



Augmenting Graphical User Interfaces with Haptic Assistance for Motion-Impaired Operators

C. T. Asque^{a,*}, A. M. Day^a, S. D. Laycock^a

^a*School of Computing Sciences, University of East Anglia, Norwich, NR4 7TJ, UK*

Abstract

Haptic assistance is an emerging field of research that is designed to improve human-computer interaction (HCI) by reducing error rates and targeting times through the use of force feedback. Haptic feedback has previously been investigated to assist motion-impaired computer users, however, limitations such as target distracters have hampered its integration with graphical user interfaces (GUIs). In this paper two new haptic assistive techniques are presented that utilise the 3DOF capabilities of the Phantom Omni. These are referred to as deformable haptic cones and deformable virtual switches. The assistance is designed specifically to enable motion-impaired operators to use existing GUIs more effectively. Experiment 1 investigates the performance benefits of the new haptic techniques when used in conjunction with the densely populated Windows on-screen keyboard (OSK). Experiment 2 utilises the ISO 9241-9 point-and-click task to investigate the effects of target size and shape. The results of the study prove that the newly proposed techniques improve interaction rates and can be integrated with existing software without many of the drawbacks of traditional haptic assistance. Deformable haptic cones and deformable virtual switches were shown to reduce the mean number of missed-clicks by at least 75% and reduce targeting times by at least 25%.

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Keywords:

Haptic assistance, haptics, computer accessibility, human-computer interaction.

1. Introduction

Access to a computer offers improved opportunities for people with motion-impairments in vocational settings, for leisure activities and communication. A computer is a highly versatile tool where both software and hardware can be developed or adapted to help overcome many obstacles that a motion-impaired person may encounter. One of the primary tasks when using a computer is to navigate the on-screen cursor using a pointing device. According to Dennerlein and Johnson (2006) the use of a pointing device accounts for 30-80% of all time spent working at a computer. A high level of dexterity is required to accurately position the cursor and maintain stability whilst operating a device switch. According to Hwang et al. (2003) symptoms such as tremor, spasm, muscle weakness, partial paralysis, or poor coordination can make standard pointing devices difficult, if not impossible, to use.

Previous studies have investigated the use of haptic feedback to assist targeting and cursor navigation. A large majority of motion-impaired computer users have difficulty maintaining cursor stability when attempting to select small targets. Many haptic techniques have been investigated to assist target selection (Keates et al., 2002; Langdon

*Corresponding Author.

Email addresses: c.asque@uea.ac.uk (C. T. Asque), amd@cmp.uea.ac.uk (A. M. Day), sd1@cmp.uea.ac.uk (S. D. Laycock)

et al., 2002b; Holbert and Huber, 2008; Asque et al., 2012b). These techniques have often shown to improve clicking accuracy and reduce targeting times. Haptic damping was shown to reduce the overall targeting times by up to 50% for some operators that experience spasm. Haptic tunnels were introduced by Langdon et al. (2002b) to improve throughput for participants that have difficulty following straight paths. Asque et al. (2012a) were able to improve cursor navigation for people with severe motion-impairments using a “haptic workbox”. The results from these studies show that incorporating the sense of touch into human-computer interaction can significantly improve a person’s interaction rates when implemented carefully. Given the positive results from these studies it is surprising that haptic assistance has not been more widely integrated with existing software. It is also surprising that haptically enabled interfaces have not been included in commercial software to improve interaction rates for able-bodied users.

One of the major difficulties is that many interfaces do not lend themselves to haptic assistance. Toolbars are often arranged in rows or columns which causes issues when the cursor has to pass through undesired neighbouring haptic cues before reaching the destination. The influence of target distracters has significantly hindered the inclusion of haptic assistance in existing GUIs. A preferable solution would be to adapt user interfaces specifically for haptic assistance and motion-impaired operators. However, manually designing interfaces for specific techniques or individuals is impractical and not scalable. The aim of this paper is to produce haptic assistance that can be integrated into existing graphical user interfaces without many of the previous shortcomings. The two techniques proposed in this study are referred to as deformable cones and deformable virtual switches. Both are designed to allow the operator to choose when they require assistance. Deformable switches are embedded into a virtual plane and provide the feedback of a snap-action tactile switch. Deformable cones emerge when penetrating the virtual plane and are designed to clamp the cursor to the target centre when clicking. By providing the choice of when to use or ignore haptic assistance the techniques are much less intrusive and the effect of target distracters is significantly less.

The remainder of the paper is organised as follows: Section 2 gives an overview of difficulties that motion-impaired operators encounter with HCI, the limitations of current haptic assistance and relevant literature on the guidelines for developing haptic assistance. Section 3 introduces the methods that have been developed to conduct the experiments. The results are presented in Section 4. Finally, the discussion and conclusions are drawn in Sections 5 and 6 respectively.

2. Related Work

The following section identifies studies that have highlighted target distracters as a major hindrance to the development of haptic assistance. This is followed by literature on producing haptic assistance for real world interfaces. Finally, it has been observed that some participants have difficulty operating the device switch and that there may be valid reasons to simulate clicking through haptic feedback.

2.1. Target Distracters

Target distracters have been highlighted as a major hindrance to the development of haptic assistance (Keates et al., 2002; Hwang et al., 2003; Holbert and Huber, 2008; Asque et al., 2012b). A target distraction occurs when the cursor has to pass through undesired haptic cues before reaching the destination. The majority of GUIs have icons arranged in rows or columns, which means that there are often many potential distracters that lie along the task axis. A study by Hwang et al. (2003) showed that the configuration of distracters surrounding the desired target can have a direct bearing on user performance. The cursor trajectories indicated that many corrections were required when exiting distracters and that there was a time penalty associated with consequent oscillation between targets. The study also showed that participants often do not make an effort to avoid distracters and tend to plough through them to reach the destination. The force feedback effect of the haptic cue will have a direct bearing on the resulting cursor trajectory. Hwang et al. go on to argue that target arrangements requiring the cursor to pass through other haptically enabled items can be detrimental to user performance and should be avoided.

Many haptic techniques impose a force when exiting a target, which can cause a large overshoot and impede the next task. The disruption is amplified in densely populated user interfaces because the overshoot will often land the cursor into an undesired neighbouring target. This has been observed most notably with 2DOF devices where target distracters make an interface frustrating to use due to regularly having to oppose erroneous forces along the task axis before reaching the destination. The literature reports that gravity wells and high-friction targets are of

greatest concern for 2DOF devices (Keates et al., 2002; Hwang et al., 2003). Dennerlein and Yang (2001) found that participants would exert a large effort to escape distracters and continue onto the desired target. Qualitative feedback indicated that this increased user frustration and effort when performing tasks. If the operator does not have sufficient muscle strength to exit undesired haptic cues then the interface may be unusable.

Gunn et al. (2009) state that there may be valid reasons for a skilled user to want to ignore assistance. Force feedback that is in operation at all times may be difficult to ignore and therefore be less effective as an aid. A 3DOF device allows assistance to be more easily ignored if required by lifting the stylus off the virtual plane and passing over distracters before re-applying the haptic interface point (HIP). However, the limitation of this approach is that it can disrupt interaction if the operator has to regularly lift the stylus off the page and then re-apply it. Initial studies by Asque et al. (2012b) produced assistance that does not subject the operator to an opposing force when exiting target distracters. Results from the study have shown that haptic cones provide substantial improvements in clicking accuracy. The technique is less intrusive on interaction than gravity wells or high-friction targets because the operator does not have to oppose a spring or frictional force to exit. Haptic cones can be exited by simply navigating up the walls. However, the cones embedded in the virtual plane can make it difficult to smoothly scroll over an interface.

A possible solution to alleviate target distracters is to use target prediction techniques to only enable the haptic cues that the operator requires. A number of studies have analysed cursor trajectory to predict the path and distance to the target (Murata, 1998; Asano et al., 2005; Lank et al., 2007). The difficulty with this approach is that people do not always follow predictable paths. Studies that have used trajectory prediction for able-bodied participants have only managed a 75% success rate of correctly predicted targets (Murata, 1998). Holbert and Huber (2008) attempted to use target prediction to reduce the effects of haptic target distracters for motion-impaired participants. Significant improvements were observed in targeting performance when the haptic effect was applied to the correct target. However, the rate of correctly predicted targets was only 23%, which meant that the overall improvement was unclear. This low performance rate was as a result of the lower predictability of data produced by motion-impaired participants and the high gain sensitivity of the 2DOF Logitech Wingman. Dennerlein and Yang (2001) state that only enabling 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 a pointing device? Without an efficient method for enabling or ignoring haptic cues the overall effectiveness of the assistance is limited by the trade-off imposed by the distracters.

The evidence from these previous studies suggests that ideally the operator would not be able to accidentally enter target distracters. A preferred method would be to perform a gesture that signifies that they require assistance. This would allow them to choose and ignore the assistance when they wish to do so. Bayart et al. (2005) have shown that partial guidance outperforms full guidance because the operator does not become dependent on the system and they are prepared when unexpected issues arise. The newly proposed techniques in Section 3.2 have taken this into consideration. If the operator accidentally performs a gesture that enables a haptic cue then the techniques provide a restoring force that helps exit that cue. The following section identifies a number of key design considerations when implementing haptic assistance.

2.2. *Guidelines for haptic assistance*

A number of studies have highlighted important considerations when integrating haptic assistance into realistic user interfaces. The previous section highlighted that haptic assistance can be intrusive because it cannot always be easily ignored. According to Oakley et al. (2002) extraneous forces that haptic widgets apply have the potential to alter the paths users wish to take, and consequently may reduce their performance and satisfaction. This assertion is upheld in a study that investigated a standard haptically augmented menu system (Oakley et al., 2001). Oakley et al. propose a number of guidelines that are based on the concept that the force presented should support, and not oppose, a user's intent. This entails drawing a balance between allowing users to move where they want as freely as possible, and providing forces to improve targeting and reduce errors.

