Using haptic feedback to enhance computer interaction for motion-impaired users

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ABSTRACT

For users with motion impairments, the standard keyboard and mouse arrangement for computer access often presents problems. Other approaches have to be adopted to overcome this. There is evidence to suggest that increasing the degrees-of-freedom, and hence bandwidth, of human-computer interaction (HCI), can improve interaction rates if implemented carefully. Haptic feedback is not really exploited in the existing HCI paradigm, so offers a potential method for broadening the interaction bandwidth by complementing the existing interaction structure. This paper describes a series of pilot studies to assess the effectiveness of two possible methods for incorporating haptic feedback into the interaction. The aim was firstly to ascertain whether the motion-impaired could detect the feedback successfully and then to assess whether the feedback may be of benefit. Two experiments were performed, one to test vibrotactile feedback and the other force feedback. The vibrotactile results were inconclusive, but the force feedback results were very positive.

1. INTRODUCTION

Computers can be a source of tremendous benefit to those with motion impairments (Busby, 1997). They offer greater freedom to participate in education and leisure activities, as well as increased job potential and satisfaction. For example, the ability to operate a word processor, spreadsheet and database is often sufficient to perform many useful administration tasks.

Users with a number of different motion impairment conditions cannot cope with most current computer access systems. Such conditions include athetoid, ataxic and spastic Cerebral Palsy, Muscular Dystrophy, Friedrich's Ataxia, Tetraplegia and spinal injuries or disorder. Frequent symptoms include tremor, spasm, poor co-ordination, restricted movement, and reduced muscle strength. Similar symptoms are also seen amongst the elderly able-bodied population from conditions such as Parkinson's Disease, strokes and arthritis. Any computer input system intended for use by people with varying physical capabilities and designed around one method of input is unlikely to be flexible enough to cope with the diverse needs and demands of the users satisfactorily. This is not to say that it might not suffice, but for extended computer usage something more flexible and with a broader bandwidth may be required.

This idea is supported by evidence that suggests increasing the degrees-of-freedom of input devices, such as incorporating finger flexion, can improve interaction rates (Zhai, 1996). Extending this principle to include more degrees-of-freedom through multiple input channels, implies that this should also yield improved information transfer rates. However, increased degrees-of-freedom in the interaction can actually increase cognitive workload if not structured carefully (Keates and Robinson, 1999). To maximise the usefulness of the additional interaction modes, it is necessary to for those modes to complement and support the existing ones.

The existing keyboard/mouse/monitor paradigm relies principally on visual feedback, often supported by sound. The use of haptic feedback is restricted to the physical interaction with the specific input device, such as feeling the mouse or touch-typing, but is under-utilised. In the current graphical user interface (GUI) paradigm, icons and windows are directly manipulated but there is no resulting touch (tactile) or feel (kinaesthesic) feedback to the manipulating limbs. This lack of *articulatory feedback* (Hix and Hartson, 1993) makes the interaction more difficult and suggests a new potential carrier channel for information. The human "feel" sense actually consists of three main senses, which are difficult to distinguish. The tactile perception system receives its information through the various *cutaneous* sensitivities of the skin. However, *kinaesthesia* or "body sense" also results from the operation of mechanoreceptors that are sensitive to forces in the skin, muscles, tendons and joints, and these are interpreted in conjunction with knowledge of efference or outgoing motor signals, visual feedback and muscle stretch receptors. Hence, kinaesthesia, is the awareness of movement, position and orientation of parts of the human body. *Haptic perception* is the active gathering of information about objects outside of the body through the tactile and kinaesthetic senses. The tactile, kinaesthetic and haptic sensations can be considered together as *tactual perception* (Loomis and Leederman, 1986).

Motion-impaired users often exhibit decreased motor control and muscle strength, but not necessarily a decreased sensitivity of touch. Consequently, if haptic feedback can be successfully incorporated into the interaction paradigm, then these users may be able to benefit from the enhanced feedback from using both touch (tactual) and feel (kinaesthesic) interaction.

There are two ways in which the use of haptic feedback may enhance the usability of interfaces for the motion-impaired. It may be possible to enrich the standard user interface with haptic textures, bumps and edges in order to signal the location of windows, buttons and regions as the mouse passes over them. This is predominantly a touch directed channel. In addition it is possible to use force-feedback within the input device to present constant forces, and tactual and vibration sensations corresponding to user interface events. This force-feedback mode has the capability of boosting or aiding user input in the case of muscle weakness and damping or restraining user inputs, in the case of muscle spasm or tremor. The sensitivity of motion-impaired and able-bodied users to haptic feedback has been demonstrated using devices such as the Phantom (SensAble, 2000**.** However, this is an expensive research tool that is unlikely to be used routinely as a general-purpose interaction device.

