needed to process the data of the tracker (Bryson, 1993). Since variability in performance among HO’s may be observed as the result of lag, it is important to understand how much lag is inherent in the system.

Accounting for factors such as the control device being used, the forcing function, display gain, control gain, and the control order in the design of systems involving manual control provides the HO the ability to generate output that is closer to the human’s desired state for that system than if these factors are not accounted for. This is true for any system involving tasks explained by Control Theory.

*Tracking*

One task to which Control Theory has been applied is manual tracking. Tracking involves a class of movement tasks in which the issue of corrective, closed-loop control is the primary focus. As CT involves reducing error between the desired state of a system and its actual state through the use of a control device, manual tracking tasks often require the HO to keep a controlled element within a target. The controlled element is often represented by a cursor on a display. The operator inputs a control signal to the cursor, which brings about a change in the cursor’s position. This change is perceived by
the controller, whereby a response decision is made. This decision is based on where the perceived stimulus is going next, as well as the amount of corrective action that needs to occur in order to maintain the cursor upon the stimulus (Jagacinski & Flach, 2003). Thus, manual tracking is a specific task that may be applied to the CT framework.

Manual tracking is a phenomenon that has been under study for a great deal of time. In 1899, Woodworth found that, as a trajectory approaches a target in a tracking task, the human controller intermittently checks the remaining error to the target (As cited in Russell & Sternad, 2001). Proportional corrections required to nullify the error are then implemented. Since this research, such discontinuities have been widely observed throughout many research studies involving tracking tasks (Russell & Sternad, 2001). Much of the research in visuomotor tracking was inspired by its use in ergonomically efficient control designs since the 1950’s (Wickens, 1984). These designs have become the basis of experimentation into the nature of control processes involved in voluntary movements in manual tracking (Russell & Sternad, 2001). The general conclusion of the aforementioned research is that these errors are the result of the central controller making intermittent corrections (Craik, 1947).

As minimizing error is the ultimate goal of the HO’s serial element role in a tracking task, commands must be followed and disturbances must be regulated. It is by doing this that the operator is able to develop a stable relationship between control input actions and the output signals displayed, if sufficient practice is provided (McRuer & Jex, 1967).

The tracking systems for which manual tracking experiments are conducted may be characterized by either pursuit or compensatory tracking demands. During a pursuit
tracking task, a participant actively pursues a moving target with a controlled object. This pursuit is conducted by moving the control device so that the controlled object is in alignment with the target cursor, and the relative error between the target and controlled object is displayed. For example, fighter aircraft must align their target cursor with a moving aircraft in a pursuit fashion before they can fire upon it.

During a compensatory tracking task, a marker indicates the amount of error between the object under control and the target track. This marker is typically at the display's center. Another cursor moves relative to the fixed cursor in a way that is proportionate to the size of the tracking error. The participant will compensate for the displayed error by moving the controlled cursor in the direction that is appropriate in order to correct the displayed error. If this is done successfully, the moving cursor will remain near the center of the target. Only the relative error between the controlled object and target track are seen on the display (Jagacinski & Flach, 2003).

The difference between the two types of tracking is marked by the fact that pursuit tracking involves a moving target, whereas compensatory tracking involves maintaining the controlled element within a stationary target. Essentially, the HO has to adhere to a track that they cannot see when conducting a compensatory tracking task, by minimizing the error between the controlled element and the stationary target. An example of a system involving a pursuit tracker is a ground-to-air missile system. Since the system involves the tracking of a moving aircraft, pursuit tracking is involved. Compensatory tracking, on the other hand, is incorporated into many air-to-ground missile systems, since a stationary target must be adhered to, and the missile is the system component that contains a forcing function. Experiments comparing the two types of tracking indicate
that pursuit tracking tasks usually result in more accurate tracking than compensatory tracking tasks when lower-order systems including lag are involved. When velocity or higher-order systems are used, the disadvantages of the compensatory tracking system involving lag are reduced. Since all systems typically involve a certain amount of lag, as previously indicated, a compensatory tracking device would provide superior control over a pursuit tracking device in a velocity system.