Miller and Zeleznik (1998) state that any force feedback applied to a user should be overridable; a user should be able to pop through, or escape from, any haptically augmented area. Kuber et al. (2007) investigated haptic assistance to aid visually impaired Internet users in web page exploration. They state that, ideally, force sensations should be short in duration, perceivable and non-intrusive. Asque et al. (2012b) propose target acquisition techniques that do not require the operator to oppose a force when exiting a haptic widget. They emphasise that haptic target acquisition techniques should guide the cursor towards the centre of a target so that if the operator slips slightly then they are less

likely to miss-click. It is important to produce techniques that do not impose forces on the operator. The reason for this is that people with decreased muscle strength or joint difficulties may not be able to use the assistance without discomfort. For example, the “snap effect” of gravity wells has been highlighted as a concern for people with joint difficulties. Similarly, the extra workload imposed by haptic damping has been identified as a concern for people with decreased muscle strength. Techniques that do not impose forces on the user will be suitable for a wider range of impairments.

According to Asque et al. (2012b) it is desirable to produce haptic assistance that does not require force calibration to optimise interaction. This is due to the fact that a motion-impaired person’s needs are not always predictable and so calibration may not necessarily be successful. For example, the operator’s needs may change in the short term due to factors such as fatigue or long term due to deterioration in impairment. Haptic techniques that do not impose forces on the operator will be suitable for a wider range of impairments. Langdon et al. (2002a) report that motion-impaired users often exhibit decreased motor control and muscle strength, but not necessarily a decreased haptic sensitivity. Studies have determined that the human hand can resolve forces as small as 0.1N (Shimoga, 1993; Doerrer and Werthschuetzky, 2002). Therefore, the force subtleties that the operator experiences need to be carefully considered. The following section identifies a number of issues that some operators have with the switch press operation.

2.3. *Switch Press*

When selecting an icon the operator is required to position the cursor accurately inside the target region and press the device switch. Many operating systems require both the click and release to be performed inside the target for the operation to execute. It has been noted that some participants have difficulty maintaining stability when clicking. The contraction of muscles when performing a switch press can result in positional disruption to the cursor for people that experience spasm or tremor. Some people find that stiffness in the wrist or fingers can make it difficult to physically perform the operation. Additionally, the surface area of many pointing device switches is quite small, which can make them difficult to locate. The feedback provided some micro switches is not always decisive and it can be difficult to determine if the click has been registered or not. This results in more errors because people tend to click more than once if they are unsure if the process has executed. A haptic device offers the potential to simulate a push-button switch to replace the functionality of the device switch.

The realistic simulation of switches has been addressed in previous studies. For example, Weir et al. (2004) developed a “Haptic Profile” to measure the subtleties of the physical characteristics of linear push switches. The system was human actuated and designed to capture a model for the switch mechanics such as, force, position, velocity, and acceleration. The data from this study can be used to synthesise realistic haptic sensations. Virtual haptic switches have been implemented by researchers in a number of studies. In terms of hardware Doerrer and Werthschuetzky (2002) investigated the force resolution and force-displacement curves using a key-simulator to emulate switches on a control panel. Miller and Zeleznik (1999) discuss the practicalities of the concept in terms of software design. They describe the force profile of a push-button switch as consisting of an initial springy region where the force increases linearly with displacement, this is followed by a sudden decrease in resistive force and a transition into a “deadband” where the resistive force is constant. Currently, there is relatively little literature regarding the use of haptic virtual switches for motion-impaired computer users. This paper evaluates the effectiveness of specifically designed haptic virtual switches, which are presented in Section 3.2.

3. **Methods**

3.1. *Cursor Analysis Techniques*

Fitt’s law is often used as the model for cursor movement in HCI. It can be used to give a measure of the trade-off between speed and accuracy, known as throughput (TP). However, the haptic assistive techniques proposed in this paper are very effective at guiding the cursor to the target centre, which makes it difficult to compute throughput. Although the overall average on-click distance to target centre line may not be zero, there were many occasions where all the participants clicked at the target centre for all repetitions. As a result, there is often no standard deviation in the click positions and it is not possible to calculate the index of difficulty required for throughput. Therefore, the main focus of the measures discussed in this section is to analyse the effectiveness of each haptic condition in assisting target selection, whilst recording the effects of distracters. Previous studies often use cursor measures proposed by

MacKenzie et al. (2001) to evaluate pointing device performance (Keates et al., 2002; Wobbrock and Gajos, 2007; Mauri and Granollers, 2007; Wobbrock et al., 2009). However, these measures concentrate on the homing phase of a point-and-click task and provide very little insight into the performance of the selection phase.

The missed-click measure alone is not very useful in analysing the effects that haptic assistance has on target selection. Asque et al. (2012b) proposed a number of measures that provide more detailed information on the clicking phase. These are presented in Section 3.1.2 to 3.1.3 and attempt to record why missed-clicks occur and determine if haptic assistance will significantly improve clicking accuracy. One of the aims of the study is to produce assistance that will reduce the effects of target distracters. Previous research has concentrated on evaluating cursor traces but have not provided measures that will quantify the effects of distracters or their intrusiveness. It is not sufficient to just look at the amount of time spent inside distracters because some participants will often lift the stylus off the virtual plane to pass over them. This is not ideal because the operator will not be provided with the support from the virtual plane and lifting off can disjoint interaction. A number of new measures have been proposed in Section 3.1.4 onwards that are designed to give a better understanding of distracters and their effect on interaction.

3.1.1. Missed-Click

A missed-click is recorded if the operator clicks or releases (or both) outside of the target region.

3.1.2. Click-Release Displacement

The click-release displacement gives a measure, in millimetres, of the Euclidean distance between the click and release. It is useful for determining how much the operator slips during the clicking phase. If an individual slips a large distance whilst clicking then it is unlikely that the target will be selected accurately. If that person has a tendency to miss-click due to slipping off the target then the click-release displacement will help give an indication as to why this is the case.

3.1.3. On-Click Distance from Target Centre Line

The on-click distance from the target centre line gives a measure, in millimetres, of how effective a technique is at providing assistance at the centre of the target. If an operator clicks at the target centre and slips then it is more likely that the release will occur within the target region. If they click at the edge of a target and then slip it is more likely that the release will result in a miss-click.

3.1.4. Time Spent on the Virtual Plane

The amount of time spent in contact with the virtual plane will give an indication of how intrusive each technique is on interaction. If the operator has to continually lift the stylus to pass over distracters then this will indicate that the technique is intrusive. The amount of time spent in contact with the virtual plane for each haptic condition will be compared to the unassisted control experiment. If the participants spend a similar amount of time in contact with the virtual plane for a given haptic condition when compared to the unassisted experiment then this infers that the effect of distracters is much less intrusive because they decided to pull off the plane less often.

3.1.5. Device Distance Travelled

It has been observed that when target distracters are present that the overall distance the pointing device travels will often increase. This is due to the operator having to perform corrections when passing through and exiting distracters. The distance travelled will give an indication of the scale of the corrections that the operator has to make in comparison to an interface that does not contain distracters. Ideally no significant differences will be observed for the new haptic techniques when compared to the unassisted control experiment.

3.1.6. Experiment Time

The corrections required when target distracters are present often means that the time to complete the task increases. The experiment time will help give an indication of how severe the effects of a certain technique's distracters are on interaction. Ideally the techniques presented in this paper will reduce the experiment time due to the ease of navigating to the target and the increased confidence in selecting it.

3.2. Experimental Conditions

The following section discusses the implementation of traditional haptic assistance and the newly proposed techniques presented in this paper. Haptic interactions have been achieved using an open source API, named CHAI3D (last accessed May 2013). The CHAI3D API uses Zilles and Salisbury's God-Object haptic rendering algorithm Zilles and Salisbury (1995). The algorithm tracks a history of contact with a surface. The position of the God-Object (proxy) is chosen to be the point which locally minimizes the distance to the haptic interface point (HIP) along a surface and a restoring spring force is calculated between the two.

3.2.1. Gravity Wells

Gravity wells are a useful user interface (UI) convention for allowing the operator to more readily select points with the assistance of force feedback (Cockburn and Brewster, 2005). A gravity well can be considered as a bounding volume with a spring force towards the centre of that volume. They are used to attract the device towards a location and will typically have a set radius of influence. The resultant spring force is calculated using Hooke's law, as shown in Equation (1). For square or rectangular buttons the displacement is clamped to an inner oblique oval that is placed inside the shape to ensure that there are no force discrepancies at the four corners.

$$\mathbf{f} = k\mathbf{x} - b\mathbf{v} \quad (1)$$

where \mathbf{f} = force
 k = spring constant, \mathbf{x} = displacement
 b = damping coeff., \mathbf{v} = proxy velocity

The spring force is designed to clamp the cursor inside the volume until the icon has been selected or the force placed on the device exceeds that limiting the gravity well. The force experienced by the operator is dependent on the displacement and spring stiffness. The maximum displacement is governed by the size of the target. A spring stiffness was chosen that produced a maximum force of 1.5N at the limits of the gravity well (ignoring the damping factor). This force level was chosen to provide a sufficient level of clamping whilst allowing the operator to overcome the force limiting the gravity well when exiting distracters.

3.2.2. Haptic Cones

Haptic cones are a technique proposed by Asque et al. (2012b) that is designed to improve clicking accuracy by clamping the cursor to the apex at the target centre. In the study haptic cones were shown to be the most effective technique for reducing the number of missed-clicks and improving throughput. One of the benefits of the technique is that no forces are imposed on the operator, which means that distracters can be easily exited without having to oppose a force. Therefore, there is not the overshoot concern that is highlighted with traditional techniques such as gravity wells. The added benefit of not imposing a force on the operator is that force calibration is not required to optimise interaction.

