A Model for Steering with Haptic-Force Guidance

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Abstract. Trajectory-based tasks are common in many applications and have been widely studied. Recently, researchers have shown that even very simple tasks, such as selecting items from cascading menus, can benefit from haptic-force guidance. Haptic guidance is also of significant value in many applications such as medical training, handwriting learning, and in applications requiring precise manipulations. There are, however, only very few guiding principles for selecting parameters that are best suited for proper force guiding. In this paper, we present a model, derived from the steering law that relates movement time to the essential components of a tunneling task in the presence of haptic-force guidance. Results of an experiment show that our model is highly accurate for predicting performance times in force-enhanced tunneling tasks.

Keywords: Haptic guidance, steering task, Steering law, Fitts' law.

1 Introduction

Steering through straight "tunnels" of different width and length is a common task when interacting with computer systems. Examples include navigating and selecting items in menus, selecting a line or sentence, and tracing to learn patterns. Researchers have introduced force-guidance as a means to assist in the task of steering through tunnels. Users' hand movements are restricted within a tunnel of specific width by imposing forces orthogonal to the movement. Examples include haptic-guided menu selection [4], hand-writing training [15], and surgical training [16]. The guiding force can be either generated by a force-feedback device, such as a Phantom haptic device [14], or simulated by software [11, 13]. Force-guidance is deemed to be a good method for facilitating steering tasks as it can not only reduce errors made by accidently exiting the tunnel, but also improve user performance [4, 6, 7].

As haptic guidance is becoming more popular in assisting steering tasks, a model is required that can predict the movement time of steering tasks in the presence of a guiding force. However, only a few studies have been carried out on this topic. Earlier work with force-guidance uses parameters best suited to the context or the task at hand [4, 6, 7, 17]. A more generic model is required that identifies the relationships

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governing tunneling with force-guidance and can better guide designers in selecting appropriate parameters for a force-guided tunneling task. Such a model could provide answers to many important questions: Does larger guiding forces always lead to better performance? Does force-guided steering extend from the steering law or does a new law dictate the relationship between parameters involved in force-guided tunneling? Should force-guided tunneling take into consideration the intensity of the guiding force? Does a given device have adequate stiffness to guide a user? Without an answer to these questions, the design of force-enhanced steering interfaces is difficult and will at best remain a task that involves significant trial-and-error work for the practitioner.

In this paper we introduce a new haptic-steering model, which is derived from the Accot-Zhai steering law [1] with the inclusion of factors that influence haptically guided tunneling tasks.

2 Related Work

We discuss prior work describing systems that improve steering tasks with haptic or tactile feedback and also discuss existing models for pointing and steering.

2.1 Models for Pointing and Steering

Fitts' law is a governing pointing and aiming [9]. It serves as a fundamental benchmark model from which other laws have been derived [1, 3]. Fitts' law models the movement time (*MT*) of the selection of a one-dimensional target of width *W* at a distance of *A*:

$$MT = a + b\log_2\left(A/W + 1\right), \tag{1}$$

where *a* and *b* are empirically determined constants. The logarithmic term is called the *index of difficulty* (ID). The larger the index of difficulty, the longer it takes to complete the task, and vice-versa.

Fitts' law was adapted by Mackenzie and Buxton [10] for selecting two-dimensional targets. The target was a rectangle of width *W* and height *H*. They found that Fitts' law can be adapted by replacing the *W* in Equation 1 by the smaller of two sides of the target. Accot and Zhai [3] demonstrated that the equation below provides a more precise prediction as it considers the effects of both width and height of the target:

$$MT = a + b\log_2\left(\sqrt{\left(A/W\right)^2 + \eta\left(A/H\right)^2} + 1\right), \tag{2}$$

where $\eta$is a coefficient to weigh the relative contributions of width and height.

In addition to pointing and selection tasks, Fitts' law can also be extended to predict movement time for goal crossing tasks [1, 2], where, the distance *A* and the height *H* of a goal determine the *index of difficulty* for the task (see Fig. 1 middle). Accot and Zhai stated that the task of navigating through a constrained path or tunnel can be considered as a series of crossing tasks, in which a crossing occurs at small intervals.

