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Modeling the Effect of Force Feedback for 3D Steering Tasks

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Abstract

Path steering is an interaction task of how quickly one may navigate through a path. The steering law, proposed by Accot and Zhai [AZ97], is a predictive model which describes the time to accomplish a 2D steering task as a function of the path length and width.

In this paper, we study a 3D steering task in the presence of force feedback. Our goal is to extend the application of the steering law in such a task and find out, if possible, additional predictors for users' temporal performance. In particular, we quantitatively examine how the amount of force feedback influences the movement time.

We have carried out a repeated-measures-design experiment with varying path length, width and force magnitude. The results indicate that the movement time can be successfully modeled by path length, width and force magnitude. The relationship evidences that the efficiency of the tasks can be improved once an appropriate force magnitude is applied. Additionally, we have compared the capacity of our model to the steering law. According to Akaike Information Criterion (AIC), our model provides a better description for the movement time when the force magnitude can vary. The new model can be utilized as a guideline for designing the experiments with a haptic device.

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1. Introduction

Path steering is a common interaction task in which users are required to quickly navigate, or steer through a path with a given length and width. Driving a car down a road, for example, is a typical steering task in the real world. Navigating through a nested menu or drawing a curve within a boundary can be considered examples in human-computer interaction.

In 1997, Accot and Zhai [AZ97] proposed that the time to rapidly steer through a 2D path is predictable given the path length and width. They empirically substantiated their claim and mathematically formulated the relationship in a *steering law*, where the steering time is expressed as a function of the path length and width. The steering law has been extensively used to model 2D steering tasks [NKK04, Pas06, GHB*06]. Accot and Zhai have also confirmed its validity on 3D locomotion tasks [ZAW04]. We [LbML11, LbML10] extended the steering law with the path curvature and orientation, and have applied it to 3D manipulation tasks.

In this paper, we introduce *force feedback* to 3D path steering tasks. Our goal is to examine how the amount of force feedback influences the efficiency of performing 3D manipulation steering tasks and how this amount can be quantitatively modeled, in addition to path length and width, in a law.

Recently, the benefit of utilizing haptic technology in human-computer interaction has been investigated. As the experimental evidence shows, the adoption of force feedback significantly improved users' efficiency and accuracy for completing pointing tasks [DY01, KMIH05, VNCL05]. Force feedback also greatly facilitated users' capability of easily and quickly performing steering tasks [DMH00, Ahl05, ZnYIS09]. There have been, however, few studies focusing on the effect of varying force magnitude (or in-

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tensity) on user's temporal performance for steering tasks. Does a stronger force magnitude always result in better performance than a weaker magnitude? Is there an interval of optimal force magnitude, within which user's performance can be significantly improved? Gaining knowledge of force magnitude in steering tasks may help us control the amount of force feedback exerted to the tasks and make better use of the haptic devices.

The contributions of the paper are summarized as follows:

- We empirically verified the steering law for 3D path steering tasks in the presence of force feedback.
- We proposed an extended steering law, introducing force magnitude as a predictor for movement time, and empirically validated the new law.
- We compared the new law to the steering law and evidenced the new law's merits in dealing with varying force magnitude.

2. Related Work

Modeling, in human-computer interaction, is a quantitative description for an interaction task. It is usually expressed as a relationship between human temporal performance and the spatial characteristics of the task. One well-formulated model is Fitts' law [Fit54], a mathematical description used to model pointing tasks. The common formulation of the law is as follows:

$$T = a + b\,\mathrm{ID} = a + b\,\log_2(\frac{L}{W} + 1) \tag{1}$$

where a and b are experimentally determined constants, L is the distance to the target, and W is the target width. The term $\log_2(L/W + 1)$ is referred to as the index of difficulty (ID) of a pointing task. Fitts' law quantitatively predicts that the time to rapidly move to a target is subject to the distance to and size of the target.