The technique is implemented by extracting the button positions from an interface and using that data to embed the cones correctly into the mesh of the virtual plane. The mesh is constructed by using Delaunay Triangulation and Figure 9 shows an example of the haptic cones embedded into the virtual plane with the GUI of the OSK overlaid on top. One of the limitations of the haptic cones is that they are in operation at all times, for all icons, which can make it difficult to smoothly scroll across the screen whilst remaining in contact with the virtual plane. Although distracters are easier to exit, it would be desirable for the operator to have the choice of entering them or not. Another limitation of the haptic cone approach is that the operator is not given any assistance to exit a target. Therefore, they have to either manually navigate the walls or pull out of the cone before performing the next operation.

3.2.3. Deformable Cones

One of the difficulties in the development of haptic assistance has been providing the operator with techniques that they can choose to use or ignore. External switches or gestures that enable and disable haptic cues can disjoint interaction and are not always intuitive. The haptic cone technique discussed in Section 3.2.2 has been shown to

improve clicking accuracy and throughput. Deformable haptic cones have been proposed as an extension to allow the user to choose when they require assistance and when to ignore it.

The virtual plane is embedded with deformable haptic cones that emerge when the operator presses into the surface, as shown in Figure 1(a). When deforming a cone the proxy is guided towards the apex, which provides good stability for clicking. The maximum depth limit of the cone is equal to the length of its shortest side so as to provide a suitable slant angle. An example of a fully deformed cone is shown in Figure 1(b). The cones begin deforming on contact as soon as they are engaged by the operator. The force applied by the user determines the depth of deformation at the cone apex. A relatively stiff surface is required to support the user's arm whilst scrolling across the screen and to ensure that the cones do not deform too easily.

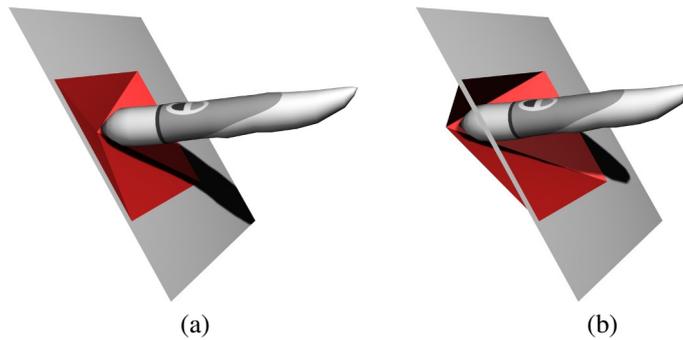


Figure 1: The deformation of a haptic cone by the virtual tool (a). A fully deformed haptic cone (b).

A new haptic rendering algorithm has been created for deformable cones because the standard God-Object approach proposed by Zilles and Salisbury (1995) does not handle both rigid and deformable objects. The cones need to be deformable in the sense that they emerge from the virtual plane but they also need to have rigid sides so as to guide the operator towards the centre of the target. The difficulty with this approach is that two forces require calculation, i.e. the restoring force of the cone apex to the surface of the virtual plane F_1 and the restoring force of the HIP to the proxy on the cone surface F_2 , as depicted in Figure 2. It is not possible to simply sum F_1 and F_2 because the resultant force would exceed the capability of the Phantom Omni. Summing the two forces would also cause a design conflict because the force experienced by the operator needs to be continuous when transitioning between the virtual plane and deformable cones.

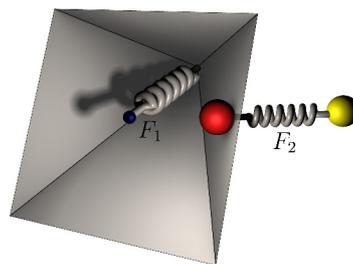


Figure 2: The two force calculations required to restore a deformable cone.

To overcome this problem the force rendering algorithm mixes the magnitude and direction of the two computed forces. The initial phase calculates the force direction based on the vector between the HIP and the proxy but the magnitude of the restoring force is governed by the depth of the cone apex in relation to the surface of the virtual plane. This ensures that the magnitude of the restoring force at a given penetration depth of the virtual plane is the same when deforming a cone, as depicted in Figure 3. Therefore, the operator will not experience any force discontinuities when transitioning between the two surfaces.

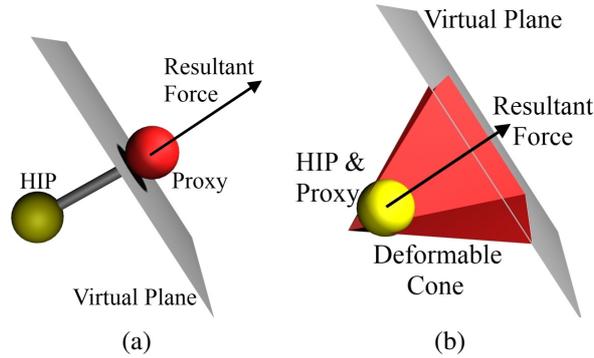


Figure 3: The restoring force of the virtual plane (a). The restoring force at the apex of a deformed cone (b).

If the magnitude of the X or Y components of F_2 exceed those calculated previously then they are used as the new resultant force. This ensures that the cone walls have sufficient stiffness to provide effective clamping at the target centre. The traditional God-Object implementation can suffer from pop-through when the proxy is in contact with a mesh that has moving vertices or geometry transformations. To avoid this issue a constraint has been added that ensures the proxy remains on the correct side of a surface.

Finally, force shading is applied to the edges of the cones to ensure that the proxy does not “catch” when passing over potential distracters. This is necessary because the operator will inevitably deform a cone slightly when scrolling over the interface. The catching effect could impact user satisfaction and disrupt the path of the cursor. No force shading is applied at the cone apex because it is the well defined edges that provide effective clamping at the target centre. The force shading is achieved using spherical linear interpolation (SLERP) between the previously calculated force vector \hat{v}_1 and the normal of the virtual plane \hat{v}_2 . The threshold u of the SLERP is governed by the distance of the proxy from half way up the cone wall to its shared edge with the virtual plane, as shown in Figure 4 and Equation (2).

Consider two vectors \hat{v}_1 and \hat{v}_2 , and find the angle between them:

$$\omega = \cos^{-1}(\hat{v}_1 \cdot \hat{v}_2)$$

Given a parameter $u \in [0, 1]$, the slerp is:

$$\text{slerp}(u, \hat{v}_1, \hat{v}_2) = \hat{v}_1 \frac{\sin((1-u)\omega)}{\sin(\omega)} + \hat{v}_2 \frac{\sin(u\omega)}{\sin(\omega)} \quad (2)$$

Given that the proxy will slide towards the apex whilst deforming a cone, it is almost certain that the click will be performed at the target centre. The clamping at the apex means that it is very unlikely that the operator will slip off the target (a problem noted by Brewster (1998)). Although there is a physical workload cost associated with deforming a cone, it is anticipated that the ability to navigate the interface with less intrusion from distracters will outweigh this. If the operator accidentally enters a deformable cone then they are provided with assistance when exiting it, in the form of the restoring spring force. As the operator climbs the cone wall it will begin to reform, which reduces the slant angle and makes it easier to exit.

3.2.4. Virtual Switch

To accurately position the cursor within a target and operate the device switch can be a challenge for many people with physical disabilities. Section 2.3 identified a number of difficulties that motion-impaired computer users encounter when clicking. The virtual switch proposed in this paper is designed to simulate a push-button switch through haptic feedback. A virtual switch is placed around each icon within the interface and embedded into the virtual plane. The concept is based on existing assistive technologies, such as keyguards, that are designed to reduce

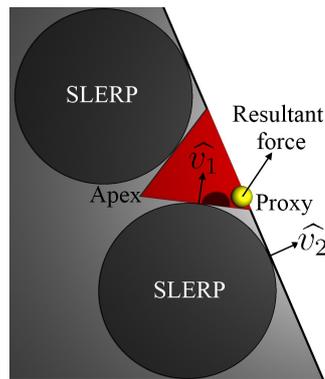


Figure 4: The SLERP of a deformable haptic cone with the virtual plane.

unintentional key presses. The keyguard is a metal or plastic plate that is overlaid on top of the keyboard. The operator activates individual keys by poking through access holes.

One of the major difficulties that motion-impaired operators encounter is slipping off a target whilst clicking (Brewster, 1998; Trewin et al., 2006). It is likely that a flat surfaced switch would encounter this issue. The haptic cone proposed in Section 3.2.2 is an effective method of clamping the proxy to the target centre without imposing a force on the operator. Therefore, a pyramid shaped cone has been used for the surface of the virtual switch. The concept of the technique is presented in Figure 5.

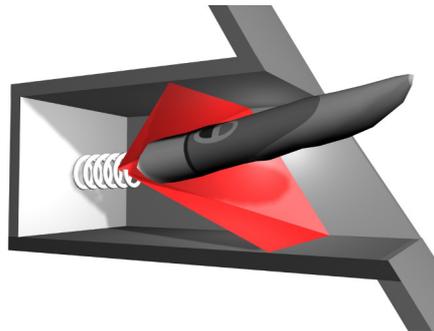


Figure 5: The concept of pressing a haptic virtual switch.

Snap-action tactile switches are used in industry to provide decisive feedback. The simulation of a tactile switch will help provide appropriate haptic feedback to the operator. When engaging a virtual switch the user will experience a restoring force until the spring is fully compressed, as shown in Figure 6(a). Once the spring is fully compressed the force is disengaged until the switch reaches home, as shown in Figure 6(b). This provides the snap-action feedback of a tactile switch. The click is registered once the switch reaches home and an audio accompaniment confirms that the operation has been successful. Figure 6(c) shows the spring force that helps restore the operator to the surface of the virtual plane. To avoid switch bounce the release is only registered once the spring reaches a third of its restored displacement. This is accompanied by audio feedback to confirm the operation is complete.