In addition to their advantages in the use of higher-order systems, compensatory tracking devices are also advantageous in tracking systems involving low frequencies, such as when a pilot must keep a moving aircraft onto a flight path, and the aircraft does not often deviate from its intended course. When little change is involved in a tracking device, the predictive ability of the HO provided by the compensatory tracker is most evident (Poulton, 1974). The reason for this is that humans naturally vary in their ability to control tracking systems. Whenever increases are made in the amount of operator control required to achieve optimal tracking performance, more variability among operators with regard to this measure will be observed. Therefore, decreased control gain may be of greater value in a compensatory tracking device, as opposed to a pursuit tracker due to fewer sine wave output oscillations associated with lower control gain. Consistent with this approach, the finding that increased display gain results in fewer tracking deviations (Doherty & Wickens, 2001) suggests that a compensatory tracking device would have more predictive ability with a higher display gain system because of lower frequencies associated with tracking deviation. An example of a system that would benefit from such system dynamics is a jumbo jet that is en-route making a trans-Atlantic flight. Display gain would be high in this example, and few changes in direction would
be required. In this case, a compensatory tracking device would provide optimal pilot performance, since the task is to adhere to a designated flight path.

In concept, the variation in participant performance for a tracking task may be affected by the combination of both control and display factors. This was the focus of Buck’s (1980) study of a pursuit-tracking task, in which the displayed control device target width and display target width were manipulated. The width of the controlled device represented on the display that was actually controlled by the joystick and the target width varied. Buck hypothesized that movement time is determined by the width of the target on the control device, and that target width accounts for the effects that the control/display gain ratio have on the participant in a tracking task. This hypothesis was based on previous studies involving overshooting of system output in positioning tasks. His results indicate that both control and display target widths affected tracking performance. Fine adjustment time, also called overshoot time was affected by the widths of both the control target and the display target. Gross movement time, also referred to as acquisition time, was only affected by the width of the control target. He inferred that when the target width of the display is held constant, increasing control target width enhances motor performance by decreasing the ratio of control gain to display gain. Based on this finding, it is evident that benefits may be drawn from a further investigation into the independent effects that each of these factors has on tracking performance.

If an optimal control to display gain ratio (C/D ratio) can be achieved for any given system, it could balance the trade-offs between movement times associated with gross and fine movements in control positioning. For instance, Gibbs (1962) found that
Gross movement time could be reduced with high C/D gain. It seems that, when large deviations in the desired state of the system are present, higher control gain paired with lower display gain is the optimal solution. However, high C/D gain led to increased fine adjustment movement times, and a lower level of C/D gain is therefore desired. Ultimately, optimal C/D gain is going to be dependent on the control-display interface.

McCormick and Sanders (1982) provide a guideline for obtaining an optimal C/D ratio. Essentially, they state that the optimal C/D ratio is a function of the type of control device, the size of the display, the tolerance permitted in setting the control such as the amount of control gain, and other system parameters such as lag. The problem is that there is no single formula for determining the optimal C/D ratio for any given system. Therefore, this ratio must be determined experimentally, incorporating the display under contemplation. It is very important that this ratio is found, however, because it has been recognized as one of the most important factors in designing displays that incorporate continuous control.

Hypotheses

Main effects were expected for both control gain and display gain. Specifically, it was expected that, for this particular tracking system, tracking performance would improve as control gain decreased. Therefore, tracking deviations would become larger as control gain increased. In addition, it was expected that tracking performance would improve as display gain increased, meaning that tracking deviations would be larger with lower levels of display gain. Thus, a negative relationship between control gain and display gain as they impact tracking performance was anticipated. An interaction of the
two variables was also expected. Specifically, optimal tracking performance was expected with the combination of the highest level of display gain with the lowest level of control gain. Less of an advantage to tracking performance was expected with the combination of a medium level of display gain with a low level of control gain, and a low level of display gain combined with the lowest level of control gain was expected to bring about poorest tracking performance. Conditions involving the highest amount of control gain in combination with any of the levels of display gain were expected to result in improved performance compared to that of the low display gain/low control gain condition. Figure 3 provides a graphical representation of the experimental hypotheses.

