Force-Feedback Improves Performance For Steering and Combined Steering-Targeting Tasks

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ABSTRACT
The introduction of a force-feedback mouse, which provides high fidelity tactile cues via force output, may represent a long-awaited technological breakthrough in pointing device designs. However, there have been few studies examining the benefits of force-feedback for the desktop computer human interface. Ten adults performed eighty steering tasks, where the participants moved the cursor through a small tunnel with varying indices of difficulty using a conventional and force-feedback mouse. For the force-feedback condition, the mouse displayed force that pulled the cursor to the center of the tunnel. The tasks required both horizontal and vertical screen movements of the cursor. Movement times were on average 52 percent faster during the force-feedback condition when compared to the conventional mouse. Furthermore, for the conventional mouse vertical movements required more time to complete than horizontal screen movements. Another ten adults completed a combined steering and targeting task, where the participants navigated through a tunnel and then clicked a small box at the end of the tunnel. Again, force-feedback improved times to complete the task. Although movement times were slower than the pure steering task, the steering index of difficulty dominated the steering-targeting relationship. These results further support that human computer interfaces benefit from the additional sensory input of tactile cues to the human user.

Keywords
Mouse, pointing device, force-feedback, haptic, steering task, targeting task, Fitts' Law, index of difficulty

INTRODUCTION
When the computer mouse was developed some 30 years ago, it ushered in a new era in computer human interfaces. The advantage of a virtual finger to point and interact with a computer graphic user interface was immediately recognizable, clearly contributing to the mouse's rapid public acceptance. Now 30 to 80 percent of computer work involves the mouse [9]. Since then, engineers and inventors have abandoned the task of building a better mousetrap to build a better mouse. That challenge, however, has proven to be as tricky. Most results to date have focused on industrial design of the mouse more so than producing a new technology for the pointing device.

Derived from telerobotic applications [12] the use of force-feedback technology in computer input device designs has long been a hot topic in the development of computer gaming, computer-aided design, surgical training, and other simulated environments [11]. Yet little has been established regarding its utility in everyday window-type computer desktop environments, an area made still more interesting in light of the ever-increasing numbers of computer-related musculoskeletal disorders [4]. Dennerlein and Yang [5] suggest that the addition of force-feedback might reduce the musculoskeletal loading during computer mouse use, a possible risk factor for chronics musculoskeletal disorders of the upper extremity.

The more general human computer interface (HCI) problem of finding a quantitative means with which to measure the performance of human motor control during completion of simple tasks is much older and better understood. Fitts [8] arrived at a quantitative predictor for movement time in peg-in-hole (targeting) type tasks. He presented the following relationship, known as Fitts' Law, for estimating movement time (*MT*) needed for successful completion of these targeting type tasks:

$$MT = a + b\log_2\left(\frac{A}{W_T} + c\right) \quad (1)$$

where A is the distance from the starting position to the target, W_T is the width of the target, and a, b, and c are empirically determined constants. The logarithmic portion of the equation is defined as the index of difficulty for a targeting task (ID_T):

$$ID_T = \log_2\left(\frac{A}{W_T}\right) \quad (2)$$

For HCI design Fitts' Law provides a practical method for comparing the performance of two different pointing devices during an identical targeting-type tasks, specifically the point-and-click operation. A set of computer programmed tasks can be chosen based on their respective indices of difficulty. Then, a human subject can be asked to perform this set of tasks twice, once using each of two different interfaces. Assuming that all other experimental conditions remain constant for the two tests, Fitts' Law thus provides a hard measure with which to gauge the performance of the two interfaces against each other. Hasser et al. [8] used these means to show that the display of tactile cues through a force-feedback mouse for pointing tasks improved movement times when compared with a standard mouse.