Trewin et al. (2006) state that accidental clicks are a major source of error for people with motion-impairments. One of the advantages of the virtual switch is that it requires a conscious effort to operate and so it is less likely that a missed-click will occur accidentally. Clicking operations can only be performed on areas that contain virtual switches and so accidental presses of the device switch will be filtered out. When engaging a virtual switch the proxy is guided towards the apex, which means that it is almost certain that the click will be performed at the target centre. It is very unlikely that the operator will slip off a target due to the effective clamping at the apex.

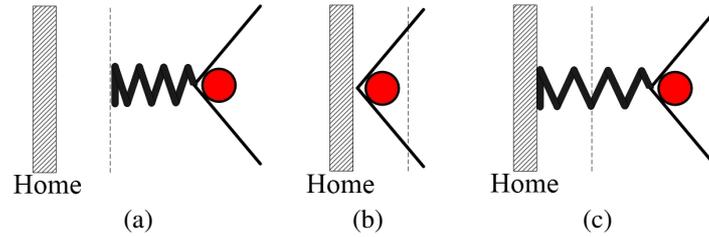


Figure 6: The operator presses the surface of the switch opposed by a spring force (a). When the spring is fully compressed the force is disabled (b). Once the switch reaches home then the restoring spring force is engaged (c).

3.2.5. Deformable Virtual Switch

The deformable virtual switch combines the virtual switch and the deformable cones discussed previously. If the operator wishes to select a target then they can press into the virtual plane at locations containing deformable switches, as shown in Figure 7(a). The deformation of the cone is included in the initial travel of the switch where the operator begins to compress the spring, as shown in Figure 7(b). Once the cone is fully deformed there is slightly further travel before the switch reaches home, as shown in Figure 7(c). The snap action then occurs and is processed in the same way as the virtual switch. When engaging the deformable switch the proxy will slide towards the apex, which will ensure that the click will be performed at the target centre. The clamping at the apex means that it is very unlikely that the operator will slip off the target.

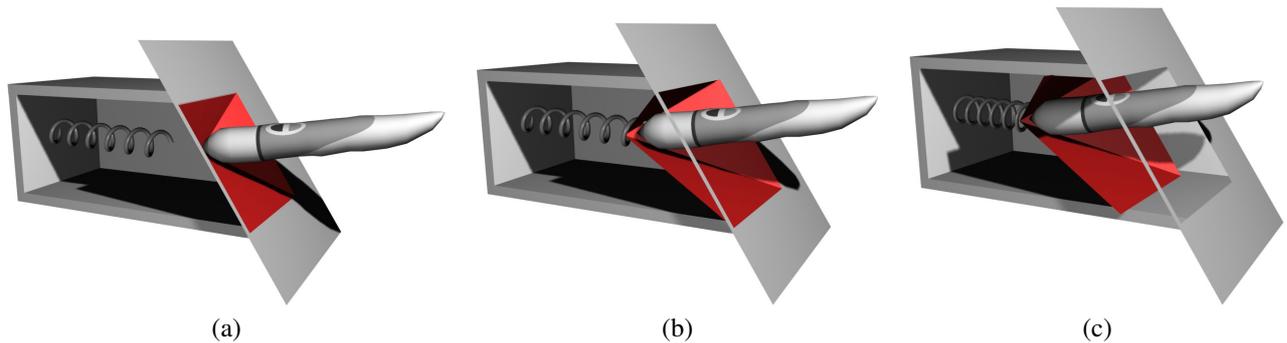


Figure 7: The deformation of a haptic switch surface by the virtual tool (a). A fully deformed haptic switch surface (b). Compressing the spring of a deformable virtual switch once the surface is fully deformed (c).

3.3. Experimental Setup

3.3.1. Device Comfort - Haptic Virtual Plane

During a preliminary study some participants experienced arm ache due to not having a surface to rest the stylus against. The response to this problem was to introduce a haptic virtual plane that the operator may lean against for additional support. An example of this is shown in Figure 8. The technique is especially useful when working at the upper extremities of the workspace (where the wrist rest has less effect) because the user can place their elbow on the desk and rest against the virtual plane. A virtual ceiling is positioned in parallel to ensure that the proxy is always the same perpendicular distance away from the virtual plane regardless of the device's y-position. All of the haptic assistive techniques are applied to the surface of the virtual plane or embedded in it.

Previous studies endorse the use of multimodal interaction to aid the selection of small targets (Cockburn and Brewster, 2005). Ideally the operator would be provided with visual cues to help with the understanding of the techniques and to reinforce the haptic interactions. To overcome this issue a semi-transparency is applied to the GUI window, which is positioned on top of the main viewport in the OpenGL window. It can be difficult to perceive the

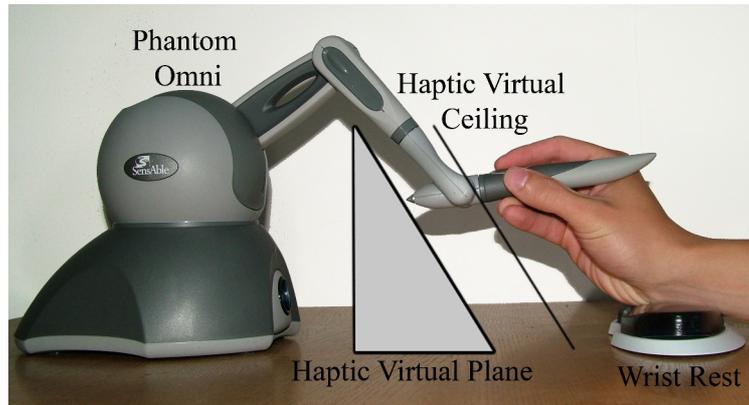


Figure 8: The concept of a haptic virtual plane.

depth perspective of the virtual tool in relation to the virtual plane on a two-dimensional display when using a 3DOF device. The literature proposes a number of techniques to aid depth perception. The first is to use lighting in the form of a spotlight at the end of the tool where the intensity and spot size will be proportional to the distance away from a surface. The second approach is to overlay a “texture gradient” grid over the virtual plane. Finally, the operator is presented with multiple viewports to aid the visualisation of the tool in the 3D workspace. These depth perception techniques can be observed in Figure 9 when using haptic cones.

3.3.2. Point-and-Click Tasks

Many previous studies rely on the ISO 9241, Part 9 (1998) standard for pointing device evaluation when performing point-and-click tasks. The experiment is a multidirectional task that contains targets arranged in a circular layout. The operator is required to click the highlighted icon. The major limitation of the ISO 9241-9 task is that it is inappropriate for evaluating haptic assistance when target distracters are a concern (Asque et al., 2012b). The evenly spaced, circular layout does not take into consideration the effects that target distracters may have on interaction. The majority of real world interfaces contain toolbars that are arranged into multiple rows or columns that could potentially contain other haptic cues. Therefore, the ISO 9241-9 task has only been used in Experiment 2 to investigate the effect that target size and shape have on the performance of the haptic techniques.

The Windows on-screen keyboard (OSK) has been chosen as the primary interface to evaluate the haptic assistive techniques in Experiment 1. The densely populated GUI will provide a more realistic and extensive evaluation of the effects of target distracters. The experimental task requires the participant to perform fifty successful selections to produce a predefined sentence using the OSK. The target key is highlighted in red to remind the participant which character is next in the sequence. In order to reach the next key in the sequence the operator has to exit the current one by sliding along the surface of the virtual plane or by lifting the tool off the surface to pass-over. The same sentence was used throughout the study to ensure that the index of difficulty did not change. This enables post-test comparisons to be made between haptic techniques for measures such as experiment time and the total distance travelled. The structure of the sentence was: “WE ARE USING THE PHANTOM OMNI AND HAPTICS TO TYPE.”. This sentence was chosen because it has a variation of direction changes and distance between letters. The participants were familiar with the structure of the sentence from the practice sessions. This was not an issue because in real world applications the user would know which letter they are going to type or the icon they are going to select. The dimensions of the character keys were 7.1mm × 7.1mm in device displacement and the spacebar dimensions were 45.9mm × 7.1mm. A time limit was not imposed on the experiment and so the duration was dependent on the individual’s ability to complete the task. Data collection begins once the first target is selected and continues until the sentence is completed. Any selections of surrounding keys were recorded for the cursor analysis but ignored in the textbox sentence. i.e. the operator was not required to delete undesired key selections. A click is only registered if the proxy is in contact with the virtual plane. This ensures that the operator has used the assistance and its characteristics can be recorded. Visual feedback is provided through an OpenGL window to help support interaction with haptic

cues. A semi-transparency is applied to the OSK window to allow the features to be seen behind, as shown in Figure 9.

