Evaluating Factors that Influence Path Tracing with Passive Haptic Guidance

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Abstract. A very common task in medical applications and motor-skill training is to trace a path. However, when designing a haptically guided interface, designers need to consider the choice of several parameters in the design. These include the real-time function for bringing back the user to the right path, the effect of the path's curvature on tracing, and the amount of haptic force needed for guiding the user appropriately. In this paper, we describe the results of an experiment that was designed to assess the effect of several design factors that can influence the performance of path tracing tasks. Our results show that the shape of the path has an effect on the amount of deviation from a path. Additionally, we found that a high amount of stiffness is preferred over low stiffness. Finally, the type of force profile that haptically guides the user, particularly the slope of the function, is also an important factor in path tracing tasks. We discuss our results with implications for designs of systems necessitating haptic force feedback in constrained path tracing tasks.

Keywords: Haptic guidance, haptic interface, motor skill training, force feedback.

1 Introduction

Tracing a path accurately is important in many tasks including medical applications and motor-skill training. Medical applications such as tele-ultrasound scanning and bronchoscopy require an operator to guide a probe along a defined path obtained from one or more video streams. Significant deviations from the path (this happens when an ultrasound probe is lifted too far off the patient's body) during a trace will result in incoherent images or can harm the patient (both ultrasound and bronchoscopy). Motor-skill learning is contingent on a number of factors: motivation, practice, learning strategies, and guidance techniques. However, physical guidance is of particular importance because if a learner is unable to trace a trajectory and stay on the path, he/she would not learn the properties of the trajectory in the first place, negatively impacting learning regardless of motivation levels, amount of practice or any other factor. It would be unrealistic to expect any gains in learning outcomes if the guidance was flawed.

M.E. Altinsoy, U. Jekosch, and S. Brewster (Eds.): HAID 2009, LNCS 5763, pp. 21–30, 2009.

Recently, haptic-guidance systems have been widely used in facilitating precise path tracing in medical applications [13, 14, 15] and in motor-skill training systems [2, 4, 7, 8, 11, 12]. In these systems, the haptic guidance ensures that users would not significantly deviate from the intended path. The intensity of the constrained force is considered an important factor in constraining a user's hand movement within an ideal trajectory. However, numerous other parameters can affect the user's ability to accurately trace a path. These include the force profile that maps the changes in force magnitude as a function of the distance of deviation from the path, and the effect of path or track shape on tracing performance. The contribution of this paper is largely an exploration of which parameters influence haptic path tracing. This knowledge can in turn be used by designer given the constraints of the system they are designing for. In the next section, we briefly present related work and then the results of one experiment we carried out to address the effect of these factors on haptic guidance tasks.

2 Related Work

The concept of haptic guidance can be traced back to "virtual fixture" [9]. Recently, haptic feedback for accurate path tracing has been applied to numerous applications. Tao et al. [12] demonstrated the value of a hand-writing system that teaches novices to write Chinese characters. They use haptic feedback forces that guide the hand on the right track when the student deviates from the path traces defined by the tutor.

Feygin et al. [3] evaluated the effects of different feedback conditions on users' ability to trace paths. They found that haptic+visual feedback facilitated the highest amount of learning. They also found that the shapes of the trajectories used in their study had an effect of learning performance. Similarly, Yang et al. [16] demonstrated that some trajectories of shapes are easier learned than others. Pastel [6]'s study showed that negotiating a 90° corner is more difficult than negotiating a 45° or 135° corner. Their study also revealed that users tended to make shortcut at corners by "cutting off the corner". However, it is not clear whether this is also the case when haptic guidance is provided. In particular, little is known about the extra provisions that are necessary in the haptic guidance system for assisting users to trace shapes of different curvatures.

Many of the existing haptic-guidance systems provide variable constrained force such that the force magnitude changes as a function of deviation from the path. For instance, Avizzano et al. [1] used a linear force function to generate constrained force. Kim and Yang [5] implemented various force functions (linear, logarithmic, and exponential) in their handwriting training system. But they did not conclusively suggest which types of force profiles provide sufficient accuracy for path tracing.

