Target Acquisition with Force Feedback: The Effect of Different Forces on the User's Performance

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Abstract. Besides realistic haptic rendering of objects, haptic feedback can also be used to provide an abstract feedback channel. This can either be realised by a tactile or a force feedback stimulus. When using forces, care has to be taken that the user's performance is not influenced in a negative way. However, as it is not obvious to determine a suitable force, and currently not many guidelines exist. Therefore, in this paper we investigate the influence on some important parameters that define a force (shape, duration and amplitude). In order to compare different forces, we propose to use the definite integral (Force Integral, *FI*) which combines the considered parameters. From the conducted experiment we learn that the *FI* can be used (within bounds) to make an estimation of the result of the force. Besides this, we also found that above a given *FI* value, the user's performance degrades significantly.

1 Introduction

Over the last decade haptic feedback, which exploits our human sense of touch, has been gaining importance. Haptic feedback, in the form of tactile feedback or force feedback [1] has the ability to provide a very direct feedback loop closely coupled with the user's action (motion). Practical applications applying force feedback often try to render the generated forces as realistic as possible, to provide the user with a natural sensation. Several simulation applications may serve as examples of this approach [2].

In contrast with the generation of realistic forces, other research focuses rather on the *extra informational channel* provided by haptic feedback, independent of the realism of the generated forces. This extra feedback provides users with additional information during their interaction as such that their experience or their performance can be improved. Very often, examples of this kind of feedback can be found in the domain of tactile feedback, including 'Tactons' [3] or the use of a haptic belt for navigation at sea [4]. This extra haptic channel can also be established by using abstract force feedback, e.g. to support pointing tasks in a desktop application or in a virtual environment.

This support can be achieved by *assisting* the user, e.g. using 'gravity wells' (a 'snap-to' effect that pulls the user's pointer to the centre of the target) [1,5]. Using gravity wells showed small non-significant improvements in time, while reducing the error rate.

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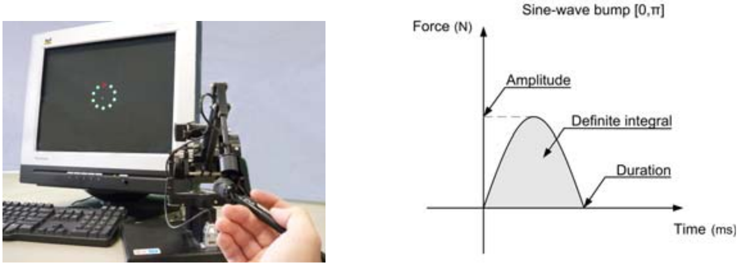


(a) (b)

Fig. 1. (a) Setup of the experiments: Phantom haptic device and the ISO 9241-9 tapping circle on the screen. (b) An illustration of the force evolution of a sinusoidal haptic bump over time. The grey shaded area is the definite integral, which in this paper we refer to as the force integral (*FI*).

However, in more complex situations where distractor targets are present, gravity wells become disturbing [6,7].

Alternatively, forces can be applied by giving *feedback* in the form of a bump or a vibration as soon as an event occurs. Akamatsu et al. [8] and Cockburn et al. [9] used tactile vibrations to indicate when the mouse cursor hovered a target. They both found that tactile vibration could improve the performance in certain situations although they reported that the vibration could make users miss small targets. In the context of a virtual environment, Vanacken et al. [10] applied a small sine-wave force of a short duration to indicate when a user had switched between indicated targets. No significant performance benefits were found, but small improvements in time were seen.

Force feedback that assists the user, such as gravity wells, can be detrimental and has no guarantee to be beneficial for the performance of the user. On the other hand, force feedback used as extra feedback has showed possible beneficial possibilities in user interfaces but it is unclear how to assure the design of the feedback does not have a negative outcome on the performance of the user. Currently not many guidelines exist to support designers in defining the parameters, this implies that the design is mostly performed using 'trial-and-error' until suitable values are found.

