Effects of Type and Strength of Force Feedback on Movement Time in a Target Selection Task

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Future cockpits will likely include new onboard technologies, such as cockpit displays of traffic information, to help support future flight deck roles and responsibilities. These new technologies may benefit from multimodal feedback to aid pilot information processing. The current study investigated the effects of multiple levels of force feedback on operator performance in an aviation task. Participants were presented with two different types of force feedback (gravitational and spring force feedback) for a discrete targeting task, with multiple levels of gain examined for each force feedback type. Approach time and time in target were recorded. Results suggested that the two highest levels of gravitational force significantly reduced approach times relative to the lowest level of gravitational force. Spring force level only affected time in target. Implications of these findings for the design of future cockpit displays will be discussed.

INTRODUCTION

The implementation of NextGen into the National Airspace System (NAS) will likely involve the introduction of new tools onto the flight deck, such as the three-dimensional (3-D) Cockpit Display of Traffic Information (CDTI), being developed at NASA Ames Flight Deck Display Research Laboratories (Granada, Dao, Wong, Johnson, & Battiste, 2005). The CDTI will enable pilots to create new flight plans with a graphical interface that will require precise inputs from the pilots. These inputs can be difficult due to the unstable nature of the cockpit environment, the small display size that will likely be required, and the potential need for manipulation of the 3-D display. The use of force feedback with the CDTI has been studied as a potential method for allowing operators to make quick and accurate inputs (e.g., Robles et al., 2012).

One type of task that is often performed on a CDTI is a targeting task, where the operator needs to select a target on the screen by moving the cursor from its current position to a desired position. This type of task resembles the movement time task utilized in research on Fitts' Law. Several Fitts' Law studies have examined the effects of a variety of force feedback techniques. In particular, force feedback utilizing an attractive (i.e., gravitational) force has been found to routinely reduce task completion times, error rates, and subjective ratings of musculoskeletal discomfort in many human-computer interaction tasks (e.g., Ahlstrom, 2005; He & Agah, 2001; Oakley, McGee, Brewster & Gray, 2000). However, these studies only examined conditions in which force feedback was present or absent, with very little research devoted to determining the optimal level of gravitational force needed for effective performance in a given task.

Akamatsu and MacKenzie (1996) made an attempt to understand the benefits of a friction-based force feedback by segmenting simple point-and-click movements into its constituent parts. The authors divided the target selection task into two main phases of movement: the approach stage and the selection stage. According to the authors, the approach stage begins as soon as the task starts and ends when the cursor crosses the target boundary, which marks the beginning of the selection state. The selection stage itself can be divided into stopping and clicking, which is marked by the moment the cursor ceases movement. Akamatsu and MacKenzie (1996) found that the use of friction-based force feedback reduced stopping time, but had no effect on approach time. They concluded that the shorter stopping times found in the force feedback condition were due to the ability of participants to respond to tactile stimuli more quickly than visual stimuli. The absence of an effect of force feedback on approach time, the authors argued, was most likely due to the fact that the type of force feedback used in Akamatsu and MacKenzie's study had no effect on movements outside of the target area.

Hwang, Keates, Langdon, and Clarkson (2003) used Akamatsu and MacKenzie's (1996) notion of approach and selection time to examine the effect of gravity wells on target selection. The authors recorded cursor trajectories in the presence of force feedback and target distracters. Hwang et al. (2003) found that gravity wells reduced both approach and selection times. The authors hypothesized that force feedback increased the speed of the cursor once it entered the gravitational field of the target, resulting in shorter approach times. Once the force feedback took control of the cursor, the rate of movement increased compared to the speed of cursor movement without force feedback. Since the last stages of movement require the most precise adjustments, and therefore take relatively longer to complete, the use of force feedback can be understood as relieving operators of the most difficult aspect of target selection (Meyer, Abrams, Kornblum, Wright,

& Smith, 1988). The benefit of force feedback during approach time is thus largely explained by its ability to both guide and complete fine motor movements more quickly and more accurately than movements performed without the aid of gravity wells. As with Akamatsu and MacKenzie (1996), Hwang et al. found that selection times were shortest during trials where force feedback was present.