In 1997, Accot and Zhai proposed the steering law [AZ97] for path steering tasks. The general idea of the steering law hypothesizes that a path steering task is composed of an infinite number of goal crossing tasks, each of which could be separately modeled by Fitts' law. For a path with a constant width, the steering law can be simply expressed in the following formula:

$$T = a + b\,\mathrm{ID} = a + b\,\frac{L}{W} \tag{2}$$

where a and b are empirically determined constants, and L and W are the length and width of the path.

The steering law has been adapted to various environments. For instance, Kattinakere et al. [KGS07] proposed to take the "height" of a path into account, which leads to a 3D steering law:

$$T = a + b\,\sqrt{(\frac{L}{W})^2 + \eta(\frac{L}{T})^2} \tag{3}$$

where η is an empirically determined constant and T represents the thickness of the path above the display. We [LbML11] evaluated the effect of path curvature and orientation in a 3D steering task and modeled the effect in a formula below:

$$\log T = a + b\,(\log\frac{L}{W} + c\rho + d\cos(\alpha) + e\cos(\beta) + f\sin(\beta) + g\cos(2\beta) + h\sin(2\beta)) \tag{4}$$

where ρ is the path curvature, and α and β are two factors for describing the path orientation. In Keefe's work [Kee07], they also examined the effect of path curvature and orientation, but several new laws (see Equation 5.20-5.23 in [Kee07]) were proposed in the presence of force feedback.

Though the use of force feedback to enhance human computer interaction has often been discussed, it was not until 2009 that Yang et al. [YIBB09] took the first step toward modeling the effect of force feedback for a 2D steering task. They considered the intensity of a force guidance as a predictor for the steering time and derived a model based on Accot and Zhai's goal-crossing idea. The force guidance was applied in such a way that deviations from the center of the path were pulled back with a force that was proportional to the distance deviated. It resembles the effect of installing a spring at the center of the path, which is equivalent to increasing the width of the path. They modeled the task in the following form:

$$T = a + b\,\frac{L}{W + \eta \times S} \tag{5}$$

where η is an empirically determined constant, and S denotes the spring stiffness.

In this paper, we also study the effect of force feedback for steering tasks. The difference, however, is that we propose a law in the context of 3D haptic steering tasks, in which force feedback is more like a real-world-simulated task and users feel the feedback of pushing (or pulling) a ball through a tunnel. It is obvious that the effect of force magnitude should function distinctly in such a task.

3. Experiment

3.1. Apparatus and Environment

The experiment was carried out in a desktop PC environment (Figure 1) equipped with a high-end GPU. The output devices include a Samsung 67-inch 3D-capable LED DLP HDTV (1920 × 1080 @ 120Hz) and a pair of Crystal Eyes stereoscopic LCD glasses (@120Hz) to enable the Stereo3D viewing. We used a Logitech 6DOF ultrasound head tracker (@60Hz) and a Novint Falcon (a 3DOF haptic device @700Hz) as the input devices. To decrease the computational complexity, the scene was rendered @60Hz and the data were logged @120Hz. Figure 2 depicts the experimental setup. Users' motor and visual space were non-colocated, i.e. there was a distance of 0.65m between the centers of the

Figure 1: *The experimental environment. The depth cues include the stereoscopic viewing, head tracking, head lighting, a 0.72m × 0.4m × 0.4m sized wire-frame box and a chessboard pattern floor.*

visual and motor space. Subjects were seated 1.35m away from the display and were required not to rest their dominant arms on the table or armrest. To compensate the large distance between the subjects and the display, and the small motor space of the device (around 0.10m × 0.10m × 0.10m), the Control/Display (C/D) ratio [CVBC08] was set to 1/5 to visually expand the scene.

