ABSTRACT

EFFECTS OF FORCE FEEDBACK ON DISTRACTOR NAVIGATION STRATEGY AND MOVEMENT TIME IN AN AIMED MOVEMENT TASK

By

Ryan O'Connor-Dreher

May 2015

Implementation of effective onboard computer technologies into commercial cockpits will alter the current role and actions taken by pilots. These new technologies will require precise and efficient input methods due to the unstable nature of a cockpit environment. The benefits of haptic force feedback input devices have been shown in previous research. The present study investigated the effects of force feedback distractors on movement time, movement path, and workload. Results demonstrated that in the presence of distractors, resistive spring force levels most strongly influenced all dependent variables. Attractive gravitational force levels had no impact on movement times and minimal impact on distractor navigation strategy. The mouse, which had no force feedback, consistently showed the fastest movement times. Since prior research has demonstrated the benefits of attractive gravitational force feedback, and participants preferred to avoid distractors with high resistive spring force, significant design implications are discussed.

EFFECTS OF FORCE FEEDBACK ON DISTRACTOR NAVIGATION STRATEGY AND MOVEMENT TIME IN AN AIMED MOVEMENT TASK

A THESIS

Presented to the Department of Psychology
California State University, Long Beach

In Partial Fulfillment
of the Requirements for the Degree
Master of Science in Psychology
Option in Human Factors

Committee Members:

Thomas Z. Strybel, Ph.D. (Chair)
Kim-Phuong L. Vu, Ph.D.
Panadda Marayong, Ph.D.

College Designee:

Amy Bippus, Ph.D.

By Ryan O'Connor-Dreher

B.S., 2011, California State University, Long Beach

May 2015

ACKNOWLEDGEMENTS

I would like to first thank my thesis chair, Dr. Thomas Strybel, for providing guidance and motivation when I most needed it, as well as Dr. Kim Vu and Dr. Panadda Marayong for their support and feedback on the design and analysis of my thesis. I am also grateful for the support received from the California State University, Long Beach Computer Engineering and Computer Science Department, especially Jose Robles, Eric Park, and Paul Sim. In addition, I want to thank NASA Ames Research Center for supporting my academic and professional career throughout my graduate history, as well as this research.

I would like to thank my family for their lifelong support and encouragement in all of my life endeavors. Finally, I am most grateful to Rachael, whose patience and encouragement were vital to this journey.

This thesis was supported by NASA cooperative agreement NNX09AU66A, *Group 5 University Research Center: Center for Human Factors in Advanced Aeronautics Technologies* (Brenda Collins, Technical Monitor).

TABLE OF CONTENTS

LIST OF TABLES

TABLE Page

LIST OF FIGURES

FIGURE Page

CHAPTER 1

INTRODUCTION

Introduction and Overview

The Federal Aviation Administration (FAA; 2013) expects commercial aviation to grow an average of 2.2% per year over the next 20 years. As such, a similar growth in the capacity of the United States National Airspace System is required to reduce the increased stress on the transportation system (NAS; Joint Planning and Development Office [JPDO], 2010).

There are concerns that air traffic controllers (ATCos) and pilots will not be able to handle the increased workload that will accompany the increase in traffic (JPDO, 2010). For instance, many legacy systems and core technologies, first developed during World War II, are unable to process and provide flight information in real-time. Furthermore, current processes and procedures do not provide the required flexibility for safe operator performance as air traffic levels grow (JPDO, 2010). Research has shown that ATCo performance decreased significantly when traffic levels were one and a half times greater than present day levels (Prevot, Homola, & Mercer, 2008). Also of concern is the structure of the national navigation system, which restricts pilots to following pre-existing flight routes (McAnulty & Zingale, 2005). This structure leads to bottlenecks in the flow of traffic, as well as increased travel times and fuel costs.

NextGen

To meet the United States future demand for the most effective, efficient, and safe transportation system, the Next Generation Air Transportation System (NextGen) Concept of Operations has been proposed (JPDO, 2010). Through new procedures and technological advances, NextGen concepts should reduce costs, travel times, and operator workload, as well as improve safety and security. These changes are expected to drastically transform the roles and responsibilities of operators within the system.

One operation concept, Trajectory Based Operations (TBO), will dynamically adjust flight paths in real time (JPDO, 2010). This concept was designed to address issues of high operator workload and inefficient navigation and will be used as a mechanism for managing air traffic. Currently, ATCos monitor radar screens to visualize, predict, and manage the separation of aircraft. TBO will transfer the responsibility for modifying flight plans and maintaining separation to the flight deck. As such, pilots will no longer solely follow pre-existing flight routes, but instead create their own conflict-free, custom routes. This increased control is expected to benefit the needs of airlines (i.e., reduced flight time and by extension, less fuel consumption), as well as the NAS (i.e., fewer flight bottlenecks and more precise arrival times). Under TBO, the roles of the ATCo and the pilot may shift in that the ATC will manage overall traffic flows, instead of individual aircraft, whereas pilots of NextGen-equipped aircraft will manage their own routes, instead of solely executing ATCo commands.

In order to provide pilots with information about surrounding traffic, weather, and terrain, commercial aircraft will require new onboard avionic technologies such as higher resolution positioning systems (e.g., Global Positioning System [GPS]), technology capable of broadcasting location information to other entities (e.g., Automatic Dependent Surveillance-Broadcast [ADS-B]; JPDO, 2010), and devices to provide pilots with integrated information to maintain awareness (e.g., Cockpit Display of Traffic Information [CDTI]; Alexander & Wickens, 2001). The GPS and ADS-B technologies will achieve better positional accuracy for both the pilot and ATCo, ensuring optimal flight plan deviations and more precisely calculated arrival times (JPDO, 2010). The CDTI provides flight crews with data regarding current and future states of ownship, other aircraft relative to ownship, surrounding traffic, terrain, and weather. This information is necessary for optimal route planning and separation management as it provides pilots with a heightened awareness of their surroundings (Williams, Yost, Holland, & Tyler, 2002). CDTIs could include conflict detection and resolution tools, automated route modification tools, and precise spacing functions (Dao et al., 2009). These tools are predicted to support better collaboration between pilots and ATCos.

Along with these desirable benefits of CDTIs come potential limitations that must be accounted for; the CDTI, as currently designed, is not sufficient to optimize operator performance in the cockpit. The most obvious constraints involve the nature of the cockpit: movements ranging from vibrations to turbulence and limited real estate (Rorie, 2013). Limited space requires the CDTI interface to be small, which increases the difficulty and workload of input tasks for pilots. The unstable nature of the cockpit reduces selection accuracy, which, in turn, increases task completion times. Also of concern is the increased time pilots need to spend with their “heads down” to perceive, comprehend, and manipulate the display (Williams et al, 2002). With regard to the general cockpit display, a CDTI could add unnecessary clutter to the workspace or alter the pilots' standard scan patterns, resulting in increased workload (Joseph, Domino, Battiste, Bone, & Olmos, 2003). To address these concerns, NASA's Flight Deck Research Group has developed a Cockpit Situation Display (CSD; NASA Flight Deck Research Group, 2004) that condenses information from the surrounding airspace into a 3D volumetric display (Dao et al., 2009). The CSD is used in experimental simulations with a mouse, but can be implemented in a cockpit. The majority of tasks with these tools involve using simple motor movements to manipulate the aircraft, such as drag-and-drop, point-and-click, and click-and-drag. Considering the benefits and limitations of these tools, a proper input device is needed in the cockpit that will reduce task completion times and error rates, manipulate targets in three dimensions on a small display (Granada, Dao, Wong, Johnson, & Battiste, 2005), and overcome the physical limitations of the cockpit (i.e., limited space, unstableness, limited range of human movement).

In addition, the feedback a user receives when handling an input device is typically visual, which occurs between the location of the cursor and a target. The visual feedback may consist of a change in the cursor's size or representation, a change in the target's characteristics, and so on. This visual feedback further stimulates the human visual system, which is already taxed by other information on the display. In light of this, stimulating multiple senses through multi-modal feedback is a promising method that can reduce or distribute loads across the senses. As such, human-computer interfaces should engage as many human senses as possible, as multi-sensory feedback more closely resembles real-world interactions (Akamatsu & Sato, 1994).

A particularly underutilized sensory modality for digital manipulation and feedback within NextGen is the human haptic system. Since the majority of common tasks with a tool like the CDTI involve simple motor movements, a haptic device that assists and informs the operator should include both visual and auditory stimuli. Such a haptic device could address the limitations of a purely visual system. A human-computer interface, such as the CDTI, needs to be tested with respect to the speed-accuracy tradeoffs in order to assess the effectiveness of haptic devices.

Fitts's Law

In the Human-Computer Interaction (HCI) literature, the most common method to predict movement time *(MT)* is by using a Fitts's Law task (Fitts, 1954). Fitts's Law predicts aimed movement time (MT) as a function of both the *distance traveled* from the starting location to a target and the *target's size*. Fitts's Law models point-and-click tasks such that longer MTs occur with longer travel distances and smaller targets whereas shorter MTs occur with short travel distances and larger targets.

The relationship between the target's distance (A) and width (W) is defined as the Index of Difficulty (ID) of the target selection task (Fitts, 1954). The ID is analogous to the number of bits of information that must be transferred for successful communication, or, in the case of aimed movement, the number of bits needed for successful target selection (MacKenzie, 1992). A larger ID is considered to be a more difficult aimed movement task that requires more time to complete successfully. In the Fitts's Law equation, MT increases linearly with ID (Fitts, 1954).

$$\text{Fitts's Index of Difficulty: } ID = \log_2(2A/W)$$

$$\text{Fitts's Law: } MT = a+b(ID)$$

Fitts's Law has been utilized for nearly a century due to the robustness of its model, among other benefits. It has been shown to effectively explain the relationship between movement times and movement difficulty (ID) for a variety of input devices, such as computer mice, joysticks, and eye trackers (e.g., Card, English & Burr, 1978; Jagacinski & Monk, 1985; Kantowitz & Elvers, 1988). In addition, Fitts's model has helped to explain why some tasks are more difficult than others, indicating that more difficult tasks overload human information processing capacities (Rosenberg, 1992). Researchers have also used Fitts's Law due to its ability to compare task difficulties via one straightforward value, the ID, which collapses distance and size (MacKenzie, 1992).

Haptics and Haptic Technology

The term haptics refers to anything associated with the sense of touch. Unlike the visual system, however, the haptic system not only receives sensory input, but is involved in the manipulation of the environment. The haptic system can be broken down into numerous components. First, all proprioceptive senses (vestibular, kinesthetic, and cutaneous) fall under the category of haptics. As such, proprioception refers to all sensory information regarding the state of the body. Vestibular senses refer to the sensations of balance, spatial orientation, and movement. Cutaneous (which literally means "skin") senses refer to sensations of pressure, temperature, and pain experienced through the skin. Within cutaneous senses, one finds tactile sensations, which refer to sensations of pressure or vibration on the skin (to be discussed later). The final group of haptic sensations, kinesthetic senses, refers to the sensation of bodily motion experienced through the muscles, tendons, and joints. Within kinesthetic sensations is force feedback, which is the focus of this paper. Force feedback refers to the sensation of mechanical information received through the kinesthetic system, such as the application of force, pressure, or vibration (Oakley, McGee, Brewster, & Gray, 2000).

Haptic technology simulates mechanical and visual feedback for the user (van Mensvoort, 2002) and has the ability to produce more natural, immersive interactions between the physical and digital worlds. This technology typically simulates mechanical feedback through an input device, such as a mouse or joystick. The device may vibrate, apply pressure, or even force itself in a direction determined by the software. The quality of the haptic feedback is directly dependent on the quality of the physical device and the manipulation of the device's feedback. Visual feedback is typically provided via the display. As a user moves the mouse or joystick, the cursor on the display also moves in the same direction and distance proportionate to the user's movement. Haptic force feedback technologies specifically apply *forces* to an input device, and the user *experiences* these forces mechanically. The force experienced may simulate a gravitational pull toward an object, a repulsive force away from an object, or even the features of an object, such as the bump of a button. Research has shown that humans are able to integrate this haptic information with visual information in an optimal fashion (Ernst & Banks, 2002). Humans also respond faster to haptic stimuli than to visual stimuli, a finding that has been underutilized in human-computer interactions (Calhoun, Draper, Ruff, Fontejon, & Guilfoos, 2013; Ng & Chan, 2012; van Erp & van Veen, 2001).

Before moving further into the domain of haptic force feedback technology, it would be pertinent to discuss its precursor: haptic tactile technology. Tactile devices present feedback to the cutaneous sense to indicate an interface affordance to the user. A study by Akamatsu, MacKenzie, and Hasbrouc (1995) used a tactile mouse to provide vibrations to the user when passing over a single target. The study compared targeting time, over-target time, and errors for tactile, auditory, and visual feedback. Although the results showed no difference in overall targeting time, nor any errors, the tactile feedback significantly reduced the user's over-target time (i.e., the time from the cursor entering the target until target selection) compared to audio or visual feedback. Akamatsu et al. argued that because the mouse vibration occurred immediately when the cursor moved over the edge of a target, tactile feedback allowed users to select targets more quickly by utilizing a wider area of the target. By contrast, visual feedback at the target's edge may not be as quick and precise.

Haptic force feedback, which directs cursor and/or input device movement, represents a potential alternative to simple tactile feedback. One of the first classic experiments with a force feedback enabled input device examined two haptic effects (tactile and force feedback) in terms of accuracy and movement time (Akamatsu & Sato, 1994). What is interesting about this experiment is that the researchers had to integrate tactile and force feedback capabilities into a traditional mouse, as mice with such functionalities did not yet exist on the market. In order to create tactile feedback, an aluminum pin built into the mouse's left click button lightly pressed upward on the user's finger pad, producing the sensation of touching a physical object. For force feedback, the researchers added the sensation of frictional resistance when the mouse passed over a target. This resistance was generated by the use of an electromagnet attached to the bottom of the mouse and the placement of an iron surface beneath it. The two types of feedback were only produced when the participant traveled over a target. For the experiment, Akamatsu and Sato (1994) used two targets, one 14.6 degrees counterclockwise (approximately 11 o'clock) and one 41 degrees clockwise (approximately between 1 and 2 o'clock) of the 12 o'clock position. Results showed that the tactile and force conditions produced minimal errors, but with no significant difference from the normal mouse. However, the tactile and force conditions significantly reduced the movement time to select a target compared to the normal mouse. Overall, the haptic conditions improved the completion time over the normal condition, but did not affect accuracy.

Notably, based on results that showed more diverse scattering of accurate mouse clicks on the target with tactile and force feedback, Akamatsu and Sato (1994) inferred that the tactile and force feedback information could, "increase the effective target area", or increase the perceived target size. In effect, the average accurate click distances from the target's center were *larger* with tactile and force information than in its absence. In other words, participants clicked the target more often once the mouse cursor was close to the target's center. Although, the idea that haptic feedback can create a larger perceived target size than with visual information alone has persisted to this day, the following factors limited Akamatsu and Sato's early study: a small sample size of five, the use of only two targets, no variation in target sizes, only two target angle positions, and only 50 trials total per participant.

Force feedback aids not only in target selection, but also in movement to a target. In a study by Dennerlein, Martin, and Hasser (2000), mouse-generated force feedback was found to improve movement time in "steering" to a target, as well as target selection time compared to a traditional mouse without force feedback. In this study, a gravity well, or attractive basin, gently pulled the mouse and cursor into the center of a digital 2D tunnel (Experiment 1), as well as into the center of a target at the end of the tunnel

(Experiment 2). The tunnel was a straight vertical or horizontal path meant to simulate movement similar to that of navigating a vertical or horizontal menu on a computer application. In Dennerlein et al.'s first experiment, movement times were on average 52% faster in the force feedback condition. It is interesting that, with the traditional mouse, vertical movements took significantly longer to complete than horizontal movements, whereas with the mouse with force feedback, there was no difference between the two directional movements. In Dennerlein et al.'s second experiment, force feedback again improved movement times to complete the task. Unfortunately, one limitation of this experiment was that the effects of force feedback on tunnel movement and target selection were not measured separately. As a result, it was difficult to determine whether force feedback gravity wells were important for allowing direct movement (simulated by the tunnel) to the target, or whether it was enough to activate gravity wells on the targets themselves.

To this author's knowledge, no other studies exist that have solely examined aiding movement to a target via force feedback tunnels. Research on haptic force feedback has mainly focused on the capability of force feedback to capture the user's cursor and/or input device. As such, the research presented from this point on has examined physically capturing the input device and digitally capturing the cursor.

Force Feedback and Variations on Cursor Capturing Functions

Researchers have proposed numerous variations of cursor-capturing functions, ranging from the simple attractive force of the gravity well (Hwang, Keates, Langdon, & Clarkson, 2003; Oakley et al., 2000; Rorie, 2013; Rorie et al., 2012; Rosenberg, 1992) to haptic funnels (i.e., as a cursor approaches a target, movement is "funneled" to the target such that the user cannot easily move outside of the funnel's barriers; Asque, Day, & Laycock, 2012) and "jumping functions" (Park, Han, & Yang, 2006), which instantaneously move the user's cursor into the target as the cursor gets close. Guidance as to which method(s) to use can be found by comparing performance results across studies.

As the most commonly utilized cursor-capturing method, gravity wells are a promising starting point. Gravity wells (also termed attractive basins) attract a user's input device to a center point, usually the center point of a target. The gravity force applicable from a target to an input device can either be constantly active, regardless of cursor positioning (although at far distances the force will be so minimal it will not be felt by the user), or activated at a specified distance from the target. In both cases, the force value will increase as the user moves the cursor closer to the target. At some point, the gravity value becomes high enough for the user to feel the "pull" on the input device. The following studies have examined simple, direct movements to single targets without distractors. These simple movements are the most fundamental targeting actions used in human–computer interactions, and are relatively easy to perform. Testing simple movements also allows a researcher to isolate movement time from other factors, such as cognitive processes.

