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Human Action Laws in Electronic Virtual Worlds

– An Empirical Study of Path Steering Performance in VR

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Abstract

This paper is concerned with simple human performance "laws of action" for three classes of tasks – pointing, crossing, and steering, as well as their applications in virtual reality research. In comparison to Fitts' law of pointing, the "law of steering" – the quantitative relationship between human temporal performance and the movement path's spatial characteristics – has been notably under investigated. After a historical review of research on the law of steering in different domains and time periods, we examine the applicability of the law of steering in a VR locomotion task. Participants drove a virtual vehicle in a virtual environment on paths whose shape and width were systematically manipulated. Results showed that the law of steering indeed applies to locomotion in virtual environments. Participants' mean trial completion times linearly correlated (r^2 between 0.985 and 0.999) with an index of difficulty quantified as path distance to width ratio for the straight and circular paths used in this experiment. Their average mean and maximum speed was linearly proportional to path width. Such human performance regularity provides a quantitative tool for 3D human machine interface design and evaluation. We also propose to use the law of steering model in VR manipulation tasks such as the "ring and wire" task in the future.

1. Introduction

Human performance regularities characterized by quantitative models not only constitute important components of human sciences, but also form the theoretical foundations for human-machine system analysis and design. This relationship is similar to laws in physical sciences and modern engineering. It is inconceivable to conduct mechanical or electrical engineering without Newton's laws and the like. Understanding human performance regularities hence holds critical importance to user interface technologies, including 3D user interfaces and other electronic virtual worlds.

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Due to the complexity of human behavior, regularities in human performance are difficult to establish, but few successful examples do exist. A class of them pertinent to the current paper can be called “laws of action” including “the law of pointing”, “the law of crossing”, and “the law of steering”. These laws quantitatively relate the human temporal performance with the spatial constraints in movement or action tasks. The best known model in this class is Fitts’ law (Fitts, 1954).

1.1 Law of Pointing

Fitts’ law has served as one of the corner stones of human computer interaction (HCI) research. Its contribution to user interface design and evaluation include principled evaluation of different input devices (Card, English, & Burr, 1978; ISO, 2000; MacKenzie, 1992; MacKenzie, Sellen, & Buxton, 1991; S Zhai, 2002), systematic comparison of two styles of interfaces such as crossing-based vs. pointing-based interaction (Accot & Zhai, 2002b), and optimization of stylus-based virtual keyboards (MacKenzie & Zhang, 1999; S. Zhai, Smith, & Hunter, 2002). Fitts’ law has also inspired novel interaction techniques such as the area cursor (Kabbash & Buxton, 1995).

Fitts’ law can be also called the “law of pointing”. It models a specific task – the Fitts’ tapping task, which corresponds to a pointing task on a computer screen. The best accepted form of Fitts’ law in the HCI field is:

$$T = a + bID \qquad (1)$$

where T is the average time to reach a target, a and b are constant and ID is the index of difficulty defined as follows:

$$ID = \log_2\left(\frac{D}{W} + 1\right) \qquad (2)$$

where D is the distance of the pointing movement and W is the width of the target.

Fitts’ law in its basic form is fundamentally one dimensional. In laboratory Fitts’ law experiments the pointing targets are typically set as strips whose size along the movement direction is set at W but its size orthogonal to movement direction is practically unlimited. Conceptually, Fitts’ law models the information capacity of the human motor system in controlling the *amplitude* of movement, as suggested in the title of Paul Fitts’ original paper (Fitts, 1954). Recently, we found that the same basic form of Fitts’ law could also apply when the target constraint is *directional*, i.e. when the size of the target is only controlled in the direction orthogonal to movement and the amplitude direction is left practically unlimited (Accot & Zhai, 2002b). When the target is two dimensional, i.e. when the directional and the amplitude constraints exist simultaneously, it has been recently demonstrated that the following model gives a more complete and accurate prediction than previous 2D Fitts’ law models (e.g. (MacKenzie & Buxton, 1992) (Hoffmann & Sheikh, 1994)):

$$T = a + bID, \qquad ID = \log_2\left(\sqrt{\left(\frac{D}{W}\right)^2 + \eta\left(\frac{D}{H}\right)^2} + 1\right) \qquad (3)$$

where W is the amplitude constraint size, H is the directional constraint size, and η is a constant typically in the range of 1/3 to 1/7. The fact that η is smaller than 1 indicates that the directional constraint is less difficult to handle than the amplitude constraint of the same magnitude.