Rorie et al. (2012) looked at the effect of an attractive force basin on target acquisition in a simulated CDTI task. The force feedback was modeled using a modified version of Newton's gravitational law. The task consisted of small target sizes (0.17 and 0.25 inches) and movement distances (0.83 and 2.50 inches), with six separate target directions relative to the start position. The task was performed with one of three input device conditions: a standard computer mouse (used as a baseline), the Novint Falcon (a 3-D gaming device) with force feedback, and the Novint Falcon without force feedback. Rorie et al. found that the presence of force feedback significantly improved the performance of the Novint Falcon. The Falcon without force feedback resulted in movement times that were 47% longer than those for the Falcon with force feedback. Additionally, the use of the force feedback led to significantly faster movement times relative to the mouse condition when participants were selecting either small or near targets. Overall, performance on the Falcon with force feedback was equal to or better than performance on the mouse in all target selection conditions. However, Rorie et al. used only one value of gravitational force, so it is unknown what the optimal force level is for simple movement time tasks.

The present study was designed to extend the findings of Rorie et al. (2012). We examined multiple levels of two types of force feedback in order to determine which combinations led to the best performance. The first type of force feedback utilized a gravitational force model, which was active while participants were outside of the target boundary, and was inversely proportional to the distance of the target. In effect, the force feedback pulled the participants' cursor towards the target via an attractive force. The second type of force feedback was based on a spring force model, which became active when the participants were inside the target boundary, providing resistance to participant movements away from the target's center. The spring force model was included in order to determine its interactive effects with the gravitational force model.

Participants performed a simple point-and-click, target selection task on a CDTI display. In accordance with the procedure used by Akamatsu and MacKenzie (1996), the effects of force feedback were determined for two distinct measures of movement time: approach time and selection time. The results are intended to inform the potential inclusion of force feedback as a method for improving inputs to future cockpit CDTIs.

Figure 1. Screen shot of simulated CDTI display with start and target icons.

METHOD

Participants

Seven males and five females (*M* = 25.83 years old) from NASA Ames Research Center participated in this experiment. All participants were right handed, over 18 years of age, and had normal or corrected-to-normal vision.

Apparatus

The experiment used two input devices, a standard Logitech optical laser mouse and the Novint Falcon. The control-display ratio (i.e., gain) of the computer mouse was reduced to approximate the C-D ratio of the Novint Falcon. The Falcon is capable of position sensing and applying force feedback in three dimensions, with an operational workspace of 4" x 4" x 4". For the purpose of this experiment, however, the device was restricted to movements in a horizontal plane parallel to the ground. The Falcon was also rotated and mounted on a stand to produce movement in the horizontal plane analogous to the mouse.

The force feedback conditions were provided via the Novint Falcon. A modified version of Newton's gravitational law equation, shown in Equation 1 (Robles et al., 2012), was used to generate an attractive force, F_g, in the direction of the target's center, where d is the distance from the center of the target, r is the radius of the target and K_1 is the gain constant. When outside the target boundary ($||d|| > r$), this gravitational force (expressed in Newtons/Pixel^2) pulled the user toward the center of the target, with the strength of the force increasing as the cursor approached the target's center. The unit vector of the distance vector ($\hat{d}$) was used to specify the proportion of the force that was to be output along both axes (x and y).

$$F_g = \frac{K_1}{\|d\|^2}\hat{d}\,,\ for\ \ \| d \| \geq r \tag{1}$$

A second force model provided stability when the distance between the cursor and the target center was less than or equal to the target radius, as shown in Equation 2.

$$F_s = K_2 \parallel d \parallel \hat{d}, for\ d < r \tag{2}$$

F_s is the spring force in Newton-Pixels, and K_2 is the gain constant. When the cursor is inside the target ($d < r$), the spring force resisted movements away from the target's center. The combination of the two models, therefore, led participants to experience an attractive force toward the target when outside its boundaries, and resistance to exiting the target once inside its boundaries. Three values of gravitational force were tested, 100, 300 and 500 Newtons/Pixel^2, and two levels of spring force were tested, 0.1 and 0.3 Newton-Pixels. These values were selected after informal pilot testing.

Design and Procedure

The experimental design depended upon the input device. For experimental blocks with the Falcon, the design was a 2 (Target Size) x 2 (Target Distance) x 2 (Spring Force Level) x 3 (Gravitational Force Level) x 12 (Target Direction) repeated measures design. All five variables were manipulated and randomized within each experimental block. For experimental blocks with the mouse, a 2 (Target Size) x 2 (Target Distance) x 12 (Target Direction) repeated measures design was used since the mouse was not equipped with the spring or gravitational force models. For the mouse, all three variables were manipulated and randomized within experimental blocks. Participants completed 22 experimental blocks (20 blocks dedicated to the Falcon and 2 dedicated to the mouse), resulting in a total of 3,168 individual target selection trials.

