Revisiting Path Steering for 3D Manipulation Tasks

Lei Liu* — CWI, Amsterdam

Jean-Bernard Martens† — Eindhoven University of Technology

Robert van Liere‡ — CWI, Amsterdam

Abstract

The law of path steering, as proposed by Accot and Zhai, describes a quantitative relationship between human temporal performance and the path's spatial characteristics. The steering law is formulated as a continuous goal crossing task, in which a large number of goals are crossed along the path. The steering law has been verified empirically for locomotion, in which a virtual driving task through straight and circular paths was performed.

We revisit the path steering law for manipulation tasks in desktop virtual environments. We have conducted controlled experiments in which users operate a pen input device to steer a virtual ball through paths of varying length, width, curvature and orientation. Our results indicate that, although the steering law provides a good description of overall task time as a function of index of difficulty $ID = L/W$, where L and W are the path length and width, it does not account for other relevant factors. We specifically show that the influence of curvature can be modeled by a percentage increase in steering time, independent of index of difficulty. The path orientation relative to the viewing direction has a more complex effect on the steering law, which is moreover for instance asymmetric, i.e. it differs when moving to the left or right.

A detailed analysis of our results indicates that a 3D steering movement can probably not be modeled as a sequence of individual goal crossing subtasks. Rather, we can postulate that the overall steering task is likely better described as a sequence of smaller movements that are closer to ballistic movements. One argument for this is that we established that the time for subtrials with continuous steering is related to ID by a power law, with an exponent in the range 0.5-0.6, rather than being equal to 1 as required by the steering law.

Index Terms: H5.1 [Information Interfaces and Presentation]: Multimedia Information Systems—Artificial, augmented, and virtual realities; H5.2 [Information Interfaces and Presentation]: User Interfaces—Interaction styles, User-centered design

1 Introduction

Path steering is a primitive interaction task that requires a user to navigate through a path of a given length and width. Navigating through nested-menus, drawing curves within boundaries, and locomotion along a predefined track are just a few examples of interaction tasks that can be thought of as steering tasks. Recently, Accot and Zhai have proposed the law of steering as a law that describes a quantitative relationship between human temporal performance and the path's spatial characteristics [1, 20]. The law was empirically verified to model human locomotion in virtual reality, in which case users were exposed to a virtual driving simulator to drive a virtual vehicle on straight and circular paths.

In the same paper [20], Accot and Zhai posed the question if the steering law could also be used to model the performance in 3D manipulation tasks. The 'ring and wire' task was given as an example; i.e. a user navigates a torus with a 6DOF (degree-of-freedom) input device across a (curved) trajectory. Note that this task requires both the position and orientation of the ring, which is substantially more complex than steering the position of a point in a plane. Since 3D manipulation tasks are very different from virtual driving tasks, it is well worth investigating how the steering law can be applied to such tasks. In order to limit the complexity, we propose to decouple the steering of position and orientation, which will result in an alternative interaction task from the 'ring and wire' task. Gaining a more fundamental understanding of the steering movement in such a task is also likely to result in design rules that are useful for the development of higher level interactive desktop manipulation techniques.

In this paper, we study a path tracing task in a virtual environment. Our goal is to verify the steering law and, if appropriate, identify other relevant factors that affect users' performance. Two experiments were conducted, in which users operated a pen input device to trace a virtual ball through paths of varying length, width, curvature and orientation. The first experiment focused on how path curvature affects the steering movement. For this, paths of different curvatures were used (see Figure 1, top). The second experiment focused on the effects of path orientation with respect to the viewing angle. Path orientation was determined by two angles: one angle specifying the rotation around x-axis, and the other specifying the rotation around y-axis. (Figure 1, bottom).

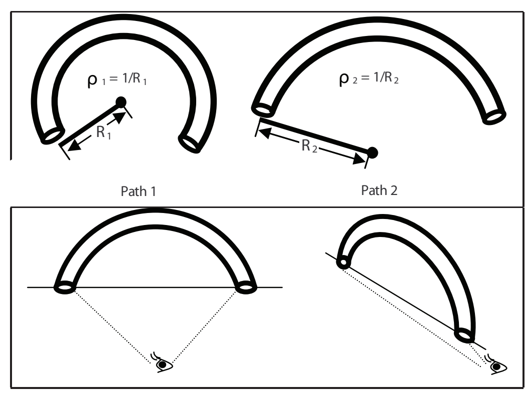

Figure 1: Two paths of the same length and width, but with different curvatures (top). The same path in different orientations (bottom).

The contributions of the paper are summarized as follows:

- We show that the steering law provides a good description of overall task time as a function of index of difficulty $ID = L/W$, where L and W are the path length and width.
- We show that the influence of path curvature can be modeled by a percentage increase in steering time, independent of index of difficulty. The path orientation relative to the viewing direction has a more complex, and as yet unmodeled, effect on the user performance in the steering task. This effect is moreover asymmetric, i.e. it differs when moving to the left or right.

*e-mail: Lei.Liu@cwi.nl

†e-mail:j.b.o.s.martens@tue.edu

‡e-mail:Robert.van.Liere@cwi.nl

- The analysis of our experimental results indicates that a steering movement cannot be modeled as a sequence of individual goal crossing subtasks. Rather, we can postulate that the overall steering movement is more likely better described as a sequence of smaller movements that are closer to ballistic movements than to steering movements. We established that the time for each individual movement is related to *ID* by a power law, with an exponent in the range 0.5-0.6, rather than being equal to 1 as required by the steering law.