Fitts' law has been also applied to 3D VR or tele-operation research (e.g. (Drascic, 1991) (Watson, Walker, Woytiuk, & Ribarsky, 2003)). There are two approaches to applying Fitts' law in 3D. One is to use it as a one dimensional task along the depth direction – the more difficult perceptual dimension in 3D. For example, the effects of stereoscopic vs. monoscopic viewing in teleoperation have been investigated in this approach (Drascic, 1991). The other approach is to extend Fitts' law to incorporate all three dimensions (e.g. (Ware & Lowther, 1997)). More specifically, in (Ware & Lowther, 1997) the minimum of the three target dimensions was taken as the target size. This approach, which is insensitive to orientation in 3D space, is less plausible because the depth dimension in 3D is much more difficult to perceive than the other two dimensions. It is improbable that pointing performance in 3D space will be independent of the movement direction in a general way.

1.2 Law of Crossing

The second class of perceptual-motor action that can be reliably modeled is goal crossing. As shown in Figure 1, the time to move (a cursor or a stylus) across two goals follows the same characterization of equation (1) and (2): $T = a + b\log_2\left(D/W + 1\right)$. Here T is the average movement time between passing the two goals; D is the distance between the two goals and W is the width of each goal (Accot & Zhai, 1997). In other words, there is a "law of crossing". Accot and Zhai (2002b). has also been shown that the goals could also be laid in different directions and the crossing action can be either continuous (stylus slides on surface) or discrete (landing the stylus before a goal and lifting it up after crossing the goal). With such a foundation, user interfaces can be designed with goal crossing, rather than target pointing, as the basic interaction action, particularly for pen-based computing. It is also possible to apply crossing actions in 3D interfaces, as pointing in VR without 2D surface is often difficult.

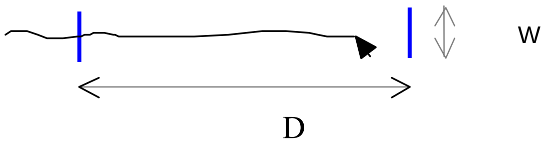

Figure 1. A goal-crossing task

1.3 Law of Steering

The third class of actions that can be reliably modeled by quantitative laws is in path steering tasks. This class of action is particularly relevant to electronic virtual worlds. Navigating through nested-menus, drawing curves, and locomotion along a particular path in a virtual reality environment are a few examples of steering tasks. We focus the rest of this paper on this class of action, particularly its applicability in 3D VR.

2. A Review of Path Steering Models

In comparison to the countless citations and great impact of Fitts' law on the study of pointing tasks, research on performance models of path steering tasks has been much lesser known. Driven by different motivations and using different methodologies in different periods of time, the "law of steering" in one form or another has been independently studied at least three times (Rashevsky, 1959) (Drury, 1971) (Accot & Zhai, 1997). The early works of Rashevsky (Rashevsky, 1959) Drury (Drury, 1971) and others (Beggs, Sakstein, & Howarth, 1974) on "movement with lateral constraint" have almost gone unnoticed in the main stream psychology, human motor control, or the HCI field, although path steering has similar importance to target reaching. In this section we briefly review and summarize the past work on path steering models.

2.1 Rashevsky's model of driving

The first reference to a path steering model is found in a dozen articles published by Nicholas Rashevsky between 1959 (Rashevsky, 1959) and 1970 (Rashevsky, 1970), mainly in the *Bulletin of Mathematical Biophysics* (see (Beggs et al., 1974) and (Rashevsky, 1970) for more references). Rashevsky's concern was exclusively to model driving, although he also used the more general term ``man-machine interaction" (Rashevsky, 1965) . The conclusion of his research was that the maximum safe speed to drive could be modeled by the following equation:

$$V_{\max} = \frac{w - 2\delta - c}{\theta\, t} \qquad (4)$$

where $V_{\max}$ is the maximum driving speed, w is the track width, δ is the distance of the boundary from the track edges, c accommodates the dimension of the car, δ is the angular error in driving, and t is the driver's reaction time. Rashevsky's work was entirely analytical – no empirical experiments were conducted.

2.2 Drury's model

Colin Drury viewed "vehicle guidance tasks" as a type of "movements with lateral constraint" (Drury, 1971). By a statistical analysis of velocity, he found that:

$$T = \frac{D\theta\, k_1 t_s}{w} \qquad (5)$$

where T is the time to complete the track, D is the movement distance, θ is the standard deviation of the angular accuracy of movement, k_1 is a constant (a ``safety factor"), t_s the sampling interval, and w the track width. Drury tested both linear and circular tunnels empirically. Drury and colleagues subsequently also built statistical models based on reward/penalty matrices and attempted to model the effect of path curvature (Drury, Montazer, & Karwan, 1987) (Montazer, Drury, & Karwan, 1988).

