Performance Improvement with Haptic Assistance: A Quantitative Assessment

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ABSTRACT

We measure the performance improvement that force feedback can provide in a virtual environment, through three experiments with, and without the assistance of haptic guidance. Performance measurements were undertaken with haptic, visual and auditory feedback alternatives. The first task investigated the use of haptic guidance mimicking reality, in the form of a simulated touchable surface of an object. The second investigated haptic guidance which waxed and waned as the user violated program rules by varying amounts. The third experiment investigated whether this latter artificial guidance would inhibit the user's free will by taking control out of their hands. The results showed that a significant improvement in both accuracy and speed was achieved by the introduction of haptics in all experiments. It also found that the haptic guidance did not take control away from the user and that they had significantly more control than with conventional warning methods. These experiments were not aimed at learning, or retention of skill, but on using haptics as an aid to improve performance during a task.

KEYWORDS: Haptics, virtual reality, user interfaces..

INDEX TERMS: H.5.2 [User Interfaces]: H.5.2.g [Haptic I/O]:

1 INTRODUCTION

The objective of the study was to examine and quantify any benefit that can be provided by haptic feedback in a three dimensional task. The study was divided into three experiments. The first experiment aimed to discover if surface haptic feedback could improve a user's accuracy when performing a task, and to measure the difference in accuracy.

The second experiment aimed to determine if external haptic guidance can assist a user in a 3D task. The third experiment measured how readily the external guidance could be treated as only advisory, and either accepted or rejected by the user, giving them the freedom to apply their knowledge and expertise to the problem as well as to receive advice from the computer system.

Twenty five participants volunteered to take part in the experiments. Ethics approval for the experiment was obtained from the University of Western Australia.

The experiments used the CSIRO Haptic Workbench 3D immersive environment [20] (figure 1) with a PHANToM™ Premium 1.5 haptic device. The software for the experiment was running on a Dell Precision 670 computer with dual 3.2 GHz processors and running the Windows XP operating system.The graphics were produced in 3D active stereo using OpenGL [19] on a NVIDIA Quadro FX 1400 graphics card. The scene was viewed in the mirror using CrystalEyes shutter glasses.

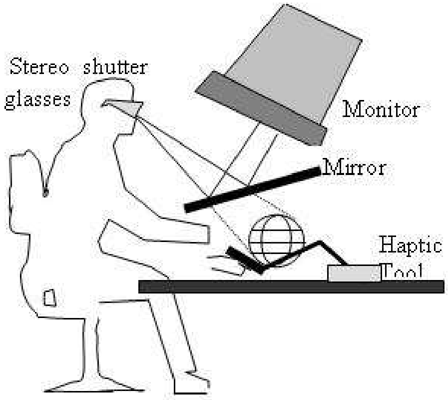

Figure 1. CSIRO Haptic Workbench

2 RELATED WORK

Our experiments investigated haptic assistance for design tasks. In 1992, Galyean and Hughes [6] found that without haptics, controlling hand position in 3D space is difficult. Four years later, while working with 3D sketching, Deering [5] discovered that correctional algorithms were required to remove hand tremor when a haptic resting surface was not available. Oakley et al. [17] found in 2000 that, with a haptic interface, task errors were significantly reduced and subjective workload measurements showed that participants perceived many aspects of workload to be significantly less with haptics. In 2002, De Haan et al. [4] found that without an appropriate feedback it is difficult to freely probe data in 3D space.

Forces which are used to influence actions in some way, separately to simulating collisions with surfaces, are often termed 'haptic constraints' or 'virtual fixtures'. The most common form of constraint is the 'snap-to' effect. Our work is directed at using both haptic surfaces and haptic constraints to improve the skills of a worker while they are doing a task. Takemoto et al. applied this technique in 2005 to assist crane operators when they are loading cargo onto ships [21].

In 2002, Marayong et al. [13] investigated the influence of assistance on performance during human-machine cooperative manipulation. They particularly studied the effect on independent user actions – the ability to over-ride the haptic guidance. They found that a compliance of 60% (i.e. the user supplies 40% of the movement effort) produced the best performance in their

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experiments. A related approach was used by Nolin et al. in 2003 [15], who compared different methods of altering virtual fixture stiffness to determine the effect on performance. Bowman et al. caution that there is a risk that introducing haptic constraints may make interaction more difficult and frustrating [2]. The third experiment of our study details the investigations into this issue by measuring the user's ability to either comply with a guiding force, or over-ride it.

