A Study of the Steering Time Difference between Narrowing and Widening Circular Tunnels

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The steering law is a robust model for expressing the relationship between movement time and task difficulty. Recently, a corrected model to calculate the steering time difference between narrowing and widening tunnels was proposed. However, the previous work only conducted a user study with straight paths. This paper presents an investigation of steering performance in narrowing and widening circular tunnels to confirm the corrected model as being either adequate or a limitation. The results show that the steering law achieves a good fit ($R^2 > .98$) without the corrected model, thereby indicating the limited benefit of employing the corrected model.

1 Introduction

Modeling human performance is one of the important topics in the various research fields of human-computer interaction (HCI). Fitts’ law [5], which has been used as the basis for robust models to predict the movement time ($MT$) required to point at a target, is an example. Tasks that are more complicated than this, e.g., drawing, writing, and navigating, have been modeled by using the steering law proposed by Accot and Zhai [1]. This model expresses the relationship between $MT$ and the task parameters, as shown in Fig. 1, as follows:

$$MT = a + b \times ID, \quad ID = \frac{A}{W}$$  \hspace{1cm} (1)

where $A$ and $W$ are the length and width of a tunnel, respectively, $ID$ is the index of difficulty of the task, and $a$ and $b$ are empirically determined constants. Equation 1 means that navigating a narrower or longer tunnel becomes a more difficult task.

Accot and Zhai [1] also derived a model for a narrowing straight tunnel (Fig. 2). The index $ID$ for a narrowing tunnel ($ID_{NT}$) is expressed as:

$$ID_{NT} = \frac{A}{W_R - W_L} \ln \frac{W_R}{W_L}$$  \hspace{1cm} (2)

Readers are referred to [1] for more detail of this derivation.

Quite recently, Yamanaka and Miyashita [11] found that passing through a widening tunnel is significantly easier than passing through a narrowing one, although the $ID$ for a widening tunnel ($ID_{WT}$)

![Fig. 1 Two common shapes in steering experiments.](image1)

Left width ($W_L$)  
Right width ($W_R$)  

![Fig. 2 Defining a narrowing straight tunnel.](image2)
is calculated to have the same value as $ID_{NT}$. This non-conformity is problematic in that the model fitness is reduced, and means that $MT$ cannot be predicted accurately. Therefore, they modeled the $ID$ difference between narrowing and widening tunnels (known as the $ID_{Gap}$) as follows:

$$ID_{Gap}(k) = \frac{A(W_L - W_R)}{kW_LW_R}, \quad (3)$$

where $k$ is an empirically determined constant. The model was used to predict the $MT$ for narrowing tunnels ($MT_{NT}$) from the $MT$ for widening tunnels ($MT_{WT}$).

However, a clear limitation of their work is that they only used straight tunnels when they conducted a user study. Previous studies [2] [3] [12] suggested that a study on steering performance should be conducted using both straight and circular tunnels, and that this could be used to evaluate the performance in linear and nonlinear (curved) movements. Therefore, several questions remain unsolved:

- Is passing through a widening circular tunnel (Fig. 3) faster than in the opposite (narrowing) direction?
- Does $ID_{Gap}$ improve the model fitness of circular tunnels?

The navigation of a narrowing or widening circular path does not form part of our daily interaction with a PC. However, the steering law holds for an isometric track point controller [2] (similar to the Circle Pad of the Nintendo 3DS video game system and the Analog Stick of the Sony PSP system) and a racing wheel controller [13]. Outside of work situations involving the PC, especially in video games (e.g., action games or car racing), we can imagine various road designs with shapes that are more complicated than a straight shape. Therefore, investigating the validity of the $ID_{Gap}$ model in nonlinear paths is also important for such game designs in addition to a fundamental ergonomics study.

To the best of our knowledge, no studies have been reported on the steering time difference between narrowing and widening circular tunnels. Thus, there are no experimental data to discuss the validity of the $ID_{Gap}$ model in circular paths. Of course, the $ID_{Gap}$ model would not be necessary if there was no difference between $MT_{NT}$ and $MT_{WT}$. However, we believe that testing the steering performance in narrowing and widening circular tunnels will provide an incremental but solid contribution to the HCI/GUI field.