2 Modeling Pointing and Steering

The pointing tasks have been well studied (e.g. [5, 8]). The best known law for modeling the user performance of pointing movements is Fitts' law [7, 12], which predicts movement time of a pointing task as a function of the distance from source to target and the size of the target. One common formulation of Fitts' law is:

$$T = a + b \log\left(\frac{L}{W} + 1\right) \tag{1}$$

where a and b are experimentally determined constants, L is the distance to the target, and W is the target width. The expression $ID = \log(\frac{L}{W} + 1)$ is referred to as the index of difficulty of the task. Although initially formulated from one dimensional experiment, Fitts' law has been extended to model two dimensional [13] and three dimensional [14] pointing tasks, respectively. In the previous papers, we have shown that the 3D pointing movement in virtual reality can often be modeled by a two-component model: an initial ballistic movement followed by a perceptually guided corrective movement [11, 16]. The conclusion was that, although Fitts' law is an excellent description of total movement time, the two-component model can give more insight into the users' performance during the movement.

The steering law, as developed by Accot and Zhai, was derived from the idea that a steering task can be broken down into a large number of segments, each of which can be treated as a goal-crossing task with the same index of difficulty. The total movement time can then be modeled by Fitts' law, with the *ID* for the whole task calculated by the sum of all the *ID*s of the segments. If the path width varies along the path, the generic steering law is expressed by the following formula:

$$T_C = a + b\,\mathrm{ID} = a + b \int_C \frac{ds}{W(s)} \tag{2}$$

where a and b are empirically determined constants, C is a curved path, s is elementary path length along C and $W(s)$ is the path width at path length s. In those cases where path width is constant along the path, the steering law can be rewritten as:

$$T_C = a + b\frac{L}{W} \tag{3}$$

with L and W representing the length and width of the path, respectively.

It is important to note that the steering law implies that movement time is only a function of the length and width of the path. This relationship is counterintuitive, since it would seem that the shape of a path should also influence the movement time. One example is that when driving from a straight road onto a roundabout, we usually have to slow down and the smaller the roundabout, the slower more likely we are to reduce our speed. Figure 1 (top) shows two paths of the same length and width, but with different constant curvatures. Intuitively, it is easier and faster to steer through path 2 than through path 1.

The steering law was initially formulated and developed to model 2D steering tasks for desktop computers with 2DOF input devices. It would seem that in 3D, path orientation is also likely to affect performance. For example, a path tracing movement in the z-direction might be very different from the same movement in the x-direction (see Figure 1, bottom).

Finally, it should be noted that, although the law of pointing (Equation 1) and the law of steering (equation 3) seem somewhat similar, they describe very different movements. In Equation 1 the index of difficulty is described by a logarithmic term, whereas in Equation 3 the relationship is linear. We will get back to this point in the discussion section.

Many HCI researchers have used the steering law to model interaction. Examples included examining scale effects by adjusting the input device's Control-Display ratio [3] (similar to semantic pointing [18, 6] for pointing tasks), evaluating the performance of multifarious input devices [2] and investigating steering around sharp corners [17]. Besides, Naito, et al. [15] has extended the application of steering law to an environment of "spatially couple style", while Grossman, et al. [9] has confirmed its validity on the Hover-widget-based steering task using Pen-Operated Devices. However, these studies were restricted to 2D desktop environments with 2DOF input devices. A notable exception is Kattinakere et al. [10], who conducted a series of experiments to validate the steering law in table top environments. Above-the-surface layers of certain thickness were used to constrain steering movements above the tabletop, a similar way of bringing "target height" into Fitts' law [4]. Our study differs from these studies in a number of ways. We investigate the steering law in a head tracked virtual environment using 6DOF input devices. Our environment is not co-located, i.e. there is a horizontal offset of 0.65m and a vertical offset of 0.3m between the physical input device and the virtual representation of the pen. The curved paths we consider are less constrained than the constrained shape of paths in most other studies.

3 Experiment

For our experiments, we have designed the *cursor and tunnel* task, as it is a more straightforward extension of the 2D steering law than the *ring and wire* task proposed by Accot and Zhai. Using an input stylus, the user pushes a virtual target ball through a tunnel. 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. The steering path width is defined as the amplitude of the cursor ball with which the cursor ball is in contact with the target ball, i.e. the tunnel width plus two times cursor ball radius (see Figure 2). The visual feedback of the stylus consists of a pen with a small cursor ball on the tip of the pen. The visual feedback of the target ball is used as the progress indicator for the task.

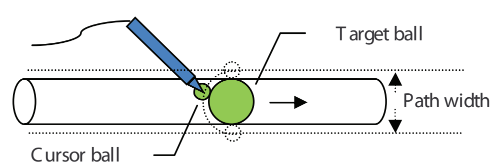

Figure 2: Cursor and tunnel task: a cursor ball pushes a target ball through a tunnel. Tunnel width = diameter of target ball; Steering path width = tunnel width + 2×radius of cursor ball = 2×(radius of target ball + radius of cursor ball)

The goal of the task is to push the target ball from one end of the tunnel to the other end as fast as possible. To push the target ball, two requirements must be met:

1. The cursor ball must intersect the tunnel.

2. The cursor ball must be in contact with the target ball.

If one of these requirements fails (for example, the cursor is not within the boundary of the path), then the user must correct for this by returning the cursor to the tunnel and continuing the task where she left off. The trial starts when the target ball is at the beginning of the tunnel and the task continues until the target ball reaches the end of the tunnel.