Modern computer interfaces, however, are more than just point-and-click targeting tasks. What can be said of more complicated HCI tasks? Accot and Zhai [1] offered the first quantitative tool for analyzing and predicting the difficulty of HCI steering tasks. A steering task (in 2D terms) requires one to move the computer's pointer a certain distance along one axis without varying more than an arbitrary amount along the opposite axis. In other words, navigating through a tunnel. Everyday examples include steering a menu and its submenus, tracing a shape in a drawing program, and moving a scroll bar down a word processor or web page. Accot and Zhai [1] proposed that the index of difficulty for an arbitrary steering task (ID_S) did not include any logarithmic element. It was simply:

$$ID_S = \frac{A}{W_S} \quad (3)$$

where A represents tunnel length, and W_S represents tunnel width. Thus, for steering tasks, the predicted movement time (MT) is:

$$MT = a + b \cdot ID_S \quad (4)$$

where a and b are empirically determined constants. As in the case of Fitts' Law, from which Accot and Zhai were able to derive this steering law, we can use this relationship as a quantitative measure for determining the performance of new interface designs.

Following Hasser's et al. [8] lead, we decided to test the effects of force-feedback on steering-type tasks. As Hasser and Goldenberg showed experimentally, the addition of a force-feedback attractive basin that pulls the mouse to the center of the desired target substantially decreased the movement time for point-and-click targeting tasks. We hypothesized that similar benefits would be observed experimentally during steering tasks.

Pilot studies indicated that movement time for steering tasks depended on the direction of the movement, perhaps due to the overall joint kinematics required for the movement. Therefore, we also hypothesized that a steering performance difference exists between horizontal and vertical movements in the virtual desktop.

Another task frequently encountered within the windows-type environment is the combined steering and targeting task. For example, within a menu driven interface, the user is required to steer down a menu *and then click on a target*. This combined steering-targeting type task is not limited to menus. Selecting text usually means clicking, then steering the cursor to the desired selection, and clicking again. Graphic design programs also make liberal use of this selection method, and spreadsheet applications. We hypothesized that the movement time is affected equally by both the steering task difficulty and the targeting task difficulty.

METHODS AND MATERIALS

Figure 1: The force-feedback mouse (*FEELit* Mouse, Immersion Co. San Jose, CA).

Force-feedback mouse

A development force-feedback mouse (*FEELIt* Mouse, Immersion Corporation, San Jose, CA) was used throughout these experiments (Figure 1). The device consists of an ordinary two-button mouse, which is attached underneath to two motors through a bar linkage. The physical connection limits the workspace to approximately one square inch and does not allow for indexing of the mouse by picking it up and replacing it on the pad. The motors in the base can be programmed to move the mouse with up to three ounces (0.84 N) of force along any x-y vector parallel with the surface of the mouse pad. By keeping continuous track of the correspondence between the mouse's virtual location on the Windows 98 ® desktop and its location within the physical workspace, the mouse can be programmed to play force-feedback effects. For example, an attractive basin programmed around an OK button on the computer desktop produces a force that physically attracts the mouse and the hand of the user operating the mouse in the direction of the button. The end result is that the user feels as if their hand is pulled into the button itself.

Steering task and software

The testing software for the experiments completed three objectives. First the program presented the test subject with steering or combined steering-targeting tasks. Second, the program recorded their performance as measured through time to complete the task and accumulated errors during an individual successful task. Finally, the software, when requested, drove the motors of the force-feedback mouse based on the force algorithm in Figure 3.

The standard steering task consisted of a field with arbitrary length and width (Figure 2). These can readily be used, as shown previously, to calculate a steering index of difficulty. Using this index of difficulty, twenty fields of varying length and width were formulated (Table 1). The movements were also assigned directions within the visual display such that, five were in a top-to-bottom direction, five were in a bottom-to-top direction, five were in a left-to-right direction, and five were in a right-to-left direction. Hence, there were 10 vertical (top-to-bottom or bottom-to-top) movements and 10 horizontal (right-to-left and left-to-right) movements. This allowed for suitable testing of hypothesis two. The order of presentation of these twenty fields was randomized.