Inspired by this observation, the aforementioned research and a first pilot study [11], the work presented in this paper investigates what force strengths, shapes and durations may be useful. In other words, we study how the force parameters influence the user's performance. We propose a rule of thumb that can be applied to combine the aforementioned parameters. This will finally allow us to formulate a guideline concerning the forces that may or may not be applied.

In this paper we define a 'force bump' as a short force with a given *duration* and *amplitude*. The amplitude of the force over time may follow a mathematical pattern such as a sine or a step function, which we define as the force *shape*. Figure 1(b) illustrates a sinusoidal bump. There are more possible parameters that may have an influence on the result of the force-feedback stimulus. Other parameters such as force directions, or device differences will be covered in future work.

To combine the parameters taken into account, we formulate a hypothesis using the definite integral of the force bump (see Figure 1(b)). This allows us to predict the influence of other force bumps with other amplitudes, shapes and durations. We verify the validity of this hypothesis in the following experiment. This hypothesis and the resulting guideline are a valuable tool for designers who want to apply force feedback for a targeting, pointing or a selection task. They can use these results to know what force values must not be exceeded.

2 Force Shape and Duration Experiment

To provide a more convenient calculation of the different parameters (shape, amplitude and duration), we apply the definite integral (Figure 1(b)). Derived from the physical relationship between the applied force and the velocity and position (where position is the double integral of the force), we hypothesise that the definite integral of the force bump may be a decent prediction of its influence on the user's behaviour. In what follows, we define the force integral (*FI*) as $\int_0^T abs(A \cdot f(t))dt$.

In this section we try to verify this assumption by measuring the results of haptic bumps with different force shapes, different durations and different amplitudes, but with the same *FI*, and compare how they relate to each other.

2.1 Apparatus

The experimental setup consisted of a regular 19-inch CRT monitor and a Phantom premium 1.0 haptic device (see Figure 1(a)). The control display gain was 1, which means that one cm physically moved with the device, corresponds to one cm on the screen. Calibrating the device learned us that forces provided by the software were nearly equal to the final forces measured at the device. However gravity compensation (unbalanced weight [12]) of 0.08N downward was required in software.

Another important factor that had to be taken into account, was the inertia and the internal friction of the device. Obviously, we desire values that are as low as possible because a higher friction and higher inertia may interfere with the haptic bump (e.g. 'smooth out' the force bump). As the Phantom premium is designed to keep these values as small as possible, this device suits our needs.

2.2 Participants

Ten participants (two females and eight males) served as participants in this experiment. Participants were selected among co-workers and had an age between 25 and 31 years old with an average of 27. All participants except one were right-handed and used their dominant hand during the experiment.

2.3 Procedure

A simple multidirectional point-select task, as described in ISO 9241-9 [13], was used for this experiment. Ten targets were placed in a circle on the screen (see Figure 1(a)). The diameter of the circle was determined at 6 cm and the size of a target at 0.7 cm (we use physical measures rather than pixels, since pixel sizes vary from display to display). This task has a Fitts' index of difficulty of 3.26 bits, a measure typically used in Fitts' law experiments to indicate the difficulty of the task [14]. This value is chosen to be comparable to the task difficulty of a typical icon selection task [15,16].

We also took into account the implications of the movement scale; the limb segments of the user involved in the task depend on the physical distance that has to be covered [17,18]. Usually, the operation of desktop haptic devices is situated in the range of the wrist and fingers. Therefore a 6 cm distance appeared to be a good value [19], as it will adhere to typical movements to be expected with the device.

During the test, the ten targets were highlighted one after the other and users were requested to select (by pointing and clicking) the highlighted target as efficient (fast and accurate) as possible. Highlighting is altered between opposite sides of the circle so that it requires the user to make movements equally distributed among all directions with a maximum distance between the targets.

As the task to perform was a 2D selection task and the haptic device we used is a 3D input device, a vertical guiding plane restricted the task to two dimensions. In order to make sure that users did not use the guiding plane as extra support, as such that the forces had less impact on their movement, we provided them with extra visual feedback about their position inside the guiding plane. The background colour was completely black within a certain offset of the guiding plane and faded to white the more the user pushed into the plane. Users were instructed to avoid having a grey/white background.