3.1 Environment and Apparatus

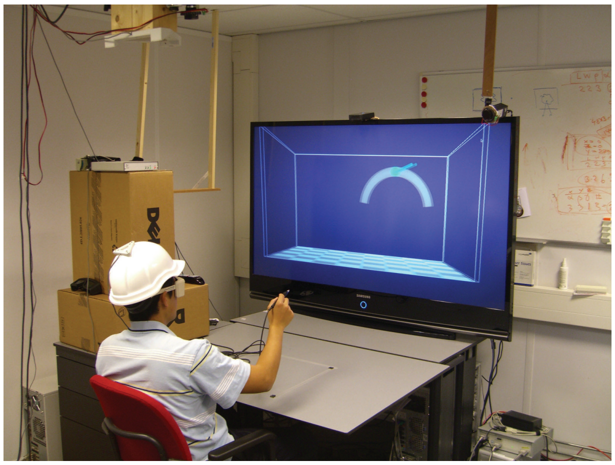

Figure 3: The experimental environment: a head tracked stereo display and a 6DOF input stylus. Several aspects were added to create better depth cues during the experiment, including the stereoscopic viewing, head tracking, head lighting, wire-frame box and the chessboard pattern floor.

The experimental setup was performed in a head tracked stereoscopic desktop virtual environment with a 67-inch display (Figure 3). Subjects were seated 1.35m from the display (Figure 4). The origin of the visual space was 0.4m in front of the display and 0.6 above the desktop. The origin of the motor space was set to 1.05m in front of the display and 0.3m above the desktop. The Control-Display ratio was always set to 1.

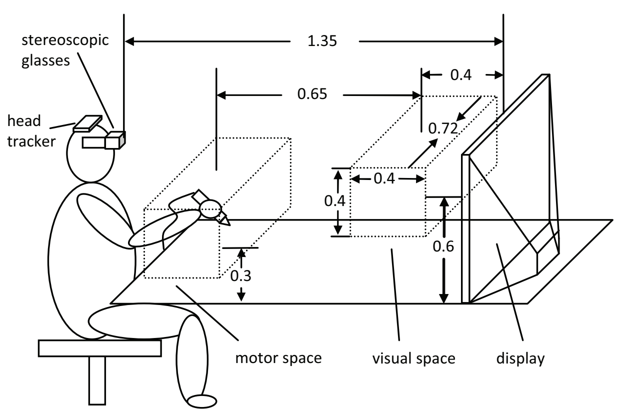

Figure 4: The experimental setup (units: meter): Motor and visual space were not co-located, i.e. there is a horizontal offset of 0.65m and a vertical offset of 0.3m between the motor space and the visual space. C-D ratio=1.

As shown in Figure 3, the tunnel was drawn as a semi-transparent 3D tube through which the cursor ball could easily be seen. A 0.72m × 0.4m × 0.4m wire-frame box with a chessboard floor was drawn around the tunnel.

For the specific apparatus, we used a desktop PC with high end GPU, a Samsung HL67A750 3D-capable LED DLP HDTV, a pair of Crystal Eyes stereoscopic LCD glasses, a Polhemus FASTRAK connected by one 6DOF stylus tracker, and an ultrasound Logitech of 6DOF for head tracking. The resolution of the display was set to be 1920×1080 @ 120 Hz. The end-to-end latency was measured to be approximately 80ms using the method proposed by Steed [19].

3.2 Subjects

12 right-handed subjects voluntarily participated in the experiment. There were 2 females and 10 males, varying in age from 28 to 31. Half of the subjects had previous experience with virtual environments.

3.3 Procedure

We have conducted two repeated measures design experiments. For Experiment 1, paths of varying length, width and curvature were used. Curvature is defined as $\rho = 1/radius$, such that a path can be thought of as a segment on a circle of a given radius. The path was positioned in the xy-plane with the start of the path at the origin. The path lengths were chosen to be 0.24m, 0.30m and 0.36m so that participants needed to traverse a reasonable distance and were not required to move the body to accomplish the mission, but the arm. The radius of the cursor ball was fixed to 0.005m, while the variable target ball had the radius of 0.010m and 0.015m, resulting in two path widths, 0.03m and 0.04m respectively. Five typical curvature values 0, 4, 8, 12, 16m^{-1} were selected for the experiment (see Figure 5). There were three repetitions per combination, resulting in $5 \times 3 \times 2 \times 3$ trials ($curvatures \times lengths \times widths \times repeats$) per subject.

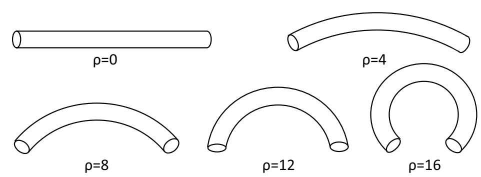

Figure 5: Experiment 1: 5 paths of different constant curvatures. The five curvature values were well-selected so that they were in arithmetic progression and corresponded to the circle of radius of inf (straight line), 0.2500m, 0.1250m, 0.0833m, 0.0625m. The maximum value was chosen in such a fashion that no circular path overlapped when different path lengths were designated. We also made sure that the difference between any two values was big enough to significantly affect the movement time.