The vibrotactile feedback in the following experiments was generated using the Max/MSP graphical programming environment (Dobrian, 1995) on an Apple Macintosh. This environment was originally developed for electronic music and multimedia applications and as a result has good real time capabilities. It has been applied to the acquisition and processing of interaction data (Vertegaal, 1998). It uses signal processing capabilities to generate low frequency audio signals related to cursor position. These were transmitted to the user via the input device through the use of electro-mechanical drivers, such as loudspeakers.

Force feedback has recently been used to haptically enhance action games using joysticks such as those made by Microsoft and Logitech. Its implementation is based on the industry standard I-Force protocol for haptic feedback devised by the Immersion Corporation (Immersion, 1999). This protocol describes a library of haptic sensations usable for games such as explosions, inertia and friction, blows and shudders, as an extension of DirectX under MS Windows. This technology can also be applied for general user interface purposes and it is currently marketed by Immersion, in an extended form for desktop applications, as TouchSense. The first non-experimental device on the market to use this extended protocol is the Logitech force-feedback mouse used in this research. This device is, in principle, capable of generating both tactual and force-feedback haptic interactions with the user as a result of its very wide range of movement generation capabilities.

This paper describes trials carried out with motion-impaired users at the Papworth Trust using vibrotactile and force feedback in tasks representative of the standard User Interface. The principal research question at this stage, is whether haptic feedback can be of any benefit in the computer interaction for motion-impaired users. There are a number of specific experimental questions:

(1) Can motion-impaired users perceive tactual feedback?
(2) What is the sensitivity of motion-impaired and able-bodied users to vibrotactile and force feedback?
(3) Can haptic feedback be used to enhance motion-impaired users' ability to use standard interfaces?

2. EXPERIMENTS

2.1 Introduction and General Aim

Three experiments were designed as pilot studies to examine the feasibility of using haptic feedback systems for motion-impaired users. The users were all residents of the Papworth Trust (Cambridge, UK), a charitable organisation dedicated to the care of the motion-impaired, and are detailed in Table 1.

The first experiment involved exposing motion-impaired users to a restricted range of vibrotactile feedback. This range, in terms of spatial frequency of stimuli, amplitude and frequency of vibration, was chosen to cover the range of able-bodied haptic capabilities derived from previous experience with these devices. There were three vibrotactile feedback mechanical actuators (1) a small loudspeaker stuck on a standard PC mouse, in contact with the thumb or one of the user's fingers (2) a medium sized loudspeaker held under the fingers of the non-mouse manipulating hand; (3) a powerful low-frequency driver mounted on a wooden plate below the mouse-pad that vibrated the whole mouse contact area. The users' sensitivity was measured as the quality of sensations and detection rates.

The second experiment used the sensitivity information from the first to present a systematic and controlled set of haptic stimuli, varying the parameters described above, with the intention of investigating quantitative properties of sensitivity, such as threshold. The users' sensitivity was measured in terms of detection rates.

Table 1. *Motion-impaired users from the Papworth Trust*

User	Description
PV1	Athetoid Cerebral Palsy, spasm, wheelchair user
PV2	Friedrich's Ataxia constant tremor, wheelchair user
PV3	Athetoid Cerebral Palsy, ambulant
PV4	Athetoid Cerebral Palsy, deaf, non-speaking, ambulant
PV5	Athetoid Cerebral Palsy, wheelchair user

The third experiment used the force feedback technology developed by Immersion in the form of a mouse input device. This device was used to provide force-feedback assistance in location of a number of pointing targets of varying degrees of distance and size, provided in an immersion demonstration program. The users' performance was measured as time to complete a number of pointing actions, and error rates, with and without force-feedback assistance.