Table 1: Tunnel Widths and Indices of difficulty (R = Right, L = Left, D = Down, U = Up)

Tunnel Width (W_S) (Pixels)	Tunnel Length (*A*) (Pixels)	ID_S	Dire-ction	Tunnel Width (W_S) (Pixels)	Tunnel Length (*A*) (Pixels)	ID_S	Dire-ction
50	250	5.0	D	20	250	12.5	R
25	150	6.0	L	40	550	13.8	D
40	250	6.3	U	20	300	15.0	R
40	300	7.5	L	25	400	16.0	U
25	200	8.0	U	30	500	16.7	L
30	250	8.3	R	15	250	16.7	D
40	400	10.0	R	30	550	18.3	R
50	500	10.0	L	25	500	20.0	L
50	550	11.0	U	20	500	25.0	D
40	500	12.5	U	20	550	27.5	D

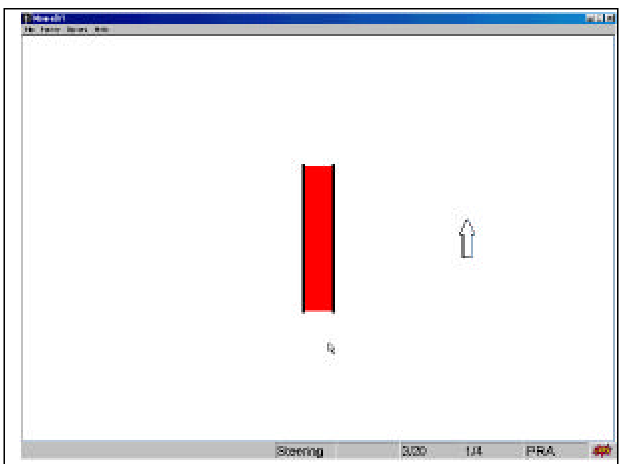

Figure 2: The steering task window. Operators had to navigate the cursor between the two solid lines in the direction denoted by the arrow on the right.

The test subject was presented with one of the twenty fields in random order. When a field was presented, the test subject enters the cursor within the zone, between the two solid lines from one of the open ends and moves to the other end in the direction of the arrow (Figure 2). Once the cursor enters the zone from the correct direction the timer was started. Exiting the field from the opposite side stopped the timer, and the results (including error count, field dimension, and field direction) were then recorded in an output file. When the subject exited the field through any other location the error count was incremented, the timer reset, and the user has to begin the field again. After successful completion, a new field is presented to the subject. This continued until the test was completed. Each of the twenty fields was presented four times, for a total of eighty test fields.

When force-feedback was turned on, the mouse rendered haptic walls that coincided with the graphic walls of the testing field, the solid black lines. The force fields of the haptic walls acted to repel the mouse and the operators' hand away from the solid lines of the testing field towards the center of the tunnel. A sufficient amount of effort by the human operator could still overcome the maximum force from the force fields (about three ounces), escaping the tunnel and failing the trial. The magnitude and direction of the force field is presented in Figure 3.

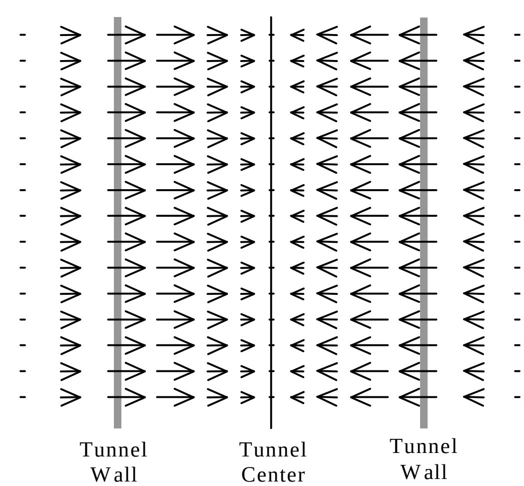

Figure 3: The steering task force field. The force magnitude was proportional to the distance from the center of the tunnel with maximum value of 0.8 N.

Combination task

For the combined steering-targeting experiment, a modified version of the steering program was used (Figure 2). Similar to the steering task, a set of ten fields with a variety of indices of steering and targeting difficulty were created. To eliminate the directional variation experienced in the steering tasks, all ten fields required left-to-right movements.

