Quantification of the Effects of Haptic Feedback During a Motor Skills Task in a Simulated Environment

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Abstract. This paper seeks to establish the quantitative effects of providing force feedback on user performance in human computer interaction. A reciprocal tapping test is employed in conjunction with Fitts' law in order to establish a measure of human performance in a simple target selection task. The test was performed using a PHANToM haptic interface, under conditions with and without the provision of force feedback. It was found that providing force feedback significantly improved subjects' movement times, but had no effect on the rate of information processing (IP) as defined by Fitts' law. However, it was shown that for conditions of ballistic movement (corresponding to a low task difficulty (ID)), there was a highly significant improvement in IP for the condition with force feedback, but no improvement when force feedback was not employed. This was deemed due to the fact that for the non-haptic condition no force cues were available, therefore the user had to rely on visual cues, hence, ballistic movement was not possible.

1. Introduction

Haptic interfaces have much to offer in the form of an intuitive and powerful form of user interface. As haptic interfaces find more purchase as desktop interface devices, their use for general human computer interaction (HCI) tasks will become more prevalent. The notion of the graphical user interface (GUI) is now extremely widespread within all aspects of the computing field, from operating systems to internet browsers, control and acquisition of information is usually achieved through clicking icons, selecting items from menus and other familiar actions. A haptic user interface (HUI) would offer the user the opportunity to interact with the data via the sense of touch. Buttons and icons could be physically pressed, files "carried" across the workspace, maybe using weight cues as an indication of their size, and mathematical functions explored haptically as well as visually. The HUI is rightfully put forward as a benefit of the introduction of haptic interfaces to the workplace. An immediate application is for blind and visually impaired users, who are increasingly excluded through use of visually dependant user interfaces.

In order to quantitatively assess the effect of force feedback on user performance in HCI, it is necessary to determine some measure by which the relative contribution may be evaluated. A simple measure of interaction is provided by Fitts' Law [1], which extends the concepts of information theory to the human motor system, thus providing a measure of information required to execute a series of movements.

1.1 Fitts' Law

Fitts postulated that the information capacity of the motor system could be defined by the ability to perform a particular movement from amongst several possibilities; the greater the number of alternative movements, the greater the information content of the particular response.

In the classic "reciprocal tapping" experiment, or "Fitts' Paradigm", as it has become known, subjects were asked to tap two rectangular plates alternately with a stylus. Movement tolerance and amplitude were controlled by fixing the width of the plates and the distance between them. Subjects were instructed to emphasise accuracy rather than speed. Fitts sought to establish the information capacity of the human motor system, though, strictly speaking, it is only possible to study the performance of the whole receptor-neural-effector system. However, given that the subject must execute rapid and uniform responses that have been highly over-learned, the experimental condition conceived by Fitts can reasonably be assumed to be limited primarily by the capacity of the motor system, in this case, including the visual and proprioceptive feedback loops.

The premise of Fitts' law is that the human motor system has a capacity for processing information that limits the speed with which movements can be performed. The index of performance defined by Fitts (IP: bits/s.) is analogous to channel capacity. IP is calculated using the specific tasks index of difficulty (ID: bits) and the time to perform the requisite movement (MT: s.).

$$IP = ID/MT \qquad \textbf{(1)}$$

ID is specified as the amount of information required to select a specific amplitude from the total range of possible movements, and is thus dependant on the amplitude of the movement (A), and the tolerance to which it must be made (target width W).

$$ID = \mathrm{Log}_2\,(2A/W) \qquad \textbf{(2)}$$

The expression is loosely based on Shannon's theorem. Thus, by varying ID (A and W), IP can be determined by recording MT over the various conditions. Fitts' thesis was that IP was constant over a range of values of ID. Using regression analysis, a linear relationship between ID and MT can be established, thus:

$$MT = a + b*ID \quad (\mathbf{3})$$

It is equation 3 that has become commonly referred to as Fitts' law. It is claimed that a measure of the information processing capacity of the motor system is provided by the reciprocal of the slope of equation 3 (i.e. 1/b). Subsequent studies, by Fitts and others, have provided evidence to support this claim. The value of IP for the human motor system is often cited as being roughly equal to 10 bits/s [2-5].