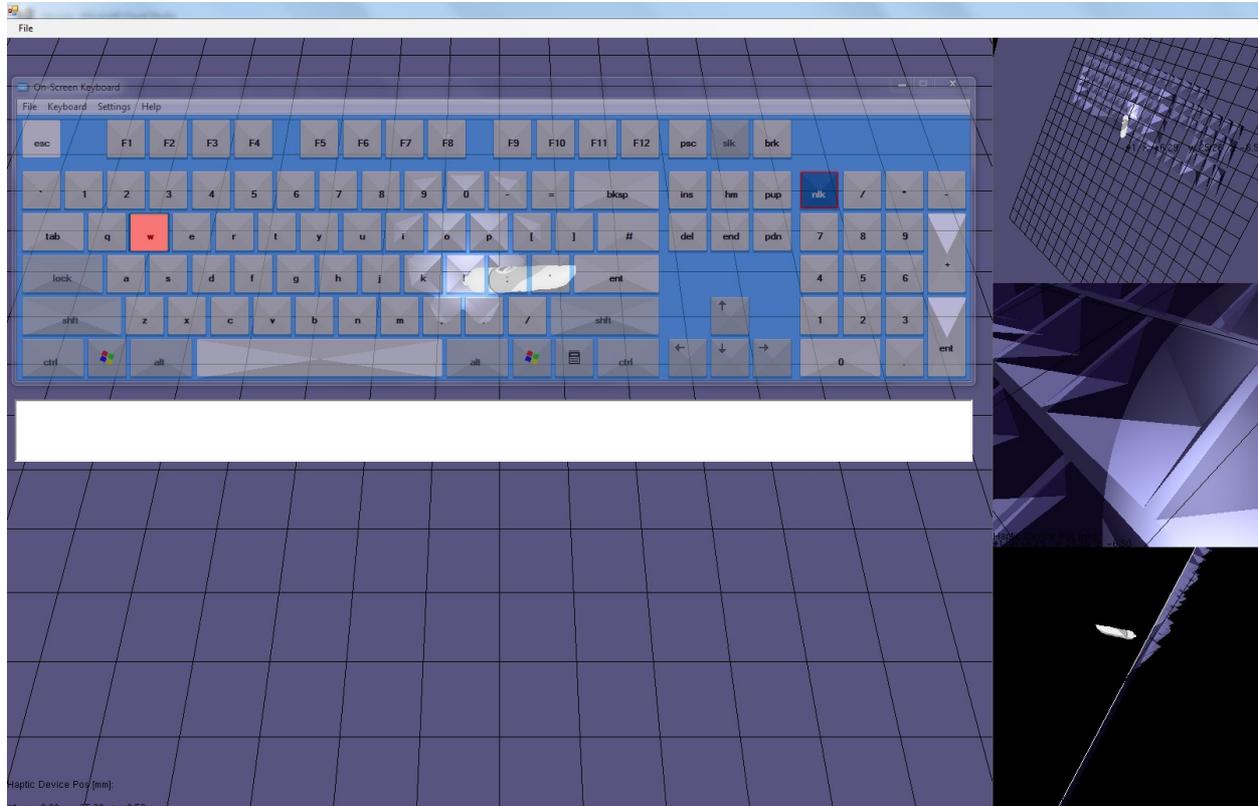


Figure 9: The semi-transparent on-screen keyboard interface with the OpenGL window behind.

3.3.3. Participants

In this study six participants with varying degrees of motion-impairment were recruited from the Norfolk and Norwich Scope Association (NANSA). Over a twelve week period the participants were encouraged to use the Phantom Omni in gaming and simulation environments. Typical tasks involved colour pairing, target shooting, haptic archery, haptic basketball and a haptic xylophone. The tasks were designed to be engaging and emphasise the 3DOF capabilities of the Phantom Omni. Another session ran in parallel where participants could familiarise themselves with the experimental task and each type of haptic assistance. The sessions were typically shared between the user group over a weekly two hour session for the twelve weeks. After this time the participants were familiar with the Phantom Omni and the experimental tasks. A brief summary of the participant's physical background has been provided in Table 1. Please note that as a result of patient confidentiality, access to medical records and assessments is not permitted.

4. Results

The results from the two experiments are presented in the following section. Experiment 1 investigates the effectiveness of the haptic assistance using the densely populated Windows on-screen keyboard. Experiment 2 uses the ISO 9241-9 task to investigate the effect that target size and shape have on the performance of the haptic techniques. These experiments were performed after the twelve weeks of practice sessions. For each cursor measure discussed in Section 3.1 (apart from experiment time spent on the virtual plane) a reduction in magnitude is desirable when compared to the unassisted experiment and will signify an improvement. All statistical analyses were performed in

Gender	Age	Disability	Details	Legend
Female	35	Cerebral Palsy	Can walk unaided, has speech difficulties and communicates through a communication aid. Principal impairment is tremor which makes finer movements difficult.	□
Male	49	Cerebral Palsy	Can walk unaided, has poor co-ordination and finds it difficult to perform finer motor control.	△
Female	49	Spina Bifida	Is an electric wheelchair user, has very good fine motor control but often takes a long time to complete the task.	●
Male	58	Cerebral Palsy	Is an electric wheelchair user. Principle impairments are muscle stiffness, spasm and co-ordination difficulties. Difficulties locating the device switch. Has speech difficulties.	×
Female	52	Cerebral Palsy	Is a manual wheelchair user. Movements can be quite slow but are well controlled. As a result error rates are low but the task can take longer to complete.	○
Male	38	Cerebral Palsy	Can walk unaided. Principal impairments are tremor and spasm which makes finer movements difficult.	+

Table 1: A brief summary of the background of the six participants within the study.

GraphPad PRISM version 6.02 (GraphPad, CA, USA). Unfortunately, subjective measures were unobtainable in this study due to communication difficulties of some of the participants.

4.1. Experiment 1 - Cursor Analysis of Haptic Assistance

The cursor analysis of a OSK point-and-click task will help determine if the new haptic techniques presented in this paper improve interaction rates and reduce the effect of distracters. Each experiment was observed by an assistant to ensure that it had been completed without any complications. The data has been described for each haptic condition using the mean and standard error of the mean (SEM), with data for each participant presented. The results are from six operators performing fifty successful selections with three repetitions. Relevant data for gravity wells and haptic cones has been included from the previous work of Asque et al. (2012b). Gravity wells have been included in this study because they are the most widely reported of all haptic assistance. Haptic cones have been included because they were the most efficient technique for reducing the number of missed-clicks and improving throughput. These will both be useful for providing a comparison to the newly proposed techniques.

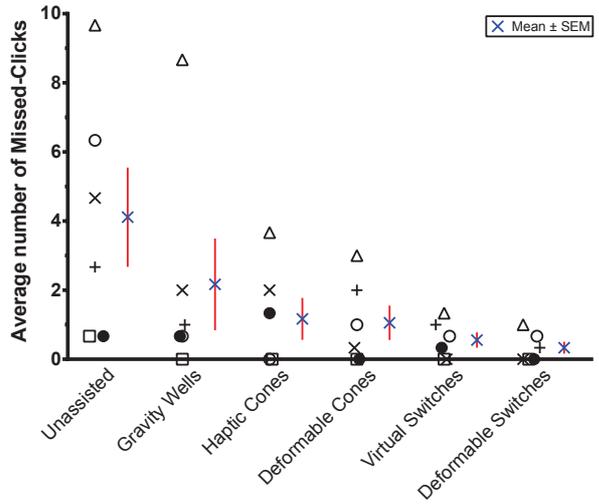
To test the null hypothesis that there were no differences between haptic conditions for each cursor measure, a repeated measures one-way ANOVA was used with planned post-test comparisons. The planned comparisons were as follows: each haptic condition against unassisted, gravity wells against deformable cones, haptic cones against deformable cones, gravity wells against deformable switches, and virtual switches against deformable switches. To correct for multiple comparisons the method of Bonferroni was used. Reported results were the ANOVA p value, (F ratio and degrees of freedom [df]), difference in means between groups for each planned comparison with 95% confidence intervals (95% CI) for the difference between the two group means, and statistical significance given multiple comparisons.

4.1.1. Missed-Click

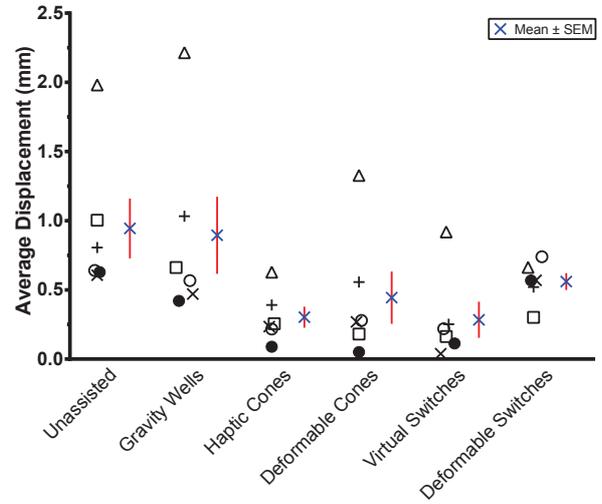
A one-way ANOVA shows that the haptic condition had a statistically significant effect on the number of missed-clicks recorded, ($F_{5,25} = 4.78$, $p < 0.0034$, $\eta^2 = 0.49$). The results shown in Figure 10(a) are promising in that deformable cones, virtual switches and deformable switches all produced a significant reduction in the mean number of missed-clicks when compared to the unassisted experiment. The statistical significance is confirmed in Table 2. The table also shows that the deformable techniques do not have any detrimental effects compared to their non-deformable counterparts. The deformable switches produced the lowest mean number of missed-clicks closely followed by haptic switches and deformable cones. The deformable techniques were shown to reduce the frequency by more than 75% of that recorded in the unassisted experiment.

