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

Shota Yamanaka　Homei Miyashita

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:

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

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:

$$ID_{\mathrm{NT}} = \frac{A}{W_R - W_L} \ln \frac{W_R}{W_L} \qquad (2)$$

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})

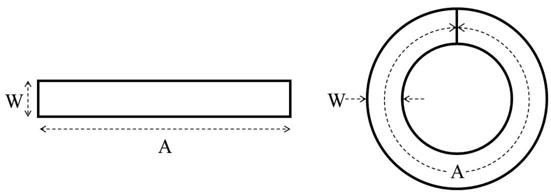


Fig. 1 Two common shapes in steering experiments.

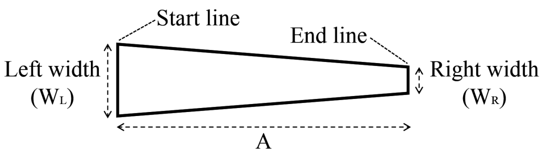


Fig. 2 Defining a narrowing straight tunnel.

狭まる・広がる環状経路を通過する時間差に関する調査
山中祥太, 明治大学大学院理工学研究科, 日本学術振興会特別研究員 PD, Graduate School of Science and Technology, Meiji University, JSPS Research Fellow (PD).
宮下芳明, 明治大学総合数理学部先端メディアサイエンス学科, Department of Frontier Media Science, Faculty of Interdisciplinary Mathematical Sciences, Meiji University.
コンピュータソフトウェア, Vol.33, No.4 (2016), pp.116–121.
[研究論文 (レター)] 2016 年 2 月 26 日受付.

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:

$$ID_{\mathrm{Gap}(k)} = \frac{A(W_L - W_R)}{kW_L W_R}, \qquad (3)$$

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}. Our work aims to investigate the performance difference in circular tunnels to confirm the adequateness or limitations of the ID_{Gap} model.

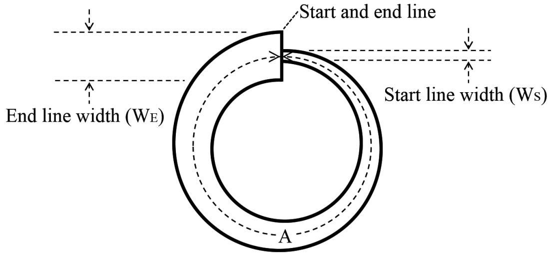


Fig. 3 A widening circular tunnel.

2 Related Work

Steering tasks, also known as trajectory-based tasks [1] and path-following tasks [6], are common operations in graphical user interfaces (GUIs), e.g., for selecting an item from cascaded menus. The steering law has been shown to be valid under numerous conditions, such as changes in the input device [2], changes in control-display gain [3], changes in the cursor size [8], changes in the friction of the surface of a pen tablet [10], changes in the start position [12], three-dimensional input [4] [7], and a driving simulator [13].

Although the law is very robust, several revisions of the model have been proposed. When W is too large, users do not require the entire path width, and thus the model fitness decreases. Kulikov et al. [6] proposed a corrected model taking this "effective width" into account. Pastel [9] suggested that corners in tunnels should be considered as a factor affecting MT, because users "cut off" a corner (i.e., users would pass as far toward the inside of the corner as possible). Yamanaka and Miyashita [11] proposed a corrected model, ID_{Gap}, to determine the difference in IDs of narrowing and widening tunnels. Their model shows a good fit ($R^2 > .99$) with straight tunnels, but the fit with nonlinear tunnels remains uncertain. Besides discussing the ID_{Gap} fitness, we do not know whether MT_{NT} is longer than MT_{WT} in circular paths. Therefore, 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.

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,

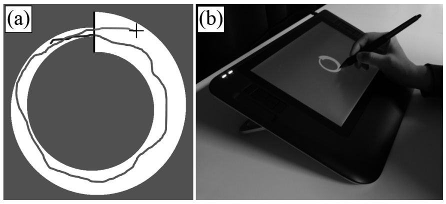


Fig. 4 (a) All the information displayed on the screen for the case of the narrowing tunnel, and (b) the experimental setup.

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.

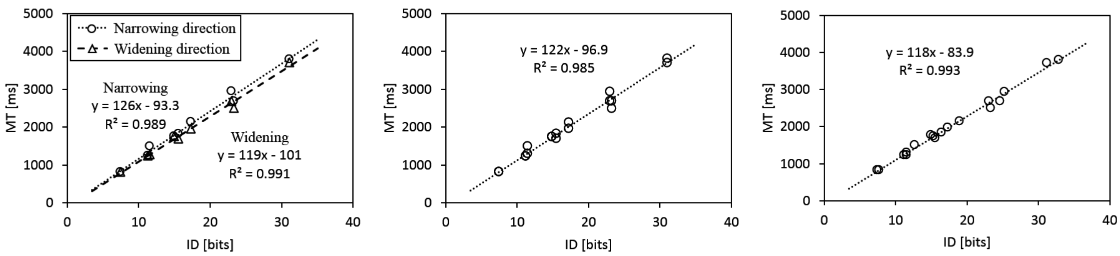
3.3 Participants

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 (A) × (3 (W_S) × 3 (W_E) − 3 (excluding $W_S = W_E$)) = 18, 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”



(a) Relationship for both directions (b) Pre-correction relationship (c) Post-correction relationship with $k = 20.0$

Fig. 5 MT **versus** ID**.**

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 $MT_{\mathrm{WT}} = 1957$ ms and $MT_{\mathrm{NT}} = 2073$ ms, respectively.