In Park et al.'s (2006) study, gravity wells led to better performance than a "jumping function," yet there was no difference in performance compared with a normal mouse condition. The "jumping function" moved the cursor to the center of a target instantaneously once the cursor was within a specified range of the target. Therefore, the user would not get the visual feedback experienced when the cursor travels to a target, because the cursor would jump instantly. To begin trials, participants selected a "Start" button and moved the cursor in one of eight directions vertically, horizontally, or diagonally toward a rectangular target dialog box where they selected one of three buttons: “Yes,” “No,” or “Cancel.” The movement time, number of misclicks, and participants’ subjective preferences with respect to the gravity well, jumping function, and normal mouse were recorded. The gravity wells outperformed the jumping function in all performance measures (movement time and accuracy). Gravity wells benefited movement time over the normal mouse for targets with larger gravity activation areas extended out from the target’s center. Both cursor capturing functions reduced the number of target selection errors (misclicks) compared to the normal mouse, but the jumping function significantly increased task completion time. Participants preferred the gravity wells and found that the jumping function interfered most with the task. Park et al. concluded that the visual feedback missed during a ‘jump’ may be integral to seamless perception-action target selection.

In a study by Oakley et al. (2000), gravity wells and a different haptic cursor-capturing function (a haptic recess effect) led to faster movement times, fewer errors, and lower workload ratings than with other haptic feedback techniques and the control condition. The four haptic effects tested were texture, friction, recess, and gravity wells. These were felt by participants via a 3D force feedback stylus. The haptic texture effect produced “ridges” or bumps that the user could feel when passing over an activated target area. Haptic friction dampened the velocity of the stylus. The haptic recess effect produced a virtual “hole” that the haptic device fell into; to exit the recess, users were required to “climb” out by lifting their input device vertically in physical space. The control condition was simply the stylus input device without any haptic assistance.

For their first experiment, Oakley et al. (2000) instructed participants to select one of four buttons diagonal from the center. The time it took participants to find the correct button location influenced final movement times. The haptic recess produced significantly faster movement times than the gravity wells. The gravity wells produced fewer errors than for all other conditions. The haptic recess produced fewer errors than friction and texture, but not gravity wells or the control. To measure workload, a modified version of the NASA TLX was used (Hart & Wickens, 1990). Participants consistently indicated lower workload scores for the gravity wells and haptic recess than for the other conditions. A major limitation of this study was that the participants’ cognitive processes influenced movement times. Purely mechanical measurements should not include a “time to find the target.” When designing the optimal configuration of an input device to support operator performance, the key is to discover issues and solutions that are not confounded by cognitive processes. In doing so, such configurations can be applied universally.

In Asque, Day, and Laycock’s (2012) study, two haptic target acquisition techniques—haptic cones and haptic funnels—were proposed as alternatives to gravity wells. Haptic cones do not pull the input device or cursor into the target, but rather implement an invisible field around the target, which causes an input device to fall into the target and clamp to the target’s center. The haptic funnel creates a V-shaped funnel to guide the user toward the target’s center, preventing the input device from moving outside of the funnel once the funnel has been established. To exit distracting funnel-activated targets, the user moves his or her input device in the opposite direction from which it entered. Asque et al.'s experiment with motion-impaired individuals found haptic cones to be the most effective technique of the three, decreasing the number of misclicks and reducing movement time. However, a small sample size (*n* = 6) comprised of motion-impaired users does not reliably rule out the potential benefits of gravity wells among other populations.

In an experiment with both motion-impaired and able-bodied users using a force feedback mouse, Langdon, Keates, Clarkson, and Robinson (2000) found that targeting performance was drastically improved and the benefit of gravity wells increased with the disabled users' level of impairment. Langdon et al. presented the users with a GUI pointing task wherein they were asked to select 10 targets in sequence on a map of North America. Each subsequent target began flashing as soon as the previous target had been selected until all 10 targets had been clicked. The gravity well was activated only for the flashing target. Task completion times and error rates for misclicks both showed significant improvements with force feedback. The times to complete trials were reduced by 30–50% compared to no force feedback.

Previous research at the Center for Human Factors in Advanced Aeronautic Technologies (CHAAT) has suggested that force feedback most improves movement times for small targets, close proximity targets, and targets in diagonal directions (Rorie et al., 2012). These findings are consistent with prior research that has found the mouse to be ideal for vertical movements and force feedback for diagonal movements (MacKenzie & Buxton, 1992; Whisenand & Emurian, 1996). Rorie et al.'s (2012) research examined the effect of gravity wells in a CDTI environment with no air traffic.

The researchers found that the device used (the Novint Falcon) performed as well as or better than the mouse when gravity wells were enabled. The Falcon with force feedback reduced MT by 30% compared to the Falcon with no force feedback. The most promising findings were that when force feedback was utilized, target selection performance met or exceeded that of a traditional mouse, despite the fact that participants had extensive experience with a mouse as opposed to with the Falcon.

A follow-up study (Rorie, 2013) extended these findings by varying the gain levels of gravitational and spring force feedback. While gravitational feedback attracts movements toward a target, spring force applies a force to resist movements away from a target's center once the cursor is inside the target boundary. For Rorie's study, two measures described overall movement time (OMT): approach time to target (affected by an attractive gravity force) and time inside target (affected by a spring force feedback that helped to maintain the cursor inside the target until selection). Of the three gain levels tested (strength of the gravity wells in Newtons/sec), 300 NPS and 500 NPS resulted in faster MTs than 100 NPS, with comparable OMTs to the mouse. Consistent with earlier findings (Akamatsu, et al., 1995), the resistant spring force was found to reduce the time inside target for all conditions. However, spring force had less effect on OMT than attractive force feedback, which accounted for 75% of the movement time. Based on this research, the optimal force levels recommended for the Novint Falcon are an attractive gravity force of 300 NPS and a resistant spring force of .3 NP (Newtons per pixel). Overall, these findings suggest that there is an ideal combination of gravity and spring force feedback that can optimize device stability and movement times. One major limitation of this research was that the cursor movement path was not analyzed.

Discovering how users navigate to and stay within a target could provide additional insights for determining correct gain levels and potential input device problems.

In a follow-up analysis of Rorie's (2013) data, results showed that the performance gains from force feedback could be explained by increased cursor speed and decreased path error (i.e., the path error was defined as deviation from the straight line path to the target) (Koltz, Rorie, Robles, Vu, Marayong, Strybel, & Battiste, 2014). However, gravitational force only affected approach error and speed for targets close to the start location (i.e., the effects of attractive gravity are not subjectively noticeable at long distances). That is, compared to longer distances, over short distances, force feedback assists movements for a larger percentage of the total travel path. Koltz et al. (2014) mentioned that for force feedback research, path error may be more critical as the cursor approaches the target, because target selection requires increased accuracy.

Multiple, Force Feedback Enabled Gravity Wells Interference

Most studies of gravity wells have examined their performance when only one target in the display is force feedback enabled. In a realistic interface or environment, such as the CDTI in a cockpit, multiple targets and distractors are present. These may be in close proximity to one another or even directly interact with one another. When multiple items produce force feedback, the user's cursor may be captured by the attractive pull of undesired distractors as the cursor travels toward the target. This effect may detrimentally affect performance, completely canceling out any benefits of force feedback.

A limited number of studies have investigated performance in the presence of multiple gravity wells, finding both positive and negative effects on performance. In a study by Dennerlein and Yang (2000), participants performed better in a "point-and-click" task with multiple force feedback distractors along the cursor trajectory than without force feedback. Dennerlein and Yang compared users' performance on target selection tasks by varying the number of force feedback enabled distractors (no FF / 1 target FF / 1 target 1 distractor FF / 1 target 2 distractors FF / 1 target all distractors FF). The target and distractors were always presented vertically or horizontally from the start point, such that as the number of force feedback distractors increased, the more distractors participants had to move through to select the target. Results indicated that participants simply "plowed through" distractors with no cost to performance, but with increased costs to the perceived levels of difficulty and discomfort as the number of distractor gravity wells increased. Movement times ranged from 22% to 28% faster in all force feedback conditions compared with no force feedback.

In Wall, Paynter, Schillitoe, Wright, and Scalli's (2002) study using a virtual 3D "point-and-click" task with multiple gravity wells, force feedback was shown to improve accuracy in selecting targets, but not movement time. In the experimental task, participants were required to use a haptic stylus to click on a sphere in the center of a virtual 3D box to begin each trial and then to select a visually indicated target sphere. Target spheres were located in 12 positions in 3D space—eight in the corners of the 3D box, and four along each of the four walls horizontal to the center. A force feedback enabled distractor sphere was present between the center sphere of the box and each target sphere. Although accuracy was improved, targeting times were not improved. The authors indicated that the poor movement times were likely due to the hindrance of movement by the distractors.

Tornil and Baptiste-Jessel (2005) demonstrated that force feedback can decrease operator performance when applied to multiple stimuli. Participants used a force feedback mouse to select a start circle at the top right corner of the screen. Movement times were not recorded until the cursor left this start circle. Targets were presented one at a time in 10 different locations. When enabled, resistant spring force feedback pulled the cursor back to the center if it overshot the target. Tornil and Baptiste-Jessel measured four conditions: (1) no force feedback or distractors; (2) no distractors, but force feedback pulling the cursor back to the center if it overshot the target; (3) screen filled with distractors, some of which applied the same force feedback as the target ("worst case"); and (4) same as condition 3, except that the intensity of the force feedback weakened as the mouse moved faster. Results showed that there were no differences in performance between conditions 1 (w/o force) and 2 (w/ force), which suggested that there was no benefit to forces activated upon entering the target compared to no force. In condition 3, force feedback distractors increased movement times by nearly 24% compared to conditions 1 and 2. In condition 4, the adaptive force level only reduced the performance decrement by about 7% from condition 3.

Monk (2014) manipulated the multiple levels of force feedback with distractors in a CDTI environment and found that the benefits of force feedback discovered in the aforementioned studies were reduced in the presence of distractors. Four equidistant distractors, with equal levels of force feedback per task, surrounded targets in each condition. Distractors were either placed in-line with direct movements to the target or out of the direct path to the target. The mouse (with no force feedback) consistently yielded significantly faster movement times than either of the two force levels tested for all target directions, sizes, and distances. Furthermore, the 100 NPS and 300 NPS force levels resulted in no difference in movement times, contradicting Rorie's (2013) previous findings without distractors. Target direction, which typically shows benefits for diagonal movements, showed no benefits for force feedback in the presence of distractors. The larger target and distractor sizes resulted in longer movement times; these findings are inconsistent with Fitts's Law, which states that it should be quicker to navigate to large targets.

To summarize, distractors detrimentally reduced movement time in Monk's (2014) study. However, this study did not measure the movement paths taken by participants to navigate through or around distractors. An examination of cursor movement paths may reveal trends in participants' distractor navigation strategies. For example, people may completely avoid distractors altogether or "plow through" them (Dennerlein & Yang, 2000). The key is to determine which method of distractor navigation produces optimal performance in the presence of distractors with varying levels of force feedback. This knowledge will help researchers to devise the proper design solutions to overcome distractor issues with force feedback.

Current Study Purpose

In order to safely and successfully adopt NextGen technologies into the National Air Space (NAS), the correct tools must be implemented into cockpits to assist operator performance and relieve workload. Tools such as the Cockpit Display of Traffic Information (CDTI) help to inform pilots of their surroundings and provide them with simple tools to plan for aircraft actions. The major concern for the current research is to devise a method to allow for precise movements in an unstable cockpit environment.

Prior research has shown force feedback gravity wells to be a promising method for decreasing movement times and error rates in point-and-click tasks. However, in previous studies, the benefits of this method were found to decrease in the presence of force feedback enabled distractors, or users indicated physical discomfort. Distractors have also been found to decrease the benefits found with attractive force feedback. In order to devise a method to overcome the issues with force feedback distractors, it is essential to understand the strategies people use to attempt to handle distractors.

In this experiment, a force feedback enabled input device was compared to a traditional computer mouse by measuring movement time to targets with distractors and the number of times the cursor crosses through distractors. The current research examined force feedback within an advanced aeronautic computer interface, the CDTI, currently used at NASA research centers. The goal of this research was to determine whether force feedback is effective when spring force and gravity force are manipulated separately in the presence of distractors. The current study differs from previous force feedback research in multiple ways. First, the navigation path people choose in the presence of force feedback distractors was a variable of interest in this study. Understanding the strategies operators choose to handle force feedback distractors (i.e., avoiding or plowing through them) can help to determine the most effective force feedback configurations that will allow participants to most efficiently move to and select targets. Another important factor in this regard is workload. Force feedback configurations should not increase workload. If operators must cross through force feedback distractors, it is essential that workload levels do not increase, as this could negatively affect performance. It was expected that participants' distractor navigation strategy would depend on the magnitude of both the attractive and spring forces. With lower attractive and spring force values, participants were expected to easily navigate *through* distractors. With higher attractive and spring force values, participants were expected to *attempt to avoid* distractors completely, causing a higher cognitive and physical workload.

CHAPTER 2

METHOD

Participants

Participants consisted of 12 volunteers from the Psychology Department at California State University, Long Beach (CSULB), who participated for a total of 3 hours each over a period of 3 days. They were compensated $30 for their participation. Gender was not balanced. Participants were given the opportunity to schedule their own participation dates and times.

Apparatus

Participants sat in a psychology laboratory at CSULB and completed the experiment on a desktop computer with a color monitor. The testbed, a picture of the Cockpit Display of Trajectory Information (CDTI), was used to simulate the experimental interface. The testbed provided the operator with the position, heading, speed, and altitude of ownship and information about surrounding traffic. For an example of this environment, see Figure 1 below. The experimental stimuli (target and distractors) were presented on the CDTI screenshot, and participants' reaction times and movement path data were recorded in text files by the testbed program.

Participants responded to stimuli using two input devices: a standard optical laser mouse and the Novint Falcon. The Falcon was designed for force feedback and non-feedback use in a video gaming environment. As such, it is capable of position sensing and applying force in three dimensions (4" x 4" x 4" workspace). By design, its

FIGURE 1. Screenshot of experimental program. Display was 8” x 8”, showing the start point (center), distractors (middle, white), and target (top left) icons.

orientation is with the control stick pointing horizontally outward towards the user. However, for the purposes of this experiment, the device was oriented vertically in order to more closely resemble the positioning and movements of a computer mouse in the same 2D plane; this vertical orientation also more closely resembled the orientation of aside or center stick in a cockpit. The participants could use any of the three buttons on the Falcon’s hand grip to select the target. The Falcon’s grip height was set at the same level as the participant’s armrest in order to minimize physical strain. A Logitech laser mouse served as the second input device. The computer monitor was adjusted so that the center of the display was positioned at eye level for each participant. Participants sat approximately two feet from the computer screen.

Force feedback was active on the Falcon. As the participant moved to within the target gravitational boundary ($||d|| > r$), a modified version of Newton’s gravitational law equation [$F = (K / ||d||$^2) $\hat{d}$ [when $d > r$]] (Robles et al., 2012) was used to produce an attractive force to the center of the target or distractor. This force guided the Falcon and the cursor to the center of the target/distractor. The force strength increased as the cursor

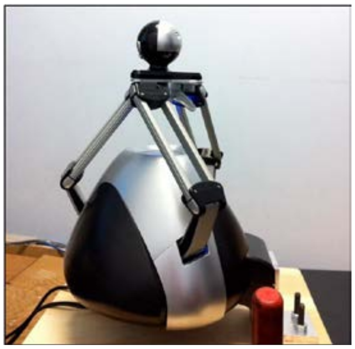

FIGURE 2. Screenshot of the Novint Falcon force feedback device.

approached the target/distractor center. This force was inversely proportional to the magnitude of the distance ($\|d\|$) between the cursor location and target center, squared. The unit vector ($\hat{d}$) was used to determine the proportion of the force output along both axes (x and y).

To provide stability when the Falcon reached the target (i.e., when the distance to the target center <= target radius), a spring force model was applied (Robles et al., 2012). Once inside the target, the spring force slightly resisted the participants' movements away from the target's center. The level of resistance increased the farther the cursor moved from the target's center, up until the target boundary was exited [$F = (K_2 * \|d\|)\ \hat{d}$ [when $d <$ £ r]]. A distance vector ($\hat{d}$) was used to determine the proportion of the force to be applied to the x-axis and the proportion to be applied to the y-axis. With both the attractive and spring forces, participants subjectively experienced a pull toward the targets while outside of target boundaries, and a resistance to exiting the target or distractor once inside its boundaries (Rorie et al., 2012).

Procedure

Participants were briefed and asked to fill out a consent form, demographics questionnaire, and screening form. The screening form ensured that participants were right-handed with normal to corrected-to-normal vision. The experimental task was explained, and the participants were allowed to ask questions. Then, the experiment began with five practice blocks: one block with the mouse and four blocks with the Falcon. The experimental blocks were run over 3 days for 1 hour each day. A total of 2,304 individual trials (less than 2 seconds each) were completed by each participant, or 768 trials per day.

For each trial, participants performed a point-and-click aimed movement task using either the mouse or the Novint Falcon. A green center circle was selected to activate each trial. Once the start icon was selected, the target appeared and three distractor circles were shown between the start location and the target. Participants moved the cursor as quickly and as accurately as possible toward the red target circle, while strategizing how to handle the white distractor circles. Once the target was selected, the next trial was indicated by another green start circle. The participants had the freedom to choose when to start each trial, and they were able to take rest breaks between trial blocks. This procedure was repeated for 768 trails a day over the 3 days. After all experimental blocks were completed, participants were briefed on the purpose of the study and thanked for their involvement.

Experimental Design

This experiment was a 2 (device: mouse / falcon) x 2 (gravitational force level: low / high) x 2 (spring force level: low / high) x 2 (stimuli size: small target and distractors / large target and distractors) x 2 (target direction: left / right) x 2 (distractor distance: close / far from target) x 2 (distractor spread: tight / spread) repeated measures design (see Table 1 and Figure 3 below). Movement time, distractor navigation strategies ("plow throughs" or avoidance), and workload were measured. Pilot tests were run to determine the number of distractors, location of distractors, and the format of the experimental blocks. The two levels of gravitational force chosen (100 and 300 NPS) were the same as those used in Monk's study (2014), and the two levels of spring force (0.1 and 0.3 NPP) chosen were the same as those used in Rorie's study (2013).