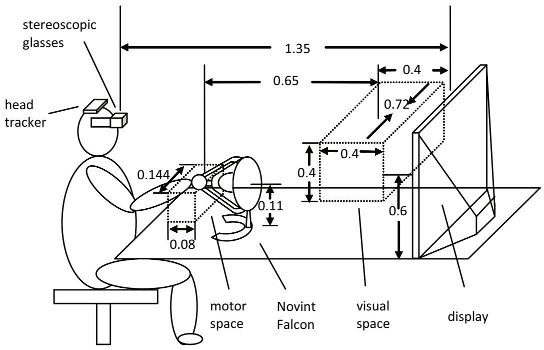

Figure 2: *The experimental setup (units: meter). The motor and visual space are not co-located and C/D ratio = 1/5.*

3.2. Subject

Twelve right-handed subjects voluntarily participated in the experiment. All subjects had normal or corrected to normal vision. Two of them were females and eight had previous experience of working with virtual environments. The subjects' age ranged from 28 to 35, with an average of 31.7.

3.3. Task

We adopted a 3D *ball and tunnel* interactive path steering task (see Figure 3, left), which was proposed by us in [LbML11, LbML10]. The task is different from the general *ring and wire* [ZAW04] (see Figure 3, right) task in the sense that the orientation of the input device is not playing a part in the ball and tunnel task. It is a more straightforward extension to the 2D steering tasks [AZ97].

The subjects were required to hold the Falcon's grip, represented as a small spherical cursor (*cursor ball*) in the virtual environment, to push a big spherical target (*target ball*) through a 3D tunnel. The tunnel was always positioned in x-y plane with depth of zero. The target ball is constrained to the boundary of the tunnel, so that the width of the tunnel is defined by the diameter of the target ball and the target ball can only move in one direction, i.e. along the tunnel. The goal of the task is to push the target ball from one end

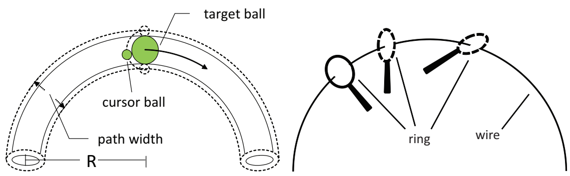

Figure 3: *The* ball and tunnel *task (left) and* ring and wire *task (right). In the ball and tunnel task, a cursor ball pushes a target ball through a tunnel. Tunnel width = diameter of target ball; Steering path width = tunnel width + 2 × radius of cursor ball.*

of the tunnel to the other. Subjects were required to navigate through the tunnel as fast and accurate as possible. In view of the task difficulty, subjects were allowed to make mistakes and were given the opportunities for correction. This occurs whenever the subjects steer the cursor ball beyond the boundary of the tunnel, i.e. the cursor ball is not in contact with the target ball, and is defined as a *correction phase*. In the correction phase, the target ball remains where it was until the subjects steer the cursor ball back to the target ball and resume the task where they left off. The target ball, under such circumstances, functions as a progress indicator and remembers the last position in the tunnel before the cursor ball is derailed. The phase when the target ball is pushed through the tunnel is defined as a *steering phase*. Both cursor and target ball are colored green in the steering phase, and changed to red in the correction phase. As the maximum range that can be reached by the cursor ball during the steering phase defines the boundary of the steering task, the valid path width is not the tunnel width, but the sum of tunnel width and two times the cursor ball radius instead (see Figure 3, left).

In the steering phase, Falcon generates smooth and continuous force feedback as the subjects steer the cursor ball and push the target ball through the tunnel. As shown in Figure 4, the haptic feedback is rendered to closely resemble the physical forces that would occur in the real world. The force $F3$ is a resultant force that is composed of a reacting force

$F1$ exerted by the target ball, equal and opposite to the force that is exerted to the target ball by the cursor ball, and a friction $F2$ at the point where target ball and cursor ball contact, i.e. $F3 = F1 + F2$. A constant magnitude is applied to $F2$. Though the magnitude of $F1$ is fixed in one trial during the experiments, it may vary among different trials. Our aim is to investigate how the movement time is influenced by the magnitude of $F1$. The current study focuses on the type of force that is applied (approximately) along the direction of the movement so that a guiding force perpendicular to the direction of the movement, e.g. dragging the cursor ball back to the tunnel center once a deviation is detected or applying a force as the cursor ball is in contact with the boundary of the tunnel, is not rendered in this work. To avoid jerky movements, we introduced a damping factor to the force, which also takes the previous force direction into account. The effect of $F1$ in such a task simulates a push feedback. During the experiment, we also implemented a pull feedback that is equal but opposite to $F1$. Under the circumstances, the cursor ball and target seemed to have the opposite magnetic fields and the cursor ball was attracted by the target ball such that users felt dragged along the tunnel. These haptic navigation tasks can be found in many applications, such as assisting users in controlling a 6DOF input device in a blood vessel in medical simulation or guiding the blind in walking on a street.

