The Effect of Multiple Haptic Distractors on the Performance of Motion-impaired Users

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Abstract. The effect of multiple haptic distractors on target selection performance was examined in terms of times to select the target and the associated cursor movement patterns. Two experiments examined: a) The effect of multiple haptic distractors around a single target and b) the effect of inter-item spacing in a linear selection task. It was found that certain target-distractor arrangements hindered performance and that this could be associated with specific, explanatory cursor patterns. In particular, it was found that the presence of distractors along the task axis in front of the target was detrimental to performance, and that there was evidence to suggest that this could sometimes be associated with consequent cursor oscillation between distractors adjacent to a desired target. A further experiment examined the effect of target-distractor spacing in two orientations on a user's ability to select a target when caught in the gravity well of a distractor. Times for movements in the vertical direction were found to be faster than those in the horizontal direction. In addition, although times for the vertical direction appeared equivalent across five target-distractor distances, times for the horizontal direction exhibited peaks at certain distances. The implications of these results for the design and implementation of haptically enhanced interfaces using the force feedback mouse are discussed.

1 Introduction

Force feedback gravity wells, i.e. attractive basins that pull the cursor toward the target, have widely been shown to improve user performance in target acquisition tasks. Hasser *et al* [1] found that this type of force feedback effect, provided by a FEELit mouse, could improve targeting time and decrease errors. Oakley *et al* [2] reported a reduction in errors with gravity wells implemented on a PHANToM.

One group of people for whom gravity wells have been shown to be of particular benefit are motion-impaired computer users. Motion-impaired users often have difficulty with accurate cursor control [3]. Symptoms such as tremor, spasm, muscle weakness, partial paralysis, or poor coordination can make standard pointing devices difficult, if not impossible, to use. Keates *et al* [4] found that gravity wells provided through a Logitech Wingman force feedback mouse could improve the time required by motion-impaired users to complete a "point-and-click" task by as much as 50%.

Furthermore, the greatest improvement was observed for the most severely impaired individuals.

Most studies of gravity wells, however, have examined performance when force feedback was enabled on a single target only. For the successful implementation of force feedback in a realistic interface, issues surrounding haptic effects for multiple on-screen targets remain to be addressed. With more than one gravity well enabled, a user's cursor may be captured by the gravity wells of undesired *distractors* as it travels toward a desired target. This has the potential to cancel out the benefits of the force feedback, possibly yielding poorer performance than in its complete absence.

There have been few studies investigating performance in the presence of multiple haptic targets. Dennerlein and Yang [5] found that even with multiple haptic distractors along the cursor trajectory, performance in "point-and-click" tasks was greatly improved over a condition with only visual feedback. Study participants most often just plowed through the distractors, but at a cost of increased user frustration and effort. In contrast, Oakley *et al* [6] reported an increase in time when static attractive forces were enabled on multiple targets. This condition was, at best, not optimal, and at worst, detrimental to performance and subjective satisfaction when compared to the purely visual condition. Wall *et al* [7] found that in the presence of distractors, gravity wells improved accuracy, but not the time taken for 3D targeting tasks.

Given the conflicting reports of these studies, the use of multiple haptic targets is an area that warrants further investigation. Furthermore, not only have results differed with varying experimental setups, force feedback input devices, and working environments, but the benefit of gravity wells in the presence of distractors has also been shown to differ with users' capabilities. Hwang *et al* [8] reported that while the presence of a distractor directly in front of a desired target yielded poorer times for able-bodied users than in the complete absence of force feedback, the same was not true for motion-impaired users for whom the gravity wells were still beneficial. This illustrates the need for explicit studies of users with different capabilities.

This paper presents two studies of motion-impaired users performing "point and click" tasks in the presence of multiple distractors. The first study investigates how the spatial relationship between a target and distractors affects task completion time. In addition to using the traditional measure of task completion time to capture performance differences among target-distractor arrangements, cursor trajectories throughout trials are also examined to help establish *why* the differences exist [9]. The insights gained from the cursor paths form the basis for the second study reported here, which investigates the effect of target-distractor spacing on a user's ability to reach a desired target when caught in a distractor.

2 Investigating The Target-Distractor Spatial Relationship

An experiment was conducted to investigate the performance of motion-impaired computer users in "point and click" tasks when a target and two or more distractors are all haptically enabled. Users performed "point and click" tasks for eight different spatial arrangements of target and distractors (see Figure 2), both with and without gravity wells on all potential targets. The hypotheses were as follows:

H1: Force feedback gravity wells would significantly improve task completion times when compared with the no force feedback condition.