The experiment was run over 3 days, with a total of 24 trial blocks (8 per day). To establish a baseline, eight blocks using the standard computer mouse were run—four at the beginning of the experiment and four at the end. Gravity force level was counterbalanced across participants and experiment days, varying the combination of gravitational and spring forces presented over the course of the experiment. Each combination of gravitational force level and spring force level was constant within a trial block and across four blocks in sequence. Within each trial block, two target locations, two stimuli sizes, two distractor distances, and two distractor spreads were randomly presented 12 times for a total of 96 trials per block.

TABLE 1. Independent and Dependent Variables

Independent Variable	Levels	Values
Gravitational Force Level (2 levels + baseline)	Baseline/No Force Low High	0 NPS 100 NPS 300 NPS
Spring Force Level	Low High	.1 NP .3 NP
Stimuli Size (target & distractor)	Small Large	20 px radius 30 px radius
Target Location	Left Right	-45˚ 45˚
Distractor Distance	Near Target Far from Target	92 px 184 px
Distractor Spread	Tight together Spread apart	5 px 30 px
Dependent Variable	Measure	
Movement Time	Milliseconds	
Distractor Navigation Strategy	Average number of times the cursor crossed through distractors over all trials	
Workload	NASA TLX	

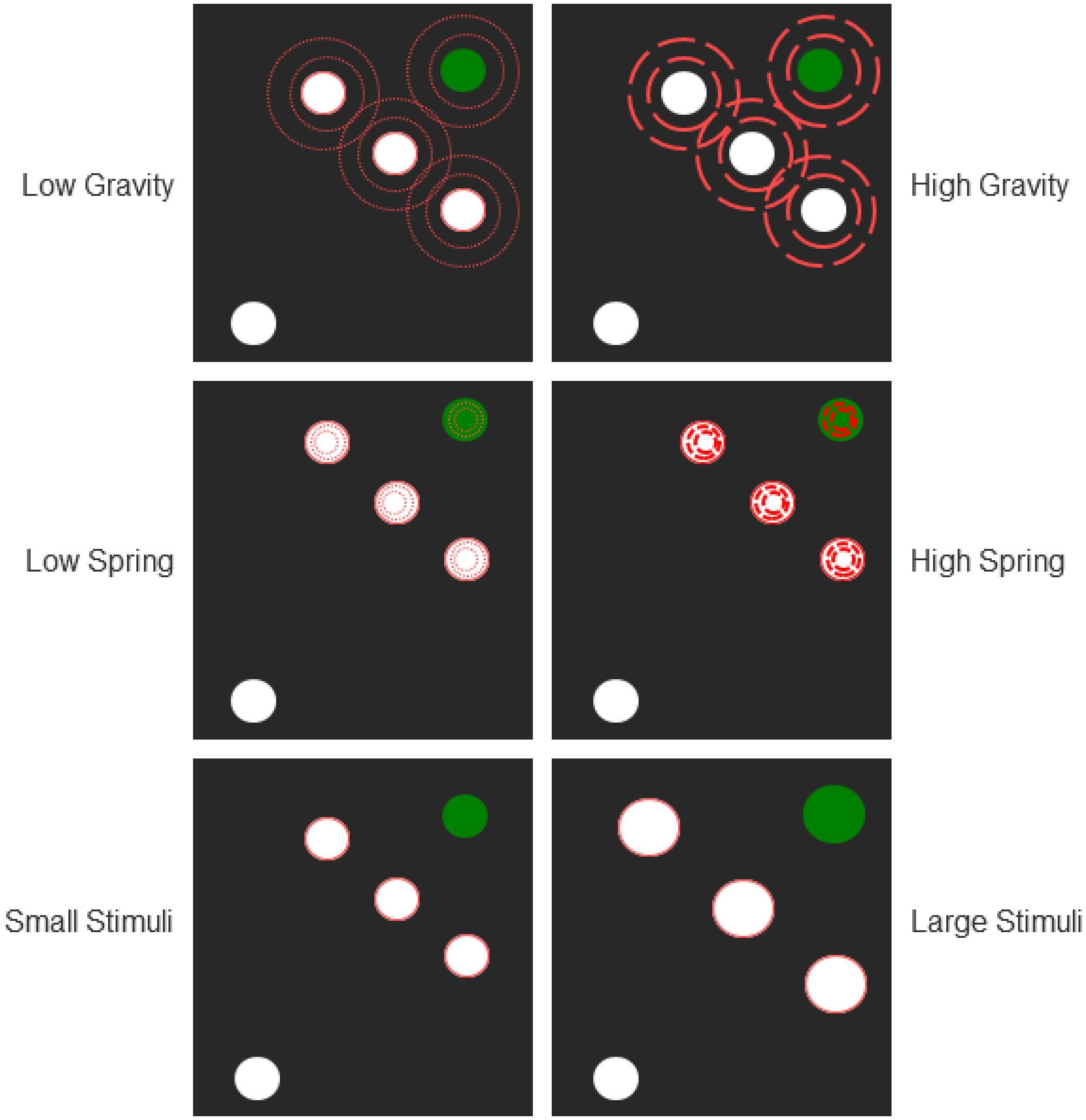

FIGURE 3. Visual depiction of the first three out of six independent variables shown above. The remaining three variables are shown in Figure 4 on the next page.

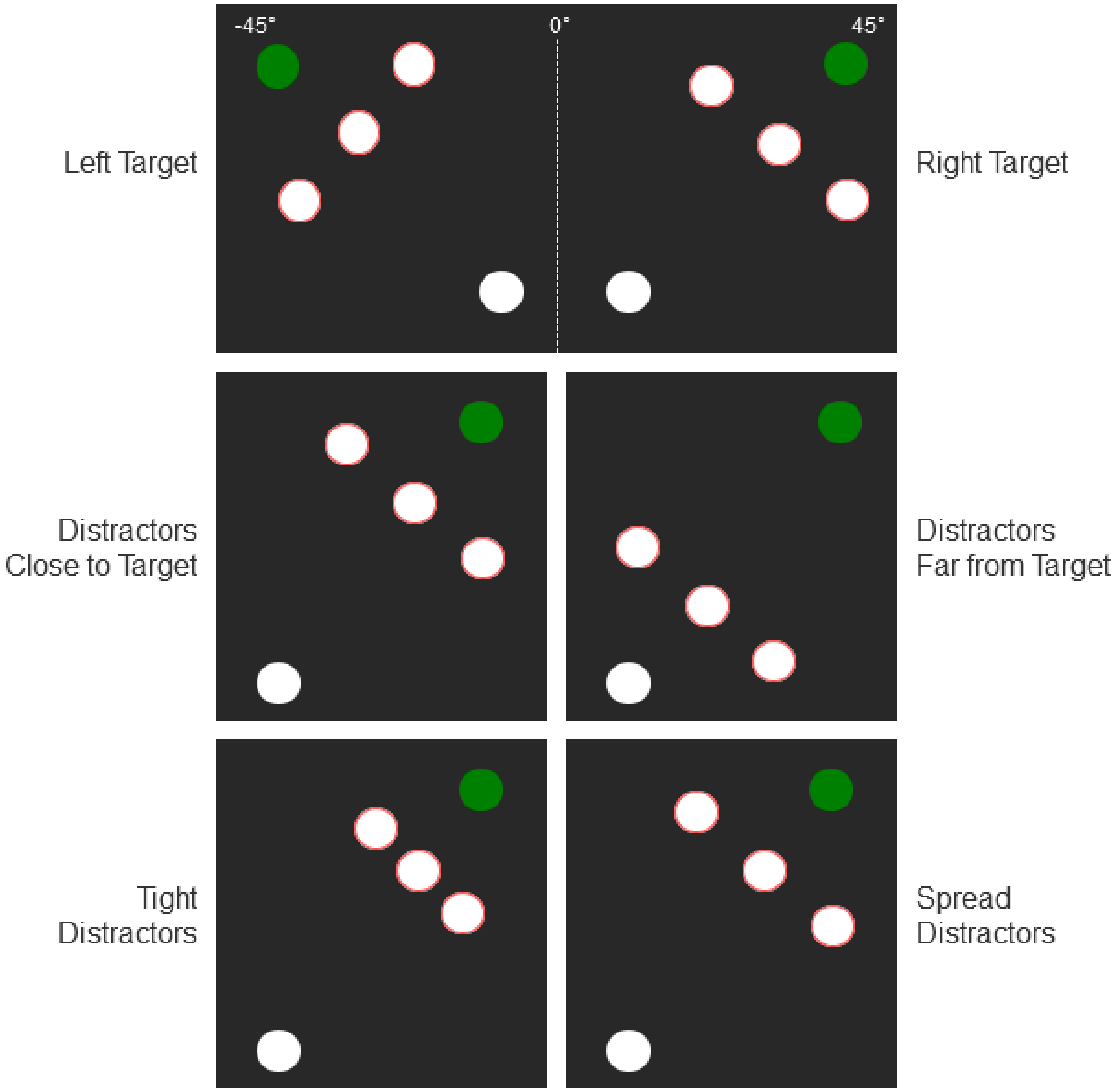

FIGURE 4. Visual depiction of the last three out of six independent variables shown above, but not all combinations of the IVs. For example, the combination of spread out, large stimuli is not shown.

CHAPTER 3

RESULTS

This experiment was a 2 (device: mouse / falcon) x 2 (gravitational force level: low / high) x 2 (spring force level: low / high) x 2 (stimuli size: small target and distractors/ large target and distractors) x 2 (target direction: left / right) x 2 (distractor distance: close / far from target) x 2 (distractor spread: tight / spread) repeated measures design. It is important to note that during the two experimental blocks when participants used the mouse as the input method instead of the Falcon, the design became a 2 (stimuli size) x 2 (target direction) x 2 (distractor distance) x 2 (distractor spread) repeated measures design, since the mouse was not enabled with force feedback information (i.e., no spring force or gravitational force feedback was provided).

Three different dependent measures were collected: movement time (MT), distractor navigation strategy, and subjective workload ratings. MT was the total elapsed time between the selection of the start icon and the selection of the target icon. Distractor navigation strategy (DNS) was conceptually defined as the strategy participants chose to handle distractor stimuli (i.e., either to avoid distractors or to plow through them). DNS was mathematically defined as the average number of times the cursor crossed through distractors over all trials. To determine if the cursor crossed through a distractor, the cursor path was recorded by sampling the X and Y coordinates of the cursor position every 16ms. If at any time a sample x,y coordinate was located within the circumference of the distractor stimuli, it was considered to cross through the distractor stimuli. Lastly, subjective workload ratings were the perceived workload participants experienced while using the mouse without force feedback, or the Falcon with gravity or spring forces.

Because all variables were manipulated within subjects, a repeated-measures analysis of variance (ANOVA) was employed for all analyses. An alpha level of .05 was used for all analyses. Correlations between MT and DNS, MT and workload, and DNS and workload were run to determine the relationships between the dependent variables. None of the correlations were significant, $p > .05$, indicating that the dependent measures were unrelated. For an overview of the major findings, see Table 2 below.

TABLE 2. Overview of Major Findings

Force Level	Movement Time (MT)	Distractor Navigation Strategy (DNS)	Relative Workload Trends
None - Mouse	Fastest overall	Avoid small, spread distractors.	Low
Low Gravity	No effect	No effect	Moderate
High Gravity	No effect	Minimal effects, but when paired with high spring, avoid distractors close to the target when the target was on the right.	Moderate
Low Spring	Faster than gravity	Minimal effects, but stronger affects than gravity forces. Effects when the target was on the right, distractors were close to the target, and paired with high gravity.	High
High Spring	Fastest of the force conditions	Highly affects DNS. Tend to avoid distractors with high spring in the majority of cases, especially when the distractors were close to the target, and most frequently for close right distractors.	High

Movement Time

Mouse

As mentioned, the analyses involving trials with the mouse utilized a 2 (stimuli size) x 2 (target direction) x 2 (distractor distance) x 2 (distractor spread) design, since the mouse was not enabled with force feedback information.

When participants used the computer mouse, there was a significant main effect of stimuli size, $F(1,11) = 285.79$, $p <.001$. In particular, participants were able to select large targets ($M = 762.64$ ms, $SEM = 24.59$ ms) significantly faster than they could small targets ($M = 893.24$ ms, $SEM = 28.96$ ms). There were no effects for the other variables, and there were no interactions.

Force Feedback

To view the main effects and interactions for movement time, see Table 3 in the Appendix. When participants used the Novint Falcon with force feedback, there was a significant main effect of spring force, $F(1,11) = 9.379$, $p < .05$, on MT. In particular, the higher .2 NPP spring force level ($M = 917.94$ ms, $SEM = 29.10$ ms) resulted in significantly faster MTs than the lower .05 NPP spring force level ($M = 965.26$ ms, $SEM = 25.79$ ms).

A main effect of stimuli size on MT was found, with participants selecting large targets ($M = 896.10$ ms, $SEM = 28.22$ ms) faster than they did small targets ($M = 987.10$ ms, $SEM = 25.16$ ms), $F(1,11) = 111.93$, $p < .001$.

A main effect of distractor distance on MT was found, with participants selecting the target faster when the distractors were farther from the start target ($M = 917.11$ ms, *SEM* = 23.83 ms) compared to when distractors were closer to the target (*M* = 966.09 ms, *SEM* = 29.25 ms), *F*(1,11) = 38.64, *p* < .001.

Interestingly, there were no main effects of gravity force level, nor any significant interactions with gravity force level, *p* > .05.

The main effects for MT were all qualified by at least one interaction. The first interaction—between spring force level and stimuli size—found that MT depended on the size of the stimuli, *F*(1, 11) = 52.85, *p* < .001 (see Figure 5). The simple effects of spring force level were examined at each level of stimuli size. When participants encountered the smaller stimuli, the higher spring force level (*M* = 933.33 ms, *SEM* = 24.46 ms) resulted in significantly faster MTs than the lower spring force level (*M* = 1040.88 ms, *SEM* = 27.75 ms), *F*(1, 11) = 56.68, *p* < .001. There was no significant difference between spring forces with the larger stimuli. The simple effects of stimuli size were then examined at each level of spring force. When the spring force was low,

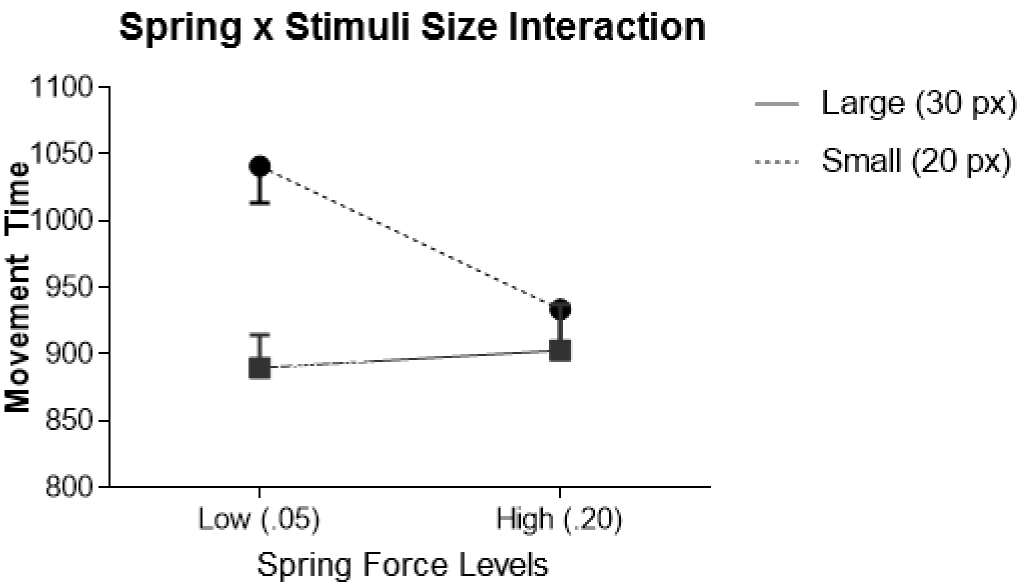

FIGURE 5. Mean movement time by stimuli size and spring force level.

participants selected large targets (*M* = 889.64, ms, *SEM* = 24.57 ms) faster than they did small targets (*M* = 1040.88 ms, *SEM* = 27.75 ms), *F*(1,11) = 261.36, *p* < .001. An interesting result was that there was no significant difference between stimuli sizes for the high spring force levels.

The second interaction—between spring force level and target direction—found that MT depended on the direction of the target, *F*(1, 11) = 5.53, *p* < .05 (see Figure 6). The simple effects of spring force level were examined at each level of target direction. When participants selected targets to the right, the higher spring force (*M* = 898.56 ms, *SEM* = 28.95 ms) resulted in significantly faster MTs than the lower spring force (*M* = 961.35 ms, *SEM* = 25.94 ms), *F*(1, 11) = 15.88, *p* < .01. There was no significant difference between spring force levels for targets located to the left.

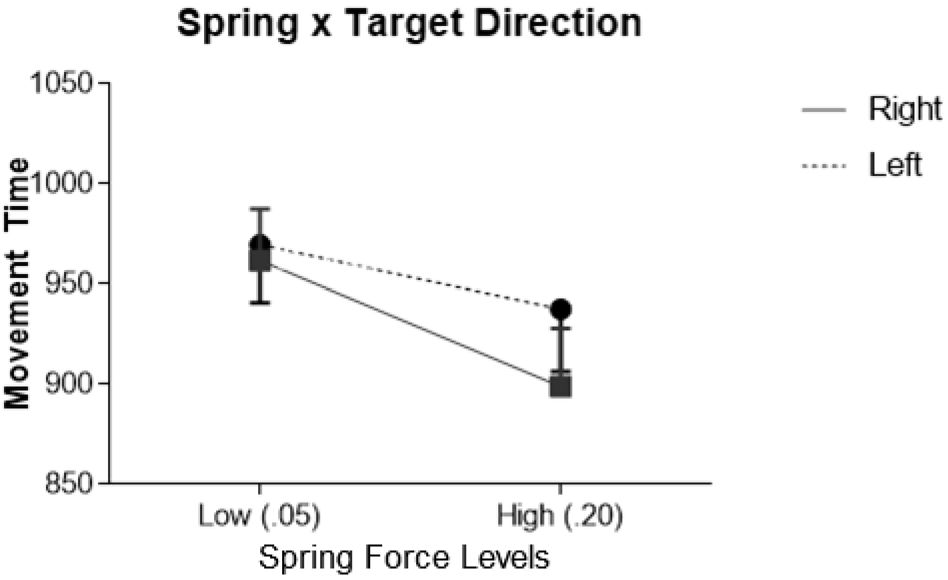

FIGURE 6. Mean movement by target direction and spring force level.