Constraints have also been used in surgical systems to assist and guide a surgeon [3], [8]. More recent work in 2005 [18], indicated that point-attraction virtual fixtures could assist in a surgical task. The difference between passive constraints which form boundaries, and active constraints, which move the user in a desired direction, is discussed by Komerska and Ware [9]. They also describe hard, 3D barriers in [10] and haptic navigation widgets in [11]. They state that ".. haptic forces should be used to provide constraints on user tasks, rather than mimic physical object forces." [9] (page 270). However, our work indicates that haptics can usefully be applied in both of these ways.

In 2005, Grane and Bengtsson [7] found that mental workload was less with a haptic and graphic interface (using a tactile mouse), than with graphic only or haptic only. Basapur et al. [1] compared graphical and audio warnings with tactile vibrations, finding the latter to provide similar human performance to visual feedback. Our work differs in that the haptic feedback contains directional information (a force as opposed to a tactile stimulation). This is significant in that the feedback both alerts and advises the user on an action, whereas the tactile mouse only alerts the user.

The 2005 work by Tavakoli et al. [22] investigated the use of a visual indicator of force applied in a suturing task. They found that the fatigue of checking the visual indicator interfered with the short term benefit. Our experiments compared haptic guidance with a visual and audio indicator as well as a combination of both.

O'Malley et al. describe that "shared control", with haptics providing assistance to a user in a task, can enhance performance, though not necessarily improve training, in a task[16].

Basapur et al. undertook similar studies, but with tactile vibration instead of haptic forces. This

3 EXPERIMENT ONE: SCULPTING

The object of experiment one was to test the hypothesis that haptic feedback assists a user to perform a fine, accurate dextrous task in 3D. Participants were asked to carefully sculpt some virtual clay and the experiment measured how accurately they performed, both with and without the haptic ability to touch the surface.

The clay sphere was modelled as a surface skin, rather than a solid volume. This allowed the tool to pass through the clay surface (by exceeding a threshold force) to become located on the inside. This ability allowed the user to correct indentations by stroking from the inside out, as well as to smooth protrusions from the outside.

3.1 Experiment Design

The experiment employed a two level design with one independent and one dependent variable. The independent variable was the presence or absence of haptic feedback. The dependent variable was the accuracy of sculpting the virtual clay. The level of significance was chosen as 0.05.

At the start of the experiment, the virtual clay ball that was presented to the user had some randomly spaced lumps on one third of the surface. The user's task was to smooth out the lumps. They performed the task twice; once with haptic feedback and once without, with half the participants using haptics first and half using it last.

3.2 Measurement and Analysis

The performance was measured in terms of accuracy of the sculpted surface compared with a perfect sphere. The positions of the vertices of the triangles after sculpting were measured as data points. The variation in distance from an average, in the form of a standard deviation, was used as a measure of error. Typically, subjects took about 10 minutes to perform each of the tasks.

The initial performance-measure was taken as the mean of the standard deviations measured over all participants, firstly with haptic feedback and then without. This was calculated as 0.179cm for the haptic trial and 0.250cm for the trial using no force feedback (figure 2).

The p value returned from a paired T test on the logarithmically transformed error data is 0.0435, which is statistically significant (less than the significance level of 0.05). (A logarithmic transformation was necessary to obtain a sufficiently homogeneous distribution of data points.) It can be seen from this result that performance by the subjects in this experiment was significantly better using haptic feedback.