Figure 3. Graph of Experimental Hypotheses.
Methods

Participants

The study consisted of a total sample 90 students for the experimental portion, and 18 students for the pilot study, all being from Embry-Riddle Aeronautical University (ERAU). The sample size was determined through a pilot study, during which the estimated effect size of the independent variables was determined. Recruitment for participation was conducted by offering extra credit in the students’ undergraduate courses. Participants were required to have 20/20 corrected visual acuity, such that performance variability could not be attributed to participant sightedness. Although participants were not required to be of a certain gender, gender information was collected, such that this factor could be included in the analysis to determine if it played a significant role in participant performance. Since visuo-spatial/motor coordination differences have been observed among those with right- and left-handedness because of the dominance of the left hemisphere in this domain (Rushworth, Krams, & Passingham, 2001), the handedness of the participant was recorded. Participant age was not controlled, as little age variability was expected amongst ERAU students, although age information was recorded to be included in the analysis.

Instrument/Apparatus

Tracking performance was observed in a two-dimensional display environment. The study was conducted using the compensatory tracking portion of a generic manual tracking program. Since first-order systems are a large part of manual control in aviation, the tracking system utilized this level of control order.
The tracking system incorporated a low-frequency forcing function.

Compensatory tracking was incorporated in the study. This was due to the advantages that compensatory tracking devices provide in low frequency, first control-order systems. The test was displayed via a projector onto a white background in the Human Factors laboratory in the Lehman Building at Embry-Riddle Aeronautical University. Although the use of a joystick has been shown to provide best transfer from the controller’s input to the tracking system in recent research involving compensatory tracking tasks with first control-order tracking devices (Jagacinski & Flach, 2003), a mouse was used by the participants in the tracking task as the control device. This decision was due to practical considerations in finding a joystick that is compatible with the tracking software. It is not expected that the difference in performance associated with this type of tracking device will be very large in comparison to the performance that would result from the use of a joystick.

There was no controller time delay or lag added to the tracking trials. A forcing function was incorporated into the system, such that the cursor would not stay within the bounds of the target without the application of input from the participant.

Design

Three conditions of display gain were incorporated into a first control-order compensatory tracking task display, which required participants to adhere to a target stimulus using a first control-order mouse, represented by a cursor on the display. The manipulation of the amount of display gain was exercised by varying the size of the visible area on the tracking device within which tracking took place. Thus, the display
size was manipulated in order to provide these three levels of display gain. A projector was used to display the tracking device and manipulate display gain levels. In order to achieve variations in display gain, the projector was moved further from the wall on which the projection took place. Meanwhile, the distance that each participant sat from this wall remained constant at 171 cm. This distance was used in previous research by Vercher, Volle, & Gauthier (1993), and is therefore an adequate seating distance from the display, and does not result in a seating distance that affects visual acuity. As there were three levels of display gain, the condition with the least amount of display gain consisted of a 15” display size. Because participants were seated 171 cm from the display, a visual angle of 13.5° was created. The next level of display gain increased X2, such that a 30” display of the tracker was visible, and a visual angle of 26.7° resulted. The third level of this variable included a display which increased X3 of the first condition. This provided a 45” display size of the tracker, and a visual angle of 39.1°.

The amount of control gain provided to the participants was also manipulated. The software package allows control gain to be set anywhere between a 1.0 and 10.0 interval. This interval constitutes a linear increase in control gain. For the purpose of this experiment, levels of 1.0, 2.0, and 3.0 control gain were used, as the results from a pilot study indicated significant differences in participant performance between these levels.

Pairing the three levels of display gain with the three levels of control gain, resulted in a 3X3 design structure. A different set of participants were placed in each condition. Thus, participants were studied in a completely between-subjects format.
Each participant was tested a total of ten minutes, in five blocks of two-minute trials.

The structural format for this experiment is as follows:

<table>
<thead>
<tr>
<th>Display Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 X 15”</td>
</tr>
<tr>
<td>Control Gain</td>
</tr>
<tr>
<td>3.0</td>
</tr>
</tbody>
</table>

Figure 4. Experimental Design.

The dependent variable under study was controller compensatory tracking ability. Performance pertaining to this factor was measured by participants’ abilities to adhere to the target stimulus within the tracker’s display. More specifically, this performance was measured by each participant’s average RMSE tracking deviation from the three trials in each condition, which the software program automatically generated.

Procedure

Pilot Study. Any task involves a certain amount of learning. As a result of this learning, performance tends to increase over trials. In order to gain an understanding of where, on a timeline, familiarity with the tracking task no longer had an influence on the tracking performance of the participants, a pilot study was conducted for all levels of the experiment. There were two participants per level for the pilot study. Thus, a total of 18 participants were tested during the pilot study. Similar to the experiment, tracking performance was observed over a period of ten minutes, including five two-minute trials. The RMSE tracking deviations were measured at 60 Hz. Performance was poorer in the
beginning than at the pilot study's conclusion for each participant. The first trial was excluded from the analysis because it was discovered that performance had leveled-off after this trial. Therefore, trial number one was considered a practice trial. Thus, the variability in tracking performance scores that may be attributed to learning were accounted for in the study by following this procedure.