Based on the model of goal crossing, they introduced the steering law [1] for modeling performance time of steering through a constrained path, as follows:

$$MT = a + b\int_C ds / W(s)\,, \tag{3}$$

where C is the constrained path, and W(s) is the width of the path at point s. It has been demonstrated that the steering law is sufficiently general, and, in addition to modeling common trajectory-based interactive tasks such as navigation and selection of cascading menus [4], it can also be applied to locomotion tasks in virtual reality environments [19].

The steering law is valid for paths of any shape with variable length and width. Equation 4 gives a simplified version, which captures the relationship between the variables along a straight path with a constant width. This version of the steering law is commonly used in modeling novel interactive techniques in GUI environments, as most of the trajectory-based tasks in GUI environments involve steering through straight tunnels [4, 8].

$$MT = a + b\left(A / W\right). \tag{4}$$

Recently, Kattinakere et al. [8] extended Equation 2 for tasks requiring steering in three dimensional tunnels. They showed that, all three dimensions of the tunnel affect task completion time. Their model is expressed as follows:

$$MT = a + b\sqrt{\left(A / W\right)^2 + \eta\left(A / T\right)^2}\,, \tag{5}$$

where A is the length of the tunnel, W is width of the tunnel, T is the height of the tunnel, and η is an empirically determined constant determining the relative contributions of W and T.

2.2 Force-Enhanced Steering

Research has shown that the performance of steering tasks can be improved by providing users with tactile feedback during the movement along a path. Campbell et al. [5] demonstrated that, while navigating through a circular tunnel, the chance of accidently steering outside of the tunnel can be significantly reduced by providing tactile feedback at the sides of the tunnel. They also showed that, if tactile feedback can be provided along the center of the path, users can perform the task faster. Forsyth and MacLean [7] also showed that, task completion time of a steering task can be improved significantly by providing a guiding force towards the center of a path.

A study by Dennerlein et al. [6] involved moving a mouse cursor using a regular mouse or a force-feedback mouse through a small tunnel, which was placed either horizontally or vertically. The force-feedback mouse generated a guiding force that physically pulled the cursor to the center of the tunnel. They showed that task completion time can be improved significantly with force-guidance. They also revealed that, without force-guidance, it took longer to steer through vertical tunnels than horizontal tunnels, whereas with force-guidance the speed difference between vertical and horizontal tunneling was reduced. They also demonstrated that the steering task assisted by force-guidance can be modeled using Equation 4.

Similarly, Ahlström [4] showed that the task of navigating a force-enhanced cascading menu can be modeled using Equation 4. The guiding force was simulated in software. For items with no submenu, the guiding force pushed the mouse cursor to the center of the path. For the items with a submenu, the force pushed the mouse cursor towards the submenu. Ahlström's study showed that force fields can decrease menu selection times by 18% on average.

Although [4] and [6] show that force-enhanced steering tasks can be captured using Equation 4, they do not include relevant parameters such as the stiffness of the haptic device or the strength of the guidance force. If these are to be used in haptic guidance systems, a model is necessary that includes these parameters. In the next Section, we describe the derivation of a haptic-steering model based on the steering law.

3 Model of Force-Enhanced Steering Tasks

Force-guidance is based on the premise that deviations from a central path are pulled back to the center of the tunnel. This reduces inadvertent deviations from the tunnel. Furthermore, users are required to spend extra effort to get out of the tunnel. Conceptually, this form of force-guidance has an effect similar to increasing the width of the tunnel. Therefore we propose an initial model that is inspired by the steering model discussed above. In our model, the guiding force is assumed to increase the width of the tunnel. For the steering task, we first propose a model for the *goal crossing* task. Our model for force-enhanced goal crossing task is expressed as follows:

$$MT = a + b\log_2\left(A/\left(W + \eta \times F\right) + 1\right), \qquad (6)$$