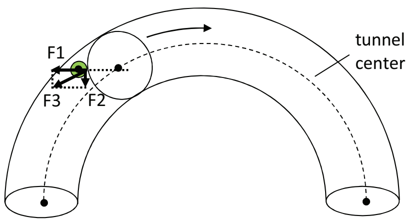

Figure 4: *The force feedback generated by Falcon.*

3.4. Procedure

We have conducted an experiment with a repeated-measures design, in which paths of varying length and width, and force $F1$ with varying magnitude are introduced. The specific settings for each property include:

- path length (L): 0.24, 0.30 and 0.36m;
- path width (W): 0.03 and 0.04m;
- force magnitude (F): -0.6, -0.4, -0.2, 0, 0.2, 0.4, 0.6, 0.8, 1.0N.

A positive F actually indicates how much resistance is applied to the subjects while they are pushing the ball. The greater the value, the bigger the resistance. Intuitively, a negative F implies how much assistance is applied to the task. This is the effect of being attracted by the target ball. The greater the absolute value, the bigger the assistance. Path properties were kept similar to that of the experiment conducted in [LbML10], except that the path curvature ρ was fixed to 8m^{-1}. Note that due to C/D ratio = 1/5, the sizes of path length and width in the motor space are only 1/5 of their visual sizes mentioned above. These settings make sure that the movement of the arm falls within the Falcon's 3D touch workspace (0.10m × 0.10m × 0.10m). Each condition (a combination of path properties and force magnitude) was repeated 3 times, resulting in 3 × 2 × 9 × 3 trials ($L \times W \times F \times repetition$) per subject. There were in total 1944 trials for 12 subjects.

Subjects were required to practice an equal number of trials under each condition before starting the experiment. Trials of an experiment were presented in a random order that differed from one subject to another. Subjects were allowed to have a break whenever they suffered from fatigue between trials. This was, however, strictly prohibited during a trial.

One trial starts when the target ball departs from the initial position and proceeds until it reaches the destination. A continuous steering without any correction on a segment of the path is defined as a *sub-trial*. Since there usually has to be correction phases involved, a complete trial can be broken into several sub-trials. The time to steer through a sub-trial is defined as the *sub-trial time*. The *steering time* is defined as the sum of all the sub-trial time within a trial, while the *correction time* is the total amount of time that is spent on the correction phase. Accordingly, a *total completion time* is the sum of the steering time and the correction time in a trial.

4. Result

The goal of the paper is to investigate the relationship between the movement time and the effect of path length (L), width (W) and force magnitude (F), and quantitatively describe the movement time, if possible, as a function of L, W and F. As the effect of L and W has been empirically verified in the steering law (see Equation 2), we consider L and W as one independent variable ID which satisfies $ID = L/W$. The sub-goal is therefore to quest for such a description that $T = f(ID, F)$. This section specifies how such a description can be statistically derived.

4.1. Data Preprocessing

To preprocess the data, the steering time, correction time and total completion time have been logarithmically transformed. Unless otherwise explicitly stated, the base for the logarithmic transformation used in this paper is 10. This is due to the fact that the data analysis in this paper involves ANOVA and regression, which requires the assumptions of independence, normality and homoscedasticity of the data.

The way the experiment is conducted ensures the independence. The fact that the transformed data (the steering time, correction time or total completion time) have a normal distribution cannot be rejected ($h = 0$), as evidence by

Kolmogorov-Smirnov test, indicates the normality. The Levene's test verifies that there is no statistically significant difference ($F_F(8,1935) = 0.2451, p_F = 0.9821$; $F_{ID}(5,1938) = 0.3990, p_{ID} = 0.8498$) between the variances of steering time among 9 Fs and those among 6 IDs, respectively, i.e. the assumption of homoscedasticity for steering time is also met in terms of the independent variables F and ID, correspondingly. The same results apply to the variances of the correction time and total completion time.