3 Experiment

The goal of this experiment was to evaluate the different factors that can influence the performance of path tracing with a passive haptic guidance system [16]. In particular we investigated the effect of path shape and force profile. Furthermore, it is anticipated that spring stiffness may affect tracing performance. We also confirm this in our study.

3.1 Participants and Apparatus

Nine students from a local university participated in this study. All of them were right-handed, and reported a normal to corrected-to-normal vision. None of the participants had any experience with haptic devices.

Haptic feedback was provided by a PHANToM Desktop haptic device [10]. The test system displayed the various paths that users were required to trace on a 300×300 square region in the middle of a 19 inch 1024×768 LCD display (0.4×0.4mm/pixel). Participants were asked to hold the stylus of the PHANToM device like holding a pen, and to control the experiment by pressing the button on the stylus. The shapes that users were asked to trace were two-dimensional and were laid out in the vertical plane (Fig. 1).

3.2 Procedure and Design

The study employed a 4×3×2 within-subject factorial design. The factors were path or Track Shape (TS), Force Profile (FP) and Spring Stiffness, or simply Stiffness (S). Trajectory shape was fully counterbalanced. Force profile and stiffness were presented in random order. The experiment consisted of 5 repeated trials. We collected a total of 4 (tracks) × 3 (force profiles) × 2 (stiffnesses) × 5 (trials) × 9 (participants) = 1080 trials. The participants were asked to trace a defined path with the help of haptic guidance, as accurately as possible. To ensure a complete trial, the participants were asked to indicate the start and the end of a trial by pressing the button on the stylus of the PHANToM device. Participants practiced for 5 minutes prior to the experiment to get familiar with the environment and procedures. We describe the various levels of conditions in the following sections.

Path or Track Shape. Participants were required to trace four trajectories, square, circle, S-shape, and 5-shape (Fig. 1). The tracks were generated by a graphical system and consisted of paths with a smooth curvature (circle and S-Shape) and two paths consisting of sharp corners (Square and 5-Shape).

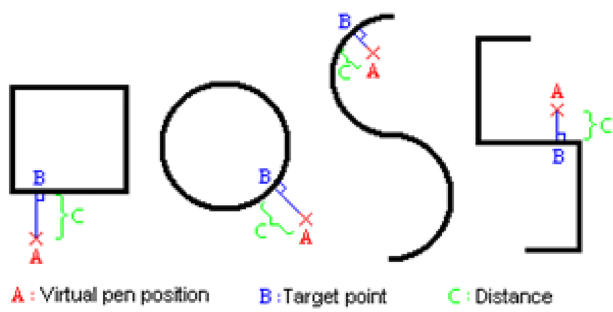

Fig. 1. The four paths used in the study. The S-Shape and 5-Shape paths were generated by slicing the square and circle in half and flipping the half pieces. All tracks consisted of the same length.

Force Profile. Similar to [5], we evaluated three force profile functions, a linear function, a logarithmic and a quadratic. The slope of these function is in the order that $S_{logarithmic} > S_{linear} > S_{quadratic}$ within the tolerance distance (within 1 pixel away from the ideal path), and $S_{quadratic} > S_{linear} > S_{logarithmic}$ otherwise. Force magnitude was computed using Hooke's Law, and more specifically defined with respect to the distance of deviation as follows:

$$\boldsymbol{Force} = K_i * Function_j(Distance) \tag{1}$$

where *Distance* is the distance between end-effector position and the target position on a given trajectory (i.e. deviation from path), subscribe *i* is either low or high stiffness (see below), and *j* is either *linear*, *logarithmic,* or *quadratic* force profiles. The constants we used for each of the force profiles are provided below and resulted in the profiles presented in Fig. 2.