H2: The locations of the distractors relative to the cursor's start position and the target location would have a significant effect on task completion times when the force feedback is on, but not when the force feedback is off.

2.1 Participants

Seven volunteers with motion-impairments participated in the study. The group represented a wide range of capabilities, exhibiting symptoms including tremor, coordination difficulties, stiffness, numbness, weakness, and reduced dexterity in the dominant hand and arm. The users were affected by Cerebral Palsy (4), Friedrich's Ataxia (1), head injury (1), and spinal cord injury (1). Although four had the same clinical diagnosis, Cerebral Palsy, the level of the impairment ranged from mild to severe.

2.2 Task

The task was a multi-directional point-and-click task, using a Logitech Wingman force feedback mouse for input. This device, shown in Figure 1, can generate a wide range of haptic effects, including vibro-tactile sensations and directional forces.

Fig. 1. The Logitech Wingman force feedback mouse.

Potential target positions, indicated by faint gray circles on the screen, were located at the centre and vertices of a regular hexagon with an edge length of 250 pixels. The centre circle was initially filled in red, and users moved the cursor inside the red target and clicked the left mouse button to select it. Once selected, the red target appeared in a new position, along with multiple distractors shown as white circles drawn with black lines. Targets and distractors were 40 pixels, or approximately 12 mm, in diameter.

The target and distractors were displayed in one of eight possible arrangements (Figure 2). To describe the arrangements, a coordinate system with its origin at the target's centre is defined. The coordinate system is oriented such that the *task axis*, i.e. the straight line connecting the cursor's starting point and the target's centre, is along the positive x-axis at 0 degrees. The eight distractor arrangements can then be described in polar coordinates as follows:

A. Two distractors, at (80 pixels, 90 degrees) and (80 pixels, -90 degrees)
B. Two distractors, at (80 pixels, -45 degrees) and (160 pixels, -45 degrees)
C. Two distractors, at (80 pixels, 45 degrees) and (160 pixels, 45 degrees)
D. Two distractors, at (80 pixels, 180 degrees) and (160 pixels, 180 degrees)
E. Two distractors, at (80 pixels, 0 degrees) and (80 pixels, 180 degrees)
F. Two distractors, at (80 pixels, 0 degrees) and (160 pixels, 0 degrees)
G. Four distractors, all at a radius of 80 pixels, spaced by 90 degree intervals starting at 45 degrees
H. Four distractors, all at a radius of 80 pixels, spaced by 90 degree intervals starting at 0 degrees.

A trial was defined to be one complete target selection. The time to complete each trial, the number of mouse clicks in a trial, and the cursor position throughout the trial were all automatically logged after the first target had been selected. After each selection, the target appeared in a new position, randomly selected from the set of adjacent positions. Data collection was then continuous for 16 subsequent trials, so the end of one selection became the beginning of the next. Breaks were taken between each block of 16 trials.

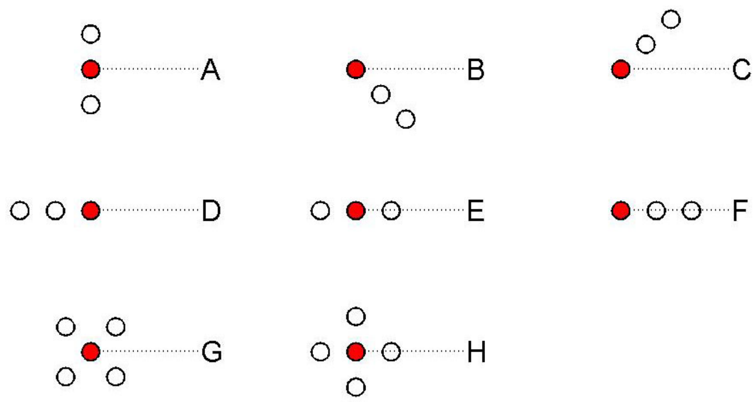

Fig. 2. The eight target-distractor arrangements.

2.3 Design

The experiment was a 2x8 factorial within-subjects design. Each user completed the "point-and-click" tasks in each of the eight arrangements, both with the force feedback *off* and *on*. When the force feedback was *off*, the Wingman operated as an ordinary mouse. With it *on*, both the target and the distractors sat at the centre of a circular gravity well with a radius two times that of the target. When the cursor entered the gravity well, a spring force pulled the mouse toward the centre of the target.