There are two main differences between Drury's model and Rashevsky's model. First, Rashevsky's model is only local, that is it describes the vehicle velocity at one time only; while Drury's model describes the time needed to track through an entire path. Second, Drury's model incorporated the notion of risk in his model with the safety factor k_1, which led to the later reward/penalty matrix model. More importantly, Drury and colleagues' work were all verified empirically (Defazio, Wittman, & Drury, 1992; Drury, 1971).

2.3 Accot and Zhai's models

Motivated by human-computer interacting tasks such as menu-navigation, Accot and Zhai more recently investigated performance models in path steering tasks (Accot & Zhai, 1997, 1999, 2001) (Accot, 2001). Their basic formulation of manual steering tasks for a generalized path (See Figure 2) is in the following integral form

$$T = a + b\int_C \frac{ds}{W(s)} \qquad (6)$$

where T is the time to successfully steer through the path C, $W(s)$ is the path width at s. $ID = \int_c 1/W(s)ds$ is considered the index of difficulty of the steering task.

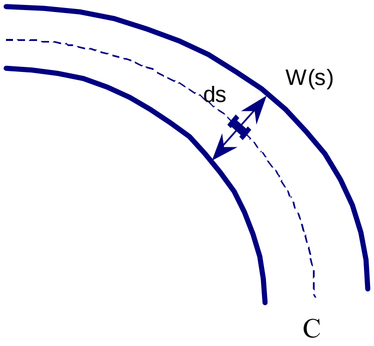

Figure 2. Generalized steering task

The main difference with Drury's model here is that the integral law is valid for any shape, not just linear or circular. Complex shapes, such as narrowing or spiral tunnels were successfully modeled and verified (Accot & Zhai, 1997). The simplest form of the integral law for straight paths with constant width, See Figure 3 (Figure 3) is:

$$T = a + b\frac{D}{W} \qquad (7)$$

where T is the time to successfully steer through the straight path, W is the path width and D the path length; a and b are constants. $ID = D/W$ is considered the index of difficulty of the task. Equation (7) also applies to circular path with constant width. This model is simpler than Drury's (Equation 5). Constant b corresponds to a few constants in Drury's model. It is unknown how to estimate the k_1 and t_s constants in Drury's model.

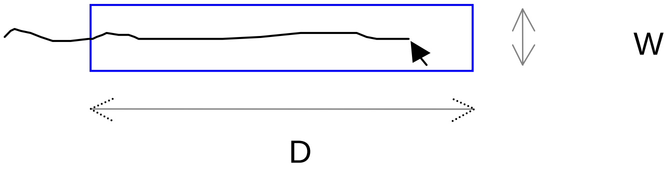

Figure 3. A straight path

Accot and Zhai also expressed the law of steering in a local form based on speed v:

$$v = \frac{W}{\tau} \qquad (8)$$

where τ is a time constant. A more complex version of the "local steering law" takes the following statistical form (Accot, 2001):

$$v = \frac{W}{2\Delta t \sigma \varphi^{-1}(p)} \qquad (9)$$

where W is the path width, Δt is the detection/reaction time to a visual stimulus, σ is the standard deviation of the movement direction error, p is the probability of making an error in the interval Δt, and φ is called the probability integral:

$$\varphi(x) = \frac{1}{\sqrt{2\pi}} \int_{-x}^{x} e^{-\frac{u^2}{2}} du \qquad (10)$$

Equation (10) is very close to Drury's model (Equation 5) except that it is local and that it made explicit the ``safety factor". For instance, knowing that the constant k_1 is equal to $\varphi(p)$ tells us that to decrease the probability of making an error from 5% ($\varphi^{-1}(0.95) = 1.96$) to 0.01% ($\varphi^{-1}(0.9999) = 3.89$) one has to reduce the movement speed by a factor two.

Accot and Zhai's work also logically bridged the steering law with the better known Fitts' law. In a thought experiment, they deemed a steering task as the accumulation of an infinite number of goal-crossing tasks (Accot & Zhai, 1997). As presented in the Introduction section, the time to cross a goal of width *W* at a distance *D* (Figure 1) follows the Fitts' law equations (1) and (2). Using the goal passing task as a stepping stone, their thought experiment placed an increasing number of goals along the movement trajectory (Figure 4). The summed up index of difficulty of N consecutive goals is:

$$ID_N = N\log_2\left(\frac{D}{NW}+1\right) \qquad (11)$$

Taking *N* to infinity, the task depicted in Figure 4 became Figure 3, and the above index of difficulty became *A/W ln(2)*, which led to the prediction that the time to steer through a linear path would follow equation (7) - the integral form of steering law for a straight path.