4.2. Modeling the effect of Path Length and Width: $T = f(L,W) = f(ID)$

In essence, modeling the effect of ID (or $\log(L/W)$) is the procedure of verifying the steering law (Equation 2) in the presence of force feedback. We have carried out a repeated-measures ANOVA for the average steering time that arises from different IDs. The corresponding results are demonstrated in Figure 5. As shown, there is a statistically significant difference between $\log(T_{steering})$ of different IDs ($F(5,55) = 135.320, p < 0.0001$). The trend that the steering time increases as the ID grows can be statistically modeled by a linear function that passes through the confidence intervals. The goodness of fit can be evaluated by $R^2 = 0.9940$ and $SSE = 0.0003$. It implies that there is a strong correlation between the model and the empirical data. The parameter estimates for the linear regression as shown in Table 1 specify that both the term constant (indicated by coefficient a) and ID (coefficient b) are significant in modeling the steering time. It is evident that the steering law can be applied to the 3D path steering tasks conducted with a haptic device. A similar data analysis has been done for the correction time and the total completion time. As shown in Figure 6 and 7, both the correction time and total completion time can be statistically modeled as a linear function of ID. As shown, the steering law can be used to predict the steering time, correction time and total completion time for the 3D path steering tasks defined in the experiment in the presence of force feedback.

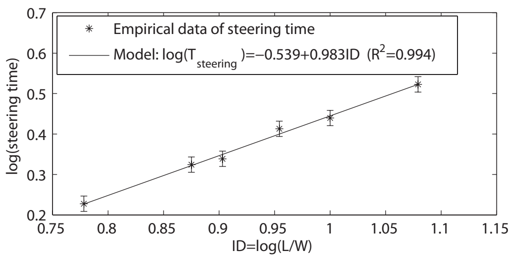

Figure 5: *The repeated-measures ANOVA for the steering time of different IDs and the linear regression. The error bars represent the corresponding 95% confidence intervals. The oblique line that crosses through the confidence intervals is the linear model fitting with Equation 2.*

	Estimate	t value	P> |t|	[95% CI]
a	-0.539	-15.0	< 0.001	[-0.638, -0.439]
b	0.983	25.65	< 0.001	[0.878, 1.090]

Table 1: *The parameter estimates of Equation 2 fitting on the empirical data.*

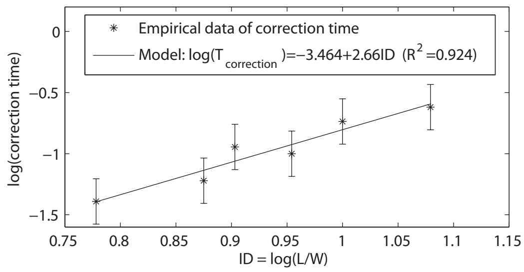

Figure 6: *The repeated-measures ANOVA for the correction time of different IDs ($F(5,55) = 11.161, p < 0.0001$) and the linear regression.*

4.3. Modeling the Effect of Force Magnitude: $T = f(F)$

In this section, we examine the effect of force magnitude F on the movement time. Trials of the same force magnitude are grouped and averaged in terms of the steering time, correction time and total completion time, respectively.