2.2 Experiment 1: Vibrotactile feedback pilot

2.2.1 Method. The motion-impaired users were presented with a task of detecting stimulus elements that were accompanied by vibrotactile haptic feedback. The stimuli represented an array of vertical lines on the screen and the users were effectively feeling when the cursor crossed one of the lines. Their detection rates were measured for a range of physical parameters: stimulus amplitude; and mechanical actuator (speaker) position and type. The stimuli were set manually by the experimenter during the trials and the data recorded by hand. In order to prevent auditory emanations from the large vibrotactile actuators providing cues to the users as to the detectability of the stimuli, a sound signal was sent to a second medium sized sound speaker, irrespective of the stimulus. The intention was that the users' would not then be aware of whether the sound accompanied a detectable stimulus.

2.2.2 Apparatus. An Apple Macintosh PowerBook G3 is used, running a Max program for generating the stimuli. The user had a separate monitor (VGA 640x480 pixels) and mouse, both connected to the same computer. The experimenter used the keyboard, trackpad and screen of the PowerBook to control the experiment. A standard USB mouse was used and the button functions were disabled. The users were free to select their preferred hand for operating the mouse.

Three actuators were used: a small loudspeaker positioned on the mouse and under the user's fingers or thumb; a medium sized loudspeaker, held under the fingers of the non-mouse hand, and a low-frequency driver, mounted on a wooden plate below the mouse pad, vibrating the whole mouse contact area. The audio output level of the Mac was set to maximum, and an external amplifier was used to drive the actuators. Only one of the two available channels was used for this experiment. The small speaker was a CPC KDS-2008, O.lW 8.Q, 019.8mm, with the speaker edge filed off to reduce the height of the speaker from 4.0mm to 3.0mm cone. The medium speaker was a Sony SRS-28 active mini loudspeakers: O.4W, 8.Q, 065.5mm, height 14.3mm. The low-frequency driver was a loudspeaker without a cone by Aura, 87.1mm in diameter, attached to the bottom of a wooden plate resting on rubber silencing blocks.

2.2.3 Task. The users were asked whether they could feel any sensations from the speaker as they moved the mouse cursor over a pattern of vertical lines. Stimuli of different frequencies and amplitudes were generated for each trial. The users were asked to report whether they had detected any haptic sensation. This was done orally by saying "yes" or "no".

2.2.4 Stimuli. The stimuli generated by the computer were variable in amplitude, wavelength (and hence frequency) and spatial distribution of the virtual pattern. It was emphasised to the users that one of the amplitude settings being used was 0, i.e. no power, to avoid any possible concern if no sensations were being discerned. Table 2 shows the full range of stimulus parameters used.

The stimuli were generated by three different actuators; these were the three speakers described above. In addition, the Aura driver was used on two different volume levels of the external amplifier. The base frequency of the stimulus was chosen to be 25 Hz or 83.33 Hz so as to avoid as the auditory sensitivity range and minimise the audibility of the haptic device in operation.

Table 2. *Stimulus parameter levels.*

Amplitude (% of maximum)	0, 30, 60, 100 %
Waveform	Triangular
Spatial frequency Distribution (line spacing / pixels)	1, 2, 4 Pixels
Frequency (Hz)	25Hz, 83.3 Hz

The virtual stimulus generated when each line was crossed by the cursor was an impulse, or delta-function. For the physical stimulus generated, this was approximated by a triangular waveform. As this was a pilot study to test whether the users could discern any sensations, it was decided not to vary the waveform, although sine and square waves were possible alternatives. Figure 2 shows a representative output from one of the speakers. Each peak corresponds to an impulse being generated as the mouse cursor crosses a line.

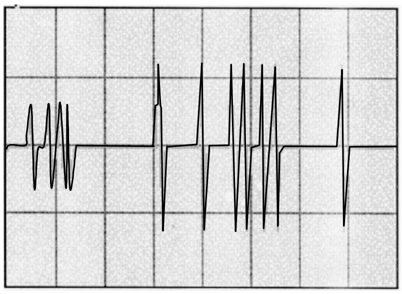

Figure 1 *Waveform resulting from cursor movement: 30% amplitude levels on the left hand side and 60% on the right.*