As defined by Accot and Zhai's model, if C is a curved path and W is constant along the path, the index of difficulty for steering through this path is:

$$ID = \int_C \frac{ds}{W(s)} = \frac{L}{W} \tag{4}$$

In experiment 1, 3 path widths and 2 path lengths were used, resulting in 6 different IDs.

For experiment 2, a path of fixed length (0.24m), width (0.04m) and curvature (corresponding to $\rho = 8m^{-1}$ in Figure 5) was in turn rotated around the y and x-axis (Figure 6). For each axis, four angles were chosen; α (rotation angle around x-axis) and β (rotation angle around y-axis) equal to $0°$, $45°$, $90°$ and $135°$, resulting in $4 \times 4 \times 3$ trials ($\alpha \times \beta \times repeats$) per subject.

Figure 7 depicts the position of a participant and the corresponding 16 orientation angles, among which only one was rendered during a trial.

In each experiment, trials were presented in a random order that was different for all subjects.

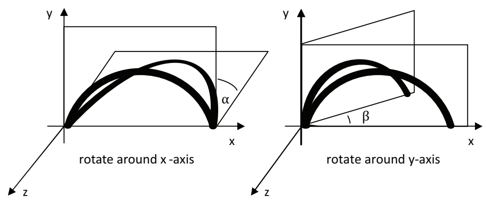

Figure 6: Experiment 2: decomposing orientation angles. Each of the 16 orientation angles was a result of rotating the original path (in xy-plane) in turn around y-axis and x-axis one of the four angles, respectively.

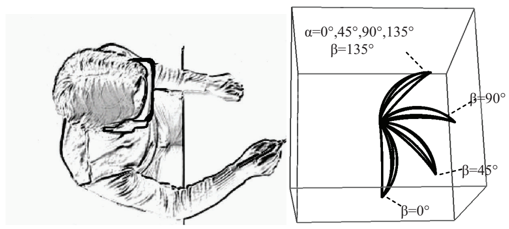

Figure 7: Experiment 2: relation between a participant and the orientation angles (top view).

4 Results

The first observation from the data is that about 60-70% of the trials could not be completed by the subjects in a single steering operation. This means that the subjects often did not succeed in keeping their pen within the boundary of the tunnel, and that they needed to spend time to correct for this, and to bring the pen back within the boundary after wandering off too far. The instances where the pen entered and left the designated boundary were used to define *subtrials*, i.e. the time intervals during which actual steering was accomplished.

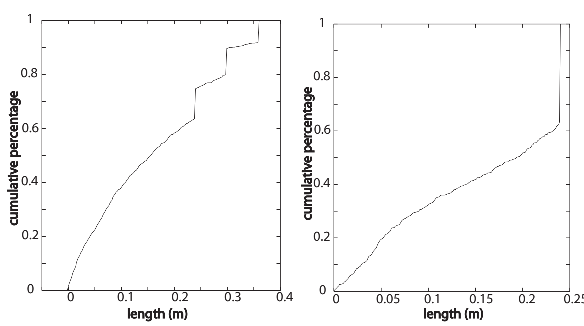

Figure 8: Cumulative histogram of path lengths for subtrials: experiment 1 (left), experiment 2 (right)

In Figure 8 we have plotted the cumulative histogram of the subtrial path lengths. The fact that path lengths other than the ones specified in the experimental setup occur is evidence for our above claim. For this, we have partitioned and analyzed the data such that the total time of a trial is equal to the steering time of the subtrials plus the correction time; $T_{total} = T_{steering} + T_{correction}$ with $T_{steering} = \sum T_{subtrials}$. Strictly speaking, the steering law as specified by Accot and Zhai should hold for subtrials.

Instead of looking for a linear relationship between the time T taken for a subtrial and the index of difficulty $ID = L/W$, where L is the path length crossed during the subtrial, we propose an alternative analysis where we look for a linear relationship between $\log(T)$ and $\log(ID)$. In appendix, we provide the reasoning for this choice.

We consider equations of the form

$$\log T = a + b \log \frac{L}{W} = a + b \log ID \tag{5}$$

to statistically test the steering law. This equation corresponds to a power-law relationship

$$T = a' ID^b \tag{6}$$

between time T and index of difficulty ID. If the exponent b does not differ significantly from one, then this can be considered as evidence that the steering law is a statistically valid description of the data. If the exponent b differs significantly from one, then this can be considered as evidence that the steering law is not the best possible description of the data.

The effect of curvature can be included by extending the model to

$$\log T = a + b \log \frac{L}{W} + c\rho + d\rho \log \frac{L}{W} \tag{7}$$

in the case where we want to include interaction between curvature ρ and ID, or

$$\log T = a + b \log \frac{L}{W} + c\rho \tag{8}$$

if we can assume that such interaction term is negligible.

4.1 Path length, width and curvature

The regression parameter estimates using the model defined by Equation 8 to fit the subtrial data are given in Table 1, in which the estimated power $b = 0.59$ is substantially different from one. No statistical evidence was found for the interaction time in Equation 7. Note in Table 1 that there is indeed a small, but statistically significant effect of the curvature (the 95% confidence interval doesn't include zero). The interpretation of equation 8 in terms of the above-specified power-law (Equation 6) is that the power b is independent of curvature, and only the factor a' is curvature dependent.