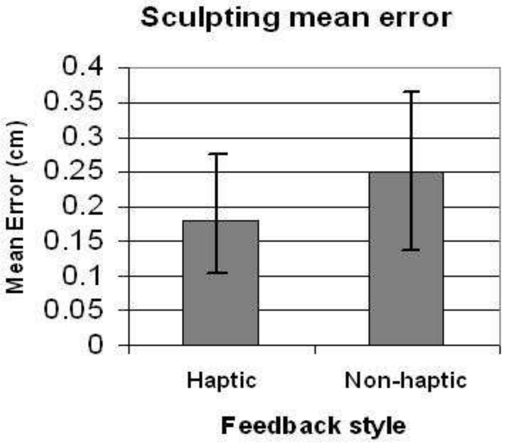


Figure 2. Sculpting Mean Error. Haptic feedback produced significantly better results

The largest improvement in performance brought on by haptics occured with those participants who had the highest average errors. By calculating the relative improvement of each individual, as a ratio of haptic score divided by an average of their haptic and non-haptic scores, we have a measure of the improvement that haptics provided them relative to their overall ability at the task. By ordering the scores, it was found that the worst 5 performers had 3.9 times larger relative improvement than the rest.

3.3 Discussion

The experiment showed that surface-based haptic feedback assists a user to perform a fine, accurate dextrous task in three dimensions. The reason for the increased accuracy could be attributed to the user being able to apply a constant pressure against a (virtual) surface as they are controlling their hand motions. This means that their muscles are being controlled in a varying 'forward' direction (against the surface). In his book, "The Hand", Wilson [24] explains that all complex movement is achieved by the combined action of pairs of muscles aligned in the body to pull against each other. Without the haptic surface to press against, a sculptor needs to control the arm and wrist muscles firstly forward, then backward as they detect that they have penetrated too far. The body uses a different set of muscles for flexing the wrist forward (curling) as opposed to moving it backwards (extending). During forward motion three major forearm muscles work - the flexor carpi radialis, the flexor carpi ulnaris and the palmaris longus. However, backward motion works the extensor carpi radialis longus, the extensor carpi brevis and the extensor carpi ulnaris [14]. Venkadesan et al. found that a different set of neurological signals were also employed in these two actions [12]. This implies that, without surface resistance to provide the backward motion, the muscle action requires two separate mechanisms with the two different sets of muscles which must be balanced against each other to achieve a steady movement. It can be surmised that switching between two separate muscular mechanisms is a more difficult control system than constantly varying a single muscle mechanism and therefore it cannot be controlled as accurately.

The result also indicates that haptic feedback benefits lower skilled users more than those with higher skill levels.

4 EXPERIMENT TWO: FORCE AS A USER FEEDBACK MECHANISM

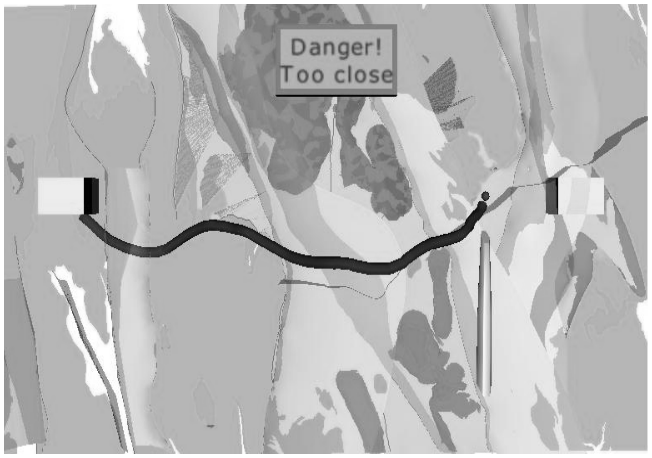
The objective of this experiment was to determine if haptics could provide a useful means of providing feedback to the user about the violation of program rules during a 3D task and if so, to measure its effectiveness compared to more traditional methods. The conventional computer feedback mechanism is that of a pop-up dialog box, often accompanied by an audible alert. This has some disadvantages in that it is binary (it cannot provide a continuously varying degree of feedback), and it uses screen space, and can be disruptive to the work flow. Other systems involve screen widgets which can provide a degree of continuous feedback, but these also have the problem of taking up screen space and diverting the user's attention away from the task. A haptic, guiding force may be able to steer a user away from an error condition without these problems. This force was modelled as a repulsion from a 3D point, with its magnitude decreasing linearly with distance up to a cut-off point. The intention of the experiment was to provide a quantitative measure of the degree to which haptic feedback can assist in this case.