Finally, force feedback appearing in the form of a force bump with given shape, duration and amplitude was activated at exactly half-way in the path to the next target. Note that in this basic experiment, the forces serve as a distractor without beneficial goal. This experimental approach should allow us to investigate the user's performance when different forces are applied.

2.4 Independent Variables

As mentioned before, in this experiment we investigate how the user's performance is influenced by the applied forces when parameters such as force shape (S), duration (T) and amplitude (A) are altered. These parameters are all combined in the *FI*.
We consider the following shapes with the following duration:

- A sine wave over half a period, 75 milliseconds ($S=sin_{[0,\pi]}$, $T=75ms$)
- A step function, 40 milliseconds ($S=sqr$, $T=40ms$)
- A sine wave but with a longer duration, 110 milliseconds ($S=sin_{[0,\pi]}$, $T=110ms$)
- A full sine wave $[0,2\pi]$ of 75 milliseconds. It is interesting to see how this shape will behave as it produces positive and negative forces ($S=sin_{[0,2\pi]}$, $T=75ms$)

The amplitudes of the different forces are chosen as shown in Table 1, so that the *FI* of each n^{th} line is the same.

The force integral values (*FI* = 0.0, 9.55, 19.10, 28.65, 38.20, 47.75, 57.30, 66.85, 76.39, 85.94 and 95.49) and the shapes S ($sin_{[0,\pi]}$, $T=75ms$; sqr, $T=40ms$; $sin_{[0,\pi]}$, $T=110ms$ and $sin_{[0,2\pi]}$, $T=75ms$) serve as the independent variables during the design and analysis of this experiment.

Table 1. Equivalent force amplitudes calculated using the force integral value and the definite integral

Force Integral	$\sin_{[0,\pi]}$ (75ms)	sqr (40ms)	$\sin_{[0,\pi]}$ (110ms)	$\sin_{[0,2\pi]}$ (75ms)
0.0	0.0N	0.0N	0.0N	0.0N
9.55	0.2N	0.24N	0.14N	0.2N
19.10	0.4N	0.48N	0.27N	0.4N
28.65	0.6N	0.72N	0.41N	0.6N
38.20	0.8N	0.96N	0.55N	0.8N
47.75	1.0N	1.19N	0.68N	1.0N
57.30	1.2N	1.43N	0.82N	1.2N
66.85	1.4N	1.67N	0.95N	1.4N
76.39	1.6N	1.91N	1.09N	1.6N
85.94	1.8N	2.15N	1.23N	1.8N
95.49	2.0N	2.39N	1.36N	2.0N

2.5 Design

A repeated measures within-participant design was used. The independent variables *FI* and *S* combined in a fully crossed design resulted in 44 combinations in total (11 *FI*s and 4 *S*s).

Each participant performed the experiment in one session lasting about 25 minutes. The session consisted of 5 blocks with each block containing the 44 combinations repeated 3 times in a random order. For a total of 132 trials per block, this resulted in 660 trials per participant. Between each block, users were obliged to take a break of at least 15 seconds to minimise fatigue during the test. Before starting the experiment, participants were given all 44 conditions in random order to familiarise them with the task. During the experiment, the time it took to select a target was recorded, as well as the amount of errors made during selection.

2.6 Results

In a first step, we investigated the general learning effect during our experiment by comparing the results of the different blocks based on the trial completion time. As a result, the first two blocks were removed to eliminate the results of any learning effect (*Block* ($F_{4,36} = 8.7$, $p < .0001$)).