4.1.2. Click-Release Displacement

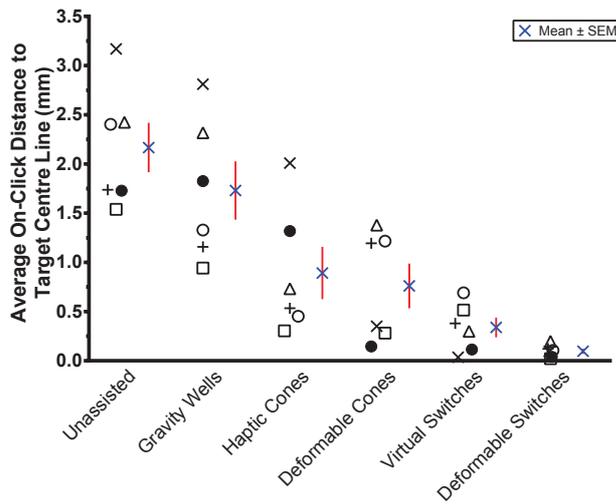
A one-way ANOVA shows that the haptic condition had a statistically significant effect on the mean click-release displacement, ($F_{5,25} = 7.63$, $p < 0.0003$, $\eta^2 = 0.60$). Figure 10(b) and Table 2 show that haptic cones, deformable cones and virtual switches were able to significantly improve the results for the click-release displacement compared to the unassisted condition. This is most important when using a device switch where both the click and release need to be accurately positioned inside the target. Deformable virtual switches reduced the mean click-release displacement



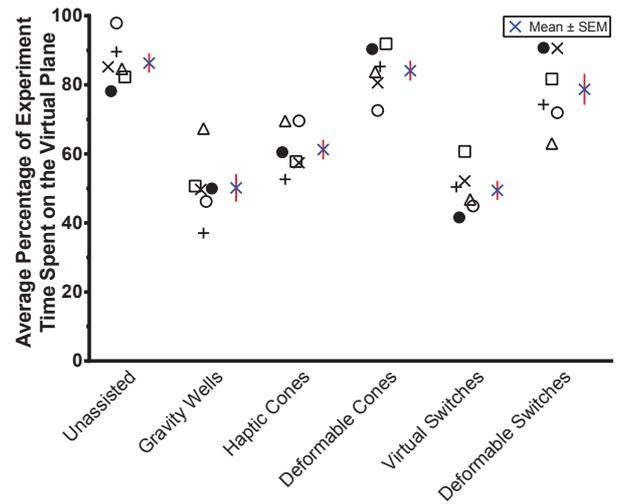
(a) The number of missed-clicks recorded over fifty successful selections for each haptic condition with three repetitions.



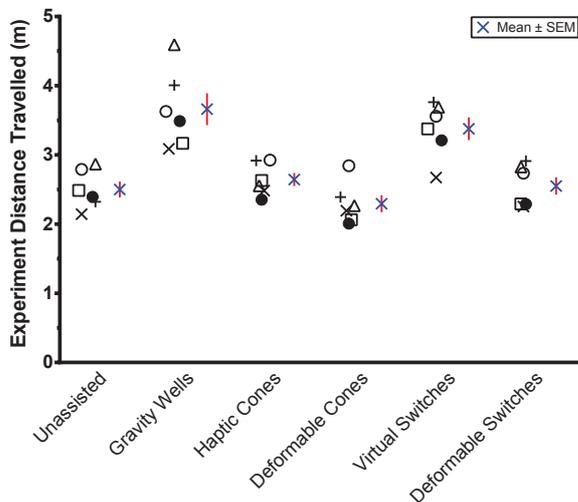
(b) The successful click-release displacement recorded over fifty successful selections for each haptic condition with three repetitions.



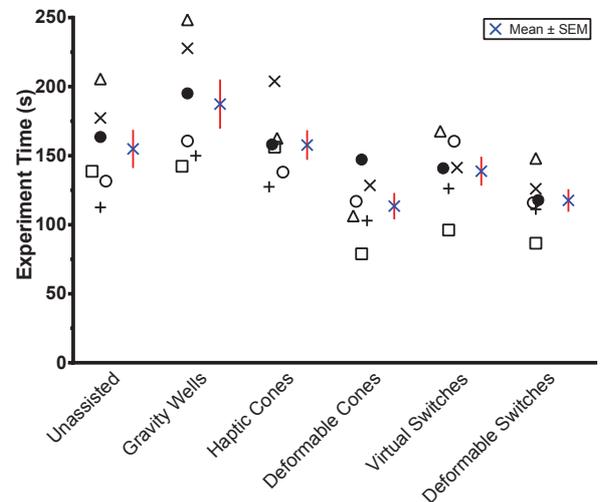
(c) The on-click distance to target centre line recorded over fifty successful selections for each haptic condition with three repetitions.



(d) The percentage of experiment time spent on the virtual plane recorded over fifty successful selections for each haptic condition with three repetitions.



(e) The experiment distance travelled recorded over fifty successful selections for each haptic condition with three repetitions.



(f) The experiment time recorded over fifty successful selections for each haptic condition with three repetitions.

Figure 10: The results of the cursor analysis for each haptic condition.

compared to the unassisted experiment but the statistical significance is not confirmed in Table 2. This is less of an issue for the virtual switch techniques because the release will be recorded when the spring is restored regardless of whether the proxy is accurately positioned inside the target or not. The click-release displacement measure is most useful for comparing the techniques that require the device switch to be operated.

4.1.3. On-Click Distance to Target Centre Line

A one-way ANOVA shows that the mean on-click distance to target centre line differed significantly across the haptic conditions, ($F_{5,25} = 16.1$, $p < 0.0001$, $\eta^2 = 0.76$). Gravity wells were the only haptic condition to not show significant improvements in guiding the operator to the target centre line when compared to the unassisted experiment, as shown in Figure 10(c) and Table 2. Deformable virtual switches produced the most significant improvement, closely followed by the virtual switches and deformable cones. Both deformable techniques were more effective at guiding the operator to the centre of the target than the traditional gravity well and the statistical significance is confirmed in Table 2. Accurate selection at the target centre is important because if any unwanted movements occur the operator is more likely to acquire the target. Unwanted movements at a target's edge may draw the cursor off the target and result in a missed-click.

4.1.4. Percentage of Experiment Time Spent on the Virtual Plane

The amount of time spent in contact with the virtual plane will give an indication of how intrusive each technique is on interaction. The unassisted experiment will give a benchmark for the natural amount of time that the operator will spend in contact with the virtual plane. A one-way ANOVA showed that the effect of the haptic condition was significant on the amount of time spent in contact with the virtual plane, ($F_{5,25} = 22.3$, $p < 0.0001$, $\eta^2 = 0.82$). Table 2 shows that the participants spent significantly less time in contact with the virtual plane for gravity wells, haptic cones and virtual switches in comparison to the unassisted experiment. This will be as a result of not being able to easily pass over the distracters and therefore lifting off the virtual plane. It is clear from the results in Figure 10(d) that a much greater percentage of the experiment was spent in contact with the virtual plane when using the deformable cones and deformable virtual switches in comparison to the other techniques. This is confirmed in Table 2 where the traditional haptic conditions, that are in operation at all times, spent significantly less time in contact with the virtual plane in comparison to both deformable techniques. This infers that the effect of distracters for the deformable techniques is much less intrusive on interaction because the operator decided to pull off the plane less often to pass over potential distracters. This will be credited to the fact that the operator can choose when to use or ignore the assistance.

4.1.5. Experiment Distance Travelled

Ideally the operator will move the shortest distance over the course of an experiment, i.e. they will take the most direct routes. If the distance travelled for a given haptic condition is significant compared to the unassisted experiment then this will indicate that the operator has had to make further corrections due to the effect of distracters. A one-way ANOVA showed that the difference in experiment distance travelled between the haptic conditions was statistically significant, ($F_{5,25} = 28.4$, $p < 0.0001$, $\eta^2 = 0.85$).

It was observed that participants often travelled further when using gravity wells due to having to make corrections after exiting and overshooting distracters. This assertion is upheld in Figure 10(e) and Table 2. The results presented in Figure 10(e) indicate that the techniques that are in operation at all times result in the cursor travelling a greater distance over the course of the experiment. This is confirmed in Table 2 where gravity wells and virtual switches both showed statistical significance compared to the unassisted, but are significantly worse. The deformable techniques allow the assistance to be ignored more easily and do not show significant differences in the distance travelled when compared to the unassisted experiment.

4.1.6. Experiment Time

It has been observed that experiment time would often increase in densely populated interfaces when using intrusive techniques, such as gravity wells, due to having to fight and exit distracters. A one-way ANOVA showed that the haptic condition had a statistically significant effect on the mean experiment time, ($F_{5,25} = 11.5$, $p < 0.0001$, $\eta^2 = 0.7$). The results in Figure 10(f) indicate that the experiment time reduces the most when using assistance that can be easily ignored. This is confirmed in Table 2 where deformable cones and deformable virtual switches were the only

techniques to show statistical significance compared to the unassisted experiment. All the other techniques that are in operation at all times either worsened the experiment time or had no significant effect. Both deformable techniques showed significant improvements over traditional gravity wells.

4.1.7. Results of multiple comparisons

To provide information on the statistical significance of the improvements a repeated measures one-way ANOVA was performed with planned post-test comparisons. Since the null hypothesis was rejected a Bonferroni multiple comparison was used to determine which means are different. The results are shown in Table 2.