Figure 8 illustrates the repeated-measures ANOVA for the average steering time of different force magnitudes F. There is statistical evidence ($F(8,88) = 83.052, p < 0.0001$) showing that the difference between the steering time of various F is significant. In addition, the effect of F seems different between positive and negative values, which indeed represents different types of force feedback (push and pull). As F grows in the positive interval, the steering time drops till a valley ($F \in [0.2, 0.4]$), after which it goes up. The tendency that the steering time before and after the valley is symmetric very much resembles a parabola that describes a quadric relation-

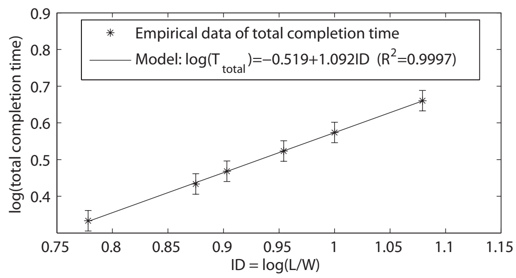

Figure 7: *The repeated-measures ANOVA for the total completion time of different IDs ($F(5,55) = 76.595, p < 0.0001$) and the linear regression.*

ship between $\log(T_{steering})$ and F. For the case $F < 0$, the steering time decreases as the absolute value of F increases. The trend, however, does not appear to be linear. Instead, the amount of decrease in the steering time becomes smaller as F deviates from 0. It is preferable to exponentially model this relationship, since steering time can not go below a threshold due to human motor system. We propose to model

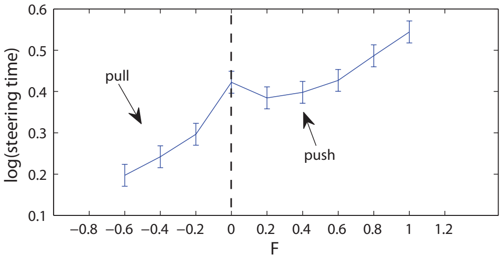

Figure 8: *The repeated-measures ANOVA for the steering time of different force magnitude.*

the effect of force magnitude in a piecewise function below:

$$\log(T) = \begin{cases} a_1 + b_1\ \mathrm{F} + c_1\ \mathrm{F}^2 & (F \geq 0) \\ a_2 + b_2^{\mathrm{F}} & (F < 0) \end{cases} \quad (6)$$

where a_1, b_1, c_1, a_2 and b_2 are empirically determined constants, and F is the force magnitude, with positive value representing a push feedback and negative a pull.

As shown in Figure 9, the steering time can be statistically modeled by Equation 6. The goodness of fit for the two models can be evaluated by $R^2 = 0.9832$ $(F >= 0)$ and $R^2 = 0.9519$ $(F < 0)$. Table 2 and 3 specify the related parameter estimates. As evidenced, each of the parameters in the tables is significant ($p < 0.05$) for modeling the steering time. Analogous to the analysis above, we have performed

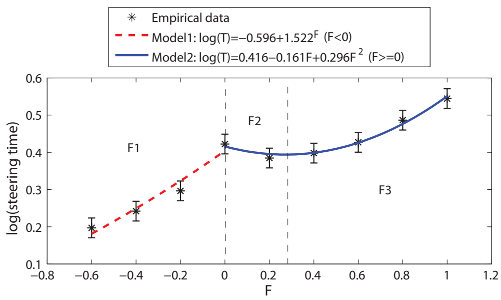

Figure 9: *Modeling* $\log(steeringtime)$ *as a function of* F. *The dotted red curve is the model when a pull feedback is applied, while the blue solid curve is the model using a push feedback.*

	Estimate	t value	P> |t|	[95% CI]
a_1	0.416	45.398	< 0.001	[0.387, 0.445]
b_1	-0.161	-3.738	0.033	[-0.298, -0.024]
c_1	0.296	7.156	0.006	[0.164, 0.428]

Table 2: *The parameter estimates of Equation 6 ($F >= 0$, top) fitting on the empirical data.*

	Estimate	t value	P> |t|	[95% CI]
a_2	-0.596	-26.25	0.001	[-0.694, -0.498]
b_2	1.522	13.31	0.006	[1.030, 2.014]

Table 3: *The parameter estimates of Equation 6 ($F < 0$, bottom) fitting on the empirical data.*

the same procedure for the correction time and total completion time. The results also indicate that Equation 6 can be used to model the correction time and total completion time.

