Haptic Force-Feedback Devices for the Office Computer: Performance and Musculoskeletal Loading Issues

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Pointing devices, essential input tools for the graphical user interface (GUI) of desktop computers, require precise motor control and dexterity to use. Haptic force-feedback devices provide the human operator with tactile cues, adding the sense of touch to existing visual and auditory interfaces. However, the performance enhancements, comfort, and possible musculoskeletal loading of using a force-feedback device in an office environment are unknown. Hypothesizing that the time to perform a task and the self-reported pain and discomfort of the task improve with the addition of force feedback, 26 people ranging in age from 22 to 44 years performed a point-and-click task 540 times with and without an attractive force field surrounding the desired target. The point-and-click movements were approximately 25% faster with the addition of force feedback (paired t-tests, $p < 0.001$). Perceived user discomfort and pain, as measured through a questionnaire, were also smaller with the addition of force feedback ($p < 0.001$). However, this difference decreased as additional distracting force fields were added to the task environment, simulating a more realistic work situation. These results suggest that for a given task, use of a force-feedback device improves performance, and potentially reduces musculoskeletal loading during mouse use. Actual or potential applications of this research include human-computer interface design, specifically that of the pointing device extensively used for the graphical user interface.

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 graphical user interface (GUI) was immediately recognizable, clearly contributing to the mouse's rapid public acceptance. Now, depending on the specific task at hand, 30% to 80% of computer work involves the mouse (Johnson, Dropkin, Hewes, & Rempel, 1993). Accompanying this increase in use has been an increase in the incidence of work-related musculoskeletal disorders in the office workplace (U.S. Department of Labor, 1998). Prolonged work on video display terminals has been linked to these disorders (e.g., Bergqvist, Wolgast,

Nilsson, & Voss, 1995; Faucett & Rempel, 1994). However, only general risk factors, not the exact injury mechanisms, are well understood. Along with motion, posture, and vibration, the *force* exerted during a repetitive task is a risk factor (Armstrong, Martin, Franzblau, Rempel, & Johnson, 1995; Silverstein, Fine, & Armstrong, 1986).

Development of alternative pointing devices, reported in the literature, has focused on altering musculoskeletal loading by changing posture (e.g., Barr, 1996) or by changing the required muscle functionality using an alternative device (e.g., the trackball; Beaton, DeHoff, Weiman, & Hildebrandt, 1987). The parameters investigated in these studies range from measuring muscle activity via electromyography to measuring the posture of the whole arm. Unlike

the force displacement characteristics of the computer key switch, these technologies provide the operator with no tactile information that could aid completion of the given task.

Force-feedback, or haptic, devices provide tactile cues through the display of forces using motors and linkages with the aim of increasing human operator performance in both virtual and telerobotic environments (Rosenberg, 1994; Sheridan, 1992). For telerobotic applications, the forces encountered by the remote manipulator are measured and redisplayed locally for the human operator. This valuable source of feedback aids the human controller in determining the actual state of the robot. In the virtual environment a model of the environment displays tactile cues, such as simple bumps or attractive force field basins, around target icons via the haptic interface device.

Several studies have considered the implementation of tactile feedback in computer pointing devices, particularly those used for interacting with virtual desktop environments. Akamatsu, Sigeru, and MacKenzie (1994) examined a multimodal mouse that varied friction during movements and displayed a vibration when crossing boundaries of interest. Hasser and Goldenberg (1998) and Eberhardt, Neverov, West, and Sanders (1997) examined the effects of attractive force fields (or attractive basins) located around target icons, which pull the mouse and cursor toward the center of the target icon, on the performance of a point-and-click task. For most of these studies, the time to complete a given task improved with the display of tactile cues. However, the musculoskeletal effect of using force-displaying technology in computer peripherals is still unknown.

The goal of this laboratory-based study is to further investigate the application of tactile feedback technology in the office setting. The task to be analyzed is the fundamental point-and-click operation with the pointing device. The study tests two hypotheses. First, task performance, as measured by the time to complete the task, improves with the addition of an attractive basin force field around the desired point-and-click target. Second, the perceived difficulty and exertion required of the task, as measured via a psychophysical questionnaire,

decreases with the addition of the same tactile cues. The study further explores the issues surrounding implementation of force-feedback devices in the office environment.