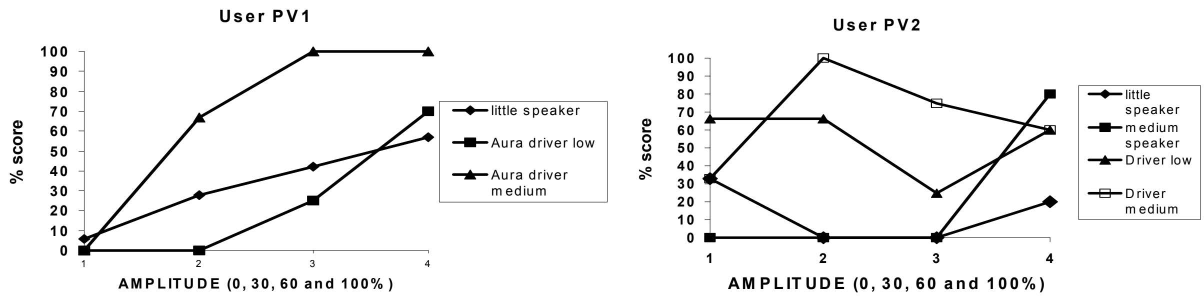

Figure 2a & 2b. *Users PV1 and PV2 detection scores for different amplitudes and actuators*

2.2.5 Results. The data recorded was entered into a spreadsheet program for analysis, plotting and descriptive statistics. The number of false positives at the 0% amplitude level gives a qualitative guide to the reliability of the results from a particular user. However it does not provide an absolute quantified measurement, as it is only an indicator of the user being able to identify that *no* output is being generated. It does not provide a guide to how well a user can determine that an output *is* being generated. That is indicated by the remaining values in the graph.

User PV1 performed the task using the small speaker and the large Aura driver at high and medium output levels. From Figure2a it can be seen that PV1 had a relatively low number of false positives at the zero amplitude level for all three actuator types. However, only the Aura driver on high power, with larger amplitudes of stimulus produce results near the 100% recognition rate. All of the other results can be explained away as chance because of the $p = 0.5$ likelihood of guessing a correct answer and the low number of samples taken ($N<5$). Consequently, the results are generally inconclusive about PV1's ability to discern the vibrotactile output. User PV2 used the same speakers as PV1, with the addition of the medium speaker providing a fourth actuator type. Figure 2b shows the results observed from this user. There is a high level of false positives across most of the actuator types, indicating a difficulty discerning the stimuli. This is supported by the results for the non-zero amplitude settings, which appear to be random in nature.

User PV3's performance indicated high sensitivity. There were no false positives at 0% amplitude and consistent 100% recognition rates for all the high amplitude variations of stimuli spatial frequency, and actuator type, suggested that this user was widely sensitive to vibrotactile haptic stimuli. Consequently, the tasks were repeated with a wider range of stimuli for this user to assess whether his capability was uniformly good across more different conditions. These included changing the spatial frequency distribution, how far apart the line stimuli were. The 30% amplitude stimuli showed some differentiation between conditions. For the small speaker, the sparse, low frequency stimuli were poorest, and the fine spatial frequency stimuli better. However, the medium speaker stimuli were detected at low and high frequencies. Interestingly, when the user was instructed to apply pressure to the small speaker in gripping the mouse, effectively squashing the output, the detection rate fell to chance levels.

The pattern of results suggest that the users' ability to perceive the haptic stimuli depended on the extent of their ability to grip and position the mouse and actuator. Hence, PV2, who has to resist tremor and grip the mouse using the middle finger joints, was not sensitive to the vibrational stimuli. However, PV1, who had comparable sensitivity and manipulation skill to able-bodied users, showed high levels of sensitivity. The results from PV3 were close to chance and the presence of some false positives suggests that they may be inconclusive.

2.3 Experiment 2: Vibrotactile feedback: initial results

The second experiment used the same experimental set-up, but with systematic variation of amplitude, stimulus frequency, and spatial frequency within a range suggested by the pilot experiment. Again the motion-impaired users were presented with a task of detecting stimulus elements accompanied by vibrotactile feedback, effectively 'feeling' a pattern of vertical lines. The detection rates were measured for a range of physical parameters: spatial frequency (i.e. line separation); stimulus amplitude; and mechanical actuator type and position. To reduce order effects and the effect of improvement with practice, a full randomised design was employed, with all 24 combinations resulting from varying the parameters amplitude, frequency, and spatial distribution on the levels as described in Table 1 above. The actuator position was varied to achieve maximum effect under the user's direction. To minimise the effects of auditory pollution, a second speaker was used in conjunction with the larger speakers to provide masking noise. This arrangement proved partially successful in achieving this, making the sound output less obvious, although not removing it completely.