4.4. Modeling the Combined Effect of Path Length, Width and Force Magnitude: $T = f(L, W, F) = f(ID, F)$

As shown above, the effect of ID and F has been separately examined. In this section, we aim to combine the models proposed in section 4.2 and 4.3, and generate a comprehensive model that involves both ID and F as the independent variables. The new model is shown as follows:

$$\log(T) = \begin{cases} a_1 + b_1\ \mathrm{ID} + c_1\ \mathrm{F} + d_1\ \mathrm{F}^2 & (F \geq 0) \\ a_2 + b_2\ \mathrm{ID} + c_2^{\mathrm{F}} & (F < 0) \end{cases} \quad (7)$$

Fitting Equation 7 onto the steering time, we manage to find a satisfactory goodness of fit ($R^2 = 0.9653$ $(F >= 0)$ and $R^2 = 0.9514$ $(F < 0)$). The parameter estimates shown in Table 4 and 5 indicate that all the terms appearing in Equation 7 are statistically significant for modeling the steering time. Similarly, there is also statistical evidence showing that Equation 7 can be used to successfully predict the correction time and total completion time.

	Estimate	t value	P> |t|	[95% CI]
a_1	-0.529	-14.172	< 0.001	[-0.605, -0.453]
b_1	1.014	25.951	< 0.001	[0.934, 1.094]
c_1	-0.161	-4.133	< 0.001	[-0.240, -0.082]
d_1	0.296	7.917	< 0.001	[0.220, 0.372]

Table 4: *The parameter estimates of Equation 7 ($F >= 0$, top) fitting on the empirical data.*

	Estimate	t value	P> |t|	[95% CI]
a_2	-1.512	-24.77	< 0.001	[-1.639, -1.385]
b_2	0.983	15.24	< 0.001	[0.849, 1.117]
c_2	1.522	28.32	< 0.001	[1.411, 1.634]

Table 5: *The parameter estimates of Equation 7 ($F < 0$, bottom) fitting on the empirical data.*

5. Discussion

As shown in Figure 9, to analyze the effect of force magnitude, we divide F into three intervals ($F1, F2$ and $F3$) based on the monotonicity of the function. $F1$ is the area when $F < 0$ and a certain amount of pull is applied to the device. The minus sign only implies that the force exerted to the device is opposite to the direction it should have been exerted in a ball-pushing task. Rather than feeling pushed (a resistance), the subjects are pulled toward the direction in which they operate the input device. The type of force actually facilitates the subjects by moving to the direction they were expecting and the absolute value of F indicates the amount of assistance. It is intuitive to find out that the steering time decreases as the amount of pull increases. As seen from Figure 9, however, the reduction in steering time becomes smaller as the force increases, indicating that there must be an F, around which no significant reduction in steering time can be observed. Due to the limited number of force magnitude (four points in $F1$), the model we proposed in Equation 7 (for $F < 0$ part) may slightly vary in the face of more data points. Our focus is to show such a trend, instead of an extremely accurate model.

$F2$ and $F3$ are the intervals when $F >= 0$. This is a more realistic case when a resistance haptic feedback is provided as the subjects push a target ball through a tunnel. It is interesting to witness that the steering time falls with the growth of the resistance in $F2$. In a real world task, the fact may contradict our common sense, since the resistance usually leads to a longer steering time. In virtual reality, however, this is the argument for utilizing haptic feedback in human-computer interaction. For our experiment, the steering time reaches its valley at point $F = 0.27N$, after which it goes up again. It illustrates that without force feedback, the steering tasks in virtual reality can be time-consuming. With an appropriate amount of force guidance, the efficiency for the steering tasks can be reasonably improved, whereas with too much force feedback, the efficiency may be dramatically deteriorated. We can imagine that there must be an F in interval $F3$ which makes the tasks too difficulty to accomplish so that the time required to navigate through the tunnel is almost beyond our tolerance. We are not interested in introducing larger resistance, but in figuring out a proper amount of force feedback, once applied, can improve the efficiency for path steering tasks. The model we proposed as in Equation 7 can be used to quantitatively determine the value of F for the shortest steering time and serve as a guideline for introducing an appropriate force magnitude in the steering tasks.