Coef.	Value	[95% Conf. Interval]
a	-0.318	[-0.337, -0.299]
b	0.592	[0.573, 0.612]
c	0.005	[0.004, 0.006]

Table 1: Regression parameter estimates on subtrial time (fitting onto Equation 8).

The correspondence between the raw data and the model can be assessed in the left plot of Figure 9 where only the effect of ID is illustrated. The right plot illustrates the effects of both ID and ρ on the steering time. The influence of curvature is evident as a shift in the curves (the slope is the same), or equivalently, a percentage change on the time required that is independent of ID.

The fact that the steering law is not able to closely approximate the actual steering taking place during subtrials doesn't exclude the possibility that the steering law might be an appropriate description for the total performance time. Indeed, the regression parameter estimates in Table 2, and the data shown on the left of Figure 10 indicate that a power-law (Equation 6) with an exponent b is close to one, and a factor a' that increases with curvature, provides a good description for the complete trial steering time.

What can be concluded from the data in the right plot of Figure 10 is that the correction time required to successfully complete the task increases rapidly with increasing ID and ρ. More precisely, a power law (Equation 6) with an exponent in the range $2.5 - 3.0$ (i.e. much steeper than a linear increase with ID) is needed to describe this relationship.

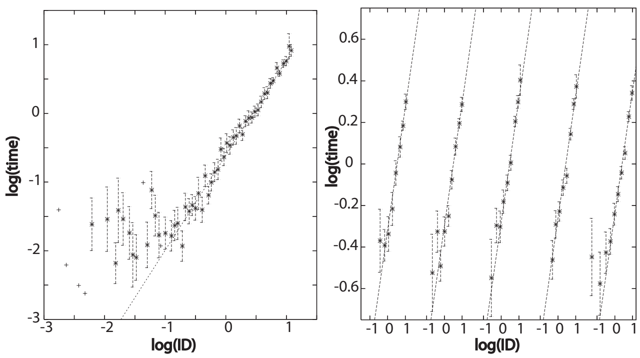

Figure 9: Subtrial time from experiment 1 fits onto different steering models. Left: subtrial time as a function of ID (Equation 5). Right: subtrial time as a function of ID for the five different values of curvature ρ (Equation 8).

Coef.	Value	[95% Conf. Interval]
a	-0.634	[-0.687, -0.580]
b	0.969	[0.913, 1.026]
c	0.008	[0.007, 0.009]

Table 2: Regression parameter estimates on steering time (fitting onto Equation 8).

4.2 Path orientation relative to the viewing direction

In experiment 2, 4 different α values were selected, including rotating the path (in xy-plane) $0°, 45°, 90°$ and $135°$ around the x-axis respectively, while always making subjects' viewing perpendicular to the display. The same values has been designated to β as well (Figure 6).

Fitting the subtrial time of experiment 2 onto the model described in Equation 5, we find that a power law (Equation 6) with an exponent $b = 0.73$. The corresponding data are illustrated in Figure 11.

To find out how the angles α, β (independent variables) and the interaction between them affect total movement time, steering time, correction time and the number of corrections (dependent variables), we adopted the two-way repeated-measures ANOVA for each of the dependent variables. Analogous to the analysis in the previous section, data has been first transformed logarithmically

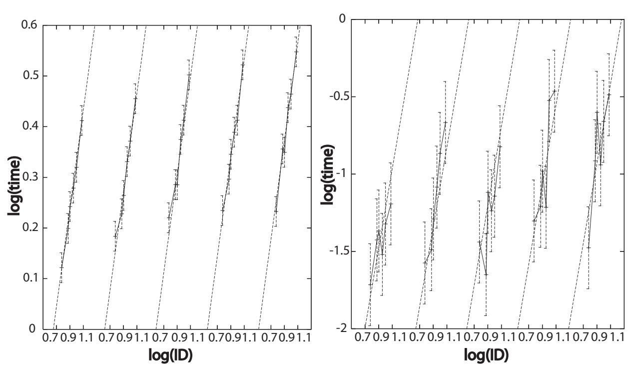

Figure 10: Left: Complete trial steering time as a function of ID fits onto Equation 8, see Table 2 for regression results. Right: complete trial correction time as a functions of ID fits onto Equation 8.

.

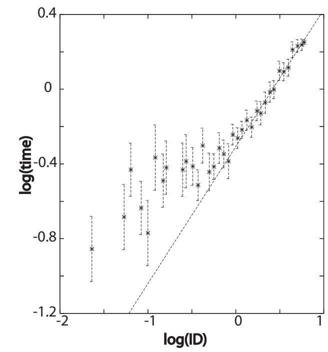

Figure 11: Data from experiment 2: subtrial time as a function of ID fits onto Equation 5.

so that they approximately observe a Gaussian distribution. Table 3 exhibits the ANOVA results, taking steering time as the dependent variable. As indicated, the difference in steering time that arises from α ($p = 0.4307$) is not significant. The influence of α in total movement time, correction time and the number of corrections is not significant, either ($p_{tot} = 0.4313; p_{cor} = 0.4167; p_{\#cor} = 0.4507$). In fact, the statistical evidence is insufficient to claim that α affects the dependent variables.