A standard, Fitts' Law task was employed. On each trial, a green start circle (located in the center of the display) and red target circle (located at a specific direction and distance) was presented on a screen shot of the CDTI, as shown in *Figure 1*. The program had an 8" x 8" active display and was presented on a 50" x 29" computer monitor (pixel resolution: 1920 x 1080). Participants selected the green start circle to begin a trial and then moved their cursor as quickly and accurately as possible to the red target circle, clicking anywhere inside the target. After target selection, the start circle, along with the next target, appeared on the screen.

The dependent variables were approach time and selection time, or time inside target as shown in *Figure 2*. Approach time was measured as the elapsed time from the

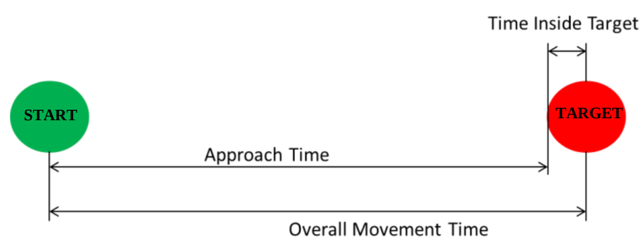

Figure 2. Graphical Depiction of the Movement Components Measured in Current Study

selection of the start icon to the penetration of the target boundary. Selection time or time inside target was defined as the time from the moment the cursor crossed the target boundary until the target was clicked.

RESULTS

For the data obtained with the Novint Falcon, separate 2 (Target Size) x 2 (Target Distance) x 2 (Spring Force) x 3 (Gravitational Force) x 12 (Target Direction) repeated measures ANOVAs were performed on the two dependent measures of approach time and time in target. Huynh-Feldt corrections were used for sphericity violations when appropriate. For brevity, we report only the effects of force feedback, target distance, and target size here (for additional details see Rorie, 2013).

Approach Time

A significant main effect of target distance was obtained, with the far target distance (*M* = 793.32ms, *SEM* = 21.23ms) resulting in significantly longer approach times than the close target (*M* = 512.58ms, *SEM* = 13.53ms), $F(1, 11) = 3428.88$, $p < .001$. A significant main effect of gravitational force level was also found, $F(1.07, 11.74) = 33.48$, $p < .001$. As shown in *Figure 3*, the relationship between approach time and gravitational force can be described by an exponential decay function (r^2=.94). Both the 300 Newtons/Pixel^2 gravitational force level (*M* = 629.00ms, *SEM* = 18.44ms) and the 500 Newtons/Pixel^2 gravitational force level (*M* = 596.34ms, *SEM* = 22.97ms) resulted in significantly faster approach times than the 100 Newtons/Pixel^2 gravitational force level (*M* = 733.51ms, *SEM* = 19.43ms).

Although the main effect of spring force level was not significant, an interaction between gravitational force level and spring force level was obtained, $F(2, 22) = 6.22$, $p = .012$, as shown in *Figure 3*. For a gravitational force of 100 Newtons/Pixel^2, approach times were faster with 0.1 Newton-Pixels than observed for 0.3 Newton-Pixels. At the higher values of gravitational force, approach times decreased, but no effect of spring force was observed. Moreover, approach times for the Falcon at 300 and 500 Newtons/Pixel^2 were equal to, or slightly lower than, the approach times for the standard mouse. Approach times were not significantly affected by the size of the target. Gravitational force also interacted with target distance, $F(2, 22) = 12.85$, $p < .001$. For both distances, approach times decreased with gravitational force, but a greater decrease in approach time was observed for the gravitational force at the far distance.

As expected, performance on the computer mouse was significantly affected by target size, $F(1, 11) = 56.74$, $p < .01$, and target distance, $F(1, 11) = 453.74$, $p < .001$. There were no significant interactions (p's > .05).

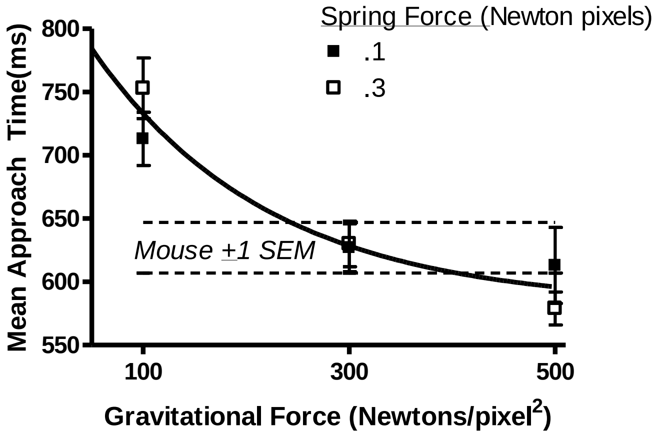

Figure 3. Mean approach time (±1 SEM) as a function of gravitational and spring force levels, compared to approach times with the mouse (no force).