In Section 4.2 and 4.4, we have statistically demonstrated that both the steering law (Equation 2) and the model we proposed in this paper (Equation 7) provide satisfactory goodness of fit ($R^2 > 0.95$) using the data in our experiment. However, a greater R^2 does not necessarily imply a better model when the number of independent variables appearing in a model differs from that of other models. A better way to compare between models is to adopt the Akaike Information Criterion (AIC) [Aka74], which was developed to find the model, among a candidate set of models, that best explains the data with the fewest free parameters. In this paper, we adopted an improved criterion that is defined as Akaike's second-order corrected Information Criterion (AICc) [HT89]:

$$AICc = n\ln(\frac{RSS}{n}) + 2K + \frac{2K(K+1)}{n-K-1} \tag{8}$$

where K is the number of parameters in the model (including constant term and error term), n is the number of observations and RSS is the residual sum of squares.

The AICc of the two models has been shown in Table 6 and 7. Table 6 compares the steering law with the upper formula in Equation 7, i.e. the case of $F >= 0$. Therefore, the data for $F < 0$ are not taken into account. In Table 7, we compare the steering law with the lower formula of Equation 7 and the data for $F >= 0$ have been removed. This explains why different AICc values are obtained for the same model. The proposed law, as demonstrated above, provides smaller AICc in comparison with the steering law, indicating that the proposed law loses less information when used to model the steering tasks with varying force feedback. The same conclusion applies to the correction time and total completion time, i.e. Equation 7 gives a better description for the correction time and total completion time than the steering law.

Model	K	RSS	AICc
$\log(T) = a + b\,\mathrm{ID}$	3	20.9	-1301.7
$\log(T) = a + b\,\mathrm{ID} + c\,\mathrm{F} + d\,\mathrm{F}^2$	5	19.6	-1325.1

Table 6: *AICc comparison: steering law vs. proposed law (Equation 7, $F >= 0$)*

Model	K	RSS	AICc
$\log(T) = a + b\,\mathrm{ID}$	3	14.2	-861.6537
$\log(T) = a + b\,\mathrm{ID} + c^{\mathrm{F}}$	4	12.2	-902.3461

Table 7: *AICc comparison: steering law vs. proposed law (Equation 7, $F < 0$)*

The experiment conducted in this paper only includes the path with a fixed curvature ($\rho = 8$). If we examine a more general case in which the path curvature can vary between the trials, we may find that path curvature is another significant parameter for predicting the movement time, as it is shown by our previous studies [LbML11, LbML10] in the absence of force feedback. We hypothesize that the effect of path curvature in the presence of force feedback is independent of that of path length, width and force magnitude, which can be further expressed in the following formula:

$$\log(T) = \begin{cases} a_1 + b_1 \log(\frac{L}{W}) + c_1 \rho + d_1 \mathrm{F} + e_1 \mathrm{F}^2 \ (F \geq 0) \\ a_2 + b_2 \log(\frac{L}{W}) + c_2 \rho + d_2^{\mathrm{F}} \ (F < 0) \end{cases} \tag{9}$$

where ρ represents the path curvature. We need to verify Equation 9 for the 3D path steering tasks of varying path curvature and force magnitude.

6. Conclusion

In this paper, we examine the effect of force feedback for 3D path steering tasks. We have carried out an experiment with a repeated-measures design, which included variable path length (L), width (W) and force magnitude (F). As the experimental results indicate, the movement time, including the steering time, correction time and total completion time, can be statistically modeled as a function of L, W and F, each of which has been evidenced its significance. The model provides an approach to determine an appropriate interval of F, within which the efficiency of steering through a tunnel can be improved. It can be utilized as a tool for designing the steering experiments with the haptic devices.

In addition, we have also verified the application of the steering law to the haptic steering tasks and the capacity of the steering law in such tasks has been compared to our model. According to Akaike Information Criterion (AIC), our model loses less information than the steering law when it is used to predict the movement time in the F-adjustable haptic steering tasks.

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