As before, field presentation was randomized. The procedure for successfully navigating a field was the same as in the steering experiment, except that the subject would exit the tunnel into an endzone area. The subject was then required to click in the endzone area. If the subject left the endzone area before clicking in it, the trial was counted as an error and the subject repeated the trial. Also as before, each of ten fields was presented four times, for a total of forty trials. The subjects completed forty trials with and without force-feedback support.

When force-feedback is turned on, the mouse rendered haptic walls around the solid lines of the steering tunnel as discussed above. In addition, the endzone area was made into an attractive enclosure; the user's mouse was physically drawn into the endzone

Table 2: Combined task fields.

A	W_S	W_T	ID_S	ID_T
Tunnel Length	Tunnel Width	Endzone Length	A/W_S	$ID_T = -\log2(W_T/2A)$
160	40	40	4.00	3.00
170	40	30	4.25	3.50
180	40	20	4.50	4.17
180	30	20	6.00	4.17
160	30	40	5.33	3.00
170	30	30	5.67	3.50
360	20	40	18.00	4.17
370	20	30	18.50	4.62
380	15	20	25.33	5.25
350	15	50	23.33	3.81

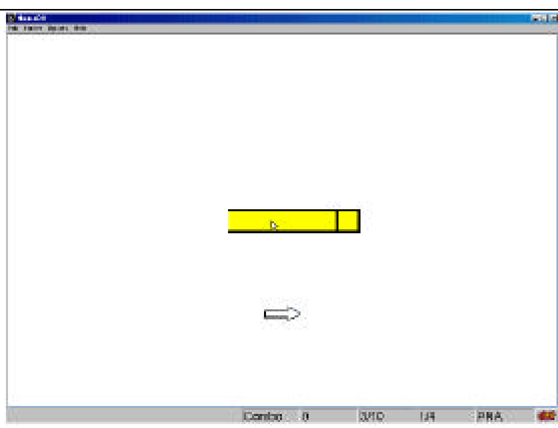

Figure 4: The Combination task. The subject navigate the cursor from the open end of the field staying within the solid lines and then stopping and clicking in the rectangle at the other end of the steering tunnel.

With our knowledge of steering and targeting, we hypothesized a hybrid steering-targeting law: that the difficulty of a combined steering and targeting task would depend in equal parts upon the difficulty of the steering and targeting components to the task.

$$MT = a + b \cdot ID_S + c \cdot ID_T \qquad (5)$$

where a, b, and c are empirically determinable constants; ID_S and ID_T are as stated in equation 2 and 3 respectively.

Subject protocol

A total of ten human subjects participated in the steering experiment and another ten participated in the combination task experiment. All subjects read and signed a consent form. The Harvard School of Public Health's Committee on Human Subjects approved the consent form and protocol. In the steering experiment, subject age ranged between 22 and 52 years. The average age was 33.8 and the median was 33. Three subjects were female and seven subjects were male. All subjects used their right hand for the experiment, which, in every case, was also the subject's dominant hand. For the combined steering-targeting experiment, subject age ranged from 22 to 47. The average age was 28.8 and the median age was 27. Three subjects were female and seven subjects were male. All used their dominant hand, which, except for one subject, was the right hand. The chair, mouse table, and monitor height were adjusted for each subject in accordance with ANSI-HFES Standard [3].

For both experiments the subjects completed the series twice, once with force-feedback and once without. The order of presentation of the force-feedback was randomized. Without force-feedback, the task takes about five minutes to complete, thus minimizing the effect of subject fatigue on the results of the later testing blocks. Each subject was also required to perform two blocks (forty fields) of practice before beginning the test.

RESULTS

Steering task and movement directions

The mean value of movement time (MT) for each of the twenty fields was calculated by first averaging the four trials within a subject and then averaging across the ten subjects.

Times to complete vertical movements were larger than the movement times for the horizontal movements for both force-feedback conditions (Figure 5). Two-sample t-test showed significance for the *without-force-feedback* condition ($p = 0.039$), but the difference for the *with-force-feedback* condition was less distinguishable ($p = 0.079$). For both cases the movement times followed a linear relationship with the steering index of difficulty and were highly correlated ($R^2 > 0.9$).