where F is the intensity of guiding force, and η is an empirically determined constant to adjust the effect of F, which is relatively small compared to A and W. While this derivation seems straightforward, there are several elements that do not make this model practical. For instance, in most force-guidance systems, the magnitude of the guiding force is variable: It varies as a function of deviation distance from an ideal path (possibly the center of the tunnel) [17]. To make the model practical, one needs to have a priori knowledge of F, which is difficult to obtain as it varies the magnitude of the force, as applied by the user using the system. We thus replace force magnitude by the spring stiffness S to represent the intensity of the guiding force. For a given deviation a higher S results in a stronger guiding force. The *index of difficulty* for the haptic guidance system can be formulated as:

$$ID = \log_2\left(A/\left(W + \eta \times S\right) + 1\right), \qquad (7)$$

where S is the stiffness of a virtual spring. Similar to [1, 8], we break the tunneling tasks into a series of N goal crossing tasks. For each goal crossing task, the width of the goal stays the same while the distance between goals is A/N. As N grows infinitely, the task becomes a steering task. Using a first-order Taylor series to approximate the *index of difficulty* for the N goal crossing tasks, we obtain

$$ID = \lim_{N \to \infty} ID_N = \frac{1}{\ln(2)} A / (W + \eta \times S). \quad (8)$$

This leads to our model of the *force-enhanced tunneling* task as

$$MT = a + b(A / (W + \eta \times S)). \quad (9)$$

In the remainder of the paper, we describe a series of experiments to validate the proposed model. Through these studies, we also gain insight into user performance patterns with respect to the intensity of guidance force, an aspect that has been unexplored in previous work.

4 Apparatus

The experiments were run on Intel Duo Core 1.66 GHz CPU with 1 GB RAM. Force-guidance was provided by a PHANToM Omni force-feedback device. The experimental interface was displayed on a 17-inch 1280×800 LCD monitor. Participants placed their dominant hand on an armrest. The height of the armrest was sufficient to raise participants' wrists to a comfortable height for manipulating the stylus. Participants were asked to hold the stylus of the PHANToM device like a pen and to perform the crossing and the steering task while the pen was allowed to slide on a plastic panel (see Fig. 1 left). The buttons on the stylus were programmed for participants to control the experimental procedure with the index finger. The test system was developed in C++ using OpenGL. The haptic guidance was implemented using the Open Haptics toolkit from SensAble Technologies [14].

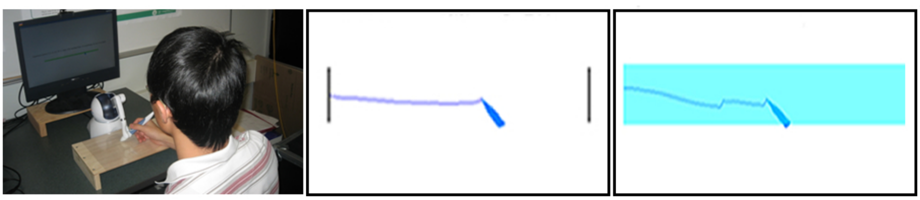

Fig. 1. Left: Experiment settings. Middle: 2D crossing task. Right: 2D tunneling task.

5 Haptic Guidance

Force-guidance was provided by the PHANToM Omni device in a passive constraint manner. The guiding force was triggered when the stylus end-effector deviated from the ideal trajectory, i.e. the middle of the tunnel, and the end-effector was dragged back to the ideal path. As in most passive force-guidance systems [17], the magnitude of the guiding force varied proportional to the distance between the end-effector and the ideal path, i.e. the force magnitude increases as the distance from the center of the path increased.

The direction of the correction force was calculated by projecting the position of the end-effector onto the central path of a tunnel. The goal was to guide the user's hand to the nearest point on the central path. Force magnitude was computed by applying Hooke's Law, *Magnitude (F)* = $S \times D$, where S is the stiffness of virtual spring, and D is the distance between end-effector position and the target position on the central path. We also added a damping system to mitigate buzzing [17].