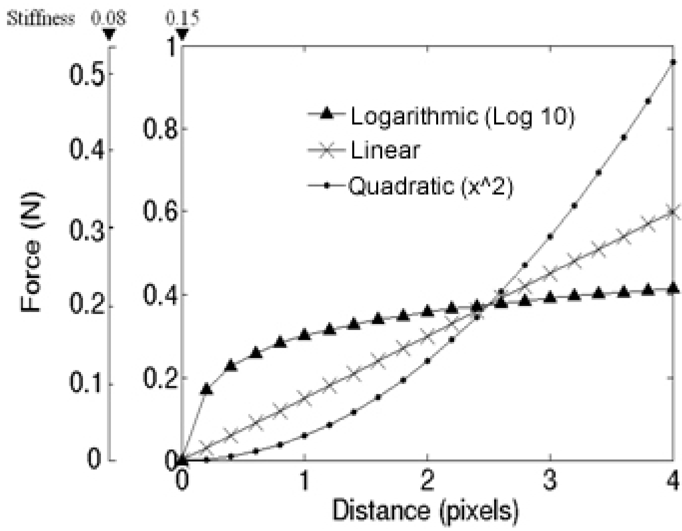

Fig. 2. Force profiles used in the experiment

Force functions which have been used are as following, where *x* is the distance in pixel.

$$\boldsymbol{F}_{linear}(x) = ax + b, \text{ where } a=1, \text{ and } b=0; \tag{2}$$

$$\boldsymbol{F}_{log}(x) = a\log_b(c*x), \text{ where } a=1.25, b=10, \text{ and } c=40 \\ (\boldsymbol{F}_{log}(x) = 0 \text{ when } x = 0); \tag{3}$$

$$\boldsymbol{F}_{quadratic}(x) = ax^2+b, \text{ where } a=0.4, \text{ and } b=0. \tag{4}$$

Stiffness. Haptic guidance was implemented in a similar way to that described in [16]. The constrained force was generated passively so that it triggered only when the stylus deviated from the trajectory. The direction of the constraint force was always perpendicular to the direction of the hand movement. Fig. 1 depicts examples of our method for finding the target point on tracks of different shapes. The aim of this method is to guide the users' hand to the nearest point on the track. Two levels of stiffness were tested in order to confirm that spring stiffness affects users' performance on tracking given trajectories. A high stiffness or *hard spring* maintained a value of 0.15 N/mm and a low stiffness or *soft spring* consisted of a value of 0.08 N/mm.

3.3 Performance Measures

We used two metrics to assess tracking performance: Error Volume and percentage on-track. Error Volume (1) is an indicator of the average deviation distance from the path.

$$Error\ Volume = \frac{\sum_{n=1}^{N_1+N_2} Dist(X_n, X_\Gamma)}{N_2} \qquad (5)$$

where X_n is the n^{th} point on a given trajectory, N_2 is the number of points deviated form the path, and X_Γ is its corresponding point on the user trajectory. Percentage on-track (2) is a measure assessing the percentage of points that were on-track. In some applications [14], maintaining a path on the track for a large percentage of the trajectory is more important than the overall deviation amount.

$$Percentage\ on\text{-}track = (N1)/(N1 + N2) \times 100 \qquad (6)$$

where N_1 is the number of points on the path. We considered a point on-track if it was within a tolerance distance (1 pixel) to its corresponding point on the ideal trajectory.

4 Results and Discussion

We used the univariate ANOVA test and Tamhane post-hoc pair-wise tests (unequal variances) for all our analyses with subjects as random factor. We present our results for both metrics Error volume and Percentage on-track.

4.1 Error Volume

There was a significant effect of Force Profile (FP) ($F_{2,16} = 22.3$, $p < 0.001$), of Track Shape (TS) ($F_{3,24} = 3.91$, $p = 0.02$) and of Stiffness (S) ($F_{1,8} = 89.1$, $p < 0.001$) on Error volume. The error volume was larger with the soft spring and smaller with the hard spring. We found significant interaction effects between FP and S ($F_{2,16} = 17.57$, $p < 0.001$), a significant interaction between TS and S ($F_{3,24} = 3.92$, $p = 0.021$) but no interaction effects between FP and TS.