2.3.1 Results. User PV2 again generated a large number of false positives for 0% amplitude conditions. In addition the results were distributed around chance for the small speaker. The large Aura driver, however, positioned underneath the non-mouse hand or the mouse platform, appeared to give rise to an increased number of positive detections in the high amplitude conditions and reduced occurrence of false positives. This may have been due to auditory detection of the speaker in operation.

User PV3 again performed almost perfectly for both small and medium speakers, with all stimulus conditions.

User PV4's detection levels were around chance for the small speaker, with some false positives. However, interestingly, detection levels improved for the large driver, over all conditions. This is interesting, as the deafness of this user prevented the hearing of possible auditory cues to stimuli that could underlie other users performance. The user reported a strong tactile sensation for the large driver.

2.3.2 Discussion. As before, the pattern of results suggest that users' abilities to perceive the haptic stimuli depended on the extent of their ability to grip and position the mouse and actuator. The inclusion of the deaf user PV4 was revealing in that his good result in the large speaker driver condition could not have been due to auditory cues and so he was definitely experiencing and discerning the vibrotactile sensations.

2.4 Experiment 3: Force-feedback

In this experiment the ability of a force feedback device to assist both motion-impaired and able-bodied users in a typical GUI pointing task was investigated. The users were presented with a simple GUI pointing task on a standard PC and the times to complete the task with and without force feedback assistance for differing levels of difficulty were recorded. The error rates from missed clicks was also recorded.

2.4.1 Method. Four motion-impaired and two able-bodied users were presented with the Immersion Corp's Connect-the-dots development, sample computer application. The program recorded the time taken to complete a sequence of point and click tasks, where the targets were distributed in a fixed, irregular pattern across the screen. Each target consisted of two concentric circles. The green coloured inner circle was the actual target to be activated by clicking on it. The blue outer circle indicated the extent of the force feedback locus of attraction, or gravity well, around the target. Positioning the cursor within the blue circle resulted in a spring force towards the green target circle. This task was repeated both with and without the force feedback active. Four motion-impaired users from those described in Table 1 participated in this experiment. The able-bodied users were University Research Associates.

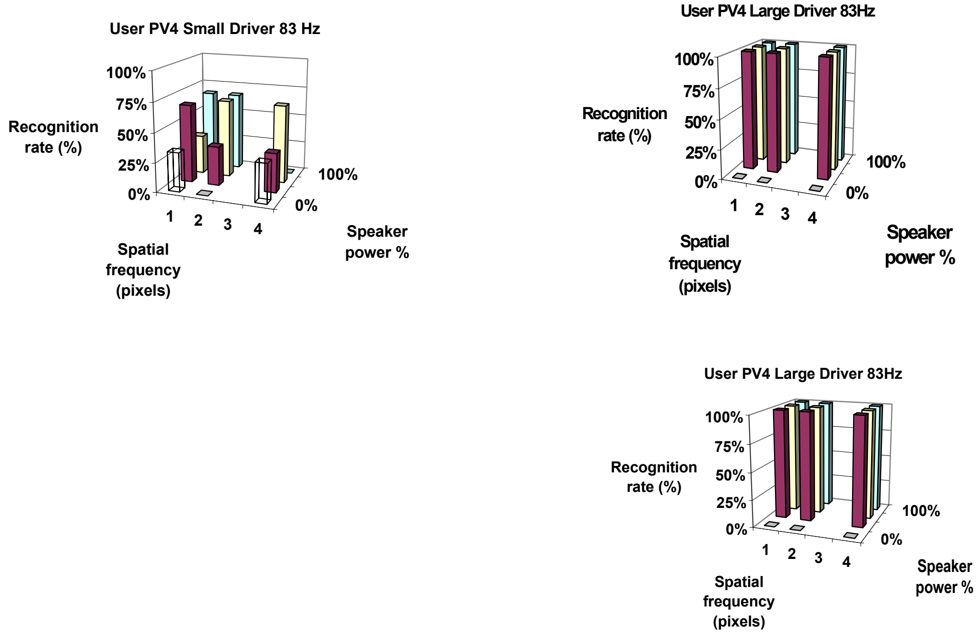

Figure 3. *Typical rates for spatial frequency and speaker power for the vibrotactile drivers at two frequencies.*