A hypothetical, mine-planning scenario was chosen for the experiment. A mine planner views 3D geological data that is complex and often fills the field of view. Therefore, any graphical feedback needs to compete with a wealth of other graphical data being presented. As a mine planner draws a proposed route for an underground decline (tunnel), they need to negotiate several, perhaps competing, constraints (e.g. tunnel gradient, curvature limitations, unstable rock). One of these may be the requirement to avoid zones of danger. The experiment was designed to test haptics — as a feedback mechanism, warning of these danger zones — against the more traditional feedback mechanisms of pop-up messages and screen graphics.

The 3D scene consisted of a 3D graphical model of geological structures (figure 3). Two yellow cubes were placed into the scene, one on the left and one on the right as the start and end points of the proposed tunnel. As the virtual pen leaves the starting yellow cube, a red cylinder is drawn along the pen's path until it enters the end yellow cube.

Eleven randomly placed centres of danger were located within the scene. Each had a 'strength' (degree of danger), and a 'radius' (extent of danger). Three types of user feedback were programmed into the scene, each being triggered when the user's actions violated one of the danger zones:

- a pop-up message with a warning sound
- a graphical arrow growing from the centre of danger.
- a haptic force pushing the user's haptic pen away.



Danger!
Too close

Figure 3. Screen shot of mine planning geological scene showing rock layers and tunnel route being drawn.

4.1 Experiment Design

The experiment employed a 25 x 5 (25 subjects, 5 treatments) two way design with a significance level of 0.05. The five treatments were the different feedback mechanisms, but two of these treatments were combinations of the three feedback types. Subjects were required to draw a proposed tunnel from the left hand yellow cube to the right hand yellow cube, keeping the tunnel as short as possible (for mine operations efficiency), but also avoiding areas of danger as much as possible (for mine safety). They performed the drawing exercise five times – each time using a different feedback mechanism to warn them of the danger zones. A Latin Squares randomisation system was used to determine the ordering of treatments for each subject. Each time a new feedback method was chosen, the danger points were redistributed to avoid learning effects.

4.2 Measurement and Analysis

The experimental software recorded three performance measures. These were the excess length of each drawn tunnel (over and above the minimum possible - a straight line), the time taken to draw the tunnel and the degree of encroachment into the danger zones. When the drawing pen was located within a danger zone, it triggered an algorithm that calculated the instantaneous degree of danger (see equation 1).

$$danger = \left(1 - \frac{\left|\vec{c} - \vec{p}\right|}{r}\right) \times m \qquad (1)$$

$\vec{c} =$ the centre of the danger zone
$\vec{p} =$ the current virtual pen position
$r =$ the radius of the danger zone
$m =$ the magnitude (strength) of the danger

The results were analysed using a non-orthagonal analysis of variance, using 25 subjects and five treatments (popup, popup+arrows, arrows, forces, forces+popups+arrows). It uses the same underlying principles as a 'T' test but uses a more complex model accommodating more than two treatments as well as order effects (i.e. effects caused by the order in which a subject experiences the treatments). For each variable, this structure allowed estimation of the differences between treatments, between orders, between subjects and the treatment-by-order interaction.

The treatments, subjects and order were all orthogonal (had no effect on each other), however the treatment-by-order interaction was not orthogonal to subject.

The analyses of variance were performed on three variables: excess distance, danger and time, in three different ways to obtain the correct terms for treatment, order, subject and treatment-by-order.

4.2.1 Excess tunnel distance

After log transfromation, there were significant differences between subjects and highly significant differences between treatments. The resulting treatment means of the log-transformed data are shown in figure 4. This shows that the ‘arrows’ treatment produced a significantly shorter tunnel distance than all other treatments except ‘force’. ‘Force’ produced a significantly shorter tunnel distance than ‘popup’ at the 5% level. Surprisingly, the combination of all three feedback methods resulted in longer tunnels than force or arrows on their own.

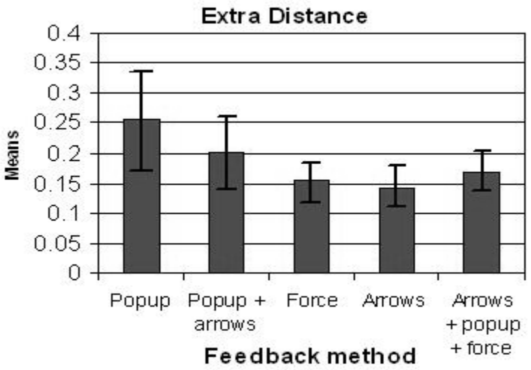


Figure 4. Excess tunnel distance drawn. Haptic feedback and graphical arrows resulted in the shortest distances.