The addition of force-feedback had two effects. First, the movement times for both the vertical and horizontal movements improved significantly, and were, on average, 52 percent faster (range 38 to 68 percent faster). Using the values averaged within subjects, the Student paired *t*-test for the movement times across indices of difficulty showed significance for all cases (p ranged from 0.000 to 0.015), except the smallest index of difficulty for horizontal movements ($p = 0.067$). Second, the force-feedback appeared to decrease the difference between the two directions of the movements (Figure 5).

Combined steering and targeting task

For the combined steering and targeting task, the steering index of difficulty appears to dominate the targeting index of difficulty. We used the Variance Accounted For (VAF) [10], the correlation coefficient (r^2), and the root mean square error as quantitative measures for the contribution of the steering and targeting

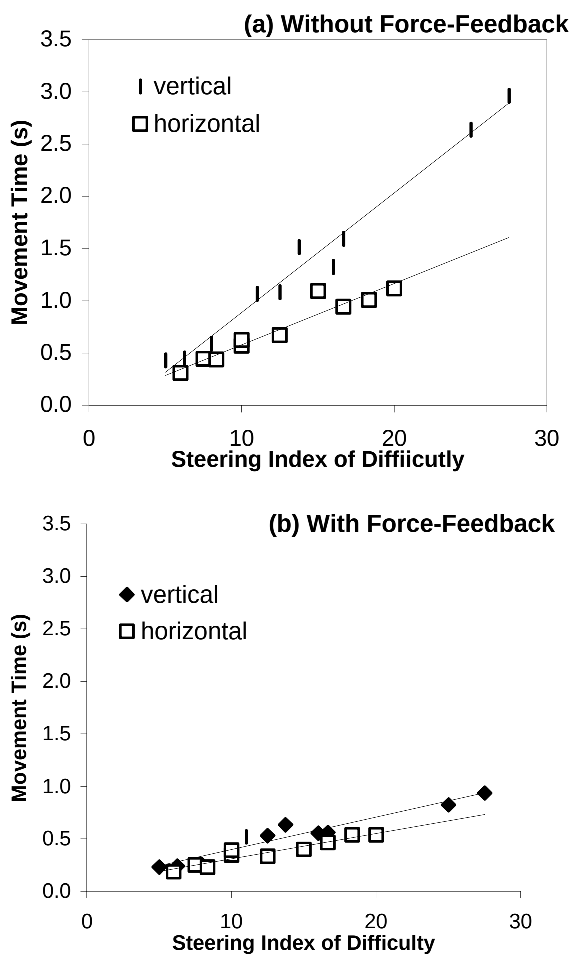

Figure 5 a and b: Steering performance comparing vertical and horizontal movements for without force feedback (a) and with force-feedback (b). For without force-feedback, the movement times for vertical movements are larger than the horizontal movements. With force-feedback (b), movement times improve for both type of movements and the difference between the two directions is less distinguishable.

indices of difficulty and linear combination (Equation 5) to the measured movement times. The combined estimate, based on both ID_S and ID_T (Equation 5) provided the best predictor of movement times followed closely by the steering estimate, which is based solely on the steering index of difficulty (Equation 4). The prediction based on just the targeting index of difficulty (Equation 1) correlated poorly with the movement times and had the largest error of on average 30%. The VAF, r^2, and root mean square errors (MSE) values for the three estimates are presented in Table 3.

The addition of force-feedback again improved performance for the combined task. Movement times significantly improved from 15 to 35 percent for the ten movements (Pair student *t*-test, $p < 0.023$)

DISCUSSION

All the data support the stated hypotheses, except for the combined steering and targeting task. The first hypothesis, the addition of a force-field that tends to pull the mouse to the center of the steering tunnel improves the time to complete the task, is evident in Figure 5. This hypothesis is also true for the combined steering task, although the improvement is smaller, 25% compared to the 52% improvement for the steering task alone. The design of the force field provides a physical valley or groove for the human operator to move the cursor along providing assistance for keeping the cursor in the middle of the tunnel. As a result the human operator spends little effort keeping the cursor aligned within the tunnel. Rather they rely on the force-feedback algorithm and mouse to provide the necessary physical guidance. This result was expected based on the evidence that force-feedback improves performance for targeting tasks [5, 6, 8]. Furthermore, the data also support the relationship between performance and task difficulty as proposed by Acott and Zhai [1].