However, Fitts' original formulation (equation 2) was inaccurate for low values of ID (< 3 bits), showing an upwards curvature of MT, away from the regression line. Welford [6] offered a reappraisal of Fitts' original data using his own formulation for ID, as follows:

$$ID = [\ (A/W) + 0.5\ ] \quad (\mathbf{4})$$

Welford qualified this as making MT dependant upon a "kind of Weber fraction in that the subject is called upon to distinguish between the distances to the far and nearer edges of the target". The formulation made the relationship between MT and ID more linear, and also ensures that ID is always greater than zero.

Gan and Hoffman [7] sought to explain the discrepancy for low values of ID in terms of "ballistic" and "non-ballistic" movements. A ballistic movement is defined as a rapid, involuntary movement which is motor programmed, and for which visual feedback is not possible. Fitts' equation is only applicable to visually controlled movements, therefore, a different relationship was required to model MT for low values of ID. It was illustrated that for each amplitude condition there was a value of ID below which there was no significant effect of ID on MT. This was defined as the ballistic region. The extent of the ballistic region increased with amplitude of movement.

1.2 Fitts' Law in HCI.

Fitts' law was first applied to HCI in Card et al [8]. Comparisons in performance were derived between a mouse and a joystick. It was shown that the mouse had an IP around 10 bits/s., which is performance comparable to that in Fitts' reciprocal tapping task, and other similar studies. The joystick, however, had an IP of roughly half this value. Analysing the data with respect to target distance, gave parallel lines of a slope roughly 0.1 s/bit (hence, IP $\approx$ 10 bits/s) with intercept increasing with target distance. Thus, the joystick could be thought of as a device that obeys Fitts' law, with half the processing capacity of the mouse, or as a device with the expected slope, but with an intercept that increases with target distance.

In a more recent study, Akamatsu et al [9] investigated the effects of multi-sensory information on performance with a mouse-type device. Tactile stimulus was added to a mouse using a solenoid driven pin that was raised through the left mouse button. This was shown to have a significant effect on motor response speeds, and allowed the subject to utilise a greater area of the target space, as they detected the onset of traversing the target boundary earlier. Despite these benefits, when questioned, subjects indicated that they preferred visual feedback to tactile.

This study aims to quantify the effects of providing force feedback during a Fitts' reciprocal tapping type test in a 3D virtual environment using the PHANToM (www.sensable.com). The primary medium of sensory feedback was via a graphical representation of the VE displayed on a monitor. The user performed the test using a PHANToM haptic interface under two conditions, with and without force feedback. Thus, given the measures derived for IP, the effect of providing force feedback to the user can be quantified.

2. Experimental Procedure

The subjects were 9 students, 5 male and 4 female, all from the Department Of Cybernetics, aged between 20 and 29. All had some degree of competence with the PHANToM, having participated in previous investigations.

Subjects were instructed to tap between the two targets alternately, scoring as many hits as possible. They were told to emphasise accuracy rather than speed. The PHANToM (model 1.5A) was positioned directly in front of the subject, who was seated for the duration of the experiment. A visual display unit was positioned immediately behind and to the left of the PHANToM, such that the framework of the device could in no way impede the subjects view of the display. The full test comprised of two blocks of 20 trials each. One block was performed with visual and haptic feedback (from here on referred to as "haptics" condition), and the second block with visual feedback only ("non-haptics").The 20 trials in each block were randomly ordered for each subject and consisted of all combinations of A = 20, 40, 60, 80 and 160 mm, and W = 2.5, 5, 10 and 20 mm. Prior to commencing the investigation, each subject was first shown an example trial using A = 40mm and W = 20 mm and allowed a 15 second practice trial, after having the procedure explained. The subject was then permitted the same period of practice with the most difficult condition (A = 160mm, W = 2.5mm) and the easiest condition (A = 20mm, W = 20mm). The subject was then allowed any further practice they felt necessary, though it should be noted that most were comfortable with the conditions and proceeded directly to the test itself. The subject gave verbal indication that they were ready for the operator to begin each trial. Each trial lasted 15 seconds from the moment the subject tapped their first target. Upon tapping a plate, visual indication was given by switching the colour of the target from red to green, and vice-versa for the other plate. Thus, the subject was given an indication of when contact was made, even in the non-haptic condition.