Another purpose of the pilot study was to determine if the levels of control and display gain had been set at adequate intervals so that performance differences would likely be observed during actual experimentation if differences actually existed. As there is limited literature on studies which have incorporated control and display gain within the context of this specific tracking system, this was a necessary measure to perform. It was assumed that the parameters established for these variables would be adequate for the experiment if main effects were observed during the pilot study. Thus, if there was a difference somewhere for each variable during the pilot study, it would be assumed that the parameters established were adequate.

Pilot study participants were first asked to read and sign an informed consent form. They were then given a short demographic questionnaire to complete. The question items on the questionnaire included the age, sex and handedness of the participant, as well as the year of college they were in, whether they play video games, and whether they are a pilot. All of these questions were included because of the suspicion of the researcher that these factors may have an impact on performance. Each participant was next as to their objective during participation. They were instructed to keep the cursor, as controlled by the mouse, within the target. The participant was then administered the five two-minute trials. Data were recorded at 60 Hz, until the entire ten-
minute observation was complete. The participant was then debriefed as to the purpose of the pilot study, and any questions that the participant had were answered.

The results of the pilot study indicated that a total of ninety participants would be needed for the experiment (10 per condition). This conclusion was based on the estimate of effect size provided by the pilot study, the fact that a completely between-subjects design was being used, and the fact that the desired power of the study was set at .80.

Experiment. Based on results from the pilot study, the procedure for the experiment remained the same. Participants first received an informed consent form to sign, acknowledging that participation was entirely voluntary. Next, they completed a demographic questionnaire identical to that of the pilot study. They were then briefed as to their objective during participation. The time to administer the informed consent form, questionnaire, and the briefing was five minutes. The ten-minute experiment was then administered, and performance data were collected 60 Hz. Upon the conclusion of the experiment, participants were debriefed as to the purpose of their participation, and questions were answered by the researcher.

Data Analysis

Data collected during the pilot study, as defined by the RMSE tracking deviation, were analyzed using a factorial analysis of variance (ANOVA). The analysis included the control gain and display gain variables, as well as the interaction of the two. The average RMSE of trials 2-5 were computed, and the natural log of that score was then used in the
actual analysis. The log of each person’s RMSE score was used in order to normalize the data, since RMSE scores are weighed more heavily the larger the deviation score is.

Post hoc tests using Bonferroni correction were used to compare mean differences following the ANOVA. This provided a description of mean differences between conditions. The confidence interval of the study was set at the 95% level of confidence.
Results

The analysis of the experimental results served three purposes. The first was to determine if there were significant effects for the main effects and interaction. The second purpose was to determine if the levels of the experiment that should result in equal ratios actually resulted in ratios of equal proportion. Finally, given these ratios, is there a linear increase in performance attributable to lower control gain/display gain ratios.

Based on the suggestion made by Vercher, Volle, and Gauthier (1993) that tracking performance could vary as a function of participant sex, this factor was included in the analysis as a blocking variable. It was discovered that it did indeed have a significant impact on performance $F(1, 89)=16.814, p<.001$.

The mean RMSE log scores for each of the conditions are as follows:

<table>
<thead>
<tr>
<th>Control Gain</th>
<th>Display Gain</th>
<th>RMSE</th>
<th>Log RMSE</th>
<th>Std. Deviation</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>15&quot;</td>
<td>.002</td>
<td>-1.966</td>
<td>0.396</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>30&quot;</td>
<td>.001</td>
<td>-2.179</td>
<td>0.220</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>45&quot;</td>
<td>.001</td>
<td>-2.246</td>
<td>0.218</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>15&quot;</td>
<td>.001</td>
<td>-1.960</td>
<td>0.304</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>30&quot;</td>
<td>.001</td>
<td>-2.117</td>
<td>0.382</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>45&quot;</td>
<td>.004</td>
<td>-1.880</td>
<td>0.613</td>
<td>10</td>
</tr>
<tr>
<td>3</td>
<td>15&quot;</td>
<td>.001</td>
<td>-1.950</td>
<td>0.234</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>30&quot;</td>
<td>.002</td>
<td>-1.994</td>
<td>0.393</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>45&quot;</td>
<td>427</td>
<td>-1.670</td>
<td>0.897</td>
<td>10</td>
</tr>
</tbody>
</table>

Table 1: Mean RMSE log scores for the combination of control gain levels 1-3 with display gain levels 1-3.
The following is the source table for the discussion of the results for the control gain, display gain, and display gain X control gain interaction that follows.