Post-hoc pair-wise comparisons for FP yielded significant differences for all pairs of functions (all $p < 0.01$). Users produced fewest errors with the quadratic function than the linear or logarithmic function (Fig. 3). Post-hoc pair-wise comparisons for TS did not yield any significant differences for all pairs of functions, except between Circle and 5-Shape ($p < 0.05$). Users produced fewest errors with the S-Shape (2.867, s.e. =0.76) followed by the Circle (2.889, s.e. =0.76), the Square (3.041, s.e. =0.76) and then finally the 5-Shape (3.373, s.e. =0.76) tracks.

Our results reveal an effect of FP on error volume. A quadratic force function facilitates a lower average error volume and best deviation margins than the other two functions (see final discussion). By mapping the mean error volumes shown in Fig. 3 to the force profile functions in Fig. 2, we found that the users were able to sense the guiding force of approximately 2.5 N and to correct wrong movements by following the guidance.

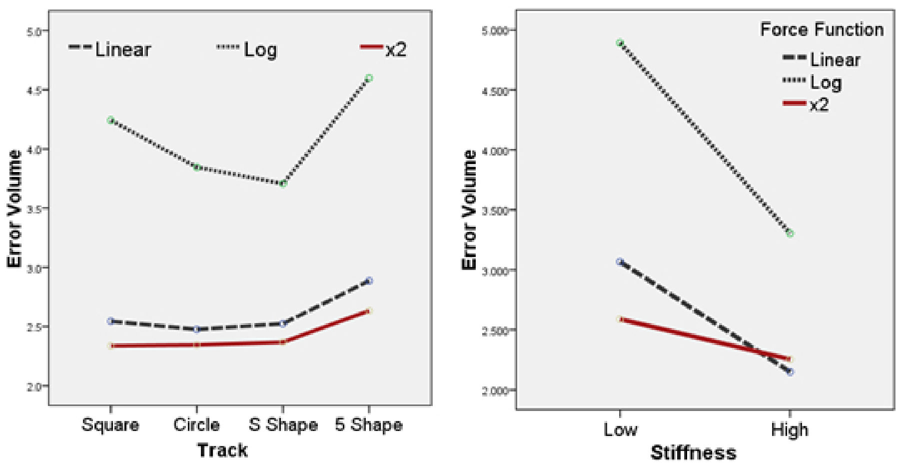

Fig. 3. Average error volume by force profile and track shape (left); and force profile and stiffness (right)

4.2 Percentage On-Track

There was a significant effect of FP ($F_{2,\,16} = 174.4$, $p < 0.001$), of TS ($F_{3,\,24} = 3.34$, $p = 0.036$) and of S ($F_{1,\,8} = 470.5$, $p < 0.001$) on average percentage of points on-track. We found significant interaction effects between FP and S ($F_{2,16} = 32.15$, $p < 0.001$), a significant interaction between FP and TS ($F_{6,48} = 2.56$, $p = 0.031$) but no interaction effects between TS and S.

Post-hoc pair-wise comparisons for FP yielded significant differences for all pairs of functions (all $p < 0.01$). Users were able to stay on the track more frequently with the logarithmic function, then followed by the linear function and then the quadratic function (Fig 4). Post-hoc pair-wise comparisons for TS also yielded significant differences for Circle and 5-Shape ($p < 0.001$), Square and 5-Shape ($p < 0.01$) and for Circle and S-Shape (p=0.048). Users produced fewest deviations with the Circle (51.8%), then Square (53%), S-Shape (56.5%) and then with the 5-Shape (59%).