Within a block of sixteen continuous trials, the force feedback condition was held constant while each spatial arrangement was presented twice. The order of appearance of the arrangements was determined using random selection without replacement. The order of the force feedback levels between blocks was counterbalanced.

3 Results

Of the study participants, one user experienced much greater difficulty performing the "point-and-click" tasks, reflected in task times without force feedback that were almost twenty times longer on average than those of the other users, and with a much greater variance. This user was consequently omitted from the current analysis. A two-factor, repeated measures ANOVA was performed on the mean task completion times for the six remaining users.

Force feedback gravity wells gave an overall improvement in task completion times ($F_{1,5}$ = 16.720, p = 0.009), reducing them by 20% (= 0.55s) over the eight target-distractor arrangements (Figure 3). There was also a significant interaction between target-distractor arrangement and the presence of force feedback ($F_{1,7}$ = 4.14, p = 0.002). Times appeared to be affected by the target-distractor arrangement when the force feedback was *on*, but not when the force feedback was *off*.

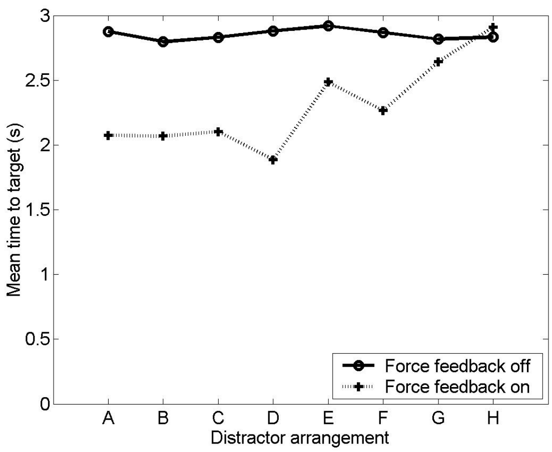

Fig. 3. Mean times to target for eight target-distractor arrangements.

The degree to which target-distractor arrangement affected performance was observed to vary with a user's level of impairment. More impaired users exhibited larger time differences among arrangements than those who were less impaired. This is similar to the relationship between the level of impairment and the magnitude of effect that was observed in [4]. Because of this high degree of variability among the users in the present study, comparisons of target-distractor arrangements gave no significant differences when data from all users were aggregated. However, significant differences among arrangements were found when data from individual users were analysed separately. Certain effects are of particular interest:

- in both arrangements A and E, targets are central to a group of three, but the orientation with respect to the task axis ensures that a distractor is in front of the target in E. For some users, times for E were significantly higher than those for A, suggesting that in these cases, the orientation encourages the cursor to be captured by the distractor, making another movement against the gravity well necessary.
- for some users, times for arrangements A, B, C, and D were not found to be significantly different. This suggests that when no distractors are located directly in front of the target, the target's position relative to the distractors does not affect times for these users.
- for one user, arrangements G and H gave significantly longer times as compared with *all* other arrangements, suggesting that for this user, the increased number (double) of distractors around the target is impairing selection.

Although the measure of task completion time can give an indication that some users perform differently for different target-distractor arrangements, this measure alone gives little information about *why* various time differences have occurred. A full understanding of users' responses to each arrangement, however, can provide a basis for designing interfaces that are better suited to user needs. For example, if features of cursor paths can be correlated with time changes or identified as the cause of time delays, the cursor paths might then be deliberately modified by the selective application of forces in specific circumstances [10]. In the next section, cursor trajectories are examined as a means of identifying cursor movement patterns that may account for time differences.

4 Cursor Trajectory Analysis

In this section, sample cursor traces from one user with Cerebral Palsy are used to illustrate how cursor trajectory analysis may help explain differences in task completion times.

4.1 Sample cursor traces

Sample cursor traces were selected from arrangements D: time = 1.33 seconds, E: time = 4.05 seconds, F: time = 2.51 seconds, and H: time = 4.62 seconds. For these traces, the fastest time was observed for arrangement D where no distractors were located along the task axis. In the other cases where distractors *were* located along the task axis, it is interesting to note that the time for sample E, with one distractor between the start point and the target, was longer than for sample F, with two distractors between the start point and the target. Finally, sample H, with double the number of distractors, required the longest time to complete the task.

Examination of the cursor trajectories can help explain these time differences. Figure 4 illustrates that in D, the user proceeds directly to the target without being affected by the distractors. In both E and F, the user has a tendency to be caught in a distractor along the task axis. The time difference between the two, however, arises primarily from the actions required to escape the distractor and reach the target.