Trial Completion Time. A repeated measures analysis of variance of the faultless selection trials showed no main effect for *S* ($F_{3,27} = 1.92$, $p = .151$) which implies that the shapes did not differ significantly from each other in trial completion time: 881.6ms for $sin_{[0,\pi]}$, *T=75ms*, 893.2ms for *sqr, T=40ms*, 874.9ms for $sin_{[0,\pi]}$, *T=110ms* and 907.5ms for $sin_{[0,2\pi]}$, *T=75ms*. This result was to be expected, as we hypothesised that the *FI* values would be the most important factor with regard to the trial completion time of the user. Analysis showed a main effect for *FI* ($F_{10,90} = 8.6$, $p < .0001$). Post hoc comparisons showed that trial completion time slightly (but non-significantly) deteriorates

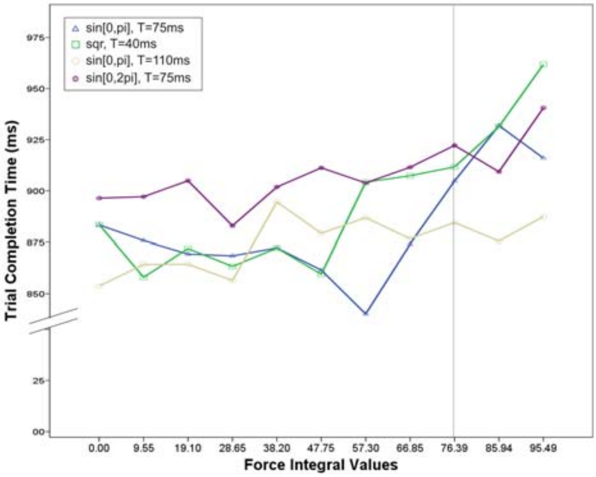


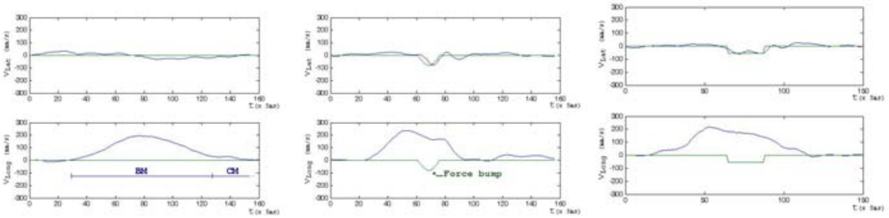
Fig. 2. Force integral values by shape. Significant deterioration is found for FI-values greater than 76.39.

while the force increases. This pattern is true until a certain *FI*-value (*FI=76.39*) from where the trial completion time deteriorates significantly ($p < 0.015$). Although the trial completion time penalty is small in absolute values, nevertheless it is significant; and moreover, as selection is such a common and frequently used action, even a deterioration of a small amount of time may induce user annoyance.

Although *S* did not show a significant main effect, it did show an interaction effect with *FI* ($F_{30,270} = 1.66$, $p < .02$). Figure 2 shows the interaction: all shapes show a similar pattern with regard to the force integral, except for $sin_{[0,\pi]}$, *T=110ms*. This shape does not seem to have an equally strong deterioration at the higher *FI* conditions. Several reasons may cause this effect, but future research is necessary to verify our suppositions: it can be argued that the less pronounced deterioration of $sin_{[0,\pi]}$, *T=110ms* is due to the lower amplitude which may be partly masked by the friction of the device. Alternatively, it can also be argued that the longer period of force activations gives more opportunity for the user's reflexes to counter the deviation and apply a compensation.

Velocity Analysis. The study of velocity profiles can provide us with a deeper understanding of the different stadia in the user's motion. Figure 3 shows a typical lateral (top graphs in each figure) and longitudinal (bottom graphs in each figure) velocity profile for different shapes for different *FI*s. We have to stress that the graphs shown in this figure are individual selection trials of individual users. It has to be noted that the entire population of all velocity profiles is subject to a large variation. However, the selected graphs give a good representation of the velocity's behaviour in general.