Time in Target

For time in target, a significant main effect of spring force level was found, $F(1, 11) = 6.82$, $p = .024$. Time in target for the 0.3 Newton-Pixels spring force value (M = 199.05ms, SEM = 12.32ms) was significantly lower than time in target for the 0.1 Newton-Pixels spring force level (M = 208.71ms, SEM = 11.37ms). The main effects of target size and gravitational force were not significant. However, an interaction was observed between target distance and gravitational force level, $F(2, 22) = 12.24$, $p < .001$. The effect of target distance depended on the level of gravitational force. As shown in *Figure 4*, less time was spent in targets for the close distance compared with the far distance for gravitational force values of 100 and 300 Newtons/Pixel^2. At 500 Newtons/Pixel^2, time in target was equivalent at both distances.

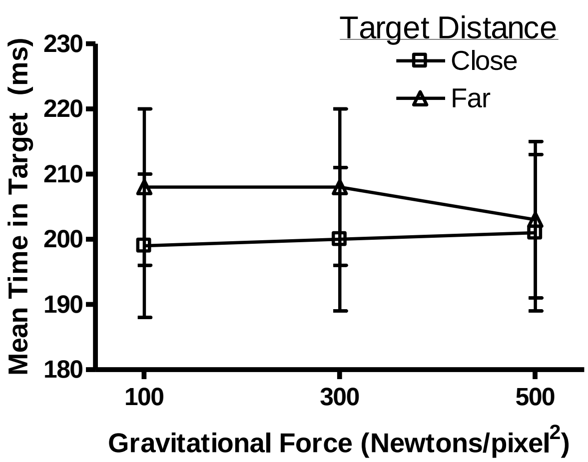

Figure 4. Mean time in target (±1 SEM) by gravitational force and target distance.

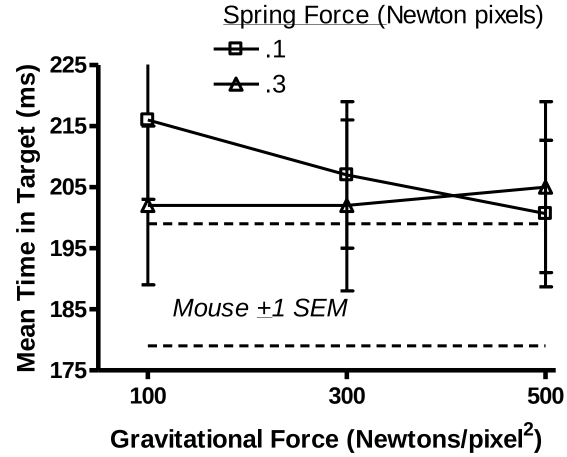

Figure 5. Effect of gravitational and spring force on mean time in target (±1 SEM) for small targets. Dashed lines represent mean time in target (± 1 SEM) for the mouse.

A significant interaction between target size, spring force level and gravitational force level was also obtained, $F(1.38, 15.18) = 12.46$, $p = .002$. This interaction is shown in *Figures 5* and *6* for small and large targets, respectively. For the 100 Newtons/Pixel^2 gravitation force, less time was spent in the target for the larger value of spring force, regardless of target size. At the two higher values of gravitational force, however, the 0.3 Newton-Pixels spring force was only found to significantly decrease time in target for large targets; small targets were unaffected by spring force at the 300 and 500 Newtons/Pixel^2 levels of gravitational force.

Analysis of performance with the mouse revealed a main effect on time spent inside the target, $F(1, 11) = 5.87$, $p = .034$. Participants spent significantly less time inside the target boundary when selecting the close target (M = 185.47ms, SEM = 8.98ms) compared to selections of the far target (M = 193.99ms, SEM = 10.15ms). There were no significant interactions on time inside target, p's > .05.

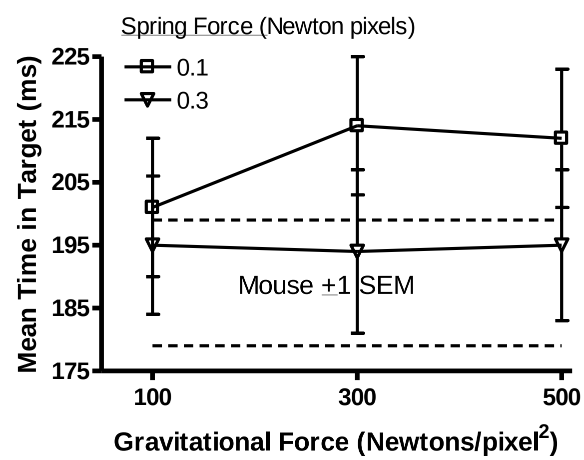

Figure 6. Effect of gravitational and spring force on Mean time inside target (±1 SEM) for large targets. Dashed lines represent mean time in target (±1 SEM) for the mouse.