As observed with error volume, participants performed significantly better with the hard spring (62%) than with soft spring (49%). This confirms that the stiffness is a critical value in the design of haptically guided systems. However, it is important to be aware that the improvement of tracing performance does not grow linearly with spring stiffness (or the intensity of guiding force). We expect a leveling-off threshold, when exceeded, the improvement of tracing performance becomes less obvious.

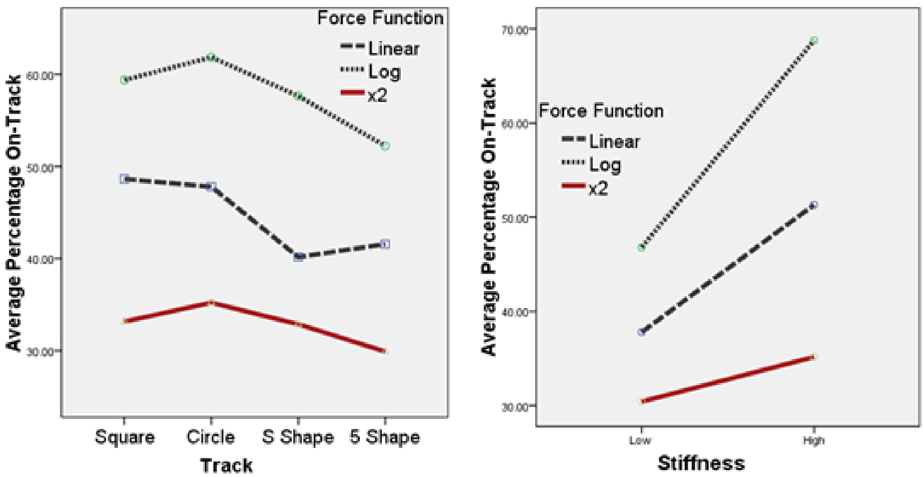

Fig. 4. Average percentage of points on track

4.3 Discussion

Interestingly, trajectory shapes with smoother curvatures revealed lower error volumes than those with sharp curves. Our observation reveals that at the edge of the curvature, users typically tend to overshoot away from the trajectory. Smooth curves do not impose this limitation as the user is making uniform movements across the trajectory. We also observe more deviation at the intersection corners in the sharper edges. This deviation is depicted in Fig. 5**,** showing the amount of deviation occurring at the extremities of sharp edges. Note that the finding showing that users tend to overshoot at sharp turns is different with what was previously reported in [6], in which the author revealed that users tended to make shortcut at corners. One possible explanation could be that when with haptic guidance, users tend to put less control on hand movement so that they move their hand by following the guiding force with inertia in the moving direction. Users only take over the control when significant errors occur, i.e. overshot a corner.

The path corners, can be one of the most important features of a trajectory, such as when learning a script or doing a precise maneuver. Failure to transfer corner information during motor-skill training could lead to poor outcomes. A possible way to reduce overshooting is to introduce strong constraint forces at corners to ensure the user makes the turn before going beyond the corners.