Source	'F'	'p'
α	0.9436(3,33)	0.4307
β	7.4036(3,33)	6.3482e-4
$\alpha \times \beta$	2.7835(9,99)	0.0060

Table 3: Two-way repeated-measures ANOVA summary table, dependent variable: logarithm of steering time ($log(T_{ST})$); independent variable: α and β. Note that β and the interaction $\alpha \times \beta$ significantly affect the steering time, while α doesn't have a significant effect.

In contrast, the effects of β on total movement time, steering time, correction time and the number of corrections are all significant ($p_{tot} = 1.0268e-5; p_{ste} = 6.3482e-4; p_{cor} = 1.4011e-5; p_{\#cor} = 6.16733e-6$), i.e. path orientations of different directions around the y-axis conclusively influences path steering. The ANOVA results confirm that at least one viewing direction results in different path steering behavior.

To further specify the effects of β, we illustrate the relationship between $\log(correctionTime)$ and β with mean and the corresponding 95% confidence intervals, in Figure 12(c). A similar plot is shown for the effects of β on the number of corrections in Figure 12(d). Generally speaking, there is a U-shaped influence where paths of 90° result in the shortest correction time and the least errors, followed by those of 45° and 135°, while those of 0° have the longest correction time and the most errors. We can interpret this result as that performing a steering task along the viewing direction or in oblique directions (the path on bottom right in Figure 1) has less opportunity to go off the track and requires less time in correction than perpendicular to the viewing direction (bottom left in Figure 1). Besides, β has a similar significant influence on the total time and steering time (Figure 12(a) and (b)), except that the valley of the U-shaped curve appears in paths of 45°, rather than 90°. Note that the average steering time to navigate through paths of 45° (moving to the right) is significantly shorter than that of 135° (moving to the left), indicating an asymmetry in performance.

As indicated by Table 3, there is also an effect of the interaction term between α and β on the steering time, i.e. the effect of β shown in Fgigure 12(b) may vary when different α values are con-

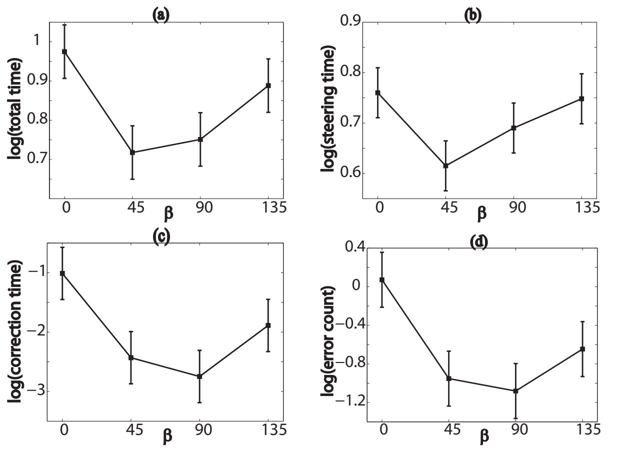

Figure 12: The effects of β on (a) total time, (b) steering time, (c) correction time, (d) the number of corrections with mean (points) and 95% confidence interval (bars).

sidered (see Figure 13). Note that the V-shaped curves are slightly different when α has the value 0° and 135°.

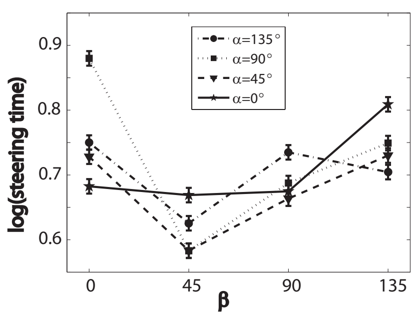

Figure 13: The effects of interaction term $\alpha \times \beta$ on steering time: with β described by x-axis and α by different lines.

5 Discussion

There are a number of issues that are raised by the experiment.

The first issue is how we better model the path steering with the known influential parameters, i.e. path length, width, curvature, etc. The index of difficulty of a steering task, according to Accot and Zhai's model, is only governed by the length and width of the steering path. Therefore path 1 and 2 shown in Figure 1, of the same path width and length, were considered to have the same ID, although this is somewhat counterintuitive. The failure of taking the path curvature into account significantly reduces its capacity when applied to different steering tasks. By including the effect of curvature as in formula 8, we provide the possibility to compare the steering efficiency on the paths of different shapes, which is beyond the scope of the Accot and Zhai's steering law where straight and circular paths have to be dealt with separately. We propose to consider a variation of formula 8:

$$\log T = a + b(\log \frac{L}{W} + c'\rho) \tag{9}$$

where ID is redefined as $\log \frac{L}{W} + c'\rho$, introducing the influence of curvature of the steering path, together with length and width.

The second issue has to do with how subjects actually decompose a steering movement into sub-movements, i.e. to get more insight into what are the elementary units in the overall movement. The subtrials that we have used in this paper are obviously not the optimal way to segment the overall trial, as a subtrial can potentially consists of several sub-movements, in agreement with Accot and Zhai's assumption. The only way to actually resolve this is to adopt a more objective way of subdividing the (sub)trials, for instance using a similar parsing method as was adopted for analyzing directed movements [16]. Since the movements of the pen and cursor ball were logged during the experiment, such analysis is feasible and planned in the near future. For now, we could hypothesize, also based on the experimentally observed value for the power function, that we expect more analogy with goal directed movements than is implied by the steering law and its theoretical derivation.