3. Results and Discussion

The index of difficulty was calculated using the Welford formulation, in order to compensate for possible anomalous effects at the extremes of difficulty. The mean across all subjects was plotted against the index of difficulty (see Figures 1 and 2) for the haptic and non-haptic conditions. A straight line fit was then derived, using linear regression techniques, of the form described by equation 3

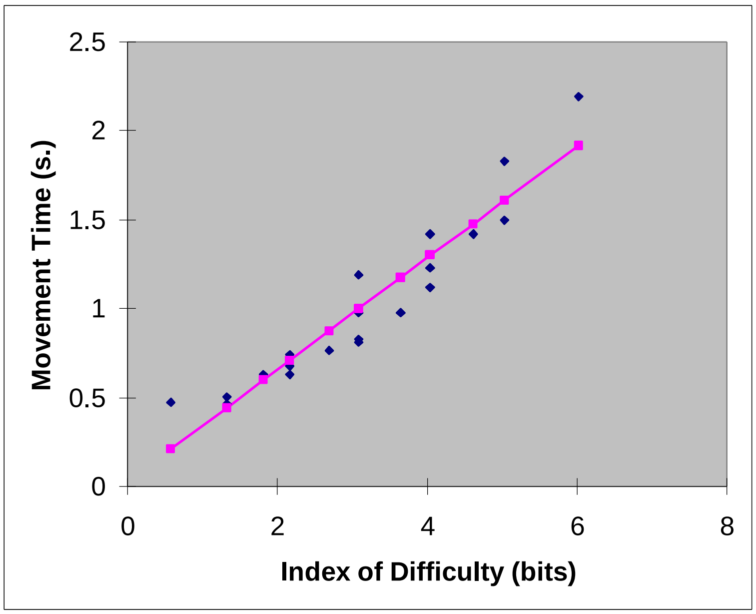

Fig. 1. Relationship between movement time and index of difficulty (Welford formulation) for haptic condition. Regression slope: MT = 0.028 + 0.314 ID.

There is little difference in the performance rates between the haptic and non-haptic conditions, suggesting that the addition of force feedback has not served to improve user performance in the reciprocal tapping task. However, the intercepts show a large difference, of almost a factor of 10. The intercept corresponds to the time spent on the target, therefore, it is hypothesised that force feedback allows the user to detect the onset of contact with the target quicker. As this would affect MT for all conditions of ID, the effect appears on the intercept instead of the slope of the graph, that is, the slope remains roughly the same, but the whole graph is shifted "down" with respect to

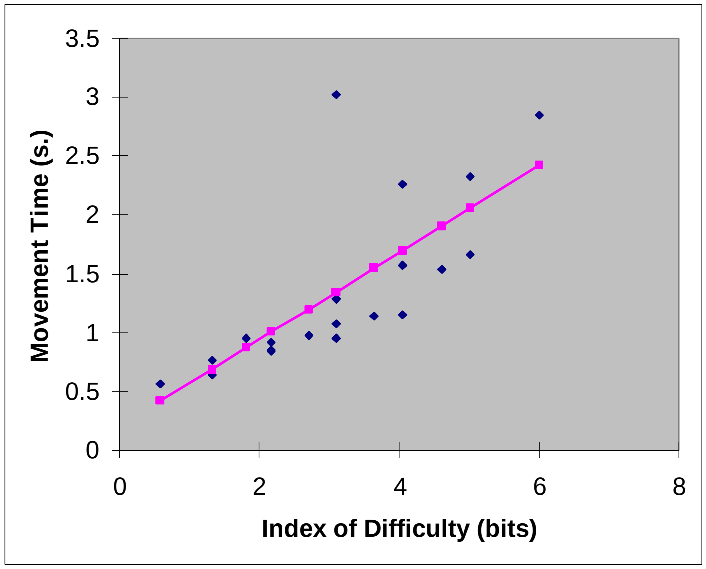

Fig. 2. Relationship between movement time and index of difficulty (Welford formulation) for non-haptic condition. Regression slope: MT = 0.2 + 0.37 ID.

the y-axis. Comparing the two regressions, it was found that the relationship between ID and MT was significantly different for the haptic and non-haptic condition ($F(2,38) = 4.67$, $p<0.05$). However, analysis of the slopes of the two regressions showed no significant difference ($F(1,36)=0.438$, $p>0.05$), hence, the difference in the two models can be attributed to the difference in the intercepts. Thus, even though the measure of IP shows no significant difference, it is clear that force feedback provides some benefit to performance.