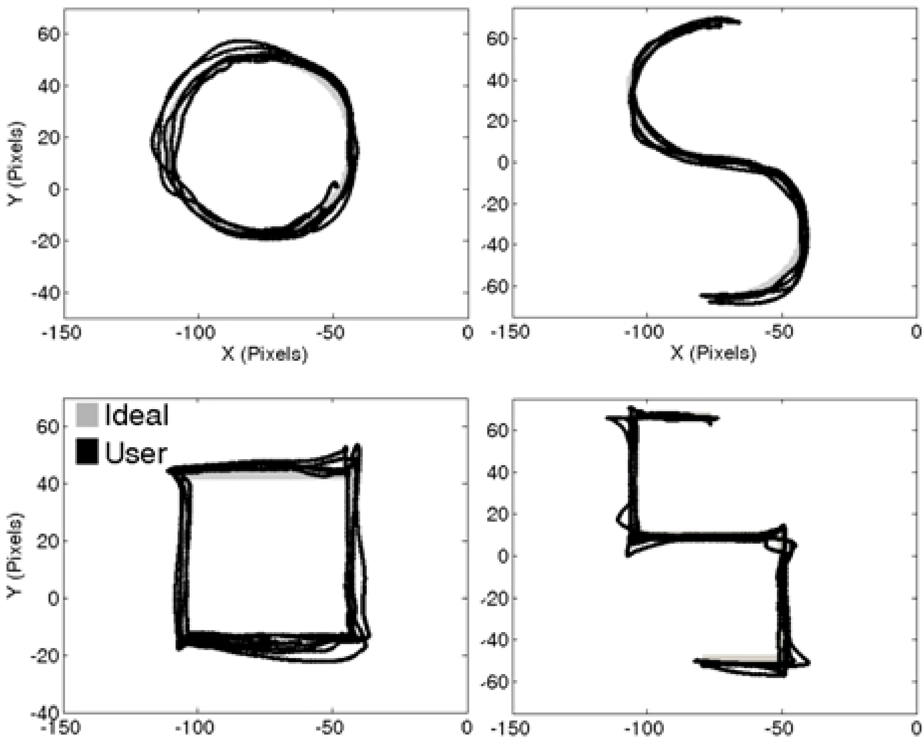

Fig. 5. Demonstration of the deviations at the intersection corners in the sharper edges

Surprisingly, while the quadratic and linear functions outperformed the logarithmic function in terms of error volume, the logarithmic outperformed both other functions with respect to percentage of points on-track. This suggests that the slope of the force profile function (see Fig. 2) has an effect on tracing performance. Furthermore, users may sense better the force when the functions have a steep slope instead of a flat slope. The linear and quadratic forces have steep slopes, so that they were more sensible to the users, and could provide better haptic constraints. As a result, the error volume for the linear and quadratic function was lower than the logarithmic function. On the other hand however, within the tolerance distance, the logarithmic function is steeper than the linear and quadratic functions. Therefore, the logarithmic generates a noticeable guiding force before the deviation becomes significant (exceeding the tolerance distance). This may explain why the user could maintain their trace on the tracks more often with the logarithmic than with the linear and the quadratic profiles.

Overall, the result suggests that designers need to take into consideration the appropriate type of force profile (and slope of the force function) based on the application in question. Ideally, the best function would be one that reduces both the error volume and facilitates the tracing of a higher number of points on track. Additionally, it is important to be aware that employing the maximum output of a force feedback device may not be necessarily helpful for achieving optimal tracing performance.

Designers need to be aware of the leveling-off threshold of the magnitude of guiding force based on different trajectories. Furthermore, designers need to employ different strategies to facilitate tracing according to the level of guidance. When provided with weak guidance, users tend to make short cut at corners. Therefore, introduction of corner threshold marks is necessary to ensure that the user crosses the corner before tracing the remainder of the trajectory. On the other hand, users tend to overshoot when following a strong guiding force. Therefore, additional constraints, such as stronger guiding force, should be useful at the corners.

5 Conclusion

In this paper we described a study measuring the effects of force profile, path shape, and spring stiffness on the performance of path tracing, in passive haptic guidance systems. The results show that all of the tested factors influence the performance of path tracing tasks. More important, the results show that users perform differently when negotiating sharp corners with or without haptic guidance. In particular, when with haptic guidance, users tend to overshot at corners. This is different to the findings reported in [6] when haptic guidance was not provided. Based on the results, we suggest that spring stiffness and/or the slope of a force profile function should be adjusted when considering changing the degree of haptic assistance at corners. High stiffness values are preferred to constrain and guide the users' movements. However, the leveling-off threshold has to be empirically determined based on the application in question. For reducing error volume and on-track percentage, a force profile with steep slope would be better suited. Overall, the linear force profile demonstrates a good balance of both error volume and on-track percentage. However, further investigation is required to identify the subtleties involved in selecting ideal force functions for tracing tasks, and the effect of these based on the underlying characteristics of the haptic guidance application.

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