![Fig. 3 A widening circular tunnel.](image-url)
3 Experiment

3.1 Task

The task started when a screen displaying a white path against a gray background (Fig. 4a) appeared on a liquid crystal pen tablet. Because the start position does not significantly affect \(MT\) [12], the start line (which also served as the end line) was always located at the top of the path. The movement direction was always clockwise; thus, participants crossed the start line from left to right.

The participant touched the tablet surface with the stylus, then navigated past the start line and finally navigated the stylus tip all the way past the end line, all the time trying to stay within the bounds of the path. Removing the stylus from the surface then displayed a screen showing a selection of the following parameters.

When the stylus approaches the tablet surface, a black cross-hair cursor of 25 pixels in length is displayed. Before crossing the start line, the cursor trace leaves a blue line, which turns red upon crossing the start line. When the stylus passes the end line, a bell is triggered to signal a successful attempt, and the cursor trace turns green. The cursor trace turns black when the cursor deviates from the path.

The following two situations produced a beep sound and caused the attempt to be suspended: when the cursor moves outside the path boundaries or when the stylus is removed from the tablet surface. The participant is then required to pick up the stylus before re-touching the left side of the start line to begin the trial again. However, only the case where the cursor deviates from the path was recorded as an error. Participants were not penalized when they removed the stylus from the surface in the current experiment (i.e., the effect of the change in width), and this was therefore not counted as an error. These conditions are similar to those of a previous study [3]. Participants were instructed to perform the required operation as quickly and accurately as possible.

3.2 Apparatus

The PC we used was a Sony VAIO Z (2.1 GHz × 4 Core, 8 GB RAM, Windows 7 Pro). The display and input device was a liquid crystal pen tablet, Wacom Cintiq 12WX (IPS liquid crystal, 261.12 × 163.2 mm, 1280 × 800 pixels), with the experimental system implemented with a Hot Soup Processor 3.4 displayed in full-screen mode. The system runs at approximately 125 Hz.

3.3 Participants

The participants were ten graduate or undergraduate university students (2 females, 8 males, average age = 22.1, SD = 1.87 years). All participants were right-handed and operated the stylus with that hand. One participant had previous experience in that he continuously used a stylus with his smartphone to take notes for approximately two years.

3.4 Design and Procedure

In our experiments, the distance \(A\) was 300, 450, and 600 pixels. The path width for both the start line \((W_S)\) and the end line \((W_E)\) was 11, 31, and 51 pixels, for which only combinations where \(W_S \neq W_E\) may be selected. The tunnel type (either narrowing or widening) was determined according to the combination of \(W_S\) and \(W_E\).

The total number of parameter combinations was \(3 \times 3 \times 3 = 27\), with the \(ID\) range between 7.47 and 31.1. These were randomly selected for nine blocks of tasks, with the first block being a practice block and the remaining eight blocks comprising the actual tasks. The data recorded for the actual tasks included a total of 18 conditions × 8 blocks × 10 participants = 1440 trials. While participants completed the practice block, the height of the seat and the position of the tablet on the table were adjusted. The angle of the tablet could also be adjusted, and all participants preferred the “stand”
mode (Fig. 4b). The total time taken by each participant was approximately 20 minutes, from the moment they received preliminary instructions until they completed all the tasks.

3.5 Collected data

The dependent valuables were MT, the error rate, the standard deviation SD that was calculated using the distances between the cursor and the centerline of a tunnel, and a time-stamped cursor trajectory. These data were collected only in the actual tunnel, depicted as the red-colored trajectory (Fig. 4a) and representing the time taken to pass the end line after crossing the start line. The MT, error, SD, and the cursor trace before the trial started (blue line) and after the trial ended (green line) were not measured as experimental data.

4 Results

In total, 1583 trials were performed. After 143 error trials were excluded, we analyzed the data via repeated measures ANOVA and the Bonferroni post hoc test. The independent variables were ID and the tunnel type.

4.1 Movement time MT

We observed the main effects of ID ($F_{8,72} = 64.676, p < .001$) and the tunnel type ($F_{1,9} = 6.177, p < .05$). Fig. 5a shows the relationship between ID and MT for both tunnel types. The post hoc test shows that the widening direction is navigated faster than the narrowing direction ($p < .05$), with average times of $MT_{WT} = 1957$ ms and $MT_{NT} = 2073$ ms, respectively.