### Tests of Between-Subjects Effects

**Dependent Variable: RMSE Log**

<table>
<thead>
<tr>
<th>Source</th>
<th>Type III Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>p</th>
<th>Eta Squared</th>
<th>Observed Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corrected Model</td>
<td>5.283</td>
<td>9</td>
<td>.587</td>
<td>3.359</td>
<td>.002</td>
<td>.274</td>
<td>.976</td>
</tr>
<tr>
<td>Control Gain</td>
<td>1.117</td>
<td>2</td>
<td>.559</td>
<td>3.196</td>
<td>.046</td>
<td>.074</td>
<td>.596</td>
</tr>
<tr>
<td>Display Gain</td>
<td>.223</td>
<td>2</td>
<td>.112</td>
<td>.638</td>
<td>.531</td>
<td>.016</td>
<td>.153</td>
</tr>
<tr>
<td>Sex</td>
<td>2.938</td>
<td>1</td>
<td>2.938</td>
<td>16.814</td>
<td>.000</td>
<td>.174</td>
<td>.982</td>
</tr>
<tr>
<td>Control Gain X</td>
<td>1.145</td>
<td>4</td>
<td>.286</td>
<td>1.638</td>
<td>.173</td>
<td>.076</td>
<td>.483</td>
</tr>
<tr>
<td>Display Gain</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Error</td>
<td>13.981</td>
<td>80</td>
<td>.175</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Corrected Total</td>
<td>19.264</td>
<td>89</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\( a \) Computed using alpha = .05  
\( b \) R Squared = .274 (Adjusted R Squared = .193)

Table 2: Source Table for ANOVA involving the main effects of control gain, display gain, participant sex, and the interaction of control gain with display gain.

### Control Gain

After conducting a factorial analysis of variance on the control gain and display gain factors, as well as the interaction of the two, and including the participant sex factor as a blocking variable, a significant main effect was found for control gain, \( F(2, 87) = 3.196, p = .046 \). The observed power for this factor was .596, and eta squared was .074.

Figure 5 below illustrates the main effect of control gain. Notice increases in performance as control gain decreases. After computing Cohen's d (refer to Appendix A) for control gain, the effect size was .560.

After conducting a Bonferroni corrected post-hoc test for mean comparisons (refer to Appendix A) on the main effect of control gain, the only difference gaining moderate
significance belongs to the levels of 1 and 3, which had a significance level of $p=.056$, as illustrated in table 3. The following graph illustrates mean differences for control gain.

![Graph of estimated means of RMSE logs across the three levels of Control Gain.](image)

**Figure 5:** Graph of estimated means of RMSE logs across the three levels of Control Gain.

The results of the Bonferroni post hoc comparison of control gain mean differences, including confidence intervals at the 95% confidence level:

<table>
<thead>
<tr>
<th>Control Gain</th>
<th>Control Gain</th>
<th>Mean Difference</th>
<th>Std Error</th>
<th>$P$</th>
<th>95% Confidence Interval</th>
<th>95% Confidence Interval</th>
<th>95% Confidence Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>Medium</td>
<td>-145</td>
<td>108</td>
<td>551</td>
<td>-409</td>
<td>119</td>
<td></td>
</tr>
<tr>
<td>Low</td>
<td>High</td>
<td>-259</td>
<td>108</td>
<td>056</td>
<td>-523</td>
<td>001</td>
<td></td>
</tr>
<tr>
<td>Medium</td>
<td>High</td>
<td>-114</td>
<td>108</td>
<td>881</td>
<td>-378</td>
<td>150</td>
<td></td>
</tr>
</tbody>
</table>

Table 3: Bonferroni post hoc comparison of RMSE log means for control gain including 95% confidence intervals.

**Display Gain**

The display gain factor was not significant, $F(2, 87)=.638, p=.531$. Power for this factor was .153, and eta squared was .016. Cohen's $d$ for display gain was .058.