6 Experiment 1: 2D Goal Crossing with Haptic Guidance

We first ran a pilot study to validate that Equation 6 works for a crossing task (see [8]) while haptic guidance is provided. If it is valid then we generalize it to the haptic steering model. The task required participants to move a cursor to cross two vertical goals of various heights. The goals were rendered with a width of two pixels. We provided a guidance force throughout the entire trial so that the guidance was available not only when the cursor crossed the goals but also when it is occurred at any position during a trial.

6.1 Participants

Three volunteers participated in this study. The participants were male and between the ages of 20 and 23. All were right-handed. Only one had previous experience with the PHANToM Omni device.

6.2 Procedure

Participants were asked to hold the stylus of the PHANToM Omni like a pen, and to move the stylus from left to right to move the cursor, which was rendered as a pen (see Fig. 1 middle), to cross the two bars. User trajectories between the two goals were displayed with a line.

To start a trial, participants were required to place the cursor inside a start region located to left of the start bar (left bar). The region rendered in red, was 5mm wide, and had the same height as the piecewise goals. Once the cursor was in the start region, participants clicked the barrel button on the stylus to indicate they were ready to proceed. The start region then turned green suggesting that the participants could begin. For a successful trial, both bars needed to be crossed from left to right. For instance, a participant who overshot a bar without crossing it, had to back-track to the left of the bar and repeat the crossing for that goal.

A trial started as soon as the start bar was crossed, and ended as soon as the end goal was crossed. Trials were presented with different heights and distances. We also varied the magnitude of the guiding force at four levels. Since humans have a relatively poor sensitivity to changes of force magnitude [18], we displayed the levels of guiding force both haptically and visually. When displayed visually, the strength of the guiding force was represented by number of stars in a way that the minimum guidance was represented by "*", and the maximum guidance was represented by "* * * *".

Participants practiced prior to the experiment. The experiment lasted 45 minutes. Participants were offered breaks between trials.

6.3 Experimental Design

The study employed a 4×4×4 within-subject factorial design, The independent variables are the width of the goals, *W* (5, 10, 15, and 20 pixels, corresponding to 5, 10, 15, 20 mm), the distance or amplitude between the goals, *A* (26, 80, 133, and 186 pixels, corresponding to 50, 150, 250, and 350 mm), and the intensity of the haptic guidance, which is represented by spring stiffness, *S* (0.05, 0.2, 0.35, 0.5). The combination of the independent variables resulted in 64 conditions, with the corresponding IDs calculated by Equation 7.

The experiment was organized into 3 blocks. Each block contained 5 threads, and each thread consisted of 64 trials each representing one *A*×*W*×*S* combination. This resulted in a total of 960 trials. Trials were presented randomly within each thread.

6.4 Results

Movement time (*MT*) was recorded between the times the cursor crossed the left and right bars. Similar to [8], we removed outliers that were more than 3 standard deviations from the group mean (less than 1% of the data). A repeated-measures analysis of variance of movement times yielded a main effect of *S* ($F_{3,6} = 8.05$, $p < 0.02$), *W* ($F_{3,6} = 36.8$, $p < 0.001$), and *A* ($F_{3,6} = 64.04$, $p < 0.001$). There were also significant interactions *A* by *W* ($F_{9,18} = 11.91$, $p < 0.001$), *S* by *W* ($F_{9,18} = 26.7$, $p < 0.001$), and *S* by *W* by *A* ($F_{27,54} = 2.49$, $p < 0.01$).

MT decreased as the intensity of the force-guidance increased. Movement time for *S* = 0.05, 0.2, 0.35, and 0.5 were 411, 359, 343, and 334ms. A post-hoc Tukey-Kramer analysis showed that movement time for *S* = 0.05 was significantly longer than the others (all $p < 0.001$), while the others did not differ significantly from each other (all $p > 0.05$).

With *S* increasing from 0.05 to 0.2, from 0.2 to 0.35, and from 0.35 to 0.5, the average completion time was reduced by 52, 16, and 9ms, suggesting that, beyond a certain threshold, the improvement on movement time decreased and leveled out as the intensity of guidance force increased. We can not confirm this statistically because of a small sample size. This question is further studied in the next experiment.