The second hypothesis, that the time to complete movements in the vertical direction of the video display is larger than the times to complete horizontal movements, is supported by the same data presented in Figure 5. The difference, however, is much less evident with the application of force-feedback. The movement direction differences may be explained by the differences in the joint kinematics required for each of the movements. One of primary means of producing horizontal mouse movement is with radial and ulnar deviation of the wrist,

Table 3: Model Fit Measures

Condition		Combined	Steering	Target
Without Force	r^2	0.98	0.98	0.52
Without Force	VAF	100%	100%	94%
Without Force	MSE	0.05 s	0.06 s	0.31 s
With Force	r^2	0.99	0.98	0.55
With Force	VAF	100%	100%	96%
With Force	MSE	0.03 s	0.04 s	0.18 s

a movement with a relatively low degree of freedom. Conversely, vertical movements require the hand to be moved in and away from the body. For small distances this movement can be achieved with some amount of wrist flexion and extension. But as the movement distances increase other joints and hence other muscles are recruited to move the mouse. For example a movement away from the body requires extension of both the shoulder and the elbow joint. Therefore, the vertical motion requires movement of greater inertia and multi-joint coordination -- a higher level of difficulty. The addition of force-feedback, which aids coordination, diminished the differences greatly. Hence the difference is more likely related to the multi-joint coordination issue. Note that the users were allowed to rest part of their arm on the tabletop, but that the chairs were armless without elbow support.

The third hypothesis, that both the steering and the targeting indices-of-difficulty equally affect the performance of a combined steering and targeting task, was not evident within these tests. Rather steering dominated, being highly correlated with the movement times whereas the targeting steering difficulties were less so. Intuitively, it is expected that the movement times for a combined task would be longer than the pure steering task, and this is the case. Comparing the data for similar steering *ID*s for the steering task and the combined task, the pure steering task is faster than the combined tasks on average by 37 and 54 percent for the *without-force-feedback* and *with-force-feedback* conditions, respectively. The addition of having to stop within the end zone thus affects the movement times, but the movement times are more related to the steering task difficulty and not the targeting difficulty. While we did take care to cover a large range of targeting and steering task difficulties (Table 2), our test cases for the combination are limited. For example, as the tunnel width increases, but the endzone remains constant one would expect the targeting difficulty to take over as the dominating index; however, the data here do not test that hypothesis.