The third interaction—between spring force level and distractor distance—found that MT depended on the distance of the distractors from the target, *F*(1, 11) =16.82, *p* < .002 (see Figure 7). The simple effects of spring force level were examined at each level of distractor distance. When participants encountered distractors far from the target, the higher spring force (*M* = 884.78 ms, *SEM* = 25.77 ms) resulted in significantly faster MTs than with the lower spring force (*M* = 949.44 ms, *SEM* = 23.57 ms), *F*(1, 11) = 24.93, *p* < .001. There was no significant difference between spring levels for distractors close to the target location.

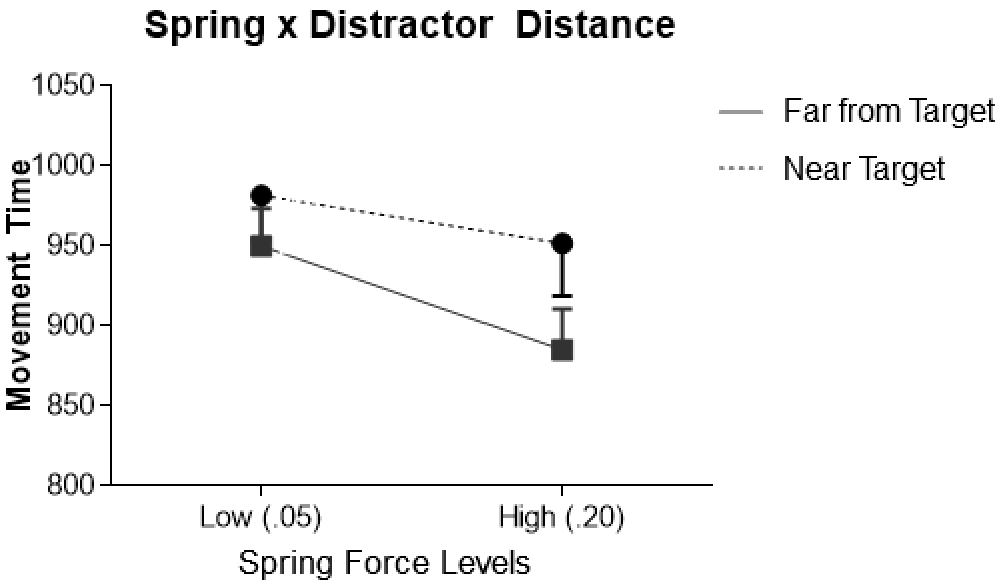

FIGURE 7. Mean movement time by distractor distance and spring force level.

The fourth interaction—between spring force level and distractor spread—found that MT depended on the distance of distractors from one another, *F*(1, 11) = 12.15, *p* < .01 (see Figure 8). The simple effects of spring force level were examined at each level of distractor spread. When participants encountered distractors positioned tightly together, the higher spring force (*M* = 907.75 ms, *SEM* = 29.41 ms) resulted in significantly faster MTs than with the lower spring force (*M*= 972.75 ms, *SEM* = 25.22 ms), *F*(1, 11) = 14.22, *p* < .01. There was no significant difference between spring force levels for distractors spread apart.

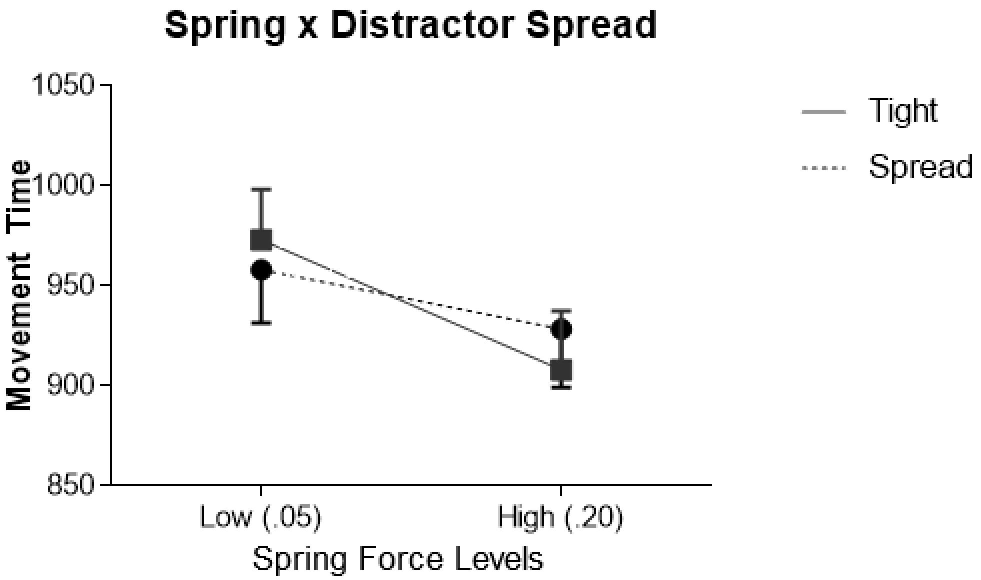

FIGURE 8. Mean movement time by distractor spread and spring force level.

The fifth interaction—between stimuli size and distractor distance—found that MT depended on the distance of the distractors from the target, *F*(1, 11) = 14.10, *p* < .01 (see Figure 9). The simple effects of stimuli size were examined at each level of distance. When participants encountered distractors close to the target, the larger stimuli (*M* = 930.97 ms, *SEM* = 31.28 ms) resulted in significantly faster MTs than with the smaller stimuli (*M* = 1001.21 ms, *SEM* = 27.84 ms), *F*(1,11) = 58.03, *p* < .001. When participants encountered distractors far from the target, the larger stimuli (*M* = 861.23 ms, *SEM* = 25.94 ms) again resulted in faster MTs than with the smaller stimuli (*MS* = 973 ms, *SEM* = 22.92 ms), *F*(1,11) = 100.66, *p* < .001.

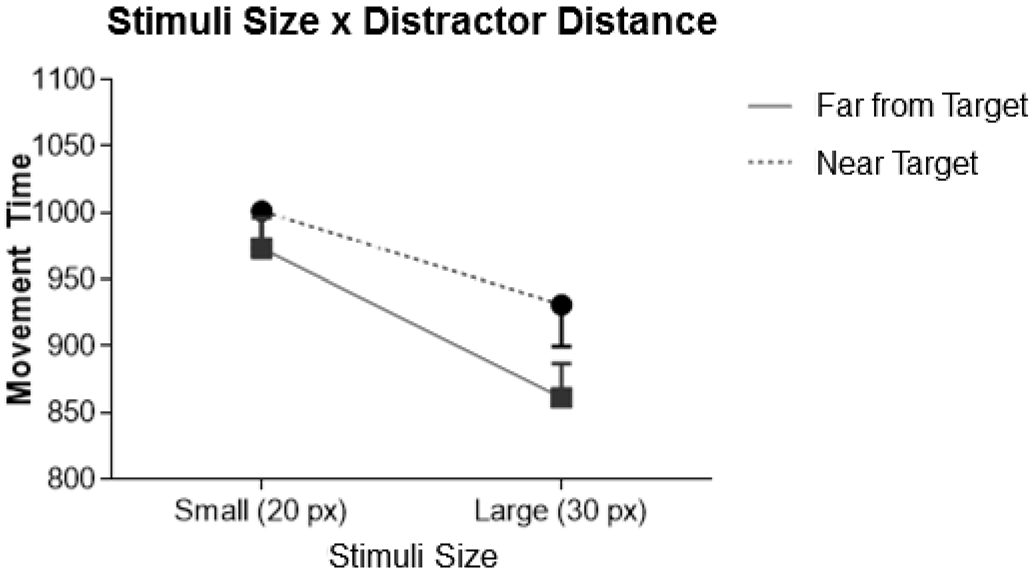

FIGURE 9. Mean movement time by distractor distance and stimuli size.

The sixth interaction—between stimuli size and target direction—found that MT depended on the direction of targets, either left or right, *F*(1, 11) = 10.82, *p* < .01 (see Figure 10). The simple effects of stimuli size were examined at each level of direction. When participants encountered targets to the left, the larger stimuli (*M* = 920.55 ms, *SEM* = 33.26 ms) resulted in significantly faster MTs than with the smaller stimuli (*M* = 985.94 ms, *SEM* = 24.80 ms), *F*(1,11) = 31.82, *p* < . 001. When participants encountered targets to the right, the larger stimuli (*M* = 871.65 ms, *SEM* = 25.48 ms) again resulted in significantly faster MTs than with the smaller stimuli (*M* = 988.27 ms, *SEM* = 28.37 ms), *F*(1,11) = 100.85, *p* < .001.

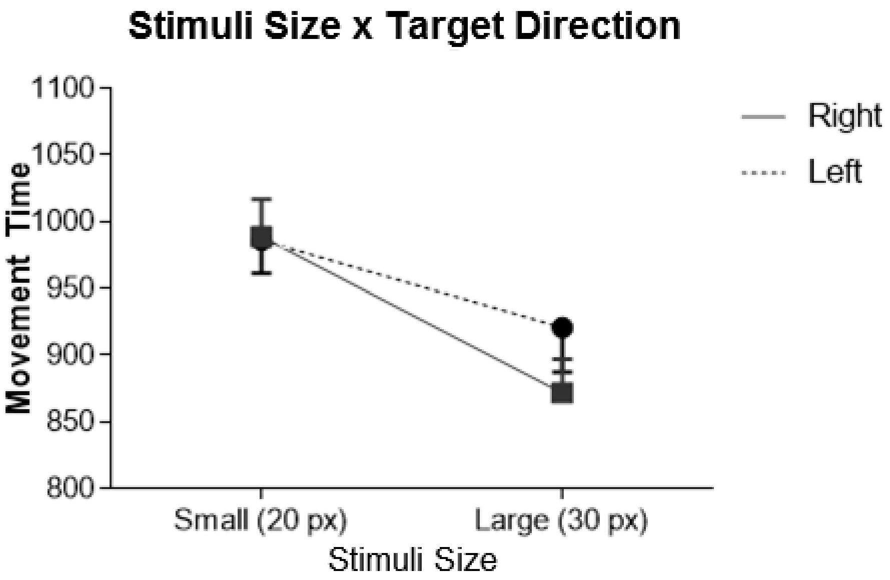

FIGURE 10. Mean movement time by target direction and stimuli size.

The seventh interaction—between distractor distance and target direction—found that MT depended on the direction of targets, either left or right, $F(1, 11) = 47.89$, $p < .001$ (see Figure 11). The simple effects of distractor distance were examined at each level of direction. When participants encountered targets to the left, MTs were faster for distractors far from the target ($M = 913.24$ ms, $SEM = 25.08$ ms) than for distractors close to the target ($M = 993.26$ ms, $SEM = 33.03$ ms), $F(1,11) = 48.47$, $p < .001$. When participants encountered targets to the right, MTs were again faster for far distractors ($M = 920.98$ ms, $SEM = 24.88$ ms) than for close distractors ($M = 938.93$ ms, $SEM = 27.99$ ms), $F(1,11) = 9.96$, $p < .01$. No higher interactions were significant.

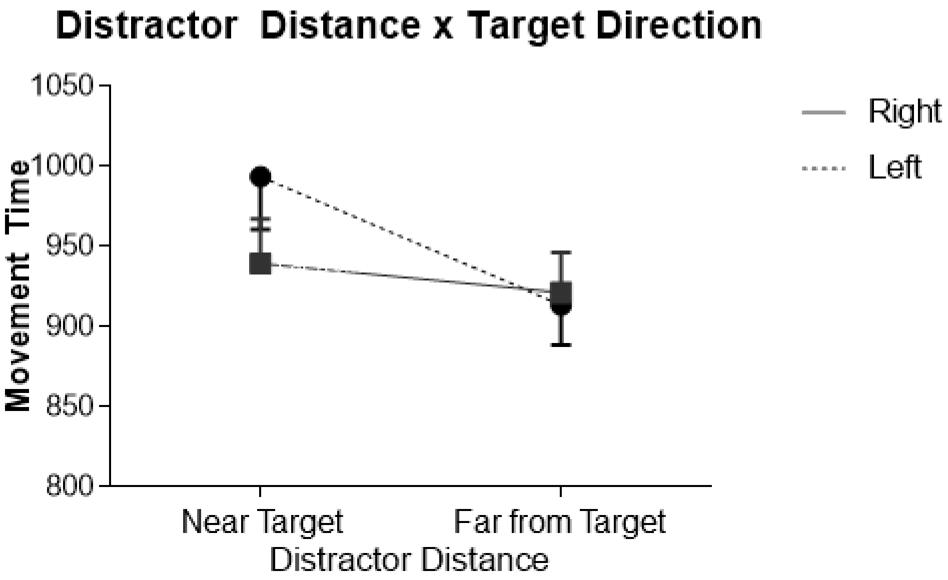

FIGURE 11. Mean movement time by target direction and distractor distance.

Mouse and Force Feedback

A within-subjects ANOVA revealed that the average MT for the mouse (*M* = 827.93 ms, *SEM* = 26.59ms) was significantly faster than for the Falcon (*M* = 940.66 ms, *SEM* = 26.18), *F*(1, 11) = 29.65, *p* < .001. To further compare participant performance with the Falcon to participant performance with the mouse, the change in MT relative to the mouse was computed. For example, if the average MT for the high gravity, high spring condition was 900 ms, and the average MT for the mouse was 850 ms, there was an increase in MT of 50ms for this force combination.

All of the force conditions produced longer MTs than the mouse. When examining combinations of spring and gravity forces, there was no significant main effect for gravitational force, *p* > .05. Significant main effects were found for spring force, *F*(1,11) = 9.36, *p* < .05, stimuli size, *F*(1,11) = 13.3, *p* < .01, target direction, *F*(1,11) = 6.61, *p* < .05, and distance *F*(1,11) = 23.4, *p* < .001. In particular, MTs for the higher spring force (*M* = 90.02 ms, *SEM* = 22.99 ms) were closer to the mouse performance than they were for the lower spring force (*M* = 137.31 ms, *SEM* = 20.46 ms). Most interestingly, force feedback MTs for the small stimuli (*M* = 93.88 ms, *SEM* = 21.42 ms) were closer to the mouse performance than they were for the large stimuli (*M* = 133.45 ms, *SEM* = 20.69 ms. This finding suggests that spring force more greatly benefits MTs for small stimuli than for large stimuli. Force feedback MTs for the right direction (*M* = 95.99 ms, *SEM* = 20.4 ms) were closer to mouse performance than they were for the left direction (*M* = 131.34 ms, *SEM* = 22.5 ms). Force feedback MTs for distractors far from the target (*M* = 89.37 ms, *SEM* = 19.11 ms) were closer to mouse performance than they were for distractors close to the target (*M* = 137.96 ms, *SEM* = 22.66 ms). All main effects were qualified by significant interactions with spring force. However, these interactions have not been reported here, because in the context of this study only the interaction between gravity and spring force feedback variables are of interest in comparison with the mouse.

Distractor Navigation Strategy

Distractor Navigation Strategy (DNS) is defined as the average number of times the cursor crossed through distractors over all trials. A value of 1 indicated that participants, on average, crossed through 1 distractor. A value of 0 indicated that participants avoided all distractors. The DNS values could be larger than 1, but not lower than 0. A number higher than 1 indicated that a participant crossed through one or more distractors per trial. If participants crossed through a distractor, exited, and reentered the distractor, this was recorded with a value of 2. This scenario typically occurred when the participant navigated through a distractor and was subsequently attracted into adjacent distractors or back into the distractor previously exited. Edge cases existed where participants crossed through all three distractors and reentered two of the distractors, which was recorded with a value of 5. These edge cases were not removed from data analysis, due to the important insights such cases can offer for the design of force feedback devices.

Mouse

When participants used the mouse, there was a significant main effect of stimuli size, $F(1,11) = 390.58$, $p < .001$, on the average number of times the cursor crossed through distractors over all trials. In particular, participants avoided distractors more often when the stimuli size was small ($M = .861$, $SEM = .01$) than when the stimuli size was large ($M = .999$, $SEM = .005$).

A main effect of direction on the average number of times the cursor crossed through distractors over all trials was found, with participants avoiding distractors significantly more often for targets to the right ($M = .92$, $SEM =.008$) than for targets to the left ($M = .94$, $SEM = .008$), $F(1,11) = 7.58$, $p < .05$. However, the average number of times participants crossed distractors for both directions was still close to 1 per trial, $M > 0.9$.

A main effect of distance on the average number of times the cursor crossed through distractors over all trials was found, with participants avoiding distractors significantly more often for distractors close to the target ($M = .922$, $SEM = .008$) than for distractors far from the target ($M = .938$, $SEM = .007$), $F(1,11) = 9.91$, $p < .01$. However, the average number of times participants crossed distractors for both distances was still close to 1 per trial, $M > 0.9$.

A main effect of spread on the average number of times the cursor crossed through distractors over all trials was found, with participants avoiding distractors significantly more when distractors were spread apart (*M* = .871, *SEM* = .01) than when distractors were tight together (*M* = .988, *SEM* = .006), *F*(1,11) = 324.38, *p* < .001. This result was expected, due to the greater chance of successfully navigating between distractors when they are spread farther apart.

The main effects for stimuli size and distractor spread on the average number of times the cursor crossed through distractors over all trials were qualified by one interaction. The interaction between stimuli size and distractor spread showed that the average number of times the cursor crossed through distractors over all trials depended on the size of the stimuli, *F*(1, 11) = 148.30, *p* < .001 (see Figure 12). The simple effects of distractor spread were examined at each level of stimuli size. When participants encountered larger stimuli, they avoided distractors spread farther apart (*M* = .986, *SEM* = .061) more often than they did distractors positioned tightly together (*M* = 1.011, *SEM* = .004), *F*(1, 11) = 12.35, *p* < .01. When participants encountered the smaller stimuli they avoided distractors spread farther apart (*M* = .757, *SEM* = .014) more often than they did distractors positioned tightly together (*M* = .965, *SEM* = .009), *F*(1, 11) = 299.27, *p* < .001. It is important to point out that the size of the effect between distractors spread far apart and close together was large.