Although none of the mean comparisons for the display gain factor were significant, it is interesting to note that there is the possibility of actual differences
occurring at the 95% confidence level. A display size of 30” could have resulted in better performance than the 15” display by .402 RMSE log points according to the lower bound of the interval, and a display of 45” could have resulted in RMSE log scores .010 points better than the 30” display. With the low level of power for this factor, it is difficult to determine if these differences actually exist. Figure 6 illustrates means for the non-significant effect of display gain.

Figure 6: Graph of estimated means of RMSE logs across the three levels of Display Gain.

The results of the Bonferroni corrected post hoc comparison of mean differences for display gain, including confidence intervals at the 95% confidence level are in the following table.
Interaction

The interaction was found to be not significant, $F(4, 87)=1.638, p=.173$. Power for the interaction was .483, and eta squared was .076. The plot of the means for this non-significant interaction is as follows:

![Graph of estimated means of RMSE logs for the non-significant interaction of control gain X display gain.](image)

Figure 7: Graph of estimated means of RMSE logs for the non-significant interaction of control gain X display gain.

Control/Display Gain Ratio

It was expected that observing equal control gain/display gain ratios would result in similar performance. This was not the case, however. When combining control gain

<table>
<thead>
<tr>
<th>Display Gain</th>
<th>Display Gain</th>
<th>Mean Difference</th>
<th>Std. Error</th>
<th>$p$</th>
<th>95% Confidence Interval</th>
<th>95% Confidence Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>15&quot;</td>
<td>30&quot;</td>
<td>.138</td>
<td>.108</td>
<td>.618</td>
<td>-1.26</td>
<td>.402</td>
</tr>
<tr>
<td>15&quot;</td>
<td>45&quot;</td>
<td>-.003</td>
<td>.108</td>
<td>1.000</td>
<td>-.291</td>
<td>.237</td>
</tr>
<tr>
<td>30&quot;</td>
<td>45&quot;</td>
<td>-.165</td>
<td>.108</td>
<td>.394</td>
<td>-.429</td>
<td>.010</td>
</tr>
</tbody>
</table>

Table 4: Bonferroni post hoc comparison of RMSE log means for display gain including 95% confidence intervals.
level 1 with a display gain level of 15", which was labeled as display gain level 1. The RMSE log score came to -1.966. Combining control gain level 2 with the second display gain level of 30" resulted in a score of -2.117. Finally, the combination of control gain level 3 with display gain level 3, which was 45", resulted in a mean score of -1.670.

Although there was no significance for the interaction of the two independent variables, there seems to be a tendency for those who use a tracking system with a lower ratio of control gain/display gain to exhibit better results. Notice figure 8 below, which illustrates this tendency. Since lower RMSE log values indicate better tracking performance, the suggestion is that a lower level of control gain, paired with a higher level of display gain, such as found in the ratio of .33, could result in better tracking performance than higher ratio tracking systems.

Figure 8: Estimated mean RMSE log values as a function of Control Gain/Display gain Ratios.

To test the differences between these ratio means, a one-way ANOVA was conducted, $F(8, 81)=1.01, p=.425$. The results indicate that there is actually no statistical difference between the ratios. Although this difference was not significant, it is
interesting to note the general tendency of very low control gain/display gain ratios to have better performance.
Discussion

The current study set out to investigate the relative contribution of control gain and display gain in a compensatory tracking task. The hypotheses outlined by the study were both supported and refuted by the findings.

The significant findings of the control gain factor followed the expected hypothesis for this variable. The hypothesis that a lower level of control gain would result in superior tracking performance was based on the finding of McRuer and Jex (1967), who noted that low control gain is beneficial when making fine corrective movements. Low frequency systems requiring fine corrective movements from the human controller tended to benefit most from lower levels of control gain. Since very little disturbance was incorporated into the task of the current study, the better tracking results of the lowest control gain level were as predicted. Notice also that the general tendency of performance as a function of the control gain factor was approximately linear in the system, showing a monotonic increase in deviations as control gain increased.