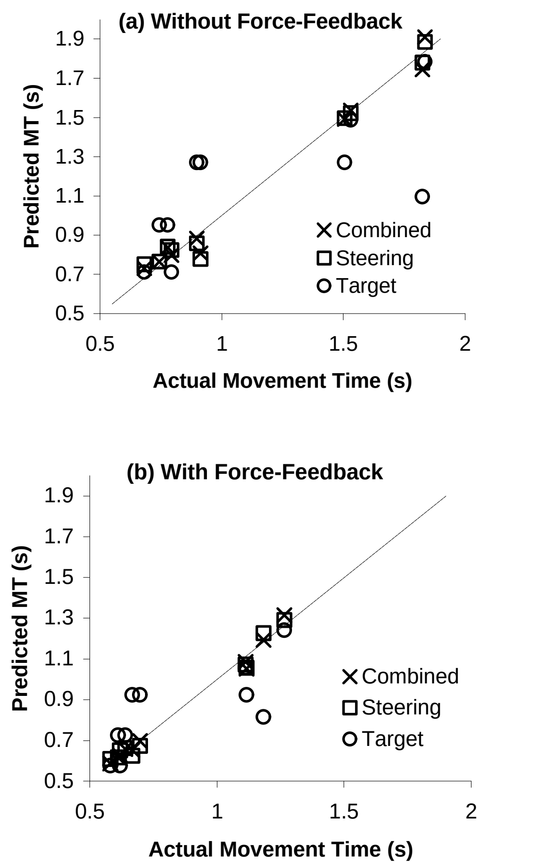

Figure 7: Performance of the combined steering and targeting task for without force feedback (a) and with force-feedback (b). The predicted values for the Combined (solid diamond), Steering (open square) and Target (open circle) were calculated from equations 5, 4 and 1, respectively. While there is little difference between the Combined and Steering predictions, there is a large difference between them and the prediction based purely on the target difficulty. Again the addition of force-feedback (b) improves movement times.

Error count data showed no significant correlation with any other test condition. This may have been due to the wide variety of approaches each subject took to completing the test. While all subjects were instructed and urged during the experiment to complete the fields as quickly as possible despite the risk of making an error, many subjects still chose to navigate the fields more carefully. With force-feedback, all fields averaged to less than one error. Without force-feedback, 17 out of 20 fields averaged to less than one error. The highest mean error was 2.35, and was from the field with an ID_S of 25.

The force-feedback algorithms presented here provide the user with assistive types of tactile cues that guide the user to complete the task. The algorithms relieve the human operator of some of the difficult motor

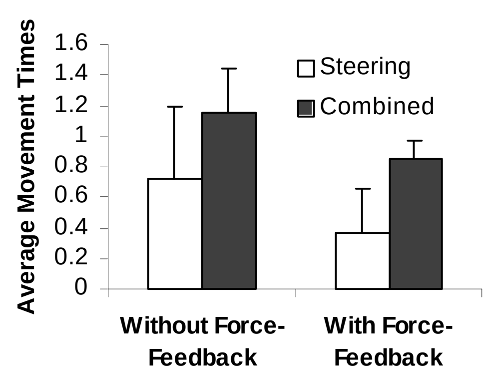

Figure 7: Differences between pure steering and combined steering and targeting task. The combined tasks take longer.

control necessary to complete a targeting or steering task. Similar to the assistive attractive basins around pointing targets [5, 8] performance for an attractive valley around a tunnel improves the steering task. Akamatsu et al [2] developed a multimodal mouse that provided simple tactile cues, such as vibrations for event detection and friction type of force when moving across certain fields. While these modes provided tactile cues, they did not assist the motor control in completing the task. As a result Akamatsu et al [2] observed small performance enhancements. Therefore, designers of force-feedback should consider the type of tactile cues and their assistive or resistive nature in order to maximize performance enhancements.

One downside of this technology is the possible display of force that does not match with the intent of the user. For example, if one gets caught in a tunnel when he or she did not intend to be inside it, the user may become frustrated with overcoming the force of the wall in order to exit the tunnel intentionally. Designers must be aware of these conflicts of interests between an intended movement and the proposed implementation of a force-feedback algorithm.

The limitations of the conclusions are quite normal for most laboratory-based studies. First and foremost are that these results are for simulated tasks in a heavily controlled environment. The performance enhancements during real tasks may be affected by other factors not examined here. For the combined task, there also may be other targeting distracters that can limit or even hinder performance enhancements. The combined task also had a limited number of task difficulties tested. Examination of the extremes would provide a more complete picture of the interaction between steering and targeting.

The human computer interface was enhanced by the addition of force-feedback systems. The system adds more sensory feedback to the human pertaining to the computer environment in which they interact. It provides yet another channel for information to be exchanged.

CONCLUSIONS

For steering task completed within the virtual environment of the computer interface, the addition of tactile cues through a force-feedback device improves performance. For our configuration, steering movements in the vertical screen dimension have more difficulty. Furthermore, the combined steering and targeting task require more time to complete than a pure steering task, but are more strongly correlated with steering than targeting index of difficulty. The implementation of these results indicates a strong potential for the use of force-feedback technology for the desktop and computer aided design regimes that heavily rely on the mouse pointing device as a primary computer interface.

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