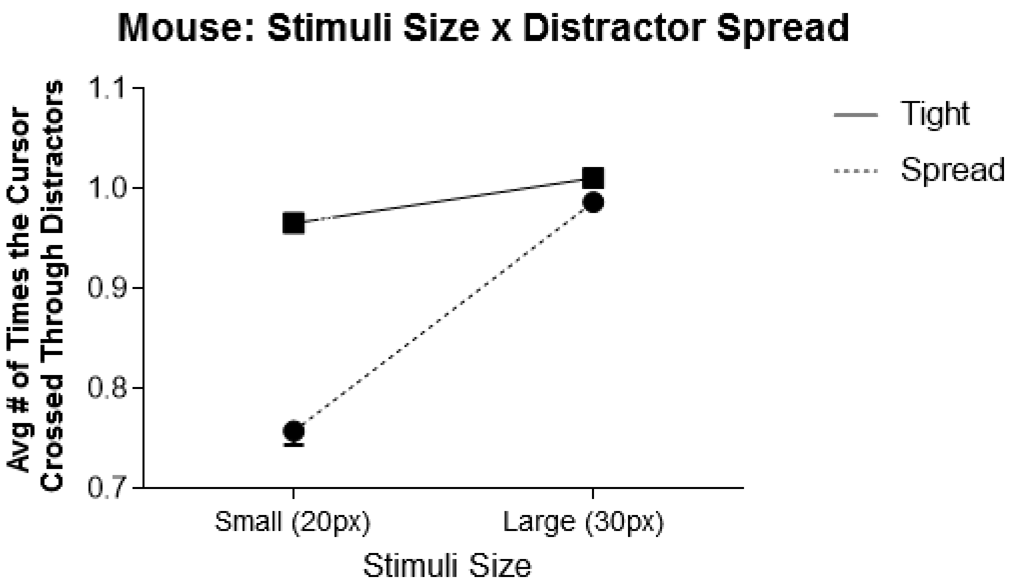

FIGURE 12. Average number of times the cursor crossed through distractors over all trials by distractor spread and stimuli size.

<u>Force Feedback</u>

To view a summary of all main effects and interactions for distractor navigation strategy, see Table 4 in the Appendix. When participants used the Novint Falcon with force feedback, there was a significant main effect of spring force level, *F*(1,11) = 16.24, *p* < .01, on the average number of times the cursor crossed through distractors over all trials. In particular, participants avoided distractors when the spring force was higher (*M* = .576, *SEM* = .071) significantly more often than when the spring force was lower (*M* = .821, *SEM* = .042).

A main effect of direction on the average number of times the cursor crossed through distractors over all trials was found, with participants avoiding distractors significantly more often for targets to the right (*M* = .661, *SEM* = .047) than for targets to the left (*M* = .736, *SEM* = .054), *F*(1,11) = 9.65, *p* < .01.

A main effect of stimuli size on the average number of times the cursor crossed through distractors over all trials was found, with participants avoiding distractors significantly more often when the stimuli were small (*M* = .642, *SEM* = .059) than when the stimuli were large (*M* = .756, *SEM* = .053), *F*(1,11) = 4.82, *p* = .05.

These main effects were all qualified by 12 significant interactions, listed below.

Direction * Distance:

The interaction between direction and distance showed that the average number of times the cursor crossed through distractors over all trials depended on the direction of the targets, *F*(1, 11) = 19.11, *p* < .001. The simple effects of distractor distance were examined at each level of direction. When participants encountered targets to the right, they avoided distractors close to the target (*M* = .612, *SEM* = .055) more often than they did distractors far from the target (*M* = .711, *SEM* = .043), *F*(1,11) = 13.40, *p* < .01. There was no significant effect for targets to the left.

Direction * Spread:

The interaction between target direction and distractor spread showed that the average number of times the cursor crossed through distractors over all trials depended on the direction of the targets, *F*(1, 11) = 6.31, *p* < .05. The simple effects of distractor spread were examined at each level of direction. When participants encountered targets to the right, they avoided distractors that were close together (*M* = .628, *SEM* = .057) more often than those that were spread far apart (*M* = .695, *SEM* = .039), *F*(1,11) = 6.01, *p* < .05. The was no significant effect for targets to the left.

Stimuli Size * Spread:

The interaction between stimuli size and distractor spread showed that the average number of times the cursor crossed through distractors over all trials depended on the spread of distractors, *F*(1, 11) = 46.33, *p* < .001. The simple effects of stimuli size were examined at each level of spread. When participants encountered distractors spread far apart, they avoided small distractors (*M* = .631, *SEM* = .047) more often than they did large distractors (*M* = .809, *SEM* = .047), *F*(1,11) = 15.67, *p* < .01. There was no significant effect for tight distractors. These findings were consistent with the findings for the mouse.

Spring * Spread:

The interaction between spring force level and distractor spread found that the average number of times the cursor crossed through distractors over all trials depended on the spread of distractors, *F*(1, 11) = 7.11, *p* < .05. The simple effects of spring force level were examined at each level of spread. Participants avoided distractors that were tight together more often when the spring force was high (*M* = .535, *SEM* = .082) than when the spring force was low (*M* = .820, *SEM* = .053), *F*(1,11) = 17.22, *p* < .01. Participants avoided distractors spread far apart more often when the spring force was high (*M* = .617, *SEM* = .061) than when the spring force was low (*M* = .823, *SEM* = .034), *F*(1,11) = 13.50, *p* < .01.

All two-way interactions were qualified by at least one significant three-way interaction.

Gravity * Stimuli Size * Spread:

Interactions involving gravity force level, stimuli size, or distractor spread were qualified by a three-way interaction between the three variables, *F*(1, 11) = 8.3, $p < .05$ (see Figure 13). Simple interactions between stimuli size and distractor spread were analyzed at each level of gravitational force. When looking only at the low gravitational level, the effect of distractor spread depended on the stimuli size, *F*(1, 11) = 20.18, $p < .001$. The simple effects of distractor spread were analyzed at both levels of stimuli size paired with the low gravitational level. When participants encountered larger distractors with low gravity enabled, they avoided distractors that were tight together (*M* = .706, *SEM* = .075) more often than they did distractors spread far apart (*M* = .802, *SEM* = .059), *F*(1,11) = 10.86, $p < .01$. When participants encountered smaller distractors with low gravity enabled, there was no significant difference in terms of distractor spread.

When looking only at the high gravitational level, the effect of distractor spread depended on the stimuli size, *F*(1, 11) = 52.37, $p < .001$. The simple effects of distractor spread were analyzed at both levels of stimuli size paired with the high gravitational level. When participants encountered larger stimuli with high gravity enabled, they avoided distractors that were tight together (*M* = .697, *SEM* = .060) more often than they did distractors spread far apart (*M* = .817, *SEM* = .048), *F*(1,11) = 34.85, $p < .001$. When participants encountered smaller stimuli with high gravity enabled, there was no significant difference in terms of distractor spread.

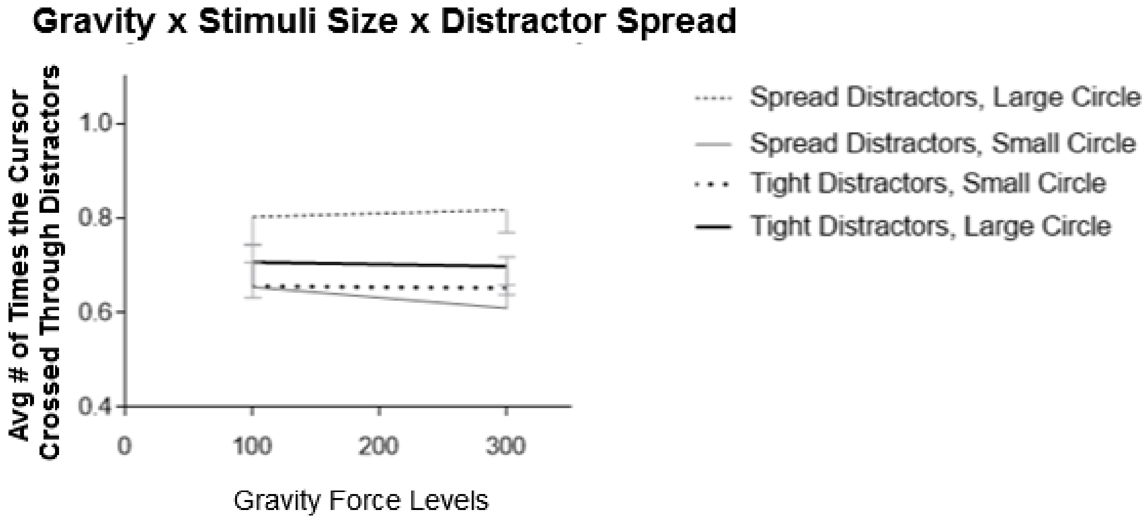

FIGURE 13. Mean number of times the cursor crossed through distractors by distractor spread, stimuli size, and gravity force level.

Spring * Direction * Spread:

Interactions involving spring force level, target direction, or distractor spread were qualified by a three-way interaction between the three variables, *F*(1, 11) = 6.37, *p* = .05 (see Figure 14). Simple interactions between spring force and distractor spread were analyzed at each level of direction. When targets were located to the left, the effect of spring force level depended on the distractor spread, *F*(1,11) = 15.15, *p* < .01. The simple effects of spring force were analyzed at both levels of distractor spread paired with targets to the left. When participants encountered spread distractors to the left, they avoided distractors more often when spring force was high (*M* = .643, *SEM* = .065) than when the spring force was low (*M* = .848, *SEM* = .038), *F*(1, 11) = 12.83, *p* < .01. When participants encountered tight distractors to the left, they avoided distractors more often when the spring force was high (*M* = .566, *SEM* = .091) than when it was low (*M* = .884, *SEM* = .055), *F*(1, 11) = 19.27, *p* < .001.

When targets were located to the right, there was no significant interaction between spring force level and distractor spread.

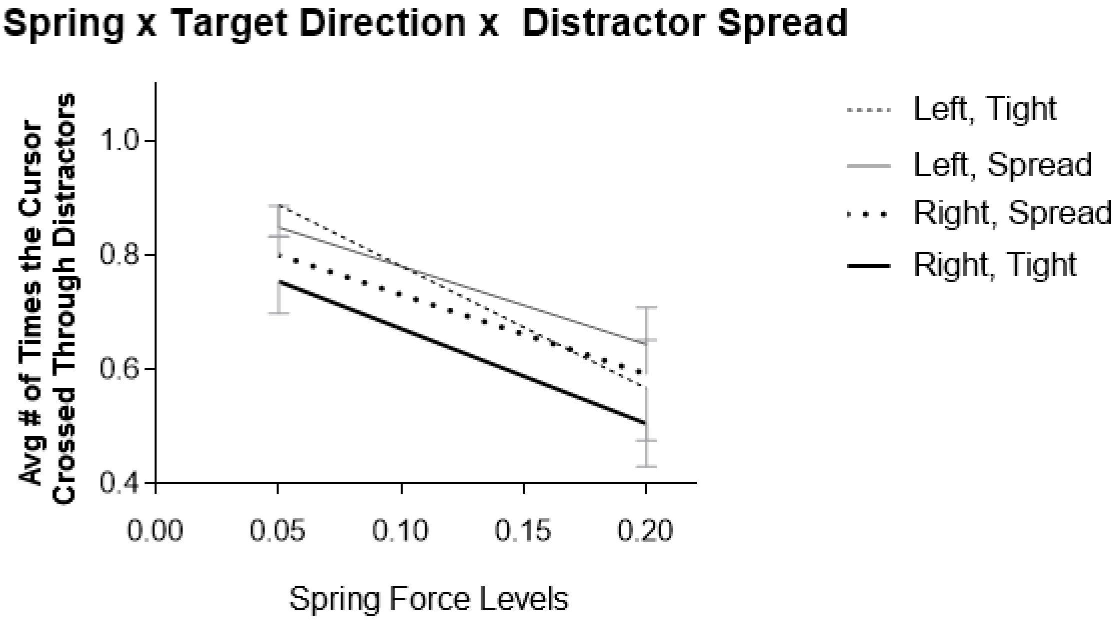

FIGURE 14. Average number of times the cursor crossed through distractors over all trials by distractor spread, target direction, and spring force level.

Gravity * Stimuli Size * Direction:

Interactions involving gravity force level, stimuli size, or target direction were qualified by a three-way interaction between the three variables, *F*(1, 11) = 5.16, *p* < .05. Simple interactions between gravity force level and stimuli size were analyzed at each level of direction. There were no significant simple interactions. Simple interactions between gravity force level and target direction were then analyzed, with stimuli size held constant. Again, there were no significant simple interactions. Since gravity force level was the variable of interest in this three-way interaction, no further simple interactions were analyzed. The three-way interaction between gravity force level, stimuli size, and direction was qualified by a significant five-way interaction, as reported later in this chapter.

Spring * Stimuli Size * Distance:

Interactions involving spring force level, stimuli size, or distractor distance were qualified by a three-way interaction between the three variables, $F(1, 11) = 7.35$, $p < .05$. Simple interactions between spring force level and distractor distance were analyzed at each level of stimuli size. When the stimuli size was small, the effect of spring force level depended on the distractor distance, $F(1,11) = 7.65$, $p < .05$. The simple effects of spring force level were analyzed at both levels of distractor distance paired with small stimuli. When participants encountered small distractors close to the target, they avoided distractors more often when spring force was high ($M = .536$, $SEM = .074$) than when spring force was low ($M = .723$, $SEM = .056$), $F(1, 11) = 15.55$, $p > .01$. When participants encountered distractors far from the target, they avoided distractors more often when spring force was high ($M = .528$, $SEM = .078$) than when spring force was low ($M = .781$, $SEM = .049$), $F(1, 11) = 17.76$, $p < .001$. When the stimuli size was large, there was no significant simple interaction between spring force and distractor distance.

The three-way interaction between spring force level, stimuli size, and distractor distance was qualified by significant four-way and significant five-way interactions, as reported later in this chapter.

Direction * Distance * Spread:

Interactions involving direction, distractor distance, or distractor spread were qualified by a three-way interaction between the three variables, $F(1, 11) = 8.99$, $p < .05$.

Since gravity and spring force were the variables of interest, no further simple interactions were analyzed, but the three-way interaction between direction, distance, and spread was qualified by a significant four-way interaction, as reported below.

Gravity * Direction * Distance * Spread:

There was a significant four-way interaction between gravitational force level, target direction, distractor distance, and distractor spread, $F(1, 11) = 4.97, p < .05$ (see Figure 15). In addition, a marginally significant three-way interaction was found for targets to the left, $F(1, 11) = 4.05, p = .07$.

For spread distractors that were close to the target, the direction of the effect differed between left and right targets. When targets were to the left, participants typically avoided spread distractors close to the target more often when the gravity force level was low than when the gravity force was high. When targets were to the right, participants typically avoided close, spread distractors more often when the gravity force level was high than when the gravity force was low.

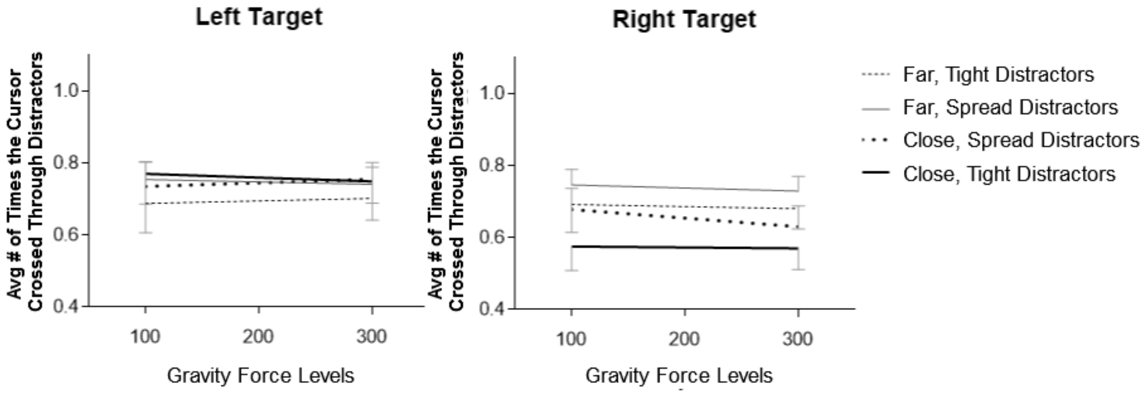

FIGURE 15. Average number of times the cursor crossed through distractors over all trials by gravity force level, target direction, distractor distance, and distractor spread.

Spring * Stimuli Size * Direction * Distance:

There was a significant four-way interaction between gravitational force level, stimuli size, target direction, and distractor distance, $F(1, 11) = 5.69$, $p < .05$ (see Figure 16). This interaction was qualified by a significant five-way interaction between gravitational force level, spring force level, stimuli size, target direction, and distractor distance. Multiple repeated measures ANOVAs were run for each level of target direction, and the interactions between the remaining variables were tested for significance. A significant three-way interaction was found only for targets to the left, $F(1,11) = 9.99$, $p < .01$.

For targets to the left, the lines were very similar. For targets to the right, participants avoided distractors more often when the distractors were large and close to the target than when they were large and far from the target, regardless of spring force level. Participants avoided distractors more often for close, small distractors than for far, small distractors. The results indicated that with right targets for distractors of the same size, participants tended to strategically avoid distractors close to the target more often, possibly due to their desire to not be caught in distractors so close to selecting the target. This four-way interaction between spring force level, stimuli size, direction, and distance was qualified by a significant five-way interaction, as reported below.