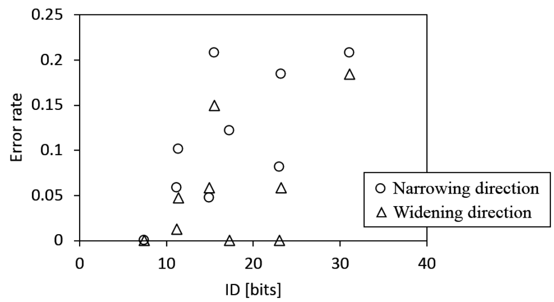


Fig. 6 Error rate versus ID**.**

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

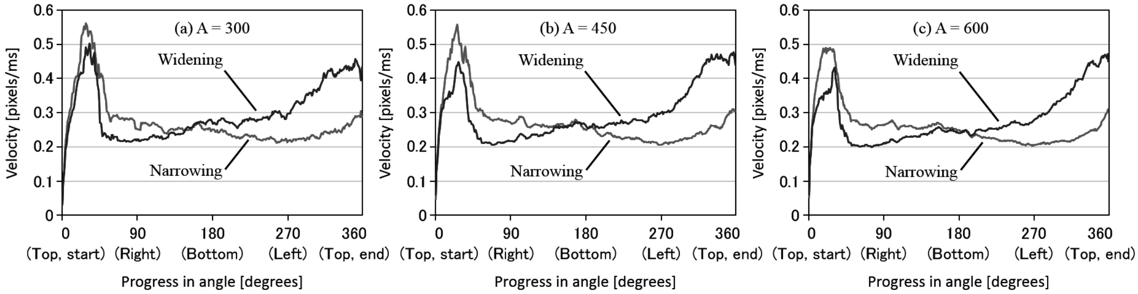


Fig. 7 Average speed profiles of all the strokes filtered by a seven-point simple moving average.

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-

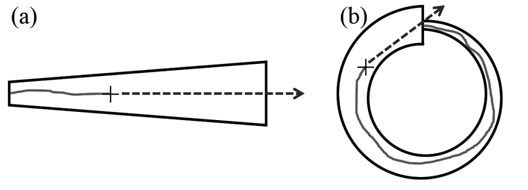


Fig. 8 Aiming goals in (a) straight and (b) circular widening tunnels.

nels, and to test the adequateness or limitation of the ID_{Gap} 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 ID_{Gap} 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

[1] Accot, J. and Zhai, S. : Beyond Fitts' law: models for trajectory-based HCI tasks, in *Proc. of CHI'97*, pp. 295–302.

[2] Accot, J. and Zhai, S. : Performance evaluation of input devices in trajectory-based tasks: an application of the steering law, in *Proc. of CHI'99*, pp. 466–472.

[3] Accot, J. and Zhai, S. : Scale effects in steering law tasks, in *Proc. of CHI'01*, pp. 1–8.

[4] Casiez, G., Plénacoste, P. and Chaillou, C. : Does DOF separation on elastic devices improve user 3D steering task performance? in *Proc. of APCHI'04*, pp. 70–80.

[5] Fitts, P. M. : The information capacity of the human motor system in controlling the amplitude of movement, *Journal of Experimental Psychology*, Vol. 47, No. 6 (1954), pp. 381–391.

[6] Kulikov, S., MacKenzie, I. S. and Stuerzlinger, W. : Measuring the effective parameters of steering motions, in *Ext. Abst. of CHI'05*, pp. 1569–1572.

[7] Liu, L., Martens, J.-B. and Liere, R. v. : Revisiting path steering for 3D manipulation tasks, *International Journal of Human-Computer Studies*, Vol. 69, Issue 3 (2011), pp. 170–181.

[8] Naito, S., Kitamura, Y. and Kishino, F. : Steering law in an environment of spatially coupled style with matters of pointer size and trajectory width, in *Proc. of APCHI'04*, pp. 305–316.

[9] Pastel, R. : Measuring the difficulty of steering through corners, in *Proc. of CHI'06*, pp. 1087–1096.

[10] Sun, M., Ren, X., Zhai, S. and Mukai, T. : An investigation of the relationship between texture and human performance in steering tasks, in *Proc. of APCHI'12*, pp. 1–6.

[11] Yamanaka, S. and Miyashita, H. : Modeling the steering time difference between narrowing and widening tunnels, in *Proc. of CHI'16*, pp. 1846–1856.

[12] Zhou, X., Ren, X. and Hui, Y. : Effect of start position on human performance in steering tasks, in *Proc. of CSSE'08*, pp. 1098–1101.

[13] Zhai, S., Accot, J. and Woltjer, R. : Human action laws in electronic virtual worlds: an empirical study of path steering performance in VR, *Presence*, Vol. 13, No. 2 (2004), pp. 113–127.

Shota Yamanaka

Shota Yamanaka is a visiting researcher at Meiji University and a JSPS research fellow PD. He received the B.E., M.E., and Ph.D. degrees in engineering from Meiji University in 2011, 2013, and 2016, respectively. His general research interests include human-computer interaction, graphical user interface, and human performance modeling.

Homei Miyashita

Homei Miyashita is a professor in the School of Science and Technology at Meiji University. Born in Firenze, Italy, in 1976, he received a bachelor's degree with a major in Image Science from Chiba University in 2001, a master's degree with a major in Music Composition from Toyama University in 2003, and a Ph.D. degree with a major in Knowledge Science from Japan Advanced Institute of Science and Technology (JAIST) in 2006. His general research interests include entertainment computing and human-computer interaction.