The lack of significance for display gain and for the interaction between control gain and display gain are a bit surprising. The hypothesis that higher levels of display gain would result in superior tracking performance was based on the findings of McRuer and Krendel (1959), as well as Doherty and Wickens (2000), who indicated that higher levels of control gain result in more aggressive corrective movements. It was therefore surprising that non-significant results were obtained after studying this factor. It is possible that the task did not include enough disturbance to bring about significant differences in tracking ability as a function of display gain. The lack of a sufficiently difficult tracking task was therefore probably the contributor to the fact that there was
very little effect size for this factor. Because the effect size of the actual experiment was smaller than that obtained during the pilot study, the number of participants observed was not sufficient to meet the desired statistical power of .80.

Although the results for the interaction effect did not turn out to be significant, the tendency of the highest level of display gain to show more marked improvements in tracking performance with lower levels of control gain than the other two levels of display gain should be noted. Referring to figure 7, it is evident that there was not much improvement in performance across the levels of control gain for the smallest display gain level. This was as hypothesized. Performance in all of the conditions of control gain for this level of display gain had mean RMSE log scores close to -1.96. Overall, there was very little effect for this level of display gain. Participant performance in the second level of display gain was slightly better than the first level across the levels of control gain. The results, although not significant, were similar in general tendency as hypothesized, and there was a larger effect for this level of display gain. The mean RMSE log score when the most amount of control gain was incorporated was -1.99. Performance then improved when the middle amount of control gain was incorporated, as the mean for this condition was -2.12. Performance then improved with the smallest amount of control gain in this level of display gain, with a mean of -2.18. Most interesting are the general tendency results of the highest level of display gain. When control gain was high, tracking performance was worse in this condition in comparison to any of the other experimental levels of control gain, with a mean RMSE log score of -1.67. Even when using the second level of control gain, performance was still worse in the highest level of display gain, with a mean of -1.88, than it was using the second level
of display gain, which had a mean of -2.12. However, the combination of the largest level of display gain with the smallest level of control gain did indeed result in best performance, as was hypothesized. The mean RMSE log score for the combination of these conditions was -2.25. So it seems that there is a greater effect for the largest display gain level across the conditions of control gain than there is for the lower levels of display gain, even though the means for control gain for this level of display gain are not exactly as hypothesized in comparison to the means of control gain for the lesser levels of display gain. The conclusion drawn from these results is that, since power was low, significance may be found and the means may appear more as planned if the study was conducted again incorporating a larger amount of disturbance in order to obtain a larger effect size.

It is also possible that an effect for display gain and the interaction could be observed if the study was conducted again using a larger sample size for this amount of disturbance. During the pilot study, the manipulation check of display gain suggested that the manipulation would be sensitive to differences in performance based on the values of display gain utilized in this study. However, this estimation was made using only two participants per level of display gain. Therefore, the final results may reflect an overestimation of manipulation sensitivity in the pilot study.

Based on this conclusion, it appears that differences in performance associated with display gain, if any at all, are so small that it takes a very large number of participants to obtain significance. Since Cohen’s $d$ was only .058, effects were very small. Since researchers such as Gibbs (1962) and McCormick and Sanders (1982) are quite adamant about their report that the ratio of control gain to display gain affects performance, the suggestion would seem to be that differences in performance associated
with display gain exist. This may be the case, but the current study did not support this claim.

Referring to the plot of control gain/display gain ratio comparisons shown in figure 8, it is interesting to note the tendency of lower ratios to result in superior tracking over higher ratios. The most dramatic improvement seems to occur when the ratio is less than one. This finding is consistent with expectations from Buck’s (1959) report that a lower control gain/display gain ratio results in better tracking. Naturally, the optimal ratio is system-dependent, and depends on the frequency of the system.

A potential confound lies in the fact that participants were not randomly assigned to groups. This was because of certain time constraints. While there is the possibility that sampling error could have increased because of non-random assignment, it is not expected that there was much of an impact on the overall findings of the experiment in this case. The pilot study was instrumental to the experimenter in learning exactly how each participant was going to be studied. Therefore, there were no noticeable differences in the way in which each participant was studied by the researcher during the experimental portion of the research.

Another potential limitation lies in the possibility that the amount of change in the display was not enough to produce adequate perceivable display gain by the participants. As the only moving object on the display was the cursor, it is possible that this did not provide enough movement to make display gain large enough to be perceived. Although the pilot study showed that there was a possible effect, this effect disappeared once more participants were observed. Indeed, recent research (Prinzel et al., 2003) indicates that changing the display size does not have a significant effect on performance.
It is evident that other findings of the experiment support previous research. The significant main effect for the task variable of control gain, with less control gain resulting in better tracking performance for this low-frequency system supports claims made by McRuer & Jex (1967). Their research indicates that low control gain shows to be beneficial when the HO must make final corrective movements onto a target.