Using a non-linear regression method, we estimated the value of η to be 28.274. In order to be consistent with [1], the *index of difficulty* (ID) was measured in pixels. Fig. 2 shows the movement time as a function of the proposed *index of difficulty*. Linear regression analysis showed that the data fit the model with an R^2 of 0.92. The equation for *MT* is given by:

$$MT = -57.1 + 158.83 \times \log_2\left(A/\left(W + 28.274 \times S\right) + 1\right). \tag{10}$$

This pilot study validated our proposed model for predicting movement time for a force-enhanced goal-crossing task. In the next experiment, we validate the proposed model (Equation 9) for the force-enhanced tunneling task.

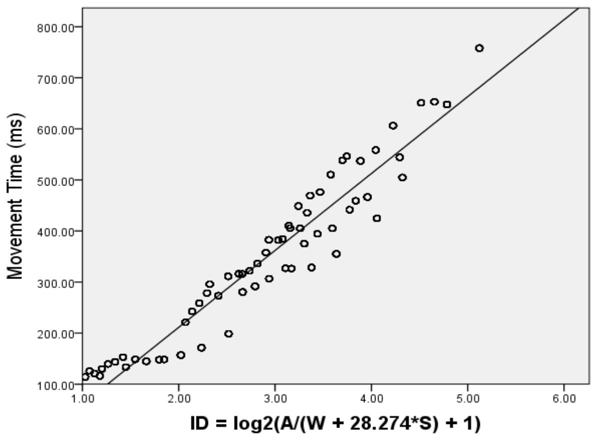

Fig. 2. Movement times by ID

7 Experiment 2: Tunneling with Haptic Guidance

The first experiment demonstrated that, when force-guidance is provided, our model of crossing can be used to predict movement time as a function of task difficulty. In this experiment, we studied haptically enhanced steering tasks. The task involved steering a cursor through prescribed tunnels. Force-guidance was provided to limit participants' hand movements within the tunnels. Similar to the first experiment, four levels of guiding force were tested. We investigated whether the proposed model (Equation 9) can be used to predict movement time for this task. We expected to determine how user performance varies with the intensity of the guiding force.

7.1 Participants

Fifteen university students participated in this study. The group consisted of 3 women and 12 men between the ages of 20 and 30. None had participated in the previous experiment. All but one were right-handed. Seven participants had experience with the PHANToM Omni device. The participants received $10 dollars for participation.

7.2 Hypotheses

Based on prior work and on the first experiment, our hypotheses were as follows:

H1: The effects of force-guidance on movement time reduce when the intensity of the force-guidance exceeds a threshold.
H2: The effects of haptic guidance on error rate reduce when the intensity of force-guidance reaches a certain threshold.
H3: Weak force-guidance result in more errors with longer and/or narrower tunnels. With strong force-guidance, the length and width of a tunnel has a weaker effect on performance.

7.3 Procedure

The procedure was similar to the first experiment. Participants were asked to steer a cursor through prescribed tunnels of different length and width (see Fig. 1 right). Force-guidance was provided to constrain participants' movements inside the tunnels. A successful trial required the participants to steer the cursor from the left end of the tunnel to the right end of the tunnel. A trial finished as soon as the cursor exited the tunnel's right end. An error occurred if the cursor exited the tunnel before the right end was reached. The tunnel was rendered in light green and turned to red if an error occurred. Similar to the first experiment, the intensity of the guiding force was displayed visually to the participants. We also displayed the error rate. Participants were asked to balance speed and accuracy so that their error rate did not exceed 3%.

A warm-up session was given to participants prior to the experiment. The entire experiments lasted 45 minutes. Breaks were encouraged during the experiment.

7.4 Experimental Design

The design of this experiment was the same as for the first experiment. A fully crossed design resulted in 64 IDs based on Equation 9. The experiment consisted of three blocks, each with 64 conditions that were presented in random order. Each condition was repeated 5 times. In total, there were 3 (blocks) × 5 (repetitions) × 64 (conditions) = 960 trials per participant for a total of 14400 trials.