METHODS AND MATERIALS

In order to test the hypotheses regarding the addition of force feedback to the computer GUI, several experimental protocols were required. First, a platform to measure the completion of a GUI point-and-click task was developed. Second, specific force-feedback algorithms for the task were implemented to aid the user in completing the task. Finally, a series of tests with human operators was carried out to obtain the data for testing the hypotheses.

The quantitative means with which to measure the performance of human motor control during the point-and-click task is based on the research of Fitts (1954). Fitts empirically developed a quantitative predictor for movement time in peg-in-hole (targeting) tasks. He presented the following relationship, known as Fitts' law, for estimating movement time (MT) needed for successful completion of such targeting-type tasks:

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

in which 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):

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

For human-computer interaction (HCI) design, Fitts' law provides a practical method for comparing the performance of two pointing devices during identical targeting-type tasks, specifically the point-and-click operation (Douglas, Kirkpatrick, & MacKenzie, 1999). A set of computer-programmed tasks can be chosen based on their respective indices of

difficulty. Then a human participant can be asked to perform this set of tasks twice, once using each of two interfaces. If all other experimental conditions remain constant for the two tests, Fitts' law provides a gauge for measuring the differences in performance between the two interfaces. Hasser and Goldenberg (1998) 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.

In these experiments computer software prompted a human user with a point-and-click task, then recorded the performance measures, movement time, index of difficulty, and number of errors, if any, for the experiment. A set of 14 circular targets (30 pixels wide with a center-to-center distance of 75 pixels) was displayed on an 800 × 600-pixel, 15-in. screen (Figure 1). During the test, one target was highlighted, and the participant was instructed to point the cursor at it and click on it as quickly as possible. Once the mouse was clicked, the computer would deactivate the target and highlight the next one so that the end of the last movement became the beginning of the next movement. The highlighted targets were presented in random order. The mouse

acceleration control panel was turned off. An electronic log automatically kept track of the distance and movement time between targets. The measured movement time for a given index of difficulty was averaged across trials within a participant and then averaged across participants.

Force-feedback algorithms to aid the user in the point-and-click task were implemented through a prototype FeelIt Mouse (Immersion Corporation, San Jose, CA), a force-feedback device. The mouse is connected to a 2-degree-of-freedom linkage system that has a range of motion of 1 in. × 1 in. For every millimeter the mouse moved, the cursor moved approximately 30 pixels on an 800 × 600-pixel screen. The linkage grounds the mouse physically so it cannot be lifted from the table for indexing the mouse and cursor. However, its movement is easily scaled to the size of the screen. Electromagnetic actuators that connect to the linkages of the 2-degree-of-freedom system apply forces through the mouse in the plane of the tabletop. The maximum force produced is 3 oz (0.9 N).

For the point-and-click task, the implemented force field attracted the mouse to the center of the desired target when the cursor came within two radii of the target center. The
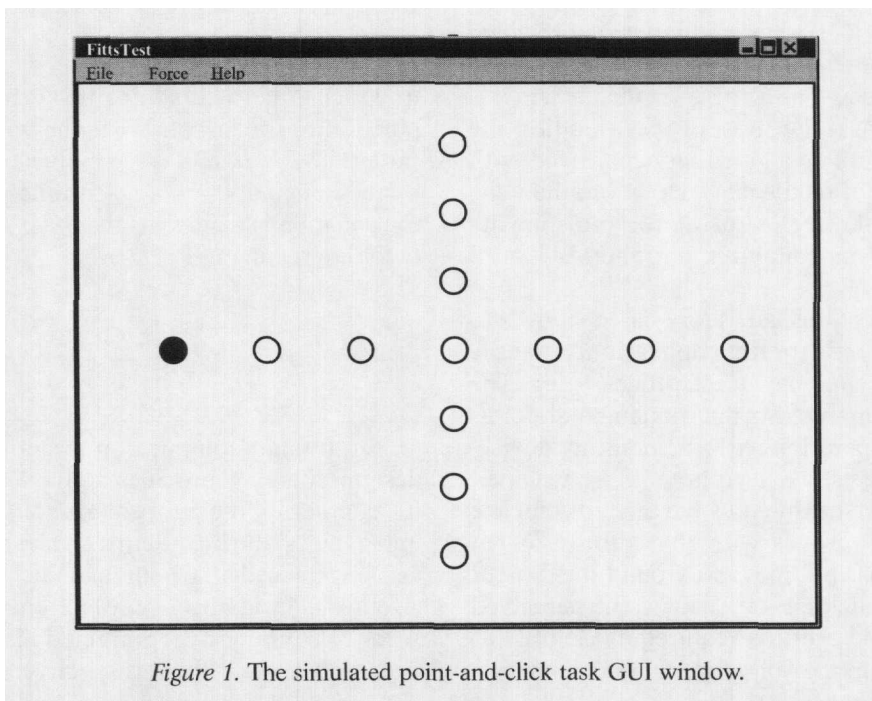

Figure 1. The simulated point-and-click task GUI window.

magnitude and direction of the force are depicted in Figure 2.