The current findings also emphasize the importance of the disturbance injection, which is a task variable mentioned by Jagacinski & Flach (2003) to have great influence on HO performance. In the case of this experiment, the disturbance injected was a force that sent the cursor moving in a direction contrary to the HO’s desired cursor position. Based on the fact that significance was not obtained for the display gain factor with a very small amount of disturbance incorporated into the system, it is quite possible that significance might have been gain had the disturbance been increased.

The learning effect that leveled off after each participant’s first trial is a prime example of the claim made by Jagacinski and Flach (2003), who indicate that manual control response decisions of the HO are made by the perceived change of the cursor’s position in response to the input of the controller. The HO learns how much corrective action is necessary to maintain the cursor upon the stimulus. It is evident that this is what occurred in this case.

Although the current investigation did not support the claims of Doherty and Wickens (2000), and McRuer and Krendel (1959) that higher levels of display gain bring about more aggressive control actions by the HO which result in better tracking performance, it is not appropriate to say that this phenomenon does not exist. The
findings of these authors could possibly be supported if the research were conducted again including measures to reduce sampling error and increase statistical power.

The current research cannot statistically support the claim that the ratio of control gain to display gain is important when considering system design involving manual control, as the ANOVA conducted on these ratio levels was not found to be significant. The research of Gibbs (1962) and the guidelines set forth by McCormick and Sanders (1982) could be supported, just as the claims of the researchers of display gain, if certain experimental measures were taken. What is interesting is that the results, although not significant, suggest the possibility that lower ratios result in better performance.

Conclusions

In conclusion, the manual control of a system involves many variables that have potential significant effects on the amount of control the HO has over the system. One way in which a manual control system may be operated is through first control-order compensatory tracking. During this experiment, human operator compensatory tracking performance was measured in a first order system with the manipulation of two variables, including control gain and display gain. The tracking device used was a generic tracking software program. It was expected that main effects would be observed for the two independent variables under study. In addition, an interaction of the two variables was expected, as they affect tracking performance. Since optimal control gain and display gain levels are system dependent, the results of this study will serve only as a baseline to which future studies involving other systems incorporating display and control gain can be compared.
Due to the non-significant findings of the study for display gain and the interaction effect, and the fact that statistical power was low for these factors, there are certainly ways in which this study could be conducted in the future that would increase the probability of gaining significant results. It is recommended that random assignment be practiced in the future for research such as this. As indicated, error variance could have increased because random assignment was not conducted. Although it is not expected that sampling error increased dramatically in the case of this research due to the fact that a pilot study was conducted and the researcher therefore gained a solid sense of how each participant was going to be observed, there is still the potential that it may have increased some.

In addition to reducing error variance associated with non-random assignment, the disturbance incorporated into the task should be increased so that a larger effect size would be generated. Since the effect size was small due to the very little amount of disturbance incorporated, more participants would have to be observed in order to gain more power. It is possible then that significance might be obtained, although it is not a certainty. The estimate of the sample size needed to reach a power of .80 that was gained from the pilot study was not adequate, and this experiment can thus serve as a better estimate of effect size given the values of disturbance, control gain, and display gain incorporated in this compensatory first control order tracking system.
References


of rapid aiming movements: Evidence for an interdependency between programming and feedback processing. *Quarterly Journal of Experimental Psychology.*


Appendix A

*Cohen’s d*

The calculation for Cohen’s d measure of effect size is based on the following formula:

\[
\text{Cohen’s d} = \frac{\text{Maximum group} - \text{Minimum group}}{\text{Pooled standard deviation}}
\]

*Bonferroni post-hoc procedure*

The calculation for the Bonferroni post-hoc test for mean comparisons is based on the fact that it makes the ability to obtain significance more difficult by adjusting alpha. Essentially, alpha, which is .05 in the case of this research, is divided by the number of comparisons being made. So, in the case of the calculation of mean comparisons for the control gain factor, alpha is adjusted by \( \frac{.05}{3} = .0167 \) because there are only three comparisons being made. For this reason, it is a conservative test, and the probability of Type I error inflation decreases.