4.2 Error rate

We observed the main effects of ID ($F_{8,72} = 6.598, p < .001$) and the tunnel type ($F_{1,9} = 8.896, p < .05$). Fig. 6 shows the relationship between ID and the error rate for both tunnel types. The post hoc test shows that the widening direction produces a smaller error rate than the narrowing direction ($p < .05$). The average error rates for the widening and narrowing directions were 6.12% (47/767) and 11.8% (96/816), respectively.

4.3 Standard deviation SD

We observed the main effects of ID ($F_{8,72} = 59.529, p < .001$) and the tunnel type ($F_{1,9} = 9.988, p < .05$). The post hoc test shows that SD becomes larger in the widening direction than in the narrowing direction ($p < .05$). The SD for the widening and narrowing directions was 2.676 and 2.341 pixels, respectively.

4.4 Speed profiles

Fig. 7 shows the average speed profiles in the tunnels. Yamanaka and Miyashita [11] displayed the speed data by showing the cursor progress on the x-axis, because their user study was conducted with
horizontal movements. In contrast, our experiment was performed with loop movements; thus, we show the progress in degrees (from 0° to 360°).

5 Discussion

5.1 Movement time $MT$

Fig. 5a shows that the steering law holds for both narrowing and widening tunnels with high accuracy ($R^2 > .98$). Fig. 5b also shows that the use of one regression expression with the steering law provides a good fit at a level that is nearly equal ($R^2 > .98$). When using the $ID_{gap}$ model, the value of $k$ was 20.0 and the fit improved slightly ($R^2 > .99$, Fig. 5c). However, the steering times in circular tunnels can be accurately predicted without separating the tunnel types (Fig. 5b), because $MT_{NT}$ was slightly longer than $MT_{WT}$. This result is in contrast to the previous study [11] that showed a poor fit using one regression expression ($R^2 = .826$). Therefore, our experiment reveals a previously unknown limitation of the $ID_{gap}$ model, namely that the benefit of using the model is limited to straight tunnels, and we cannot confirm the necessity of using the model for circular tunnels.

5.2 Error rate

The error rate for the narrowing tunnel was 92.0% larger than that of the widening tunnel. This result shows that users make more mistakes when proceeding in the narrowing direction than in the widening direction, although the shapes of these two tunnels are completely the same. The difference between the two tunnels is smaller than the difference between the corresponding straight tunnels (546% [11]); thus, circular tunnels strongly reduce the difference, both in terms of $MT$ and the error rate compared to straight tunnels.

5.3 Standard deviation $SD$

Whereas $SD$ in the widening direction was 0.335 pixels larger, the error rate was significantly lower. We observed that the larger “slippage” from the centerline of a circle did not induce more errors. This relationship between $SD$ and the error rate is similar to that for straight tunnels [11].

5.4 Speed profiles

For each different condition of $A$, users were firstly found to accelerate before slowing down along the 0-45° trajectory (Fig. 7). Subsequent to that, the speed steadily increased in widening tunnels, and steadily decreased in narrowing tunnels. In the case of narrowing conditions, the speed began to increase in the last phases (from approximately 270°); this resembles the finding for straight tunnels (Fig. 13 in [11]). However, the “changeover” between different speeds occurred at around 50% of the path length, which differs from the finding for straight tunnels, where changeover occurred at approximately 25-30% of the path length. For straight conditions, users may decide to proceed at a high speed from an early phase in a widening tunnel (Fig. 8a). Conversely, for circular conditions, users cannot aim straight at the goal until just before the goal (Fig. 8b). This could be one of the reasons behind the slight difference in the value of $MT$ between narrowing and widening circular tunnels.

6 Conclusion

We conducted an experiment to test steering performance in narrowing and widening circular tun-
channels, and to test the adequateness or limitation of the IDGap model. The experiment was conducted by retaining the same ranges of \( A \) (300 to 600 pixels) and \( W \) (11 to 51 pixels) as in the previous work [11], but the results show that the steering law holds to a high degree (\( R^2 > .98 \)) without the IDGap model. Therefore, we found a new limitation of this model: it is not necessary for circular tunnels. Of course, the slopes of the regression expressions are a little different between the narrowing and widening directions (Fig. 5a), and thus more difficult conditions (i.e., tasks of higher IDs) might require an ID correction method. Further work is required such as testing with larger/smaller circles and narrower/wider widths.

References


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