Two experiments were conducted. The first tested only two configurations. One configuration had no force fields, thus simulating a conventional mouse (no attractive basin, abbreviated No AB). The other configuration had a single active attractive force field centered on the desired target (one attractive basin, or 1 AB). For each configuration, study participants performed 40 trials, each consisting of 14 targets, for a total of 520 movements. Fourteen people (10 men, 4 women) ranging in age from 22 to 40 years participated in the study. Study participants were free of any musculoskeletal disorders in the hand that manipulated the mouse. The order of the two configurations was randomized.

For the second experiment, the practical use of force feedback was explored by testing four force field configurations. The size of the targets was also reduced to 20 pixels in diameter, less than a millimeter of mouse movement. First, no force field was presented to the user (No AB). Second, the attractive force field was activated around only the desired target (1 AB). Third, the field was activated on two targets, both the desired target and the adjacent circle (2 AB). Finally, the field was activated on all of the displayed circles (All AB). In the 2 AB and All AB conditions, these additional
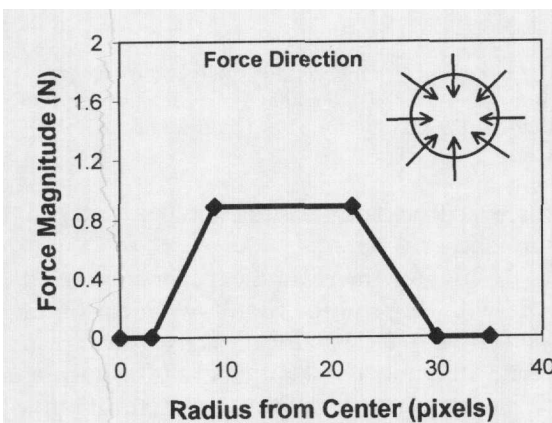

Figure 2. The force field algorithm for the attractive basin. The force pulled the cursor toward the center of the desired target with the magnitude. There is no force far from or very near the center of the target.

attractive targets, or *distractors*, simulate more realistic implementations of the force fields in a desktop environment. The order of presentation for the four configurations was randomized. A total of 12 people (7 men, 5 women), with ages ranging from 22 to 44 years, participated in the second experiment.

Participants in both experiments read and signed a consent form approved by either the Harvard School of Public Health's Committee on Human Subjects or the Stanford University Institutional Review Board. All participants used their right hand for the experiment, which in every case was also the hand normally used to operate the computer mouse. The chair, mouse table, and monitor height were adjusted for each participant in accordance with ANSI/HFS 100-1988 (Human Factors Society, 1988). Each participant was also required to perform two blocks (40 fields) of practice before beginning the test.

For both experiments, a questionnaire was administered at the conclusion of each configuration to assess perceived musculoskeletal loading. The questions, posed on a visual analogue scale modified from the Borg (1982) 10-category scale, were designed to quantify task difficulty, pain, and discomfort felt during the task, and fatigue and soreness felt after completing the task. For example, the verbal anchors on the scale for difficulty ranged from *very, very easy,* to *easy,* to *somewhat difficult,* and finally to *very difficult.* Because levels of exertion for the given task are low, we envisioned that the modified Borg scale would provide the necessary resolution to observe differences among test conditions.

For simple comparisons between two data sets, as in the first experiment, student-paired *t*-tests provided an indication of the statistical significance for the differences in these populations. For the multivariable data sets in the second experiment, Duncan's multiple range tests provided indications for possible differences among populations.