The last issue is that we need to develop a better understanding of the effect that the orientation of a stimulus, relative to the viewing angle, has on performance, and of the way the handedness of the subjects affects this. The asymmetric effect as shown in Figure 12, i.e. the difference between moving to the left (paths of 135°) and the right (paths of 45°), may attribute to the handedness, as proposed by Accot and Zhai in [1]. Since all subjects reported the right hands as the dominant hands, paths of 45° seems to be easier to steer through than that of 135°. Obtaining answers to such questions would obviously require additional data. Possibly also the hand and arm pose of the subject will have to be monitored to obtain more systematic insight into how users actually perform steering movements.

6 Conclusion

We have addressed Accot and Zhai's question if the steering law could also be used to model the performance of 3D manipulations tasks. The *cursor and tunnel* task is somewhat simpler than the *ring and wire* task proposed by Accot and Zhai, since the cursor ball is orientation independent, whereas the ring must be oriented in such a way that it doesn't intersect the wire.

We have experimentally demonstrated that the steering law is able to predict the overall performance of the cursor and tunnel task. The data analysis confirms the steering law (time proportional to $\frac{L}{W}$) for total steering time. However, we have also shown that other factors are significant. There is a systematic effect of the curvature on both the total and steering time. This effect can accurately be modeled as a percentage increase in time for increasing curvatures.

Despite that the steering law models the overall task time quite well, the original motivation for it seems not to be valid. Indeed, describing the steering movement as a repetition of small goal crossing submovements actually describes a continuous movement (equation 2). However, when only subtrials are considered (i.e. actual continuous steering time, not including correction time), the steering law as a description is clearly not valid. Our results show that time proportional to $(\frac{L}{W})^{0.6}$ is much closer to the actual data. This lies closer to the original Fitts' law, i.e. time proportional to $\log(\frac{L}{W})$, which in turn should be close to time proportional to $(\frac{L}{W})^{1/3}$ (see Figure 14). Hence, the steering behavior seems to be in between Fitts' law and the steering law. We therefore postulate that the behavior is more like a succession of small ballistic movements (a series of consecutive ballistic phase of pointing tasks) than a continuous steering. Additional research is needed to substantialize this claim.

References

[1] J. Accot and S. Zhai. Beyond fitts' law: Models for trajectory-based HCI tasks. In *CHI '97: Proceedings of the SIGCHI conference on Human factors in computing systems*, pages 295–302, 1997. 1, 6

[2] J. Accot and S. Zhai. Performance evaluation of input devices in. trajectory-based tasks: An application of the steering law. In *CHI '99: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 466–472, 1999. 2

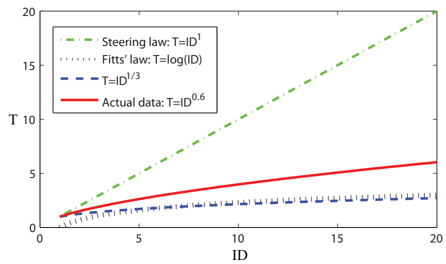

Figure 14: Movement time as a function of index of difficulty described with Fitts' law, steering law and the actual data. Fitts' law which requires a logarithm relation between movement time and the index of difficulty is very close to the function of $T = ID^{1/3}$ when ID is within a reasonable interval ([6,12] in our experiment). The actual data, described as $T = ID^{0.6}$, is closer to Fitts' law than steering law that needs to be modeled as a linear function.

[3] J. Accot and S. Zhai. Scale effects in steering law tasks. In *CHI '01: Proceedings of the SIGCHI conference on Human factors in computing systems*, pages 1–8, 2001. 2

[4] J. Accot and S. Zhai. Refining fitts' law models for bivariate pointing. In *CHI '03: Proceedings of the SIGCHI conference on Human factors in computing systems*, pages 193–200, 2003. 2

[5] J. Boritz and K. S. Booth. A study of interactive 3d point location in a computer simulated virtual environment. In *Proceeding of the ACM Symposium on Virtual Reality Software and Technology*, pages 181–187, 1997. 2

[6] N. Elmqvist and J.-D. Fekete. Semantic pointing for object picking in complex 3d environments. In *Proceedings of graphics interface 2008*, pages 243–250, 2008. 2

[7] P. M. Fitts. The information capacity of the human motor system in controlling the amplitude of movement. *Journal of Experimental Psychology*, 47(6):381–391, June 1954. 2

[8] T. Grossman and R. Balakrishnan. Pointing at trivariate targets in 3d environments. In *Proceedings of the SIGCHI conference on Human factors in computing systems*, pages 447–454, 2004. 2

[9] T. Grossman, K. Hinckley, P. Baudisch, M. Agrawala, and R. Balakrishnan. Hover widgets: using the tracking state to extend the capabilities of pen-operated devices. In *CHI '06: Proceedings of the SIGCHI conference on Human Factors in computing systems*, pages 861–870, 2006. 2

[10] R. Kattinakere, T. Grossman, and S. Subramanian. Modeling steering within above-the-surface interaction layers. In *CHI '07: Proceedings of the SIGCHI conference on Human factors in computing systems*, pages 317–326, 2007. 2