4.2.2 Tunnel drawing time

There were significant differences between subjects, between orders and between treatments. There was no order-by-treatment interaction. The resulting treatment means are shown in figure 5. The force method took the shortest time but was not significantly less than arrows. The popup method produced significantly longer drawing times than all other methods. The combination of the three methods was marginally faster than popup+arrows.

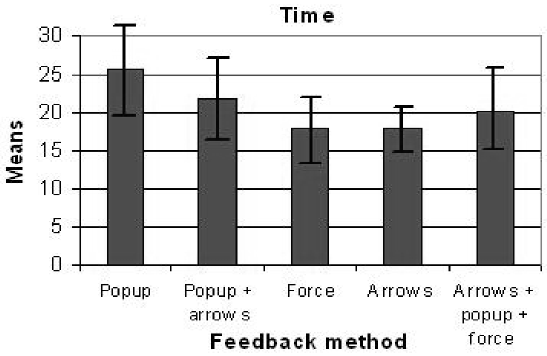


Figure 5. Tunnel drawing time. Haptic feedback and arrows resulted in the shortest times.

It was noticed that some users were becoming quite cavalier in their actions with force feedback. This was indicated by the widely varying individual time values when using force.

4.2.3 Danger encroachment

The combined analysis of variance produced the means shown in figure 6. There were significant differences between subjects and between treatments. It can be seen that the force treatment performed the best along with the combination of the three methods. Both treatments that included force performed significantly better than those without.

4.3 Discussion

These results show that using force alone as a user feedback method can improve the user’s performance, as is evidenced by the ability to avoid danger zones. Combining the force with other feedback methods (arrows and popups) did not significantly improve the navigation performance over force alone, and is therefore an unnecessary complication. Tunnel distances were best with the graphical feedback (arrows), but in a real world situation this needs to be balanced against the trade-off of an increased danger encroachment. Users were able to draw more directly to the target but cut through areas that should have been avoided, indicating that the arrows were not serving their purpose as well as forces. Popup messages performed badly on all the three measures; distance, danger and time, and should be avoided in an application of this sort.

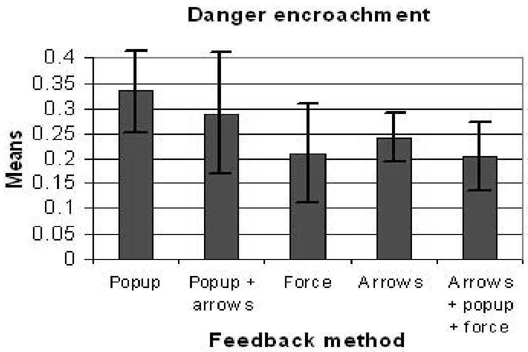


Figure 6. Means of Danger Encroachment. Modes with force feedback produced the least danger.

5 EXPERIMENT 3: ABILITY TO IGNORE HAPTIC ADVICE

There may be valid reasons for a skilled user to want to ignore the advice provided by a computer system. It could be argued that force feedback might limit this ability to ignore the advice and therefore be less effective as an aid. It is therefore important to achieve a suitable level of haptic assistance without constraining the user too much [23].

Experiment 3 was designed to test and measure the ability to ignore the different styles of user feedback. The 3D scene was modified so that the right-most danger zone was to be treated differently. The only visible difference was that this ‘special’ danger zone had a red cube-shaped centre-point instead of a yellow sphere. Participants were instructed to ignore any advice they were receiving from the system when within the special danger zone and should proceed as if no danger was being indicated. The haptic force repulsion from all danger points was the same as in experiment 2.

5.1 Experiment Design

The experiment was designed to compare the feedback styles for their influence on the user's performance when the user was trying to ignore the advice. If any one type of feedback provided a significantly greater deflection in the user's path, it can be concluded that it would be less suitable where users need to apply their own knowledge and skill into the task. It was expected that haptic feedback would be the hardest to ignore, as it provides a physical force on the user's hand. As with the earlier experiments, it employed a 25 x 5 (25 subjects, 5 treatments) two way, design with a significance level of 0.05.