7.5 Results

Movement time (*MT*) was recorded from the time the participants entered the tunnel on the left to the time of exit on the right. Similar to the previous experiment, we removed trials containing errors (1.3%). We also removed outliers more than 3 standard deviations from the group mean (1.8%). In the results reported below, Greenhouse-Geisser adjusted F-Ratios were used whenever appropriate.

A repeated-measures analysis of variance yielded a main effect of S ($F_{3,\,42}$ = 104.72, $p < 0.001$), W ($F_{3,\,42}$ = 93.55, $p < 0.001$) and A ($F_{3,\,42}$ = 237.04, $p < 0.001$). As expected, there were also significant interactions S by A ($F_{9,\,126}$ = 86.2, $p < 0.001$), S by W ($F_{9,\,126}$ = 100.83, $p < 0.001$), A by W ($F_{9,\,126}$ = 103.9, $p < 0.001$), and S by A by W ($F_{27,\,378}$ = 45.95, $p < 0.001$).

Hypothesis H1: The average movement times for S = 0.05, 0.2, 0.35, and 0.5 were 651, 494, 419, and 395ms. With S increasing from 0.05 to 0.2, from 0.2 to 0.35, and from 0.35 to 0.5, the average completion time was reduced by 157, 75, and 24ms. Post-hoc Tukey-Kramer analysis showed that movement times decreased significantly with each increase of S (all $p < 0.001$). Because of the design of this study, the results did not show the movement time improvement as the intensity of guiding force was increased. Therefore we do not know at what value the amount of improvement starts to decrease. Nevertheless, the result showed clearly that such improvements are less significant as the guiding force increases. This supports our hypothesis. Furthermore, we expected a leveling-off effect in terms of improvements to our performance after the guiding force reaches a certain threshold value.

Hypothesis H2: The number of errors for $S = 0.05$, 0.2, 0.35, and 0.5 was 108, 35, 18, and 17. The number of errors reduced by 73, 17, and 1 as S increased from 0.05 to 0.2, 0.2 to 0.35, and 0.35 to 0.5. This clearly supports our hypothesis that the reduction of the error rate reduced as the intensity of guiding force exceeded a threshold value. Unfortunately, the results do not allow us to identify the threshold. Similar to the improvement of task completion time, we expect the improvement of error rate to level off once the intensity of guiding force exceeds a certain threshold.

Hypothesis H3: Fig. 3 shows that the participants made fewer errors as the intensity of the haptic guidance increased. Eighty percent of the errors were made for $S = 0.05$ and $S = 0.2$. For these values of S, the variables A and W significantly affected error number. This effect was, however, noticeably weaker once S increased to 0.35 and 0.5. This supports our hypothesis that, with stronger haptic guidance, the characteristics (A and W) of a tunnel have less influence on the number of errors.

For some applications, for example tele-haptic surgery, driving a car [19], or learning handwriting [15], it is desirable for users to keep their movement as close as possible to the center of a path. We thus measure the effects of S, A, and W on the deviation distance between the ideal central path and user trajectory.

A repeated-measures analysis of variance revealed a significant effect of S ($F_{3, 13831} = 1689$, $p < 0.001$). Interestingly, there was neither an effect of W ($F_{3, 13831} = 4.1$, $p > 0.05$) nor of A ($F_{3, 13831} = 2$, $p > 0.05$). This indicates that stiffness is the only factor that influences deviation (see Fig. 4). A post-hoc Tukey-Kramer analysis showed that deviations decreased significantly as the intensity of haptic guidance increased (all $p < 0.001$). Similar to the improvements with movement time and error rate, our results showed that the improvement of deviation decreased as the force intensity increased.