RESULTS

In accordance with other studies (e.g., Hasser & Goldenberg, 1998), the movement times for the first experiment decreased when
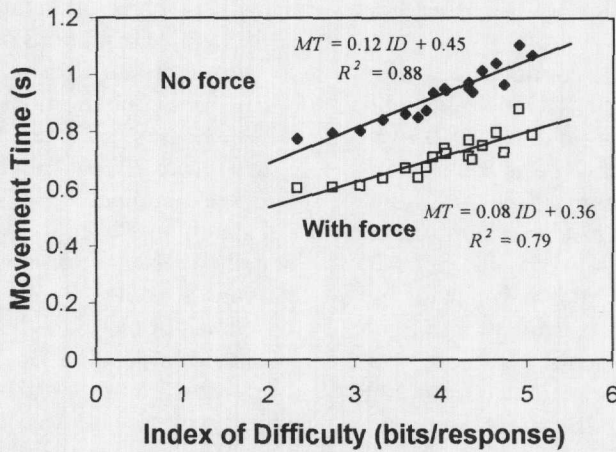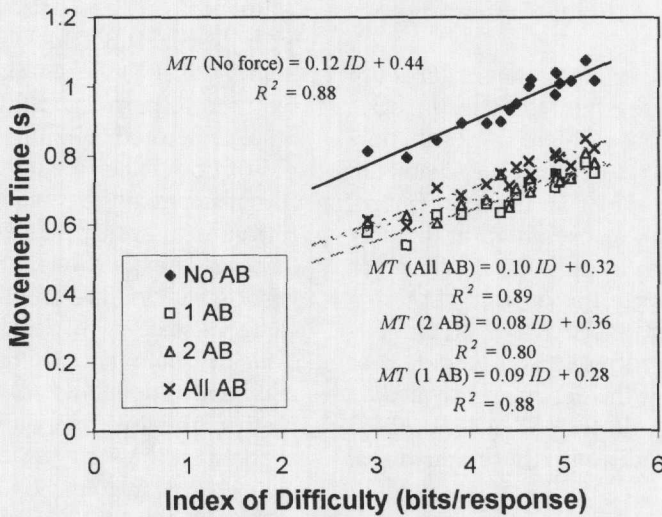
Figure 3. Movement times for the two experiments without distractors (A) and with distractors (B) present in the movement field. The four conditions tested were: no force field (No AB), a single force field surrounding the target (1 AB), two fields activated – target and adjacent (2 AB), and all fields activated (All AB). Performances increased with the addition of force-feedback.

the attractive force basin around the target was implemented (Figure 3). In the presence of a single attractive force field, participants performed 23% faster than they did without the attractive field ($t < 0.0001$). It follows that the index of performance, defined by Fitts (1954) as the index of difficulty divided by the movement time, increased. The average index of performance across movements and participants increased from 4.4 bits/s with no attractive basin to 5.7 bits/s with the attractive basin ($t = 0.0001$). Hence the implementation of

force feedback for this situation improved performance.

Results for the second experiment agreed well with those of the first. Movement times were 28% faster with the attractive force basin than without it. The addition of the distraction fields did not greatly affect the movement times from the single attractive force field. When a nearby target also had an active attractive basin (2 AB), the movement times improved 26% compared with the no-force feedback condition. When all the possible targets had an

TABLE 1: Index of Performance and Perceived Difficulty for the Four Configurations of Experiment 2

Condition	Index of Performance (bits/s)		Duncan Grouping[a]	Perceived Difficulty (cm)		Duncan Grouping[a]
	Mean	Standard Error		Mean	Standard Error	
No AB	4.7	0.5	C	2.7	0.3	A
1 AB	6.6	0.8	A	1.3	0.2	B
2 AB	6.4	0.7	A, B	2.1	0.3	A, B
All AB	6.0	0.7	B	2.8	0.4	A

Note: Values were averaged across participants (N = 12). Means with the same grouping letter are not significantly different.
[a] Duncan's multiple range test: α = 0.05, degrees-of-freedom = 44.

attractive basin (All AB), the movement times still improved 22% compared with the no-force-feedback condition. The indices of performance also improved (Table 1).

When comparing the no-force-feedback condition with the single attractive basin condition of Experiment 1, the average perceived task difficulty (p = 0.03), pain (p = 0.002), and discomfort (p < 0.001) felt during the task, and the fatigue (p = 0.03) and soreness (p = 0.24) felt after completing the task, were all less when the attractive basin was present (Figure 4a). All the differences between the two conditions were significant ($p \leq 0.05$) except for the perceived soreness.