2.4.2 Task & Stimuli. A 2D flattened projection map of North America was drawn on the screen and the 10 target locations were distributed as fixed city locations on this map. The targets consisted of two concentric circles where the outer circle was of constant diameter and filled with the colour blue. The inner circles radii differed in the difficulty conditions, with the hardest condition having the smallest diameter circle. The inner circles were coloured green. After the start signal was displayed, the user was required to move to, and click on, the inner circle of the target circle whose outer circle area was flashing. Successfully clicking on the centre circle immediately initiated flashing of the next target in the sequence. On completion of the required sequence of targets, the timer was stopped and the number of clicks outside of the target circle (misses) displayed. The elapsed time, and start and stop signals were displayed at the top of the screen. During the force-feedback trials the Immersion "WingMan" mouse was strongly attracted to the centre of the target once the outer circle was reached. During the unaided mouse trials the interface behaved as a normal point and click mouse. The program forced a complete training set on the identical stimuli before each force-feedback trial. The users performed the task using the easy, medium and hard settings and the time data recorded after each trial.

Table 3. *Time to complete trials with and without force-feedback for all users (average errors in brackets).*

		PV2	PV5	PV1	PV3	AB1	AB2
Easy	**WITH FF**	49.5 (2.4)	8.7 (0.4)	41.6 (2.0)	12.4 (0.0)	6.4 (0.0)	6.4 (0.0)
	NO FF	-	19.0 (2.8)	79.9 (10.4)	20.0 (3.0)	9.5 (1.0)	9.5 (1.0)
Med.	**WITH FF**	74.2 (4.4)	9.8 (1.0)	36.5 (1.2)	11.3 (0.4)	7.0 (0.0)	7.0 (0.0)
	NO FF	-	25.8 (2.6)	-	20.3 (1.4)	11.3 (1.4)	11.3(1.4)
Hard	**WITH FF**	-	11.8 (1.6)	-	12.2 (0.6)	8.0 (0.4)	8.0 (0.4)
	NO FF	-	24.3 (2.4)	-	21.5 (0.4)	15.7 (1.4)	15.7(1.4)

2.4.3 Results. There was a considerable improvement in both time to complete trials and error rates with the force-feedback. Typical performances were exemplified by two users. User PV2 was unable to perform the task in the unassisted mode taking as long as 364 seconds in one trial to complete half the targets on the easy setting. However this user was able to perform five trials using the force-feedback assistance, showing a substantial learning effect for the task over trials. A consistent number of 2 missed clicks for each set of 10 targets was recorded. This pattern was repeated for the two harder sets of trials although the average time to complete each set increased. User PV5 was able to perform the unassisted interface task, showing an average completion time of around 20 seconds. However, scores were substantially improved during the force-feedback assisted trials, at around half that time on average. This effect occurred for the two harder sets of trials. There was evidence of a learning effect across trials and tasks.

2.4.4 Discussion. A strong positive effect of force-feedback was observed for both motion-impaired and able-bodied users. In particular, the times to complete the trials were reduced by 30–50% of times for normal interaction modes. The improvement that occurred was so marked that motion-impaired users were, in some cases, able to equal and exceed the performance level of the able-bodied users, most noticeably in the higher difficulty settings. The error rates, as indicated by the number of missed clicks, were of uncertain origin. This was due to the lack of knowledge of the application's internal criteria for a missed click.

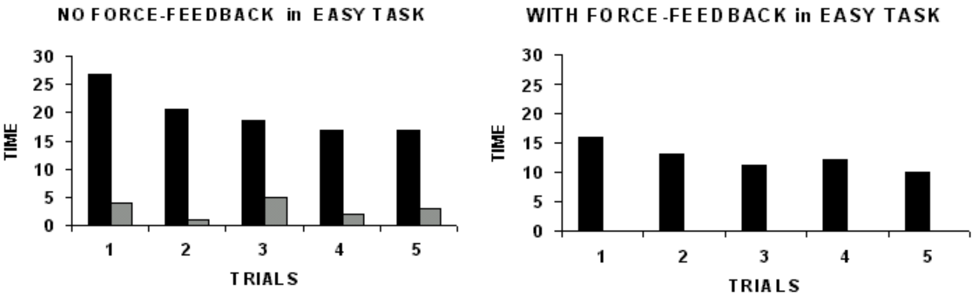

Figure 4. *Easy task trial times without (left) and with (right) force-feedback for user PV3. Grey bars are number of errors.*