Planned Comparisons			Missed-Clicks	Click Displacement (mm)	Centre Line (mm)	% Time on Virtual Plane	Distance Travelled (m)	Experiment Time (s)
Unassisted	vs.	Gravity Wells	1.9 (-0.8 to 4.7)	0.0 (-0.4 to 0.5)	0.4 (-0.4 to 1.3)	36.1 **** (20.9 to 51.4)	-1.16 **** (-1.60 to -0.72)	-32.5 (-67.6 to 2.6)
Unassisted	vs.	Haptic Cones	2.9 * (0.2 to 5.7)	0.6 ** (0.2 to 1.1)	1.3 ** (0.4 to 2.1)	25.1 *** (9.8 to 40.4)	-0.14 (-0.58 to 0.30)	-2.9 (-38.0 to 32.3)
Unassisted	vs.	Deform. Cones	3.1 * (0.3 to 5.8)	0.5 * (0.1 to 0.9)	1.4 *** (0.5 to 2.3)	2.2 (-13.1 to 17.5)	0.206 (-0.23 to 0.65)	41.4 * (6.3 to 76.5)
Unassisted	vs.	Switches	3.6 ** (0.8 to 6.3)	0.7 ** (0.2 to 1.1)	1.8 **** (1.0 to 2.7)	36.9 **** (21.6 to 52.2)	-0.88 **** (-1.32 to -0.44)	16.1 (-19.1 to 51.2)
Unassisted	vs.	Deform. Switches	3.8 ** (1.0 to 6.5)	0.4 (-0.1 to 0.8)	2.1 **** (1.2 to 2.9)	7.6 (-7.7 to 22.9)	-0.50 (-0.49 to 0.39)	37.3 * (2.1 to 72.4)
Gravity Wells	vs.	Deform. Cones	1.1 (-1.6 to 3.9)	0.5 * (0.0 to 0.9)	1.0 * (0.1 to 1.8)	-33.9 **** (-49.2 to -18.6)	1.37 **** (0.93 to 1.81)	73.9 **** (38.8 to 109)
Haptic Cones	vs.	Deform. Cones	0.1 (-2.6 to 2.9)	-0.1 (-0.6 to 0.3)	0.1 (-0.7 to 1.0)	-22.9 ** (-38.1 to -7.6)	0.35 (-0.91 to 0.79)	44.3 ** (9.1 to 79.4)
Gravity Wells	vs.	Deform. Switches	1.8 (-0.9 to 4.6)	0.3 (-0.1 to 0.8)	1.6 **** (0.8 to 2.5)	-28.5 **** (-43.8 to -13.3)	1.11 **** (0.67 to 1.55)	69.8 **** (34.6 to 105)
Switches	vs.	Deform. Switches	0.2 (-2.5 to 3.0)	-0.3 (-0.7 to 0.2)	0.2 (-0.6 to 1.1)	-29.3 **** (-44.6 to -14.0)	0.83 **** (0.39 to 1.27)	21.2 (-13.9 to 56.3)

Table 2: Bonferroni post-test multiple comparisons. The reported measures are mean difference, significance levels and (95% confidence intervals). Significance levels are reported as * for $(0.01 < p \leq 0.05)$, ** for $(0.001 < p \leq 0.01)$, *** for $(0.0001 < p \leq 0.001)$ and **** for $(p \leq 0.0001)$.

4.2. Experiment 2 - The effect of target size and shape

The results from the previous study have shown that the two deformable techniques are the most effective at improving interaction rates and reducing the effects of target distracters. For haptic assistance to be effective in real-world GUIs it needs to be generalisable for different target sizes and shape. Previous studies have often reported that the greatest improvements in performance have been observed when the assistance is used with smaller targets (Worden et al., 1997; Cockburn and Brewster, 2005). A further experiment has been conducted to investigate the effect of target size and shape on the performance of the two deformable techniques.

The ISO 9241-9 multidirectional point-and-click task has been chosen because there is more flexibility to alter the target shape and size than with the OSK. Target distracters are no longer a concern and so the task will be an appropriate interface. Eight targets are uniformly positioned around a circular layout with a diameter of 50mm. The participant is required to first click on the top target, then on the target directly opposite, then the next target in the sequence, and so on around the circular layout. The experiment was repeated for each type of assistance and each target shape and size. The order of presentation of the technique, target size and target shape was randomised. The size of the targets were categorised as follows: [small (3.5mm × 3.5mm), (7mm × 3.5mm), (3.5mm × 7mm)] , [medium (7mm × 7mm), (14mm × 7mm), (7mm × 14mm)] , [large (14mm × 14mm), (28mm × 14mm), (14mm × 28mm)]. The shape of the targets were categorised as follows: [square, wide rectangles, tall rectangles]. The results are presented in Figure 11. Please note that participant ● was unavailable for this experimental task. The data

in Figure 11 has been described for each target size using the mean and standard error of the mean (SEM). The shape is categorised into three columns for each haptic condition. Data for each participant is presented.

4.2.1. Target size

To test the null hypothesis that the target size does not have a significant effect on either the number of missed-clicks or the experiment time, a repeated measures one-way ANOVA was used with planned post-test comparisons. The planned comparisons were deformable cones against unassisted and deformable switches against unassisted. To correct for multiple comparisons the method of Bonferroni was used. Reported results were the ANOVA p value, (F ratio and degrees of freedom [df]), difference in means between groups for each planned comparison with 95% confidence intervals (95% CI) for the difference between the two group means, and statistical significance given multiple comparisons.

The results show that the haptic condition had a significant effect on the mean number of missed-clicks for **small** ($F_{2,28} = 14.26$, $p < 0.0001$, $\eta^2 = 0.5$), **medium** ($F_{2,28} = 7.18$, $p < 0.0031$, $\eta^2 = 0.34$), and **large** ($F_{2,28} = 4.59$, $p < 0.019$, $\eta^2 = 0.25$) sized targets. The results from Figure 11 and Table 3 confirm that haptic assistance provides the most significant performance increase for smaller targets. A statistically significant improvement in the number of missed-clicks was observed for all target sizes for both deformable techniques compared to the unassisted interface. Table 3 shows that the level of significance increased as the target size decreased. This is as expected because smaller targets are more difficult to select and so the assistance will have a more profound effect compared to an unassisted interface.

The results show that the haptic condition had a significant effect on the experiment time for **small** ($F_{2,28} = 13.12$, $p < 0.0001$, $\eta^2 = 0.48$) and **medium** ($F_{2,28} = 9.06$, $p < 0.001$, $\eta^2 = 0.39$) sized targets. Both deformable techniques produced a significant improvement in experiment time for the small and medium sized targets when compared to the unassisted, as shown in Table 3. No significant differences were recorded for **large** ($F_{2,28} = 2.35$, $p < 0.1139$, $\eta^2 = 0.14$) targets. This is to be expected because larger targets tend to be easier to select and so the assistance will have less of an effect on targeting times as target size increases.

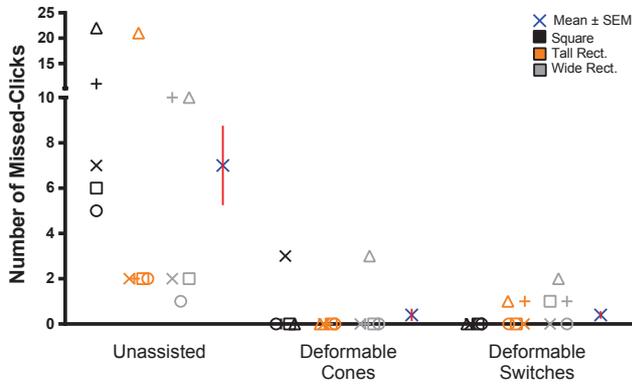
Target Size	Comparison			Missed-Clicks	Experiment Time
Small	Unassisted	vs.	Deform. cones	6.6 *** (3.2 to 10.0)	23.0 *** (11.7 to 34.4)
	Unassisted	vs.	Deform. switches	6.6 *** (3.2 to 10.0)	20.0 *** (8.6 to 31.3)
Medium	Unassisted	vs.	Deform. cones	2.2 ** (0.7 to 3.7)	5.3 *** (2.2 to 8.4)
	Unassisted	vs.	Deform. switches	2.1 ** (0.5 to 3.6)	4.3 ** (1.2 to 7.4)
Large	Unassisted	vs.	Deform. cones	0.7 * (0.1 to 1.3)	3.0 (-0.4 to 6.4)
	Unassisted	vs.	Deform. switches	0.7 * (0.1 to 1.3)	2.3 (-1.1 to 5.6)

Table 3: Bonferroni post-test multiple comparisons. The reported measures are mean difference, significance levels and (95% confidence intervals). Significance Levels are reported as * for ($0.01 < p \leq 0.05$), ** for ($0.001 < p \leq 0.01$) and *** for ($0.0001 < p \leq 0.001$).

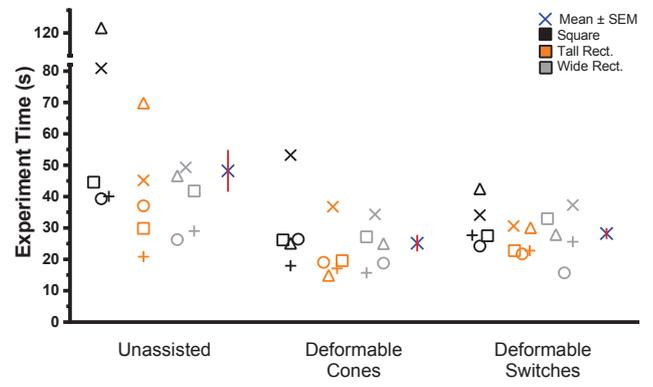
4.2.2. Target shape

A one-way ANOVA was performed to test the null hypothesis that the target shape does have a significant effect on the number of missed-clicks or experiment time. Reported results were the ANOVA p value, (F ratio and degrees of freedom [df]). There was no significant effect of target shape on the number of missed-clicks for deformable cones ($F_{2,28} = 0.33$, $p < 0.7186$, $\eta^2 = 0.02$) or deformable switches ($F_{2,28} = 2.63$, $p < 0.0896$, $\eta^2 = 0.16$). There was a significant effect on the experiment time for deformable cones ($F_{2,28} = 4.21$, $p < 0.0252$, $\eta^2 = 0.23$). Bonferroni-corrected post-test comparisons indicated that the mean (\pm SD) experiment time for squares (23.3 ± 9.5 s) was significantly longer than for wide rectangles (19.4 ± 6.3 s), though did not significantly differ from either target shape for tall rectangles (21.1 ± 7.9 s). The respective experiment times for deformable switches showed a similar pattern (24.7 ± 7.1 s, 21.7 ± 4.6 s, 22.3 ± 7.2 s), though this did not reach statistical significance ($F_{2,28} = 2.96$, $p < 0.0686$, $\eta^2 = 0.17$).