The addition of the distraction fields had a larger effect on the psychophysical parameters than on the movement times. The only condition that differed significantly from the no-force-feedback condition (No AB) was the single attractive basin (1 AB), and this was only for the perceived task difficulty (see Table 1). For the nearby attractive basin (2 AB), the psychophysical scores doubled from the single attractive basin condition, and for the All AB condition, the scores were equal to or slightly larger than for the No AB condition (Figure 4b).

DISCUSSION

The results provide evidence to support the use of a novel alternative technology for the GUI pointing input device. Until now the main channels for communication from device to user have been visual and auditory. Force feedback allows, for the first time, tactile feedback in the virtual GUI environment. The human-computer inter-

face was enhanced through the addition of force-feedback systems because more sensory feedback pertaining to the computer environment was provided to the user. The technology improved operator performance and reduced the perceived musculoskeletal loading as measured through pain and discomfort in completing the simple point-and-click task presented here.

The combination of increased performance and comfort is not surprising. The point-and-click task is a rapid, goal-directed movement and may be segmented into three stages. First, the mouse is accelerated toward the target. Second, the mouse is slowed as the cursor approaches the target. Third, a fine manipulation aligns the cursor with the specific target. The attractive basin assists in this last stage by helping to align the cursor within the target, which removes part of the task-burden from the musculature. Hence the required participation of the muscles needed for fine control in the final phase of positioning is reduced. The dynamics of the attractive basin are faster than those of the motor control, allowing for the increase in performance. The attractive basin allows the user to become, as one participant put it, "lazy" in the third phase of the movement.

Applications of the device and the attractive force-field algorithm beyond the office environment include aiding those with sensory and motor skill impairments. For example, adding the sense of touch to the Microsoft Windows environment aids the visually impaired by adding a secondary sense to the task. For young children and rehabilitating stroke patients, the technology can assist in the development of the motor skills necessary for using GUIs.
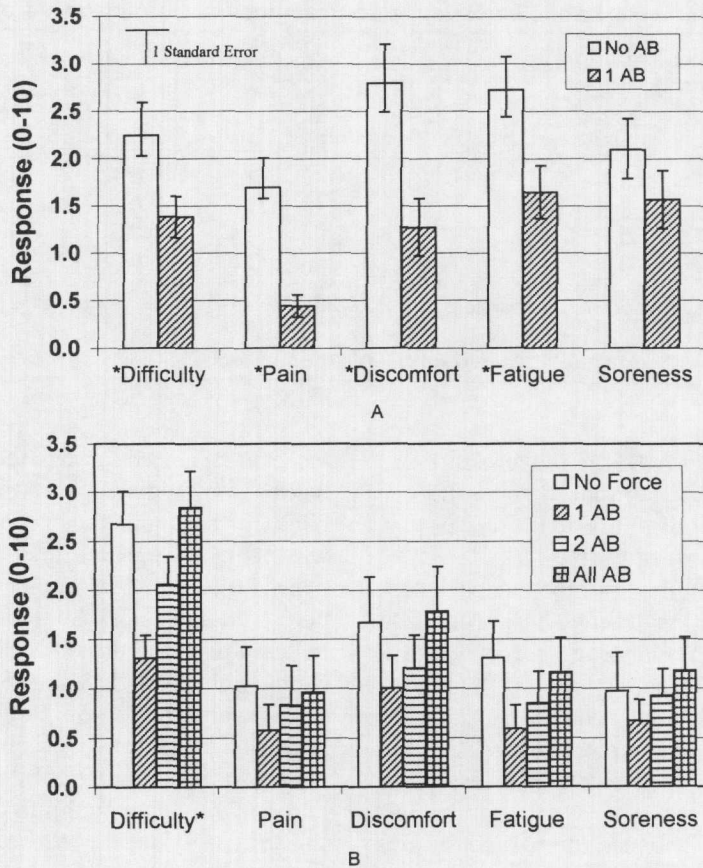
Figure 4. User-perceived task difficulty and comfort during the task. The addition of an attractive basin around a single target (A) significantly increased the ease and comfort to complete the task. The addition of distracters (B), however, decreased or eliminated these improvements. Asterisks (*) indicate significant differences.

The attractive basin is an ideal type of force-feedback algorithm for reaching a target because it aids the intended movement. The directions of the forces were aligned with the intended direction of the movement, relieving the human operator of some of the difficult motor control necessary to complete a targeting or steering task. Other types of feedback algorithms may not have the same effect. For example, friction is a force that opposes the direction of movement. It may aid in the slowing portion of a movement but will hinder acceleration and targeting portions.