A strong learning effect can be inferred across trials and across conditions. This was not unexpected as the position and order of the stimuli remained constant throughout the experiment. However, it would be expected that practice with both the force-feedback and unassisted mode of pointing would also lead to improvement for randomised orders. This remains to be tested. Clearly, a number of weaknesses of this experiment lie in the use of a development demonstrator application. This includes the lack of randomisation of distance, size and location of the stimulus targets. In addition the visual implication of the differing areas flashing borders for targets is not quantified. Finally the training trials before each force-feedback trial set is asymmetrical with the unassisted interaction modes, although it could be argued that the users have already received extensive practice in unassisted mouse pointing tasks in everyday use of PCs. The strengths of the experiment include the realism of the task and resemblance to standard GUI interactions; the use of a natural input mode in the form of a mouse and force-feedback assisted mouse; the interesting nature of the task when compared with other tedious experimental manipulations, especially for motion-impaired users.

3. GENERAL DISCUSSION

Overall the results from the vibrotactile haptic feedback are not conclusive. For the particular implementation used here, that of positioning a speaker driven by a sound signal underneath the users hand or fingers, it appears that the feedback is useful only to the most capable. In particular, the pattern of results from the vibrotactile experiments suggests that user ability to perceive the vibrotactile stimuli was affected by the extent of their motor capability to grip and position the mouse and actuator. Feedback was not available to those who gripped the mouse in a non-standard way or to those who were forced to exert damping movements to counteract tremor or spasms. However, this is not taken to suggest that vibrotactile haptic feedback aimed at stimulating the cutaneous receptors is not useful, just that this method of channelling vibration forces may not be effective. In addition, some users were able to prevent the small speaker from operating by applying force, consciously and unconsciously. This has also been observed in some able-bodied users who involuntarily contract their fingers when performing normal clicking movements, preventing the speaker from operating.

The inclusion of PV4, who was deaf, suggested that a good result for the large speaker driver may not have been due to auditory cues. However, this result is not conclusive because the user was physically more capable than a number of the other users and there was a general inverse correlation between physical capability and ability to discern the stimuli. It is worth noting that the Logitech force-feedback mouse is capable of generating forces conveying fine textures and grids and that, in addition, these forces possessed a directional component. The normal operation of this device is accompanied by minimally audible sounds that could be easily deadened or masked. Future experiments will assess the use of this device for implementing vibrotactile feedback.

The deficiencies of the experimental conditions in the vibrotactile experiments suggest that undue emphasis should not be placed on small differences within the results for the users. These deficiencies include: the use of incomplete conditions; the non-quantified learning effect over trials; the unknown effects of grip and actuator positioning; the effects of inadequate sound masking for the larger devices; the use of a narrow and incomplete range of waveforms and base vibration frequencies; and the influence of the good user role. Despite this, it was clear that users showed evidence of being sensitive to the stimuli in various vibrotactile conditions and that this was broadly correlated with their degree of impairment.

The results from the force-feedback trials strongly suggest that this method of haptically enhancing interaction with the GUI could be of great benefit to both motion-impaired and able-bodied users. An advantage of this approach that emerged from the use of the device is that it is capable of delivering both vibrotactile forces, affecting the touch, cutaneous senses and also forces of greater magnitude that can stimulate the kinaesthesic system receptors. It is capable of delivering direction and magnitude information in a mode of operation that is very similar to that of a normal mouse. Future experiments will focus on changing the properties of the locus of attraction round each target to establish optimal sizes and force feedback profiles.

4. CONCLUSIONS

Of the experimental set-ups investigated in this paper, the force feedback mouse appears to be superior to the vibrotactile speaker feedback for the enhancement of motion-impaired user interactions with GUI's. The pronounced improvements in point and click activity performance by all users suggests that force feedback devices, such as the WingMan mouse, are cost-effective methods for improving the interaction of motion-impaired users with user interfaces. Although the degree of enhancement provided by the vibrotactile feedback appeared to be inversely proportional to the degree of disability, the force feedback appeared to benefit all users and, if anything, to be of greater use to the more impaired.

In addition, there was a suggestion of reduced error rates with force-feedback and no observed evidence of increased cognitive load resulting from the introduction of haptic information. These conclusions will be tested with more rigorous experimental testing of the two types of feedback. Evidence was obtained to suggest that the vibrotactile technique may enhance interaction, but this certainly needs to be investigated further. If the correlation between capability and ability to discern the vibrotactile sensations is proven, then this may only be of limited use for more severely impaired users. Further research is also needed to establish the device positioning and stimulus properties needed to exploit this technique to maximum effect.

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