Gravity * Spring * Stimuli Size * Direction * Distance:

There was a significant five-way interaction between gravitational force level, spring force level, stimuli size, target direction, and distractor distance, $F(1,11) = 4.85$, $p= .05$ (see Figure 17). Multiple repeated measures ANOVAs were run for each level of target direction, and the interactions between the remaining variables were tested for

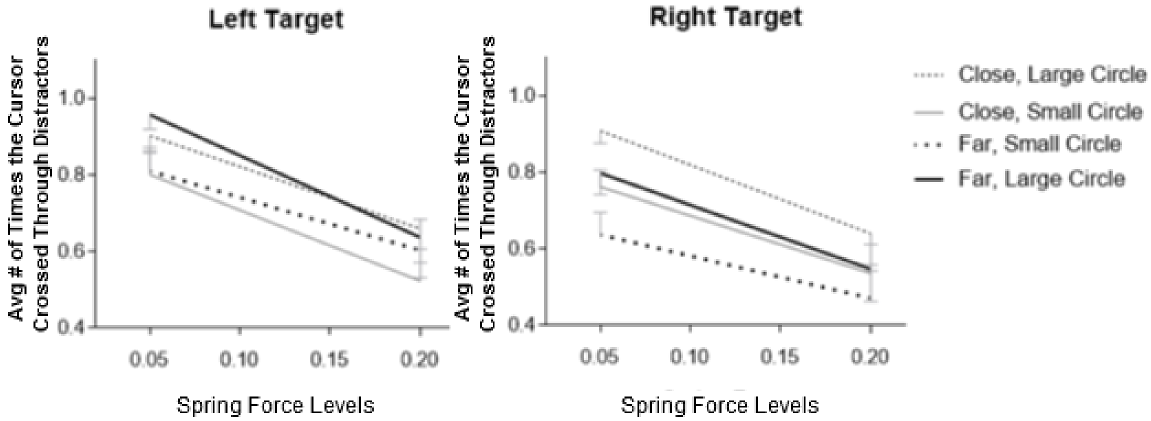

FIGURE 16. Average number of times the cursor crossed through distractors over all trials by spring force level, stimuli size, target direction, and distractor distance.

significance. A significant four-way interaction was found only for targets to the right, $F(1,11) = 5.84, p < .05$.

The figures below show the relationship trends when looking at the average number of times the cursor crossed through distractors over all trials for targets located to the right. Participants typically avoided distractors (average number of times the cursor crossed through distractors over all trials ≈ 1) when the spring and gravity force levels were high, with the exception of when distractors were large and far from the target. In this case, participants crossed through distractors more often. When distractors were close to the target, participants avoided them more often when the spring force level was low and the gravity force level high for small distractor stimuli. Participants most actively avoided distractors close to the target when the spring and gravity force levels were high, and the target was to the right. Finally, there was a tendency for participants to avoid both close and far distractors more often for low spring, high gravity force levels when the distractor stimuli were large.

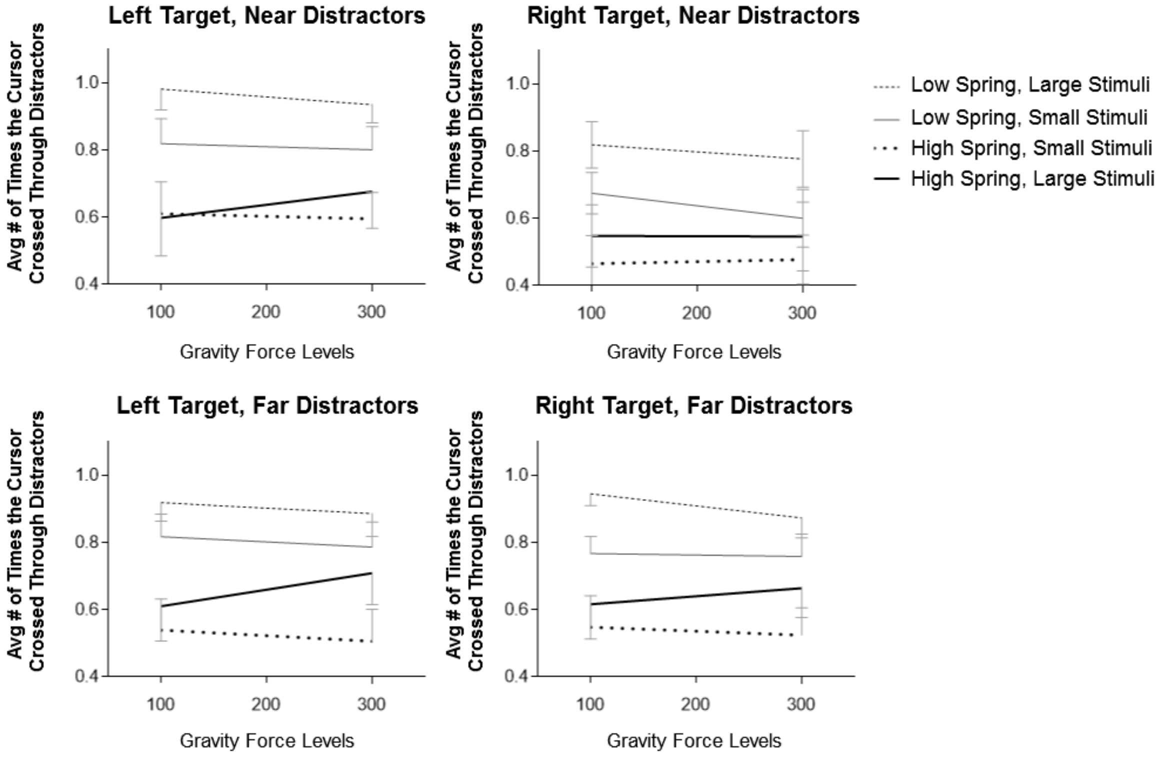

FIGURE 17. Average number of times the cursor crossed through distractors over all trials by gravity force level, spring force level, stimuli size, distractor distance, and target direction.

NASA TLX Workload Ratings

To determine whether the workload for an input device with no forces (mouse) differs from an input device with combinations of high and low gravity and spring force levels, a single-factor repeated measures ANOVA with five levels was conducted. There was no significant difference between the mouse (*M* = 19.58, *SEM* = 3.12) and the low gravity with low spring levels (*M* = 22.75, *SEM* = 3.93), low gravity with high spring levels (*M* = 29.67, *SEM* = 5.79), high gravity with low spring levels (*M* = 22.92, *SEM* = 4.87), and high gravity with low spring levels (*M* = 28.75, *SEM* = 5.20) conditions, *p* > .05 (see Figure 18). However, there was a trend that participants rated that they had experienced higher workloads for the high spring force conditions. It is important to note, however, that all NASA TLX scores were low, which indicated that participants were not working exceptionally hard to complete the tasks.

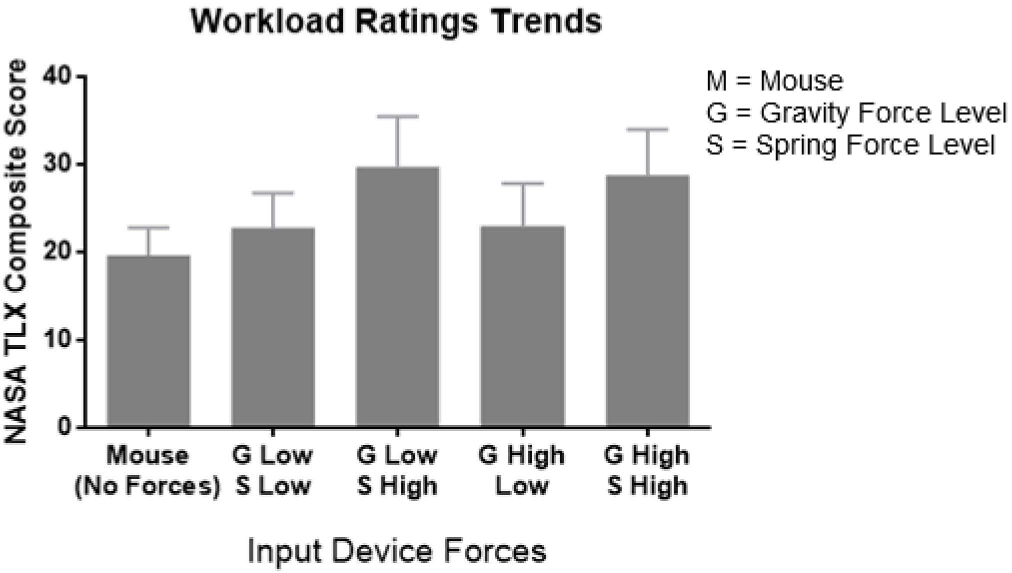

FIGURE 18. Workload rating trends by no force, low gravity low spring force levels, low gravity high spring force levels, high gravity low spring force levels, and high gravity high spring force levels.

The Big Picture

The results demonstrated that, in the presence of distractors, spring force level most strongly impacted both MT and the participants' decision to avoid distractors. Gravitational force feedback, when combined with the other independent variables, had no effect on MT and very minimal effect on the average number of times participants crossed through distractors. Although MTs were quickest with the mouse, spring force MTs were most closely comparable to mouse MTs, particularly with high spring force values. Overall, high spring force improved MTs compared to low spring and gravity forces, but also caused participants to strategically avoid distractors more often. Participants avoided high spring distractors more often than they did low spring distractors, especially when those distractors were close to the target, where fine motor precision was required for target selection. There was also a trend whereby participants rated high spring force conditions as having the highest workloads. Spring force was found to have the greatest benefit for the selection of small stimuli, resulting in an MT that was closer than large stimuli to the mouse MT.

CHAPTER 4

DISCUSSION

The purpose of this thesis was to examine the effects of distractor targets and multiple levels of gravitational and spring force feedback on distractor navigation strategy and target acquisition in a basic HCI point-and-click task within a CDTI framework. This research expanded on the findings of Monk (2014), although Monk did not manipulate the distance of distractors from the target or the spread of distractors, nor did he measure distractor navigation strategy or the participants' subjective workload. The primary goal was to assess how operators handled distractors placed in the movement path toward targets. Operator performance was measured as movement time (MT) from the selection of the start stimuli to the selection of the target stimuli. Operator distractor navigation strategy (DNS) was measured by the frequency with which the cursor crossed through distractors. Operator workload was measured as subjective perceived workload ratings. The experimental design of this study also examined the relationships between target direction and force feedback level in terms of distractor size, distractor distance, and distractor spread.

Prior research has shown that tasks with only one force feedback-enhanced target are unlikely (Tornil & Baptiste-Jessel, 2005) and that tasks with multiple force feedback distractors reduce performance compared to a mouse (Monk, 2014). To address these issues, designs with force feedback must implement optimal force feedback levels in the presence of distractors. In order to discover the keys to such design solutions, it is essential to understand operator performance and the strategies with which operators handle distractors, which is the purpose of this research. For this experiment, three distractors were placed in the movement path between the start location and the target in every condition. The color of the distractors was distinct from that of the target. In any single trial, the three distractors were equidistant from the target location, but the distractor spread (i.e., their distance from one another), distractor distance from the target, and distractor size were manipulated. The presence of distractors has been shown to increase cognitive workload (Friedman-Hill, Robertson, Desimone, & Ungerleider, 2003; Gál, Kozák, Kóbor, & Bankó, 2009) and reduce the benefits associated with gravitational (Dennerlein & Yang, 2001) and spring (Tornil & Baptiste-Jessel, 2005) force feedback.

Gravitational force feedback attracted the cursor and the input device into distractor stimuli or target stimuli boundaries while outside of the borders of the stimuli. As a result, operators felt the physical pull of the device and saw the movement of the cursor on the display. These sensations increased as they neared the stimuli. Higher gravitational levels, thus, resulted in stronger attractive forces pulling the input device toward the stimuli. This study manipulated the level of gain (in Newtons*Pixels^2, or NPS) into two levels of force feedback gain: 100 NPS and 300 NPS. Rorie et al. (2012) demonstrated that gravitational force feedback reduces overall MTs. Hwang, Keates, Langdon, and Clarkson (2003) and Rorie et al. (2013) showed that gravitational force feedback improves movement times, specifically by reducing the approach time near the target. Approach time is important to consider in this research, the approach velocities typically slow down as the participant prepares for the fine motor movements required by target selection.

In this study, spring force feedback was implemented only when the cursor was within the boundaries of the target or distractor stimuli. The force used was similar to that used by Tornil and Baptiste-Jessel (2005). The level of gain for the spring force (in Newtons per Pixel, or NP) was manipulated into two levels: 0.1 NP and 0.3 NP. The spring force resisted movements away from the stimuli's center, making it more difficult for the operator to exit. Higher levels of spring force resulted in more resistance to movements away from the stimuli. Spring force feedback has been shown to reduce movement times (Akamatsu & MacKenzie, 1996), which was consistent with findings in the present study.

Figures illustrating the results are included in the discussion below. In the discussion and figures, it is assumed that participants' velocity of movement was slowed when force feedback distractors captured the cursor. This is an assumption as velocity data was not analyzed for the present research.

Mouse

A standard computer mouse with no force feedback was used as the baseline. Mouse movement times were the fastest under all conditions. When using the mouse, participants tended to avoid small distractors and distractors spread far apart. Because the shortest distance between the start location and the target was a straight line and one distractor was always present within that line, one would expect users to cross through at least one distractor per trial. However, this was not the case, as participants crossed through one distractor in 86% of the mouse trials when the stimuli size was small, and

87% of the time when the stimuli size was spread. The other conditions typically resulted in 94% or higher distractor cursor crossings. These lower cross throughs (86% and 87%) are likely due to the fact that human point-to-point path trajectories tend to be slightly curved and smooth, instead of a straight line (Abend, Bizzi, & Morasso, 1982; Atkeson & Hollerbach, 1985; Bernstein, 1967; Flash & Hogan, 1985; Morasso, 1981; Uno, Kawato, & Suzuki, 1989). With small stimuli, and spread stimuli, the slightly curved movement path is more likely to miss the distractor stimuli located directly in the movement path to the target stimuli, as compared to when the distractor stimuli are larger or tighter together.

Gravitational Force Feedback

The results of this study demonstrated that gravitational force feedback levels, when combined with the other independent variables, had no effect on movement time and very minimal effect on the average number of times participants crossed through distractors. These results were not consistent with those of Monk (2014), who found that movement time benefited from using high gravitational force, despite the presence of distractors. For targets to the right, participants were more likely to avoid distractors close to the target location than those far from the target. In each trial, the last stages of movement required the most precise motor coordination for target selection, so it is possible that participants strategically avoided distractors close to the target as to prevent undesirable capture, and therefore longer MTs, by the distractor stimuli (Meyer, Abrams, Kornblum, Wright, & Smith, 1988). This strategic avoidance so close to the target seems to have negated the benefits of gravity wells on movement time during target selection found by Hwang et al. (2003). It is interesting that this effect was only found for targets to the right, or movements away from the body, but not for targets to the left, or movements toward the body. Prior research has found that pulling movements, or those toward the body, are associated with attracting desired objects, while pushing movements are associated with avoiding undesired objects (Cacioppo, Priester, & Bernston, 1993; Chen & Bargh, 1999; Solarz, 1960). In light of this, it is possible that participants perceived distractors in the path of right targets as more threatening to efficient movement time.

When distractors were close to the target and spread apart, participants were more likely to avoid these distractors when gravity was high than when gravity was low (see Figure 19). For low gravity forces, the likelihood of being captured by spread distractors while moving toward the target was reduced because of the lower attractive force. As a result, the participants' cursors should have been captured more often by distractors when the gravitational force was high and not the other way around, as was found. This finding suggests that for high gravitational forces, participants navigated strategically around or carefully between distractors in order to avoid capture. For low gravitational forces, participants might have seen the low attraction force as presenting a simpler obstacle to overcome. Therefore, they might have been more willing to risk navigating between the distractors, resulting in their more frequent capture.

Spring Force Feedback

Spring force levels had the greatest effect on participant MT and DNS. Indeed, spring force feedback was found to have various main effects and interactions with all of the other variables in terms of both MT and DNS. Overall, high spring force improved MTs, but also caused participants to strategically avoid distractors more often.

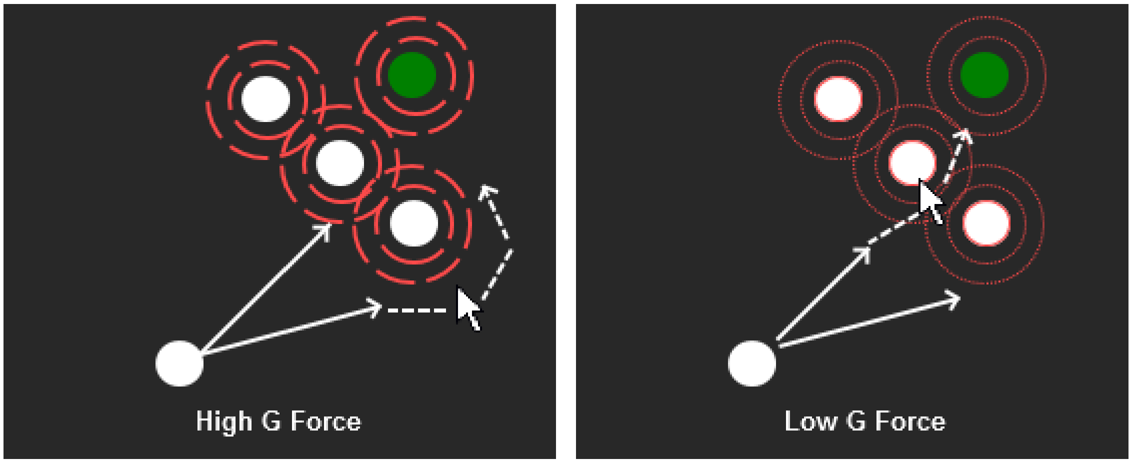

FIGURE 19. (Left) It was more likely to be captured by distractors when there was a higher gravitational pull, so participants were more likely to strategically avoid them to prevent capture. (Right) It was less likely to be captured by distractors when there was a lower gravitational force, so participants were more likely to risk navigating through the distractors. As a result, participants crossed through the distractors more often in this condition.