Finally, to validate the proposed model in Equation 9, we used a non-linear regression to estimate the value of η. We found it to be 19.619. The *index of difficulty* (ID) was again measured in pixels. Fig. 5 shows the movement time as a function of the proposed ID. A linear regression analysis gave a model fit with $R^2 = 0.98$. The equation for MT is given by:

$$MT = 32.59 + 64.69 \times A / \left(W + 19.619 \times S\right) \tag{11}$$

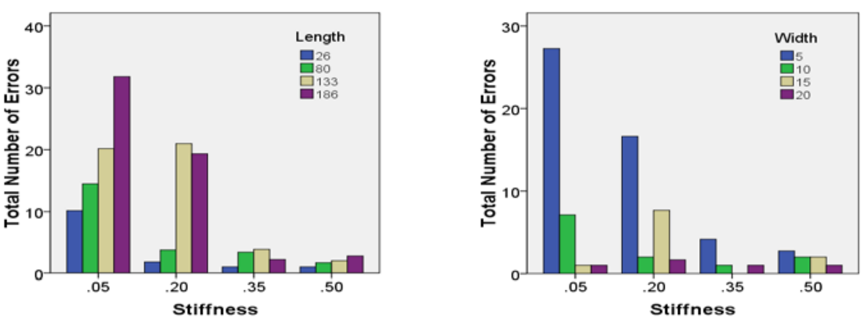

Fig. 3. Number of errors as a function of guiding forces

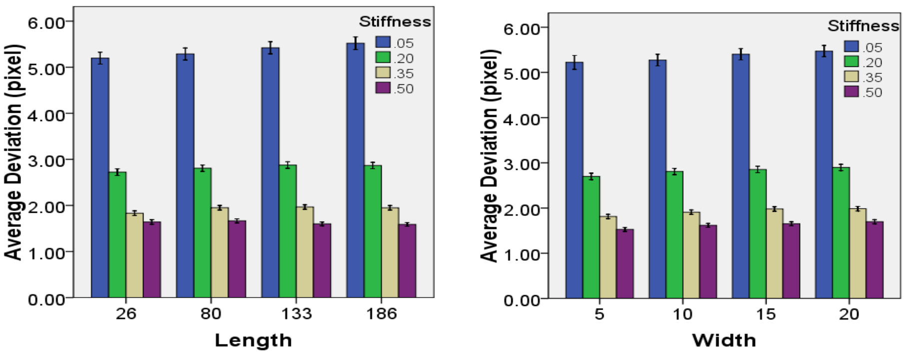

Fig. 4. Average deviation distance as a function of guiding force. Standard errors are also shown.

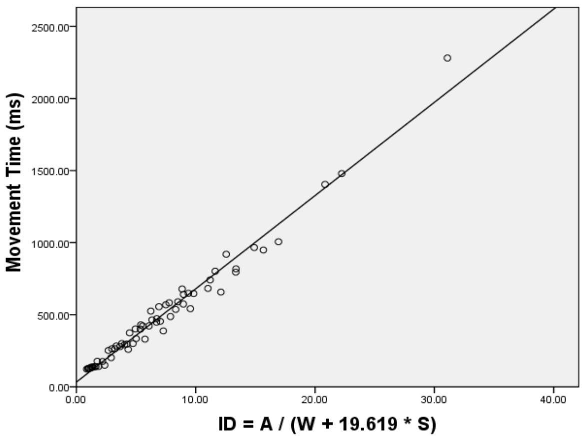

Fig. 5. Movement times by ID

The average guiding force for S = 0.05, 0.2, 0.35, and 0.5 were 0.27N, 0.56N, 0.67N, and 0.81N. Paired t-tests showed that the force magnitude increased significantly as S increased (all $p < 0.001$). We found it is also possible to model the movement time by replacing S by its corresponding force magnitude. A non-linear regression method produced an estimated value for η of 12.769. The equation for MT is as follows ($R^2 = 0.94$):

$$MT = -16.548 + 84.462 \times A / \left(W + 12.769 \times F\right) \qquad (12)$$

8 Discussion

8.1 Leveling-Off Threshold

The results of our study showed that the intensity of force-guidance affects the speed of a steering task such that the stronger the guiding force the faster users can perform