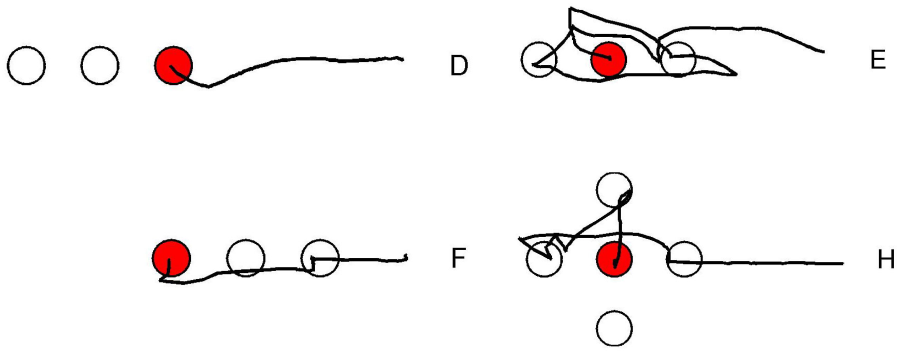

Fig 4. Sample cursor traces for target-distractor arrangements D, E, F, and H.

In E, escaping from the distractor can result in the cursor overshooting the desired "middle" target and either overshooting or becoming caught in the second distractor on the other side. In the former case, as the cursor moves back toward the target, it becomes caught in the second distractor. The user must then escape again, presenting the same problem in the opposite direction. This can sometimes result in multiple oscillations about the target, incurring a significant time gain. In contrast, this oscillation does not occur for arrangement F. Escaping from the first distractor results in the cursor overshooting the undesired "middle" distractor, and either landing directly in the desired target or overshooting it. In the latter case, the user has a good chance of returning to the target without getting caught in any more distractors. In arrangement H, the chances of getting caught in a distractor are greater, and oscillations may occur in two directions, further exacerbating the problem.

4.2 Implications for interface design

Knowing that the placement of distractors along the task axis can be detrimental to performance, the implication for haptic interface design may be to arrange potential targets in such a way that users can move between them without having to travel through other gravity wells. However, given limitations of screen sizes, this option may not always be practical. Where traversal through distractors is unavoidable, preliminary cursor trajectory analysis and observations of motion-impaired users during trials suggest that effort should be made to reduce the possibility of oscillating about a desired target.

To address this problem, Oakley *et al* [6] suggest varying the applied forces such that slower motions are opposed by lower forces. For input devices not well-equipped for rapid force changes, a less dynamic approach may be to reduce the gravity well size and/or strength. Alternatively, it may also be possible to avoid oscillations through more careful design of the spatial layout of targets on the screen. For example, where possible, target placements could be limited to "two-tiered" arrangements to avoid "sandwiching" desired targets between gravity wells. It may also be possible to set the distance between potential targets in such a way that escaping from a distractor does not force the cursor to overshoot an adjacent target. This last option is explored in the next section.

5 Investigating Target-Distractor Spacing

An experiment was conducted to investigate the effect of target-distractor spacing on a user's ability to reach a desired target when caught in a distractor. Users performed "point and click" tasks, "jumping" from distractor to target for five target-distractor distances. The task was performed both with and without gravity wells enabled, and in both horizontal and vertical directions. The hypotheses were as follows:

> H1: Force feedback gravity wells would significantly improve task completion times when compared with the no force feedback condition.
>
> H2: The direction of movement would have a significant effect on task completion times.
>
> H3: Times would increase with target-distractor spacing with the force feedback off. With the force feedback on, times would decrease with target-distractor spacing, as the likelihood of oscillating about the desired target would be reduced.

5.1 Participants

Six of the seven volunteers from the first study participated in this second study. The other volunteer (CP affected) was unable to participate for health reasons.

5.2 Task

Users were presented with four circles, equally spaced along a line on the screen. The desired target was filled in red, while the other three distractors were shown as white circles drawn with a black line. Users had to move the cursor inside the red target and click the left mouse button to select it. Once selected, the red target changed position, alternating between the two middle circles. Targets and distractors were 40 pixels, or approximately 12 mm, in diameter.

A trial was defined to be one complete target selection. The time to complete each trial, the number of mouse clicks in a trial, and the cursor position throughout the trial were all automatically logged after the first target had been selected. Data collection was then continuous for 10 subsequent trials, so the end of one selection became the beginning of the next. Breaks were taken between each block of 10 trials.