A two-factor repeated measures ANOVA was performed on the movement time data across all subjects in order to assess the relative contribution of ID and force feedback to performance. It was found that the effect of providing force feedback was significant ($F(1,8) = 10.77$, $p<0.05$), though not as significant as the index of difficulty ($F(19,152) = 9.61$, $p<0.01$), as was expected. Surprisingly, the effect of subjects was also significant ($F(8,152) = 4.73$, $p<0.01$), as was the interaction of the force feedback and ID ($F(19,152) = 2.15$, $p<0.01$). This suggests that training of subjects may be an issue to address in future studies.

The effect of providing force feedback can be likened to that of a drum-roll. The human bandwidth for limb motion is about 10 Hz [10], but it has been observed that humans can produce actions such as drum-rolls at over 40 Hz by allowing the drumstick to bounce through suitable control of the passive impedance of the hand joints [11]. Thus, by allowing the end-effector of the PHANToM to "bounce", faster movements can be performed.

Condition	Intercept (s.)	Slope (s/bit)	IP (bits/s.)
Haptic feedback, ballistic movement (ID < 3 bits)	0.354	0.086	11.63
Haptic non-ballistic movement (ID ≥ 3 bits)	-0.449	0.35	2.86
Non-haptic, ballistic movement (ID < 3 bits)	0.302	0.226	4.42
Non-haptic, non-ballistic movement (ID ≥ 3 bits)	-0.233	0.387	2.58

Table 1. Results for ballistic/non-ballistic movement under haptic/non-haptic conditions.

It seems unreasonable, however, to suggest that a subject could "bounce" between two targets of 2.5 mm width with any degree of accuracy! Thus, using Fitts' original formulation of ID (equation 2), the data was divided into "ballistic" (ID < 3 bits) and "non-ballistic" regions (ID ≥ 3 bits) for both sets of data. Calculating regression lines (summarised in table 1), the differences between the haptic and non-haptic conditions become readily apparent. Comparing the slopes of the regression lines for the haptic ballistic and non-ballistic conditions, it was found that the difference is highly significant ($F(1,16) = 52.45$, $p<0.01$). However, for the non-haptics condition, there was no significant difference in the slope, and therefore, performance, between the ballistic and non-ballistic conditions ($F(1,16) = 0.114$, $p>0.05$).

There are several related conclusions that can be drawn from this. For the non-ballistic condition, there is no significant difference between the haptic and non-haptic condition. For ballistic movements, visual feedback is not used to correct motion. Thus, when force cues are provided, performance increases drastically due to the "drum-roll" effect previously described. However, without force feedback, thesubject is forced to rely on visual cues, thus, performance does not significantly increase over the non-ballistic condition.

4. Conclusion

This paper has presented results that aim to quantify the effects of providing force feedback in a simulated Fitts' reciprocal tapping experiment. It has been illustrated that force cues provide a means to improve the performance of subjects, though only significantly so in the region of ballistic movements. It is possible to conclude that for more difficult tasks, the subject is, in fact, relying on visual cues, as illustrated by the similarity in IPs between the haptic and non-haptic conditions. Indeed, most of the subjects comments as to how performance could be improved were with regards to the nature of the visual display. It is hypothesised that the stark difference in performance between the figures for performance found in this study, and the often cited value of 10 bits/s, is due to the nature of the visual display. Displaying a 3D environment on a 2D display often confused the subject's depth perception. Adding a simple effect to aid this, such as a shadow from the haptic "cursor" may help to increase performance. It is clear, therefore, that in order to improve user performance in VEs, progress needs to made regarding how the various senses interact in order to provide a coherent illusion across several modalities.

This study has provided some insight in to the effects of force feedback on user performance, however, many possibilities still remain for future work. No analysis of errors was performed in this study, which could have an influence on results. More results need to be gathered for a better comparison of the ballistic and non-ballistic regions, and a better measure of exactly where on the ID scale the division between the two occurs. In this study, the PHANToM was positioned directly in front of the user, with the monitor slightly behind and to the left. What effect would positioning the monitor to the right of, or directly behind the PHANToM have, or, say, moving the PHANToM to the right of the subject instead of being infront? Another interesting possibility for research that may influence results is the effect of spatial disparity between the haptic space and the visual space.

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