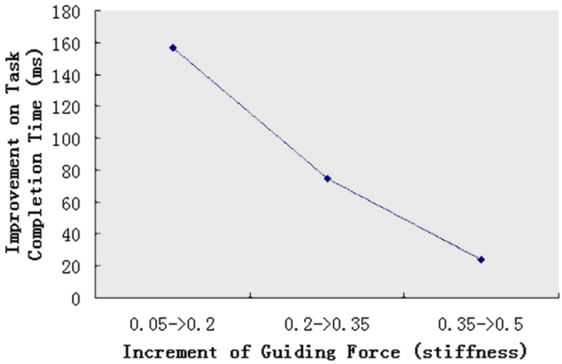

Fig. 6. Improvement on task completion time decreases as the strength of guiding force increases

the task. However, as expected, speed improvement does not grow linearly with the intensity of guiding force. It decreases as the force intensity exceeds a threshold value (see Fig. 6). This indicates that a certain a guiding force *G* is “sufficient” for assisting users to perform quickly on a haptic steering task. Increasing the magnitude of the guiding force beyond *G* does not necessarily improve task completion time. In real-world applications, we commonly see that designers employ the maximum output of the force feedback device as the force-guidance in trajectory-based tasks [17]. Our results, however, demonstrate that this is not necessary for achieving optimal performance. Therefore, being aware of the leveling-off at *G* is beneficial for designing effective force enhanced interfaces. This will be further investigated in our future work.

Note that *G* may vary based on the difficulty of a steering task. In general, a steering task is composed of several sub-steering tasks. Hence the difficulty of the task can be considered a combination of the difficulties of the sub-tasks. For instance, the difficulty of steering through an L-shape path can be considered as the combination of the difficulty of steering through a corner and steering through two straight paths. Given that the difficulties of steering through a corner and steering through horizontal and virtual paths are different [6, 12], a single *G* does not work for this case. For this reason, it is necessary to be aware of the values of *G* at different parts of a steering task, and to adjust the intensity of guiding force accordingly to achieve the best performance.

8.2 Errors and Deviations

As expected, error rates to decrease as the guiding force gets stronger. With a sufficiently strong force, errors can thus be reduced. This explains the finding that, with strong haptic guidance, the length and width of a tunnel have less influence on the error rate. Tasks such as selecting a menu item from a cascaded menu or selecting a line of a sentence in a text editing software requires the mouse cursor to be moved inside a tunnel. Failure to do so causes the task to fail. Our finding suggests that if the index of difficulty (*A*/*W*) is high, a strong guiding force is preferred. Generally, larger forces are better, but this is not the case for movement time.

Unlike general tunneling tasks, tracing a trajectory (e.g. learn to write strokes of Chinese words) requires hand movement to stay within a tunnel defined by a tolerance region while keeping the deviation as small as possible. The results showed that reducing the index of difficulty (*A*/*W*) does not necessarily make the task easier. Therefore, tracing a long path with haptic guidance may not be more difficult than tracing a short path.

We demonstrated that the proposed model can be used to predict movement time of a force-enhanced steering task. The model suggests that for passive constraint guiding, increasing the guiding force has the same effect as increasing the width of the tunnel. Therefore, if for some reasons the width of a tunnel needs to be reduced, e.g. as a result of increasing the number of menu items, the guiding force should be increased to achieve similar performance levels. Conversely, if the width of a tunnel is increased, the guiding force can be reduced.

9 Conclusion and Future Work

We presented and empirically validated a model for force-enhanced steering tasks. We derived the model from the well-known steering law [1] with the addition of the guiding force. In two experiments, we demonstrated that the proposed model can be used effectively to predict movement time for steering tasks when force-guidance is provided. The model suggests that providing guiding force orthogonal to hand movement has the same effect as enlarging the width of the tunnel. We explored user performance with respect to the intensity of the guiding force. Results show that the effects of force-guidance on movement time reduced as the intensity of guiding force increased. This suggests that the maximum force of a force-feedback device is not necessarily be the most suitable for achieving the best performance.

Future work will focus on producing design guidelines for force-enhanced interaction for specific tasks. We are also interested in finding a model for the tasks where force-guidance is provided in an active manner, i.e. when a user's hand is haptically led by the guiding force through an ideal trajectory.

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