5.3 Design

The experiment was a 2x2x5 factorial within-subjects design. The first factor was force feedback, which was either *on* or *off.* When the force feedback was *on*, all four circles sat at the centre of a circular gravity well with a radius two times that of the target. In this case, in order to move to the desired target, the user had to first escape the gravity well of the current circle. The second factor was direction - the circles were aligned either *horizontally* or *vertically* in the middle of the screen. The third factor was target-distractor spacing. The circles were spaced apart by 40, 60, 80, 120, and 160 pixels, corresponding to 2, 3, 4, 6, and 8 times the target's radius. With the force feedback on at 40 and 60 pixels, the gravity wells of adjacent targets overlapped, resulting in reduced forces in the region of overlap. At 80 pixels, the gravity wells of adjacent targets just touched.

Within a block of ten continuous trials, the conditions were held constant. The order of appearance of the twenty possible conditions was determined using a method of random selection without replacement.

6 Results and Discussion

The most severely impaired user was again omitted from the analysis, for similar reasons as for the first study. A three-factor repeated measures ANOVA was performed on the mean task completion times for the five remaining users.

A significant difference was observed between the two force feedback conditions ($F_{1,4} = 12.954$, $p = 0.023$) (Figure 5). With the force feedback *off*, there was no difference between the horizontal and vertical directions ($F_{1,4} = 2.349$, $p = 0.2$), but times increased significantly with target-distractor spacing ($F_{4,16} = 13.838$, $p < 0.001$). This result is not unexpected, as according to Fitts Law, times are expected to increase with distance to the target.

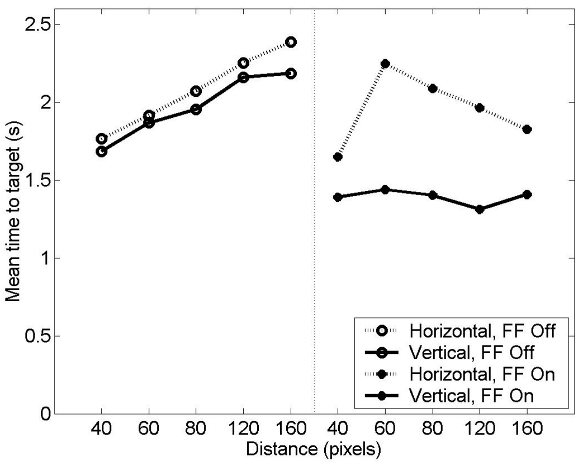

Fig. 5. Mean times to target for five target-distractor spacings.

In contrast, when the force feedback was *on*, times for movements in the vertical direction were significantly faster than times in the horizontal direction ($F_{1,4}$ = 15.792, p = 0.02). Furthermore, there was again a significant effect of target-distractor spacing ($F_{4,16}$ = 3.420, p = 0.033), but in contrast with the force feedback *off* condition, there was also a significant interaction between spacing and direction ($F_{2.123,\ 8.493}$ = 4.382, p = 0.048). While times in the vertical direction were similar for all spacings, movements in the horizontal direction exhibited an interesting trend. Examination of individual user's mean times with force feedback in the horizontal condition showed that all produced a peak or inverse quadratic function such that at a certain distance, performance was actively impaired by force feedback gravity wells.

One possible explanation for this observed peak is that in order to escape the gravity well of a distractor, the user must exert a certain amount of force that will move the cursor through a certain distance. This distance may be expected to vary with an individual's strength and ability to damp the mouse movement once the cursor has left the distractor's gravity well. If the desired target is located within that minimum distance, and if the gravity well of the target is insufficiently strong to capture the cursor, the cursor will "shoot through" the target, resulting in disruptive movements and time-consuming re-targeting.

However, it is interesting that horizontal movements are more susceptible to this effect than vertical movements. One possible explanation may lie with the mechanical properties of the force feedback mouse. Although the forces are meant to act equally in all directions, it may be that asymmetries exist, making it easier to escape gravity wells in the vertical direction than in the horizontal direction. The differences may also arise for biomechanical reasons. Mouse movements in the horizontal direction can employ a different set of muscles than those in the vertical direction, with differing inertia and control properties. For motion-impaired users, non-traditional strategies for controlling the mouse are often used (see Figure 1) which may possibly amplify those differences. The muscle groups used in generating horizontal movements may either be prone to generating greater forces than are necessary for escaping from a distractor, or less suited to rapid damping of the movement after the cursor has escaped the distractor. These asymmetries in performance with direction remain to be further investigated

At 60 and 80 pixel distances in the horizontal condition, times were poorer than in the no force feedback horizontal condition, indicating that the gravity wells were actively impairing performance. As in previous research, (e.g. [6, 8, 10]), it seems that haptics have the potential to hinder performance if not implemented in an appropriate way.