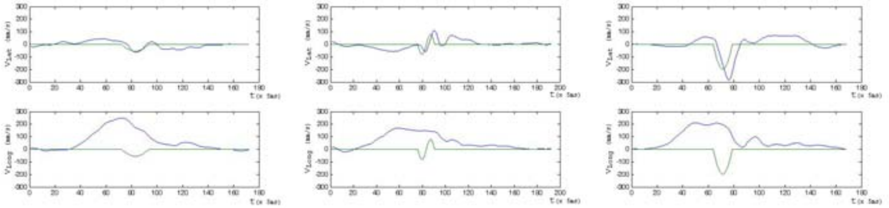
Figure 3(a) shows a selection without applied force. In the topmost graph, we see a small lateral velocity variance around zero. The longitudinal velocity behaves according to the optimised initial impulse model of Meyer et al. [20]. The ballistic movement (BM) and controlled movement (CM) are indicated in Figure 3(a).



(a) No force applied

(b) $sin_{[0,\pi]}$, *T=75ms*, *FI*=38.20

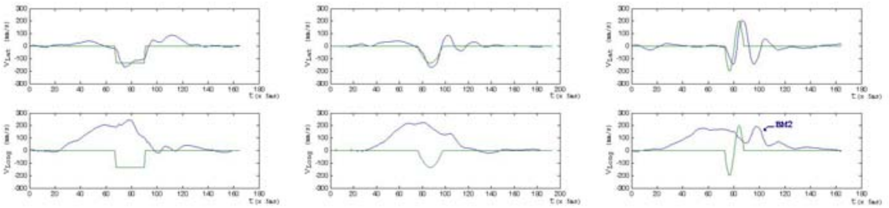
(c) *sqr, T=40ms*, *FI*=38.20



(d) $sin_{[0,\pi]}$, *T=110ms*, *FI*=38.20

(e) $sin_{[0,2\pi]}$, *T=75ms*, *FI*=38.20

(f) $sin_{[0,\pi]}$, *T=75ms*, *FI*=95.49



(g) *sqr, T=40ms*, *FI*=95.49

(h) $sin_{[0,\pi]}$, *T=110ms*, *FI*=95.49

(i) $sin_{[0,2\pi]}$, *T=75ms*, *FI*=95.49

Fig. 3. Velocity Profiles of some ‘typical’ movements: Upper graphs contains the lateral velocity (orthogonal with moving direction), lower graphs contain the longitudinal velocity (parallel with moving direction)

Looking at Figures 3(b), 3(c), 3(d) and 3(e), they represent the velocity profiles when a small force (*FI*=38.20) for the respective shapes is applied. In all cases, we see a clear influence of the bump on the lateral velocity, in the form of a small oscillation. From the longitudinal velocity profile, we can learn that it is not (or only slightly) affected by the force bump.

Figures 3(f), 3(g), 3(h) and 3(i) show the velocities when a large force (*FI*=95.49) is applied. Obviously, we see a similar but larger effect on the lateral velocity. Surprisingly however, the behaviour of the longitudinal velocity, drops down to zero immediately after the bump. This dramatic decrease of velocity is not intended as the end of the ballistic movement phase, which is confirmed by many profiles that show a new (second) but shorter ballistic movement phase (BM2 in Figure 3(i)). Manually categorizing the profiles shows that 80% of the trials ($sin_{[0,\pi]}$, *T=75ms*, *FI*=95.49) have a clear speed reduction, or even a complete halt. Probably the temporarily ‘halt’ induced by the user will help to dampen the unwanted oscillation caused by the force bump. We believe that the significant deterioration discussed in the previous sections is mainly caused by this (unconscious) speed reduction, rather than by the extra distance physically induced by the oscillation.

From the analysis in the previous section, we found that the longer sine ($sin_{[0,\pi]}$, $T{=}110ms$) behaved in a somewhat different manner. It did not show the significant trial completion time deterioration we should expect for the highest two *FI* conditions. From the analysis of the velocity profiles, we found that only 64% of the selection trials had a clear speed reduction or halt (compared to 80% for $\sin_{[0,\pi]}$, T=75ms). Figure 3(h) shows how the longitudinal velocity is less affected, with only a short speed reduction and no halt, as shown in Figure 3(g). This makes us favour the hypothesis that longer bumps give more opportunity for the user to compensate, so that (involuntarily) halting the movement to dampen the oscillation is less necessary.