Lower MTs are valuable for task efficiency, but higher avoidance strategies under such conditions have the potential to incur undesirably higher workloads for an otherwise simple task, which occurred in this study. MTs were fastest with the mouse, but high spring force MTs were only 13% slower. Considering participants' extensive experience with the mouse compared to the Falcon, these results are promising. In addition, the conditions with small force feedback stimuli showed the largest improvements compared to those with large force feedback stimuli. In any case, force feedback does not completely remove the need for fine motor movements during target selection when distractors are present.

With respect to target and distractor stimuli size, participants selected small targets faster with high spring force than with low spring force, revealing no difference for large stimuli. Participants selected the small, high spring targets faster because they avoided small, high spring distractors more often than low spring ones (see Figure 20). Participants avoided the small, high spring distractors more often probably because the high spring force was more difficult to escape than the low spring force.

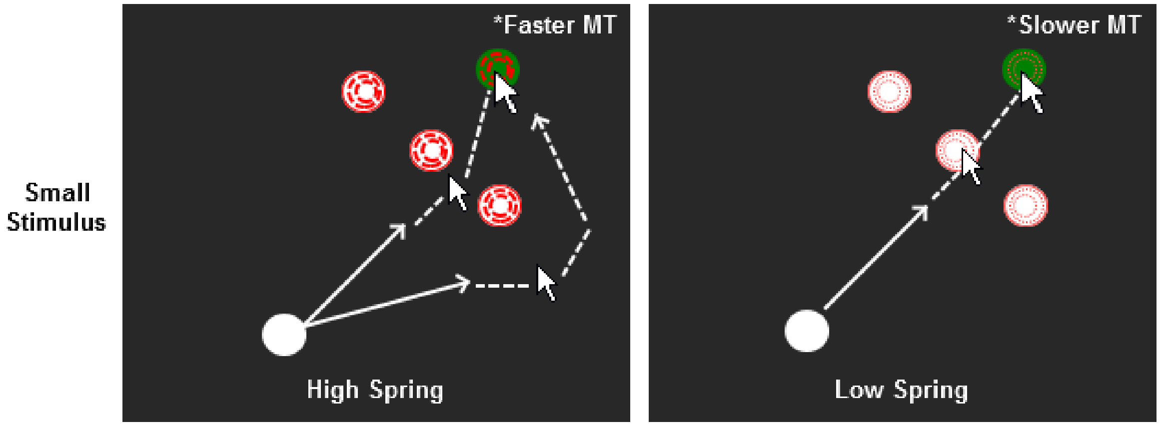

FIGURE 20. Participants had faster MTs for high spring, small stimuli because they purposely avoided distractors. Participants crossed through small distractors with low spring more often, slowing down their MTs.

Low spring forces resulted in faster MTs for large stimuli than for small stimuli, with no difference in stimulus size MT for high spring force (see Figure 21). In addition, MTs for small stimuli were closer than large stimuli to mouse performance. These results suggest that small targets gain the strongest benefits from spring force feedback—a finding consistent with that of Rorie (2013). A possible explanation is that without spring force feedback, it is more challenging for participants to stop inside small targets because they lack the level of accuracy required. High spring force level, therefore, may reduce the need for precise motor movements in completing such tasks.

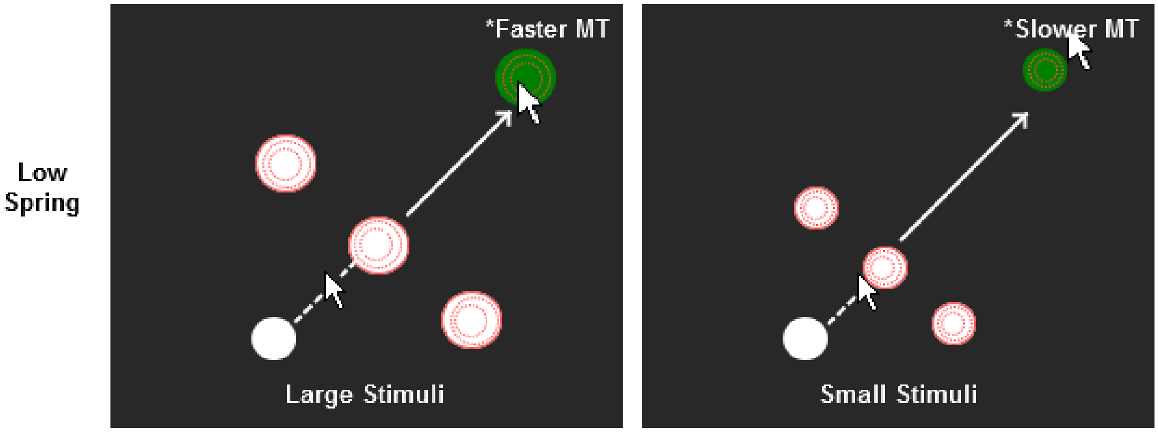

FIGURE 21. Faster MT for large stimuli.

Although, as with the mouse results, participants typically avoided small stimuli regardless of distance from the target, participants were more likely to avoid all distractors close to the target. It is possible that the participants were afraid of being captured at this late stage in a trial. This was especially true with high spring forces; MT was fastest when distractors were far from the target at high spring forces (see Figure 22). This finding is consistent with the idea that target selection is strategically more important for participants than the initial movements near their start location (Meyer et al., 1988). Selection requires fine motor movements, i.e., less speed and more precision. Using extra muscular force to plow through distractors next to a target might improve speed, but reduce accuracy at the same time, causing the cursor to overshoot the target, or worse, to be captured by other nearby distractors. Using extra force to plow through distractors far from the target still leaves ample time for adjustments in preparation for target selection. The takeaway, it seems, is that fine motor selection is still required in the presence of force feedback, and distractors close to a target must be strategically avoided. It is important to note than when the distractors are far from the target (i.e., close to the start location), participants have little time to determine a strategy to avoid the distractors. However, when the distractors are close to the target, participants have extra time to plan a movement path around distractors, if necessary. This idea could have caused the greater frequency of crossing through distractors far from the target.

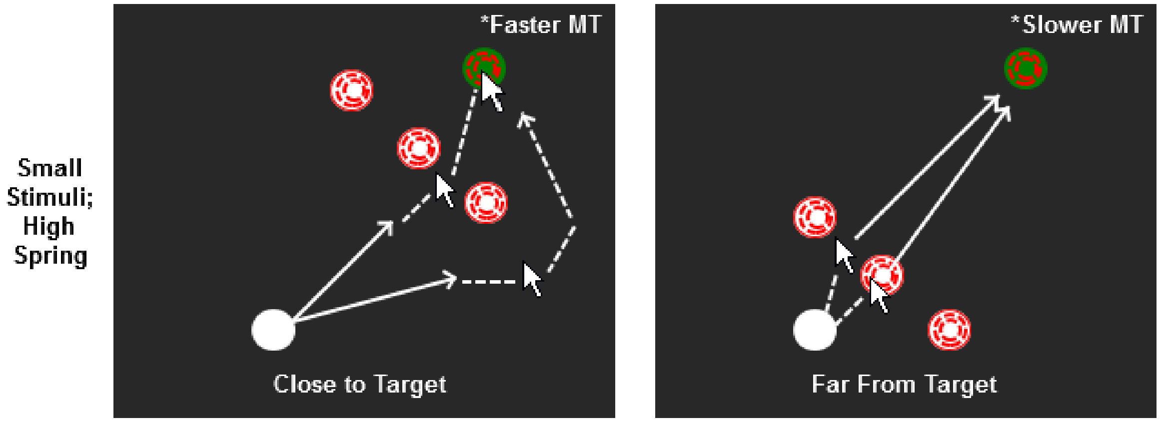

FIGURE 22. Participants typically crossed through distractors far from the target more frequently than those close to the target. High spring forces resulted in the fastest MTs for distractors close to the target.

It was hypothesized that avoidance strategy and movement time for force conditions would be affected by whether the distractors were tight together or spread apart. With the mouse, it was expected that spread distractors, and especially small, spread distractors, would be avoided more often than tight distractors. This is because there would be a higher chance of the cursor successfully navigating a path that does not pass through distractors when they are spread farther apart. This prediction was found to be true for the mouse conditions in this experiment. Spring force feedback findings were also consistent with a couple exceptions found in the interactions. At both levels of spring force, participants avoided large, tight distractors more often than large, spread distractors. It is likely that participants navigated completely around large, tight distractors, regardless of the spring force (see Figure 23). A set of three large, tight distractors could be perceived as a more complex obstacle to handle than three small distractors grouped tightly together. Thus, participants might have seen these large, tight distractors as a greater threat, avoiding them more frequently. It is important to note that for distractors grouped tightly together, high spring force resulted in faster MTs than low spring force, probably because of the improved target selection time associated with high spring force.

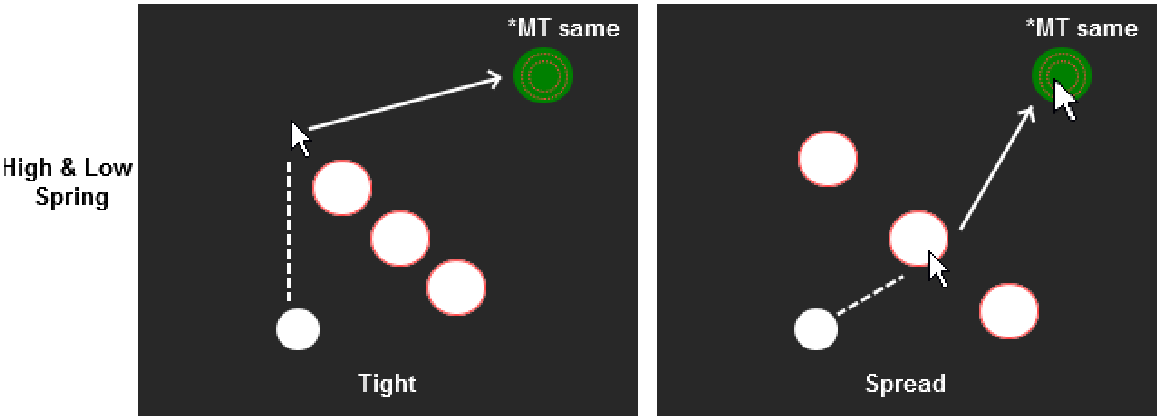

FIGURE 23. With both high and low spring forces, participants strategically avoided large distractors that were grouped tightly together.

Target Direction

Interestingly, participants avoided distractors when targets were to the right more often than when targets were to the left in both the mouse and spring force feedback conditions. For spring force, participants avoided distractors close to the target when the target was to the right. High spring forces also resulted in faster MTs for right targets, probably due to the fact that participants crossed through distractors more often for left targets, increasing MT.

CHAPTER 5

CONCLUSION

This study was designed to replicate a potential CDTI environment in order to examine participant performance and navigation strategy in a point-and-click task, implementing various levels of force feedback in the presence of distractors. Results demonstrated that in the presence of distractors, spring force most strongly impacted both movement time and participants' decision to avoid distractors. Gravitational force feedback had no impact on movement times and minimal impact on distractor navigation strategy. The mouse consistently showed the fastest movement times. However, high spring force was closest to mouse performance, with an average of 90ms longer MTs. Participants avoided high spring distractors more often than low spring distractors, especially when those distractors were close to the target, where fine motor precision was required during target selection.

For target direction, participants avoided distractors when targets were on the right more often than when targets were on the left for both the mouse and spring force feedback conditions. It seems that movements away from the body (right) possibly take a longer movement path (loop) around distractors. For force feedback, the fact that participants crossed through and were captured by distractors more often on the left may have contributed to the longer movement times for left targets.

Design Implications

The findings of this study have significant design implications—particularly the findings that high spring force results in the fastest movement times most comparable to those of the mouse, and that participants are more likely to avoid distractors equipped with high spring force. The major considerations when designing for force feedback are the tradeoffs between the strength of the force feedback, the workload on the operator, and the level of control afforded to the user. The assumption for this study was that high forces would impact the ability of operators to avoid distractors, but, in fact, the opposite was found to be true. It seems that in the presence of high spring force, and to a small degree high gravitational force, participants purposely avoided distractors to maintain a higher level of control over movement path and target selection. The fact that participants were forced to determine a cognitive strategy to avoid distractors for a simple target selection task suggests that high spring force, at best, requires additional research, and at worst, should be avoided. The general recommendation is to not use spring forces, unless the spring force is sufficiently low that it will be barely noticed by users. Gravitational forces, it seems, can be safely used, even in the presence of distractors.

The main problem with spring force seems to be that when spring force is high, participants get "stuck" inside distractors. Distractors with higher spring force require more force to escape. This, in turn, requires conscious effort (with a trend to negatively affect perceived workload). Whenever conscious effort is forced on a user during a menial task such as target selection, there is a problem with the design because workload is increased unnecessarily. Previous research has found that as workload increases, operators' awareness of the environment can be reduced (Foyle, Stanford, & McCann, 1991; McCann, Foyle, & Johnston, 1993; Brickner, 1989; Fischer, Haines, & Price, 1980; Wickens & Long, 1995).

Since target selection requires some level of fine motor movement, whenever force feedback distractors surround a target, it will require more conscious effort on the part of the user to avoid those distractors. If the target is known, spring force feedback for stimuli near the target should be disabled, while stimuli far from the target may be enabled with spring forces. Gravitational feedback is safe to use in both cases.

Limitations and Further Research

With regard to future research, additional insights could be gleaned by employing a method similar to that used in this research and by testing different implementations of force feedback paradigms. For force feedback, movement time and distractor navigation strategy are highly sensitive to spring forces. It would be beneficial to test a variety of low spring forces in order to determine an optimal level that could benefit movement time, while still allowing participants to navigate through distractors safely.

The movement path that participants preferred to navigate was not analyzed in this study. The decision to move between distractors involves a higher risk of crossing through them, whereas navigating completely around a set of distractors would result in a lower risk. Navigating completely around distractors suggests a stronger need to completely avoid distractors, rather than to risk going between them where avoidance occurs by chance. Another important aspect of movement path is in tracking paths that overshoot the target. This can be measured via cursor trajectory or by measuring multiple cursor entries into the target. Overshooting the target or multiple entries into the target suggests that the forces may be too low, or that the participant is moving too quickly or forcefully through the target.

In addition to movement path, the movement velocity from start to target would also be worth studying. Without the presence of force feedback distractors, Koltz et al. (2014) found that force feedback produces higher movement speeds as the target is approached. The presence of distractors may negate this beneficial increase in movement speed, as users are forced to slow down to choose a method for navigating between distractors.

Stimuli size may be a confounding variable. Since the distractor and target sizes changed in size uniformly in this study, there was no way of separating the differing effects of stimuli size, i.e., distractor sizes versus target sizes. Future research could examine the effect of manipulating distractor and target sizes independently in the presence of force feedback, for example, a large distractor size and small target size, or vice versa.

The number of distractors is a variable of interest for future research. In the present study, only three force feedback distractors were present in each trial. With this design, participants could choose to navigate completely around the set of distractors. Future designs could examine the effect of a large number of distractors, especially when a target is fully surrounded by distractors, forcing the operator to move through them.

Another important aspect that has been underexplored in research with force feedback (with the exception of Friendman-Hill et al., 2003; Gál et al., 2009; Oakley et al., 2000) is that of more thorough measures of workload, both cognitive and musculoskeletal. It is especially important to determine which levels of spring and gravity forces negatively impact physical and mental demand over long periods of use, as well as in a more high-fidelity environment with more distractors. Also of great importance are the subjective preferences of participants. It would be futile to build something that operators will not adopt, or worse, that consistently frustrates them.

As far as additional force feedback paradigms, it is important to test manual force feedback, which is commonly implemented in video games where precise target selection is required. This manual force feedback is activated by an action, such as an input device button click. Once the button is clicked, gravity and spring forces could pull in and retain the operator's cursor. A user could then easily move through distractors without repercussions and still gain the benefits of force feedback for the fine motor movements required during target selection. It may also be the case that higher spring and gravity forces could be implemented without negative repercussions. Such a paradigm could also manipulate automatic and manual feedback separately for gravitational and spring forces. Perhaps it is only spring force that requires manual activation. With this manual paradigm, it is expected that participants would learn to expect and rely on the activated force feedback assistance, to the point that they might experience "haptic illusions", perceiving the presence of force feedback when it has not yet been activated (van Mensvorrt, 2009). In other words, to quote van Mensvorrt, "What you see is what you feel." This expectation may increase operator target selection confidence and movement times far beyond that of the paradigm examined in the present study.

Only movements in the top diagonal left and diagonal right directions were examined in the present study. Participants may choose different navigation strategies when moving up and down or horizontally left and right.

APPENDICES

APPENDIX A

DEMOGRAPHICS QUESTIONNAIRE

Participant # ____

Effect of Distractors and Force Feedback on Distractor Management Strategy and Movement Time on an Aimed Movement Task

Please provide your age ____________.

Please circle appropriate response:

Gender:

Male Female

Are you right handed?

Yes No

Do you have normal vision?

Yes No

Do you wear glasses?

Yes No N.A.

If your wear glasses, is your vision normal when you are wearing them?

Yes No N.A.

APPENDIX B

CALIFORNIA STATE UNIVERSITY, LONG BEACH

INFORMED CONSENT FORM

CONSENT TO PARTICIPATE IN RESEARCH

Effect of Distractors and Force Feedback on Distractor Management Strategy and Movement Time on an Aimed Movement Task

You are asked to participant in a research study conducted by Ryan O'Connor, from the Department of Psychology at California State University, Long Beach. You were selected as a possible participant in this study because you are over 18 years of age, are right handed, and reported having normal or corrected-to-normal vision.

PURPOSE OF THE STUDY

Future flight decks are going to likely require new tools (e.g., the Cockpit Display of Traffic Information, CDTI) in order to present pilots with information that they do not currently have access to. Interaction with these tools may prove difficult due to the nature of the cockpit (e.g., instability from weather and turbulence, small display sizes). One potential way to help pilots achieve optimal performance with tools such as the CDTI is to introduce force feedback into the system. Force feedback would pull the pilots' selection tool towards a given target with the goal of minimizing errors and movement time. However, the presence of distractors has shown to reduce performance benefits attributed to force feedback. This study will examine the effect of distractor targets and on operator performance and strategy to avoid distractors with a point-and-click task.