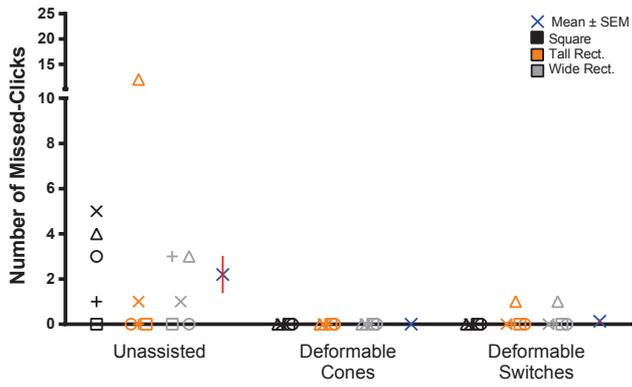
Taken together, these results suggest that target shape has a less consistent and smaller effect on the participant's performance than the haptic condition or the target size. Specifically, there was no effect on the number of missed-clicks but participants took longer to click on squares than on rectangles. However, this effect was only significant for deformable cones between square and wide rectangular targets, with the former taking 3.9s longer to target on average (95% CI 0.5-7.3s). Given that the rectangular shaped targets have twice the surface area of square targets it



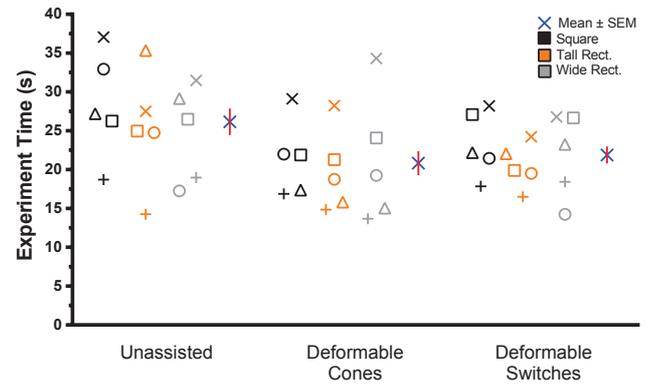
(a) The number of missed-clicks recorded for small sized targets.



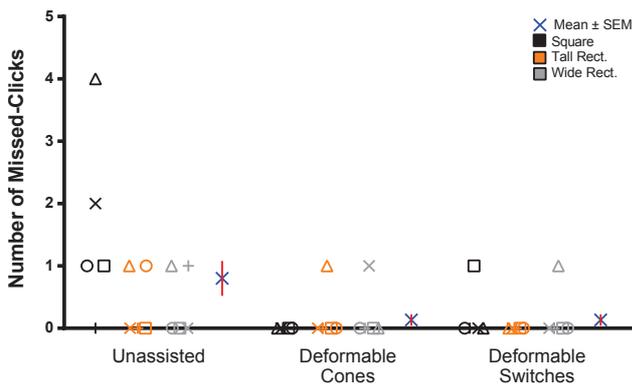
(b) The experiment time recorded for small sized targets.



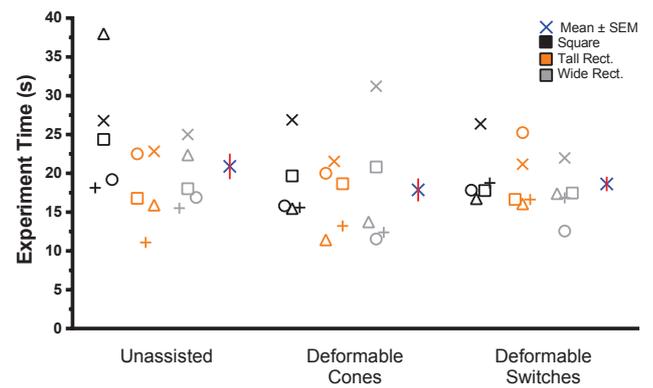
(c) The number of missed-clicks recorded for medium sized targets.



(d) The experiment time recorded for medium sized targets.



(e) The number of missed-clicks recorded for large sized targets.



(f) The experiment time recorded for large sized targets.

Figure 11: The effect of target size on the performance of each haptic condition. The size of the targets are categorised as small, medium and large.

is unsurprising that a small difference has been observed. A future experiment designed specifically to analyse shape may provide a greater insight into the effect on performance.

5. Discussion

The main goal of the study was to produce haptic assistance that would improve interaction rates for existing user interfaces without the shortcomings highlighted in Section 2. The results from Experiment 1 show that the deformable techniques proposed in this paper were the most successful at improving targeting times and reducing error rates during a realistic point-and-click task. Deformable haptic cones and deformable virtual switches reduced the mean number of missed-clicks by 75% and 92% respectively in comparison to the unassisted experiment. Many of the cursor measures help explain why this is the case. For example, the click-release displacement shows that the assistance is effective at helping to maintain a steady cursor during the clicking phase by clamping the proxy at the target centre. The on-click distance to target centre line improved significantly, which is beneficial because if the operator slips slightly then the proxy is more likely to remain within the target region when the device switch is released. The results suggest that the haptic condition has a large effect on user performance given the levels of statistical significance reported for a small sample size.

The cursor measures in Experiment 1 confirm that target distracters are less intrusive for deformable cones and deformable virtual switches. When using the deformable techniques the operator can stay in contact with the virtual plane and pass over distracters without positional disruption to the cursor. This is confirmed by the fact that there were no significant differences in the percentage of experiment time spent on the virtual plane when compared to the unassisted experiment. The average experiment time spent in contact with the virtual plane was 86% for the unassisted experiment compared to 84% and 79% for deformable cones and deformable switches respectively. Techniques that are in operation at all times such as, gravity wells, haptic cones and virtual switches are less easy to ignore and therefore participants will often spend significantly less time in contact with the virtual plane. If the operator has to lift off the virtual plane more often to pass over distracters then this will increase the physical workload and disrupt interaction. Both deformable techniques produced significant improvements in the percentage of time spent in contact with the virtual plane compared to their non-deformable counterparts. The experiment distance travelled for deformable cones and deformable virtual switches was similar to the unassisted experiment, which suggests that fewer corrections were required for distracters. In contrast, gravity wells and virtual switches significantly worsened the distance the cursor travelled, which is again likely to be caused by the necessary corrections when passing through distracters or by pulling off the virtual plane and re-applying the HIP.

Deformable haptic cones and deformable virtual switches were shown to significantly improve the experiment time by 27% and 25% respectively in comparison to the unassisted experiment. Both deformable techniques significantly improved experiment time in comparison to the traditional gravity well. This will be credited to the deformable techniques assisting during the clicking phase without the operator having to overcome undesired neighbouring distracters. The improvement is despite the fact that the experiment was performed on a densely populated interface with potential distracters surrounding the target.

Previous studies have shown that haptic assistance provides the most significant improvements for more severely impaired operators (Keates et al., 2000, 2002; Hwang et al., 2001). In this study participant Δ exhibited a tendency to slip when performing clicks. This is reflected in the click-release displacement and number of missed-clicks. The most significant improvements for participant Δ can be observed for the small targets in Experiment 2. The addition of deformable cones and deformable switches helped to prevent the cursor from leaving the target region, which reduced error-rates and improved targeting times. In contrast the motor skills of participant \square tend to be more controlled, which means that the assistance will have a less profound effect. However, in Experiment 1 the two deformable techniques were still able to reduce the number of missed-clicks to zero and improve targeting times for this person.

Experiment 2 emphasised the performance benefits of haptic assistance for small sized targets. The two deformable techniques have enabled participants to select very small targets with a low error count. The level of significance for the number of missed-clicks and experiment time was shown to increase as the target size decreased. As computer monitors increase in size and resolution it is likely that a larger gain will be required to navigate the whole of the screen. An increase in gain will reduce the effective width of the target and make them difficult to select. Haptic assistance could prove to be very beneficial for motion-impaired computer users in the future. The results from Experiment 2 suggest that the target shape has a less significant effect on participant performance.

The two deformable techniques adopt a similar approach in terms of interaction with the interface. Deformable cones allow the user to perform clicking operations with the device switch, whilst the deformable switches provide the haptic simulation of a tactile switch for people that cannot easily operate a physical one. The choice of which technique to use is dependent on the individual's preference and their ability to operate the device switch.

6. Conclusion

This paper has presented a study of incorporating haptic assistance in existing graphical user interfaces for motion-impaired operators using five separate haptic conditions. The Windows OSK was chosen as the primary interface to investigate the performance of the haptic conditions in a realistic point-and-click task.

The deformable techniques proposed in this paper were the most effective in decreasing the number of missed-clicks and improving targeting times, the two measures of performance that are most important. The new cursor measures have been useful in identifying the effects that distracters may have on interaction and how certain haptic techniques may reduce these effects. Many of the shortcomings highlighted in Section 2 have been alleviated by utilising the 3DOF interface to produce assistance that can be easily used or ignored. The ability to perform a gesture that enables the assistance has significantly reduced the effect of distracters. The operator is able to more freely use the assistance without having to oppose forces from neighbouring haptic cues. This is important because it means that distracters are no longer the limiting factor in the development of haptic assisted interfaces. The most significant improvements were observed for small sized targets, which may be beneficial in the future as computer screens continue to increase in size and resolution. It is anticipated that the results produced in this study will be useful in providing assistance that could significantly improve access to computer software. By overlaying the partially transparent window on top of the OpenGL window it has been possible to provide suitable visual cues to accompany the haptic effects. A plugin reader has been created to read the button positions and interface information for any given Windows interface that uses Win32 or WPF.

The work presented in this paper has focused on improving computer access for people with motion impairments. However, future work could prove that the haptic assistance is effective at improving interaction rates for able-bodied people. A number of studies have shown that advanced age can make cursor movement increasingly inaccurate. The general population is growing older and it is estimated that by 2020, that almost half the adult population in the United Kingdom will be over 50, with the over 80's being the most rapidly growing sector. As computer usage spreads throughout the population, computer interfaces will have to adapt to meet the needs of the user group. Haptic interaction could have a major influence on this market especially as force-feedback devices become more popular and affordable.

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