Error Rates. To analyse the behaviour of the error rate, an error was defined as when the user misclicked the correct target. The overall error rate for the experiment was 139 errors or 2.1%. The shape had no significant effect on the error rate *S* ($F_{3,27} = .657$, $p = .586$). The force integral values showed no significant effect on the error rate either, although the p-value approached the significance level *FI* ($F_{10,90} = 1.78$, $p = .076$). After the experiment, several users reported involuntary miss-clicks in case of the large force conditions, due to these forces.

3 Discussion and Implications

Our experiment investigated the user’s performance when different forces are applied during a simple multidirectional point-select task.

As expected, the shape, duration and amplitude of a force bump have influence on the user. The number of parameters, however make it difficult to compare the different forces. As a guideline we proposed to express the ‘size’ of a force bump by means of the force integral (*FI*), which can be visualised by the area below the force graph (see Figure 1(b)). Even though we do not claim that different force shapes are similar with respect to the user’s performance, they do not differ significantly. This allows a designer to use the *FI* as a good estimation of result of a force bump.

We found that above a certain force integral value, the trial completion time significantly deteriorates. From our experiment in particular, we could deduce that designing abstract force feedback with forces below a *FI*-value of 76.39 will not be harmful for the user’s performance. For the larger force integral values, we could learn from motion path analysis that the longitudinal velocity dropped detrimental immediately after the force bump. We believe that this involuntary halt is the main cause of the user’s performance penalty.

It may be clear however that *FI* is only a rule of thumb, which will have its limits in practice. Although the exact limits must be deduced in future experiments, we found that the longer sine wave ($sin_{[0,\pi]}$, $T{=}110ms$) behaves somewhat different. This can be intuitively understood from the physical properties of the human-device system.

Very short (strong) bumps ultimately will loose their effect because of the inertia, while similarly, very long (but soft) bumps will disappear by the friction of the device, or in extremis are below the user's 'just noticeable difference [21]'. But other effects such as the longer forces that are easier to compensate by the user (as could be seen from the velocity analysis) may play an equally important role, as well.

We believe that the results of this experiment have a practical benefit. As stated in the introduction, Vanacken et al. [10] use small sinusoidal forces to indicate when the user has switched to another indicated target. With a half sine wave of 25ms and peak value of 1N ($sin_{[0,\pi]}$, $T=25ms$, $A=1N$), resulting in a force integral of FI=15.92, this is below the threshold we found. Hence the force should not have any significant deteriorating effect on the user's movement, which is confirmed by the results as the authors found a small (but non-significant) improvement when force feedback was enabled.

Although our hypothesis was tested in a selection task with a constant Fitts' index of difficulty, it can also be used in other types of interfaces in which motion is involved, such as crossing based interfaces [22] or gesture interfaces [23]. Finally, Cockburn et al. [9] found that large amplitudes of tactile feedback may cause users missing small targets. We believe that in this context our approach might be applicable as a rule of thumb for tactile feedback, as well.

4 Conclusions and Future Work

We studied the effect of different magnitudes of force feedback on the user's performance in a target acquisition task. In order to facilitate a comparison of different forces across different parameters such as force shape, duration and amplitude, we proposed to use the definite integral (or Force Integral, *FI*). We found that the *FI* can be considered as a good guideline to predict the user's performance. During the experiment, we also observed that above a certain force magnitude the user's performance significantly deteriorates.

The value of this work is to provide user interface designers with a guideline to keep the calculated force integral (based upon the force shape, duration and amplitude) below the force integral values that objectively caused the performance penalty. It is important to note that the results of this investigation do not imply that force feedback below the values found in these experiments is a priori useful. *If* and *when* force feedback can be applied, is still up to the designer to decide.

We found that the *FI* rule of thumb is a good approximation *within bounds*. In future work, the extremes to which the prediction is valid should be defined more accurately. Another interesting question is whether the 'Fitts' index of difficulty' will have an influence on the results of these experiments. Finally, the Phantom haptic device was used because it has a low inertia and friction. Using other devices such as the popular Novint's Falcon, might have an implication with regard to our findings.

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