One implication of this finding for interface design is that if movement between adjacent gravity wells is unavoidable, one possible way to avoid oscillations about a desired target is to space adjacent targets by a minimum safe distance. The findings also show that the orientation of the alignment is important, in particular, that vertical alignment is preferable to horizontal ones for moving between adjacent gravity wells. Furthermore, it appears that the minimum safe distance may vary from individual to individual as a function of strength and control capability, suggesting that it may be possible to measure these properties of each person and tailor the interface to each user's individual needs.

7 Conclusion

The effect of multiple haptic distractors on target selection by motion-impaired users was examined in their effect on times to select the target and the associated cursor movement patterns. It was found that certain target-distractor arrangements could hinder performance, and that this could be associated with specific, explanatory cursor patterns. In particular, it was found that the presence of distractors along the task axis in front of the target was detrimental to performance for some users. In cases where distractors were also located behind the target, cursor trajectories suggested that the time increase could sometimes be associated with consequent oscillation between these distractors about the desired target. It was also found that for one user, surrounding a target with distractors resulted in slower selection times as compared to the no force feedback condition. This appears to be due to the increased probability of the cursor being captured by the gravity well of a distractor in the process of escaping from another distractor.

A further experiment examined the effect of target-distractor spacing in two orientations on a user's ability to select a target when caught in the gravity well of a distractor. Times for movements in the vertical direction were found to be faster than those in the horizontal direction. In addition, although times for the vertical direction appeared equivalent across five target-distractor distances, times for the horizontal direction exhibited peaks at certain distances. These peak times were sometimes even slower than times without force feedback. This difference between the orientations may be due to differing mechanical or biomechanical properties that make horizontal movements more susceptible to oscillations between distractors.

The implications of these results for the design and implementation of haptically enhanced interfaces using the force feedback mouse require further investigation. However, it seems likely that target arrangements requiring the cursor to pass through other haptically enabled items should be avoided. Where this is unavoidable, it may be helpful to align targets in a vertical orientation, and to avoid arrangements where targets are surrounded by other potential targets. It also appears that inter-item spacing may be important in designing an effective interface layout, and that the spacing may be adapted to differing conditions, strengths and sizes of haptic effect, as well as individual user needs.

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References

[1] Hasser, C., Goldenberg, A., Martin, K., Rosenberg, L.: User performance in a GUI pointing task with a low-cost force feedback computer mouse. In: Proceedings of the ASME Dynamic Systems and Control Division. American Society of Mechanical Engineers (1998), 151-156

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

[3] Trewin, S., Pain, H.: Keyboard and mouse errors due to motor disabilities. International Journal of Human-Computer Studies 50, 2 (1999), 109-144

[4] Keates, S., Langdon, P., Clarkson, J., Robinson, P.: Investigating the use of force feedback for motion-impaired users. In: Proceedings of the 6th ERCIM Workshop (Florence Italy 2000), 207-212

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

[6] Oakley, I., Adams, A., Brewster, S.A., Gray, P.D.: Guidelines for the design of haptic widgets. In: Proceedings of BCS HCI 2002. London, UK (2002), Springer, 195-212

[7] Wall , W, Paynter, K., Shillitoe, A.M., Wright, M., Scali, S.: The effect of haptic feedback and stereo graphics in a 3D target acquisition task. In: Proceedings of Eurohaptics 2002, University of Edinburgh (2002), 23-28

[8] Hwang, F., Keates, S., Langdon, P., Clarkson, P.J.: Multiple haptic targets for motion-impaired users. In: Proceedings of CHI 2003, Fort Lauderdale, FL (2003), 41-48

[9] MacKenzie, I.S., Kauppinen, T., Silfverberg, M.: Accuracy measures for evaluating computer pointing devices. In: Proceedings of CHI 2001, Seattle, WA, ACM Press, 9-15

[10] Langdon, P., Hwang, F., Keates, S., Clarkson P. J., Robinson, P. Investigating assistive interfaces for motion-impaired users using cursor movement analysis in conjunction with haptic feedback. In: Proceedings of International Conference on Disability, Virtual Reality and Associated Technologies (ICDVRAT) 2002. Veszprem, Hungary, 223-231