DISCUSSION

Previous work in the area of force feedback and movement time has demonstrated that the addition of an attractive, gravitational force pulling the cursor toward a target reduces movement times. Moreover, the improvement in movement time is found primarily in the time to approach the target (e.g., Akamatsu & MacKenzie, 1996). In the present study we obtained effects of gravitational force on approach times that were consistent with previous work. However, previous research did not examine how performance is affected by the amount of attractive force, which was the purpose of the present investigation.

We showed that approach time was a negatively accelerating function of gravitational force, such that a 300 Newtons/Pixel^2 attractive force reduced movement times by 14% relative to the 100 Newtons/Pixel^2 force, and the 500 Newtons/Pixel^2 attractive force reduced movement time by 18%. Increasing the gravitational force level from 300 to 500 Newtons/Pixel^2 was therefore found to improve movement time, but to a lesser extent than was obtained by increasing the gravitational force level from 100 to 300 Newtons/Pixel^2. The effect of gravitational force level was also compared to participant performance with a standard computer mouse. The 100 Newtons/Pixel^2 attractive force produced approach times that were 17% longer than those with the mouse, but a 300 Newtons/Pixel^2 attractive force produced approach times that were identical to those with the mouse. Finally, a gravitational force of 500 Newtons/Pixel^2 produced approach times that were 5% shorter than those with the mouse. It is worth noting that these effects of gravitational force were obtained despite the fact that our participants had no previous experience with the Novint Falcon.

By decomposing movement time into the approach and selection components we determined where each force model was most effective. Spring force primarily affected selection time, or the time in the target, prior to clicking it. Specifically, the 0.3 Newton-Pixels spring force level was found to reduce time in target by 5% relative to the 0.1 Newton-Pixels spring force level, which is consistent with the findings of Akamatsu and MacKenzie (1996). Moreover, the effect of spring force level on time in target was modified by target size and gravitational force level. The 0.3 Newton-Pixels force reduced time in target for large targets and gravitational forces of 300 and 500 Newtons/Pixel^2. For large targets, a stronger spring force reduced time in target to the levels of that obtained with the mouse. This suggests that the higher spring force, when combined with stronger gravitational forces, may assist the participant in stopping the movement once inside the target.

In summary, the optimal combination of gravitational and spring force for approach time and time in target, based on the results obtained here, would be a 500 Newtons/Pixel^2 gravitational force combined with 0.3 Newton-Pixels spring force. Moreover, improvements in performance should focus on approach time, since approach times were found to account for over 70% of the total movement time.

Future research will need to address the impact of distractors as well as the use of different input devices. These results were obtained with a single target in an empty movement field. CDTIs will most likely have multiple targets and obstacles, and the pilot may have to either choose an optimal target or avoid obstacles to reach a target. If these also contain force values, a force of 500 Newtons/Pixel^2 might interfere with movement time. By obtaining a function relating movement time to gravitational force, designers can examine tradeoffs between movement times and force feedback level. Lastly, the input device used in this study is not likely to be utilized in the field. As such, it is necessary to extend this research to examine the effects of multiple levels of force feedback on a variety of input methods that may be used in future cockpits.

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REFERENCES

Ahlstrom, D. (2005). Modeling and improving selection in cascading pull-down menus using Fitts' law, the steering law and force fields. In *Proceedings of the Conference on Human Factors in Computing Systems*. Portland, OR.

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.

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*.

He, F. & Agah, A. 2001. Multi-modal human interactions with an intelligent interface utilizing images, sounds, and force feedback. *Journal of Intelligent and Robotic Systems* (32), 171-190.

Hwang, F., Keates, S., Langdon, P. & Clarkson, P.J. (2003). Multiple haptic targets for motion-impaired users. In *Proceedings of the CHI 2003*. Ft. Lauderdale, FL.

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.

Oakley, I., McGee, M.R., Brewster, S., & Gray, P. (2000). Putting the feel in "look and feel". In *Proceedings of CHI 2000 Conference on Human Factors in Computing Systems*. The Hague, Netherlands.

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

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. In *Proceedings of the 4th International Conference on Applied Human Factors and Ergonomics, 2012*. San Francisco, CA.

Rorie, R.C. (2013). An investigation into the effects of force feedback and movement direction on an aimed movement task. (Unpublished master's thesis). California State University, Long Beach, Long Beach, CA.