5.2 Measurement and Analysis

This experiment produced similar values for all measures taken in experiment 2 for all the valid danger zones (i.e. not the last), indicating that those results are repeatable. For the special (last) danger zone, it recorded the point at which the drawn tunnel entered it and where it left. The drawn distance inside the special danger zone was recorded, along with the direct distance between entry point and exit point. A comparison of these two distances was a measure of how much the user was deflected from a straight line through the danger (see figure 7).

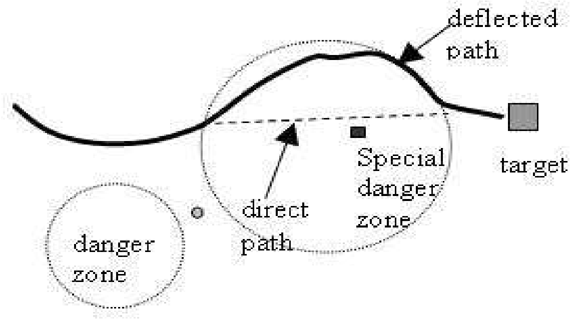


Figure 7. Measurement of unintended path deflection

To perform this comparison, the algorithm in equation 2 was used to produce a measurement between 0 and 1, the lower end of this range indicating a better ability to ignore the advice. It could be interpreted as the proportion of wasted distance brought about by the feedback advice.

$$extraLength = (inside - direct)/inside \qquad (2)$$

$$0 \le extraLength \le 1$$

$inside$ = distance drawn inside the special danger zone

$direct$ = direct distance between entry and exit points of zone

In equation 2, extraLength is a measure of inability to ignore the feedback advice. A low extraLength score indicates that the feedback method is not greatly influencing the user, an outcome that is desired in this case. The analysis of variance was performed on the extraLength variable, which had the means shown in figure 8.

5.3 Discussion

These results show that haptics was comparable to graphical arrows in the ability to ignore the advice, Surprisingly it was significantly easier to ignore haptics than a popup message. This is somewhat surprising as it seems reasonable to expect that a physical force would be harder to resist and ignore than something visual and audible. The fact that the force and arrow methods produced better results perhaps indicates that the popup may have startled users and given them no idication of what course they should take. One possible explanation for this result could be associated with the cognitive load on the user at the time. Perhaps a gently increasing force or arrow produces a lighter cognitive load on an already-occupied user, than a sudden popup message.

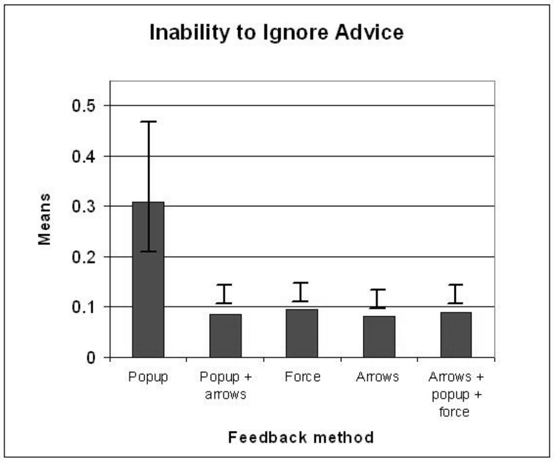


Figure 8. Difficulty of ability-to-ignore advice. Haptic feedback was not significantly worse.

6 CONCLUSION

Humans live in an environment in which touch is an every-day, integral part of their existence. It is therefore surprising that the norm in the computing world is an environment devoid of touch. When we have the ability to construct a different reality (a virtual reality) we are free to pick and choose which aspects of the real world to reproduce, which to leave out and which to modify, to suit our purposes.

Three dimensional motions are more complex than those in two dimensions. The motion of a human hand in space is the result of several individual, but co-ordinated, angular movements of the wrist, elbow and shoulder joints [14]. We have shown that performance at sculpting a surface and drawing a line in space can be measurably enhanced by providing a haptic assistance. Moreover, we discovered that this does not impede the user's free will to act against the haptic guidance. Such a result may come into play when deciding whether to incur the expense of adding haptic feedback to an application.

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