PROCEDURES

If you volunteer to participate in this study, you will take a seat at a workstation that features a computer monitor, a computer mouse, and a gaming device. You will perform a basic point-and-click task with the two different input devices provided to you. You will complete a total of 2 sessions for *up to* a total of 2 hours of participation.

There will be one experimental session with the Falcon, each with 6 blocks lasting roughly 5 minutes. Before each Falcon session, there will be 2 blocks with the standard computer mouse on your first day. On your second day, the 2 computer mouse blocks will be after the Falcon blocks. Each experimental block will contain 120 trials. You will receive rest periods following each practice and experimental block. If you need to leave the testing room during a session for any reason, you may do so without penalty. If necessary, there are opportunities for rest during the trial as well.

POTENTIAL RISKS AND DISCOMFORTS

There are minimal risks involved in participating in this experiment. The risks include eye strain (due to prolonged visual scanning on a desktop computer monitor) and wrist strain (due to prolonged use of two computer input devices). You can leave the test room at any time without penalty, and you may also discontinue your participation in the experiment at any time. There are scheduled rest periods following all practice and experimental blocks, as well as the opportunity for rest between trials.

POTENTIAL BENEFITS TO SUBJECTS AND/OR TO SOCIETY

The results of the experiment will be used to inform future research regarding the implementation of force feedback models into NextGen flight decks. The results will also be used to address gaps in literature concerning force feedback in the presence of distractors.

CONFIDENTIALITY

Any information that is obtained in connection with this study and that can be identified with you will remain confidential and will be disclosed only with your permission or as required by law. The results from this experiment will not be associated with you in any way.

PARTICIPATION AND WITHDRAWAL

You can choose whether to be in this study or not. If you volunteer to be in this study, you may withdraw at any time without consequences of any kind. Participation or non-participation will not affect your status in the university or your employment or status with CSULB. The investigator, however, may withdraw you from this research if circumstances arise which in the opinion of the researcher warrant doing so.

IDENTIFICATION OF INVESTIGATORS

If you have any questions or concerns about the research, please feel free to contact the Principal Investigator Ryan O'Connor (562-544-0577; roconnor661@hotmail.com) or his advisor Dr. Thomas Strybel (562-985-5035; thomas.strybel@csulb.edu).

RIGHTS OF RESEARCH SUBJECTS

You may withdraw your consent at any time and discontinue participation without penalty. You are not waiving any legal claims, rights or remedies because of your participation in this research study. If you have questions regarding your rights as a research subject, contact the Office of University Research, CSU Long Beach, 1250 Bellflower Blvd., Long Beach, CA 90840; Telephone: (562) 985-5314 or email to research@csulb.edu.

SIGNATURE OF RESEARCH SUBJECT or LEGAL REPRESENTATIVE

I am at least 18 years old and I understand the procedures and conditions of my participation described above. My questions have been answered to my satisfaction, and I agree to participate in this study. I have been given a copy of this form.

____

Name of Subject

____ _______________

Signature of Subject Date

APPENDIX C

TABLE 3

ANOVA OF EFFECTS AND INTERACTIONS FOR MOVEMENT TIME

TABLE 3. ANOVA of Effects and Interactions for Movement Time.

Tests of Within-Subjects Effects

Measure: MT

Source	df	F	Sig.
Gravity	1	.108	.749
Spring	1	9.379	.011
StimuliSize	1	111.925	.000
DistractorDistance	1	38.636	.000
Spring * StimuliSize	1	52.850	.000
Spring * TargetDirecttion	1	5.534	.038
StimuliSize * TargetDirecttion	1	10.821	.007
Spring * DistractorDistance	1	16.816	.002
StimuliSize * DistractorDistance	1	14.098	.003
TargetDirecttion * DistractorDistance	1	47.889	.000
Spring * DistractorSpread	1	12.154	.005

APPENDIX D

TABLE 4

ANOVA OF EFFECTS AND INTERACTIONS FOR DISTRACTOR NAVIGATION STRATEGY

TABLE 4. ANOVA of Effects and Interactions for Distractor Navigation Strategy.

Tests of Within-Subjects Effects

Measure: DNS

Source	df	F	Sig.
Gravity	1	.047	.833
Spring	1	16.235	.002
StimuliSize	1	4.818	.051
TargetDirection	1	9.650	.010
Gravity * StimuliSize * TargetDirection	1	5.616	.037
Spring * StimuliSize * DistractorDistance	1	7.361	.020
TargetDirection * DistractorDistance	1	19.126	.001
Spring * StimuliSize * TargetDirection * DistractorDistance	1	5.703	.036
Gravity * Spring * StimuliSize * TargetDirection * DistractorDistance	1	4.858	.050
Spring * DistractorSpread	1	7.111	.022
StimuliSize * DistractorSpread	1	46.323	.000
Gravity * StimuliSize * DistractorSpread	1	8.301	.015
TargetDirection * DistractorSpread	1	6.312	.029
Spring * TargetDirection * DistractorSpread	1	6.369	.028
TargetDirection * DistractorDistance * DistractorSpread	1	8.991	.012
Gravity * TargetDirection * DistractorDistance * DistractorSpread	1	4.973	.048

REFERENCE

REFERENCES

Abend, W., Bizzi, E., & Morasso, P. (1982). *Human arm trajectory formation. Brain 105*, 331-348.

Akamatsu, M., & MacKenzie, I.S. (1996). Movement characteristics using a mouse with tactile and force feedback. *International Journal of Human-Computer Studies, 45*, 483-493.

Akamatsu, M., MacKenzie, I.S., & Hasbrouc, T. (1995). A comparison of tactile, auditory, and visual feedback in a pointing task using a mouse-type device. *Ergonomics*, *38*, 816-827.

Akamatsu, M., & Sato, S. (1994). A multi-modal mouse with tactile and force feedback. *International Journal of Human-Computer Studies 40,* 443-453.

Alexander, A.L., & Wickens, C.D. (2001). *Cockpit display of traffic information: The effects of traffic load, dimensionality, and vertical profile orientation*. Paper presented at the 45th Annual Meeting of the Human Factors and Ergonomics Society, Santa Monica, CA.

Asque, C.T., Day, A.M. & Laycock, S.D. (2012). Haptic assisted target acquisition in a visual point-and-click task for computer users with motion-impairments. *Haptics, IEEE Transactions, 5* (2), 120-130.

Atkeson, C.G., & Hollerbach, J.M., (1985). Kinematic features of unrestrained vertical arm movements. *Journal of Neuroscience 5*, 2318-2330.

Bernstein, N. (1967). *The coordination and regulation of movements*. London, England: Pergamon.

Bonnetblanc, F. (2008). Pointing beyond reach: The slope of Fitts's law increases with the introduction of new effectors independently of kinetic constraints. *Motor Control, 12*, 38-54.

Brickner, M. S. (1989). *Apparent limitations of head-up displays and thermal imaging systems*. In R. S. Jensen (Ed.), Proceedings of the Fifth International Symposium on Aviation Psychology (pp. 703–707). Columbus: Ohio State University.

Cacioppo, J.T., Priester, J.R., & Bernston, G.G. (1993). Rudimentary determination of attitudes: II. Arm flexion and extension have differential effects on attitudes. *Journal of Personality and Social Psychology, 65,* 5–17.

Calhoun, G.L., Draper, M.H., Ruff, H. A., Fontejon, J.V., & Guilfoos, B. J. (2003). Evaluation of tactile alerts for control station operation. *Proceedings of the Human Factors and Ergonomics Society 47th Annual Meeting*, (pp. 2118-2122). Boca Raton, FL: CRC Press, Taylor & Francis Group.

Card, S.K. (1991). A morphological analysis of the design space of input devices. *ACM Transactions on Information Systems,* 9, 99-122.

Card, S.K., English, W.K., & Burr, B.J. (1978). Evaluation of mouse, rate-controlled isometric joystick, step keys, and text keys for text selection on a CRT. *Ergonomics*, *21*, 601-613.

Chen, S., & Bargh, J.A. (1999). Consequences of automatic evaluation: Immediate behavior predispositions to approach or avoid the stimulus. *Personality and Social Psychology Bulletin, 25*, 215–224.

CSD; NASA Flight Deck Research Group, 2004.

Dao, A.-Q.V., Brandt, S.L., Battiste, V., Vu, K.-P. L., Strybel, T., & Johnson, W.W. (2009). *The impact of automation assisted aircraft separation on situation awareness*. Paper presented at the Human-Computer Interaction International Conference, San Diego, CA.

Dennerlein, J.T., Martin, D.B., & Hasser, C. (2000). Force-feedback improves performance for steering and combined steering-targeting tasks. *Proceedings of CHI'2000 Conference on Human Factors in Computing Systems* (pp. 423-430) New York, NY: ACM Press.

Dennerlein, J. T., & Yang, M. C. (2001). Haptic force-feedback devices for the office computer: Performance and musculoskeletal loading issues. *Human Factors*, *43* (2), 278-286.

Ernst, M.O., & Banks, M.S. (2002). Humans integrate visual and haptic information in a statistically optimal fashion. *Nature (London), 415*, 429-433.

Federal Aviation Administration (2013). *FAA aerospace forecast: FY 2013-2033.*

Fitts, P.M. (1954). The information capacity of the human motor system in controlling the amplitude of movement. *Journal of Experimental Psychology*, *47,* 381-391.

Fischer, E., Haines, R.F., & Price, T.A. (1980). *Cognitive issues in head-up displays* (NASA Tech. Rep. No. 1711). Moffett Field, CA: National Aeronautics and Space Administration Ames Research Center.

Flash, T., & Hogan, N., (1985) The co-ordination of arm movements: An experimentally confirmed mathematical model. *Journal of Neuroscience, 5*,1688-1703.

Foyle, D.C., Sanford, B., & McCann, R.S. (1991). Attentional issues in superimposed flight symbology. In R. S. Jensen (Ed.), *Proceedings of the Sixth International Symposium on Aviation Psychology* (pp. 577– 582). Columbus: Ohio State University.

Friedman-Hill, S.R., Robertson, L.C., Desimone, R., & Ungerleider, L.G. (2003). Posterior parietal cortex and the filter of distractors. *Proceedings of the National Academy of Sciences of the United States of America*, *100*(7), 4263-4268.

Gál, V., Kozák, L.R., Kóbor, I., Bankó, É.M., Serences, J.T., & Vidnyánszky, Z. (2009). Learning to filter out visual distractors. *European Journal of Neuroscience*, *29*(8), 1723-1731.

Granada, S., Dao, A.Q., Wong, D., Johnson, W.W., & Battiste, V. (2005). Development and integration of a human-centered volumetric cockpit display for distributed air-ground operations. *Proceedings of the 12th International Symposium on Aviation Psychology*. Oklahoma City, OK.

Griffiths, P., & Gillespie, R.B. (2005). Sharing Control Between Human and Automation Using Haptic Interface: Primary and Secondary Task Performance Benefits. *Human Factors, 47*, 574-590.

Hart, S.G., & Wickens, C.D. (1990). Workload assessment and prediction. In H.R. Booher (Ed.), *MANPRINT: An approach to systems integration* (pp. 257-296). New York: Van Nostrand Reinhold.

Hwang, F., Keates, S., Langdon, P., & Clarkson, P.J. (2003). *Multiple haptic targets for motion-impaired users.* Presented at the Computer-Human Interaction (CHI) Conference on Human Factors in Computing Systems, Ft. Lauderdale, FL.

Jagacinski, R.J., & Monk, D.L. (1985). Fitts's law in two dimensions with hand and head movements. *Journal of Motor Behavior*, *17*, 77-95.

Joint Planning and Development Office (2010). *Concept of operations for the Next Generation Air Transportation System version 3.2.* Retrieved January 3, 2014, from http://jpe.jpdo.gov/ee/docs/conops/NextGen_ConOps_v3_2.pdf

Joseph, K., Domino, D.A., Battiste, V., Bone, R.S., & Olmos, B.O. (2003). *A summary of flight deck observer data from Safe Flight 21 OpEval-2* (DOT/FAA/AM-03/2). Washington, DC: FAA, Office of Aviation Medicine.

Kantowitz, B.H., & Elvers, G.C. (1988). Fitts's law with an isometric controller: Effects of order of control and control-display gain. *Journal of Motor Behavior*, *20*, 53-66.

Koltz, M., Rorie, C., Robles, J., Vu, K.P., Marayong, P., Strybel, T.Z., & Battiste, V. (2014). Effects of Type and Strength of Force Feedback on the Path of Movement in a Target Selection Task. *Proceedings of the 16th Annual International Conference on Human-Computer Interaction.*

Langdon, P., Keates, S., Clarkson, P., & Robinson, P. (2000). Using haptic feedback to enhance computer interaction for motion-impaired users. *Third International Conference on Disability, Virtual Reality and Associated Technologies*, (pp. 25-32) Alghero, Sardinia, Italy,.

MacKenzie, S. (1989). A note on the information-theorertic basis for Fitts's law. *Journal of Motor Behavior, 21*, 323-330.

MacKenzie, S. (1992). Fitts's law as a research and design tool in human–computer interaction. *Human–Computer Interaction*, *7*, 91–139.

MacKenzie, S., & Buxton, W. (1992). Extending Fitts's law as a research and design tool in human-computer interaction. *Human-Computer Interaction, 7*, 91-139.

McAnulty, D. M., & Zingale, C. (2005). *Pilot-based spacing and separation on approach to landing: The effect on air traffic controller workload and performance* (DOT/FAA/CT-05/14). Atlantic City International Airport, NJ: Federal Aviation Administration William J. Hughes Technical Center.

McCann, R.S., Foyle, D.C., & Johnston, J.C. (1993). Attentional limitations with head-up displays. In R. S. Jensen (Ed.), *Proceedings of the 7th International Symposium on Aviation Psychology*, (pp. 70 –75) Columbus: Ohio State University.

Meyer, D.E., Abrams, R.A., Kornblum, S., Wright, C.E., & Smith, J.E.K. (1988). Optimality in human motor performance: Ideal control of rapid aimed movements. *Psychological Review*, *95*, 340-370.

Monk, K. (2014). *Effects of distracters and force feedback on an aimed movement task in a CDTI environment* (Master's thesis). Available from ProQuest Dissertations and Theses database. (1527733).

Morasso, P., (1981) Spatial control of arm movements. *Experimental Brain Research 42,* 223-227

Ng, A.W.Y., & Chan, A.H.S. (2012). Finger Response Times to Visual, Auditory and Tactile Modality Stimuli. *Proceedings of the International MultiConference of Engineers and Computer Scientists 2012 Vol II*, Hong Kong, China, March 14-16.

Oakley, I., McGee, M.R., Brewster, S.A., Gray, P.D. (2000). Putting the feel in look and feel. *Proceedings of CHI 2000 (The Hague)*, (pp. 415-422) ACM Press.

Park, J., Han, S.H., & Yang, H. (2006). Evaluation of cursor capturing functions in a target positioning task. *International Journal of Industrial Ergonomics*, *36*, 721-730.

Prevot, T., Homola, J., & Mercer, J. (2008). *Human-in-the-loop evaluation of ground-based automated separation assurance for NextGen*. Paper presented at the 26th Congress of International Council of Aeronautical Sciences, Anchorage, AK.

Robles, J., Sguerri, M., Rorie, R.C., Vu, K.-P., Strybel, T., & Marayong, P. (2012). *Integration framework for NASA NextGen volumetric cockpit situation display with haptic feedback*. Paper presented at the International Conference on Robotics and Automation, Saint Paul, MN.

Rorie, R.C. (2013). *An Investigation into the Effects of Force Feedback and Movement Direction on an Aimed Movement Task* (Master's thesis). Available from ProQuest Dissertations and Theses database. (1522598).

Rorie, R.C., Bertolotti, H., Strybel, T., Vu, K-P. L., Marayong, P., & Robles, J. (2012). Effect of Force Feedback on an Aimed Movement Task. *Advances in Human Aspects of Aviation,* Chapter 6, 633 -642.

Rosenberg, L.B. (1992). *The use of virtual fixtures as perceptual overlays to enhance operator performance in remote environments* (AL/CF-TR-1994-0089). Wright-Patterson AFB, OH: USAF Armstrong Laboratory.

Solarz, A.K. (1960). Latency of instrumental responses as a function of compatibility with the meaning of eliciting verbal signs. *Journal of Experimental Psychology, 59*, 239–245.

Tornil, B., & Baptiste-Jessel, N. (2005). *Force feedback and performance in a point-and-click task*. Paper presented at the International Conference on Multimodal Interaction, Trento, Italy.

Uno, Y., Kawato, M., Suzuki, R. (1989) Formation and control of optimal trajectories in human multijoint arm movements: minimum torque-change model. *Biological Cybernetics 61*,89-101 van Erp, J.B.F., van Veen, H.A.H.C. (2001). Vibro-tactile information presentation in automobiles. *Proceedings of EuroHaptics 2001*, (pp. 99-104) Birmingham, UK, 2001.

van Mensvoort, K. (2002). What you see is what you feel: exploiting the dominance of the visual over the haptic domain to simulate force feedback with cursor displacements. *Proceedings Designing Interactive Systems*, (pp. 345–348) London, England.

Wall, W., Paynter, K., Schillitoe, A.M., Wright, M., & Scali, S. (2002). The effect of haptic feedback and stereo graphics in a 3D target acquisition task. *Proceedings of Eurohaptics 2002,* (pp. 23-28) University of Edinburgh.

Whisenand, T.B., & Emurian, H.H. (1996). Effect of angle of approach on cursor movement with a mouse: Consideration of Fitts's Law. *Computers in Human Behavior, 12,* 481-495.

Wickens, C.D., & Long, J. (1995). Object versus space-based models of visual attention: Implications for the design of head-up displays. *Journal of Experimental Psychology: Applied, 1*, 179 –193.

Williams, K.W., Yost, A., Holland, J. & Tyler, R.R. (2002). *Assessment of advanced cockpit displays for general aviation aircraft – The capstone program.* (DOT/FAA/AM-02/21). Washington, DC: FAA, Office of Aerospace Medicine.