[11] L. Liu, R. van Liere, C. Nieuwenhuizen, and J.-B. Martens. Comparing aimed movements in the real world and in virtual reality. In *VR '09: Proc. IEEE Virtual Reality 2009*, pages 219–222, 2009. 2

[12] I. S. MacKenzie. Fitts' law as a research and design tool in human-computer interaction. *Human-Computer Interaction*, 7:91–139, 1992. 2

[13] I. S. MacKenzie and W. A. S. Buxton. Extending fitts' law to two-dimensional tasks. In *Proceedings of the SIGCHI conference on Human factors in computing systems*, pages 219–226, 1992. 2

[14] A. Murata and H. Iwase. Extending fitts' law to a three-dimensional pointing task. *Human Movement Science*, 20:791–805, 2001. 2

[15] S. Naito, Y. Kitamura, and F. Kishino. Steering law in an environment of spatially coupled style with matters of pointer size and trajectory width. *Computer Human Interaction 6th Asia Pacific Conference - APCHI 2004*, 3101:305–316, 2004. 2

[16] C. Nieuwenhuizen, L. Liu, R. van Liere, and J.-B. Martens. Insights into 3D goal-directed movements. *IEEE Computer Graphics and Applications*, 2010. Accepted for publication. 2, 6

[17] R. Pastel. Measuring the difficulty of steering through corners. In *CHI '06: Proceedings of the SIGCHI conference on Human factors in computing systems*, pages 1087–1096, 2006. 2

[18] Y. G. Renaud Blanch and M. Beaudouin-Lafon. Semantic pointing: Improving target acquisition with control-display ratio adaptation. In *Proceedings of the SIGCHI conference on Human factors in computing systems*, pages 519–526, 2004. 2

[19] A. Steed. A simple method for estimating the latency of interactive, real-time graphics simulations. In *Proceedings of the 2008 ACM symposium on Virtual reality software and technology*, pages 123–129, 2008. 3

[20] S. Zhai, J. Accot, and R. Woltjer. Human action laws in electronic virtual worlds: An empirical study of path steering performance in VR. *Presence: Teleoperators and Virtual Environments*, 13(2):113–127, 2004. 1

APPENDIX: LOG TIME ANALYSIS

Since the data analysis that we performed in this paper is somewhat unusual, it is useful to summarize the reasons why we think that an analysis based on log(*time*) is superior over an analysis based on *time*, i.e.,

1. methodological: a regression analysis assumes Gaussian noise with (approximate) constant variance; this is clearly not the case of time where the observed variance often increases with time (and moreover, time cannot be Gaussian distributed as it is restricted to being positive).

   Looking at the cumulative histograms of the subtrial times in Figure 15, we see that the observed times have an asymmetrical distribution, which clearly deviates from the Gaussian distribution assumption made in most regression (and ANOVA) analysis methods. Taking the logarithm of time usually helps to bring the observed time distributions closer to such a Gaussian distribution, as is evidenced by the distributions in Figure 16.

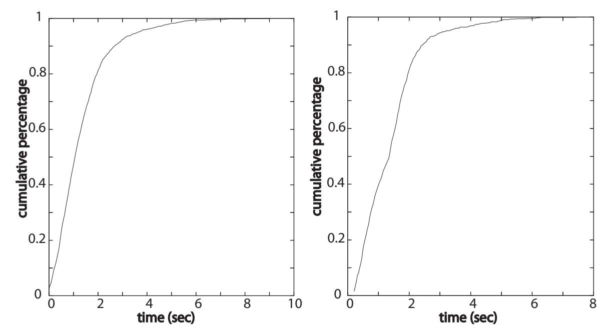

Figure 15: Cumulative histogram of subtrial time: experiment 1 (left), experiment 2 (right). Both histograms show strong deviation from Gaussian distribution

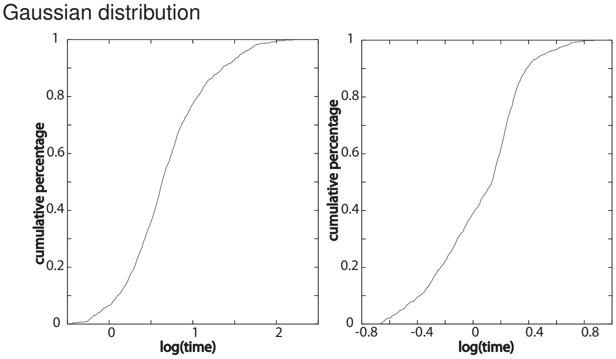

Figure 16: Cumulative histogram of subtrial logarithm time: experiment 1 (left), experiment 2 (right). After transformed logarithmically, subtrial time approximately follows Gaussian distribution.

2. modeling: linear regression on log(time) corresponds to a different class of functions (power functions that pass through the origin) than linear regression on time; as the regression lines on time in our data were observed to pass (approximately) through the origin, the power functions comprise a more general class of models.

3. interpretation: in order to test the steering law, a test to determine whether or not time varies linearly with L/W is needed; by considering a larger class of models (power functions), we can translate this in a statistical test on the power (testing whether or not it significantly different from 1).

4. communicating absolute versus relative conclusions: the different slopes that are found in linear regression lines on time translate into a shift for the regression lines on $log(time)$ (a percentage change); this is easier to communicate and moreover also shows that the effect of curvature is constant (in percentage) across IDs.