Akamatsu et al. (1994) developed a multi-modal mouse that provided simple tactile cues, such as vibrations for event detection and friction, and whose direction opposed movement when moving across certain fields. Although

these modes provided tactile cues, they did not assist user motor control in completing the task. As a result, Akamatsu et al. observed only small performance enhancements. When the force resists an intended movement, it will most likely have adverse effects in terms of both acceptability to the user and increased musculoskeletal loading.

When distractors were added to the system, system performance still greatly improved, but the user comfort and perceived task difficulty did not improve. Here the attractive force basin still assisted in the third stage of the movement, aiding the fine manipulation. The distractors were encountered during the first or second movement phases, assuming the fine manipulation occurred near the desired target.

The results suggest that users compensated

for the presence of these distractors by increasing their efforts during these phases. The participants would plow through the distractors and noted this increase in effort in their subjective questionnaires. Although a cross-hair configuration of targets was used, the location of the desired target relative to the previously clicked target was often along the vertical or horizontal portions of the cross hair. Two users compensated by choosing a path to avoid the distractors, but most participants did not avoid them.

With the presence of distractors, users were often caught in a target other than the one desired. They would then exert a large effort to escape and continue on to the desired target. This increased user frustration and effort in completing the task, as measured through the questionnaire.

Enabling only one force field is an unrealistic simulation for the implementation of force-feedback algorithms. If one confidently knew the desired target, why not then select that target automatically without using the mouse? Granted, such algorithms would be useful to train people, especially small children and those with some loss of motor skills, to use the mouse. Algorithms that simply turn on force fields around all targets will result in many frustrated users. Alternative designs may display low force values on the attractive force fields or activation of force fields around probable targets, similar to the 2 AB condition. As the results indicate, performance still improves for this condition, as do, more modestly, user comfort and perceived difficulty.

The questionnaire was designed to assess the musculoskeletal loads on the upper extremity during mouse use with and without force feedback. The questionnaire results lead us to believe that musculoskeletal loading decreases for the single attractive force basin. The questionnaire is not an objective measure of loading. An objective measure of muscle loading or muscle activity revealed through electromyography would be preferable. Such a measure would allow us to make statements more confidently about the musculoskeletal loading. Yet a study using such an objective measure would likely need extensive instrumentation. A single measurement of one muscle would provide limited information about other specific muscles. The questionnaire provides some measure, albeit subjective, of the entire system. In fact, the addition of the questionnaire provided evidence that the performance improvements in the presence of distractors might come at a cost of extra effort to escape the distractors.

This is a laboratory experiment; therefore, transferring the conclusions to a larger environment, such as the office work space, has several limitations. This simulated task was a time-condensed series of point-and-click tasks (520 over a 10-min period). Real-world GUI tasks consist of many different activities, including pointing, dragging, and steering (Accot & Zhai, 1997), all of which can have different force-field algorithms. Analysis of these different tasks is necessary to assess their effects. A longer exposure during a real work regimen would clearly be more effective in determining the long-range characteristics of adding force-feedback technology to the office work space.

In this experiment, only one parameter was varied in the Fitts' law equation: the distance between targets. We did not study the size of the target in task. As a result, we tested a limited range of task difficulties. Examination of the extremes and the target size would provide a more complete picture. Furthermore, the experiment was not balanced with gender and involved a majority of male participants (~60%). Because each participant acted as his or her own control, this should not affect the general conclusions. For the first experiment without force feedback, female participants took 20% longer to perform the task (sample t-test: $p = 0.01$). This difference was eliminated with the addition of force feedback. Although this difference was not observed in the second experiment, its presence suggests that more examinations of gender differences are merited.

Finally, the results here provide some suggestions for the design of force-feedback devices. First, they point out the need to consider effects of distractors in the field of movement and indicate that simply turning on attractive basins around all the fields may not be a proper solution. Elegant activation of specific force fields may reduce the effects of distractors. Second, force algorithms should be

evaluated to ensure they do not interfere with the intended movement of the user.

CONCLUSIONS

The data presented here suggest that the introduction of force-feedback technology in the office work space may improve performance. The psychophysical responses suggest further that force-feedback technology may also reduce the exposure of the musculoskeletal system to force – a risk factor for chronic musculoskeletal disorders – but that this technology must be introduced into GUIs thoughtfully.

ACKNOWLEDGMENTS

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