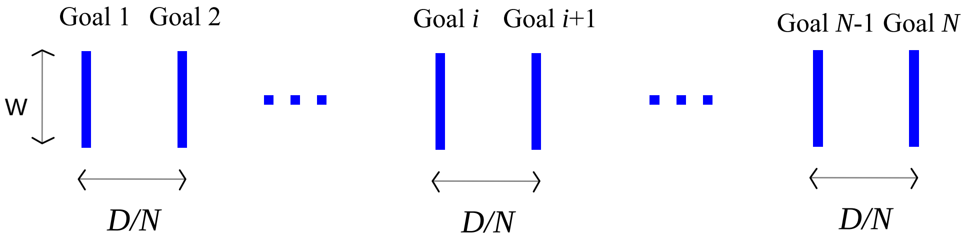

Figure 4. From goal crossing to path steering: a thought experiment

Accot and Zhai showed that the lawful relationships in steering tasks holds for paths in different shapes, such as a cone, a spiral shape, or a circle (Accot & Zhai, 1997; Accot & Zhai, 1999), all experimentally verified at greater than 0.96 fitness. They have also shown that the steering law holds when different input control devices were used (Accot & Zhai, 1999) and when the hand movement scale was varied by many folds (Accot & Zhai, 2001).

As this review has shown, at least three independent approaches motivated by different problem domains in different time periods have revealed essentially the same underlining regularity in path steering task, indicating that there is indeed a robust law of steering in human performance. Since Accot and Zhai (Accot & Zhai, 1997), there have been quite a few HCI studies instigated or influenced by the law of steering (e.g. (Accot & Zhai, 1999) (Dennerlein, Martin, & Hasser, 2000) (Gutwin & Skopik, 2003)), all in manual control tasks on 2D screen. The steering paradigm has also been adopted by the ISO standard for input device evaluation (ISO, 2000). In the next section of this paper we illustrate the applicability of the law of steering as a research and evaluation tool for 3D virtual environments, in particular locomotion in virtual environments.

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3. An empirical study of the law of steering in VR locomotion

Locomotion, moving from place to place, is a common activity in VR. Here we are particularly interested in locomotion with explicit path constraints. The difference between locomotion and manual movement lies in the frame of reference and the scale of movement. In manual movement tasks, the human operator's body is stationary and the movement scale is hence limited to the arm's length. In other words, the task is egocentric. In locomotion tasks, the human body moves in an exocentric space and in an unlimited scale.

Locomotion[1] includes walking, running, swimming, biking, driving, etc. It is conceivable that the law of steering may play a role in each of these locomotion tasks. However the speed of walking and running is typically limited by humans' physiological power, rather than by their perceptual-cognitive-motor capacity in dealing with information and control, unless the path is extremely narrow. In driving, on the other hand, power is less important a limiting factor. We hence decided to focus on virtual driving as a task to test the law of steering in locomotion.

An actual driving task involves a set of complex factors such as engine performance, road surface condition, vehicle stability, risk and safety, etc, which are besides the point of the current investigation. Due to safety concerns, previous study of steering models with actual vehicle driving can be only limited to a small range of path width ((Defazio et al., 1992), page 383). Studying path steering performance in VR affords us much greater flexibility in an "essentialized" platform.

In fact even driving simulation is a rather complex task that involves more than just information processing and control, which are the main interest of the current study. For example, the simulated vehicle will necessarily have some of the basic physical constraints of a real vehicle in terms of power (acceleration), weight (inertia) etc, not only for simulation fidelity but also to meet participants' basic expectations of driving behavior.

We conducted a locomotion experiment on a driving simulator, located at Linköping University in Sweden. Figure 5 shows a photograph of the simulator. The driver's seat, steering wheel, gas and brake pedal were identical to a modern automatic car (SAAB 9-5).

The driver's view of the road and the world were projected on three connected screens covering driver's central and peripheral vision, with 160 degrees field of view. Each screen had 1024 by 768 pixel resolution. The graphics were rendered in real time in response to driver's actions. The simulation was entirely visual-spatial. No force feedback or tactile simulation was involved.

Two types of driving path were used in the experiment – one straight the other circular, modeled after the drawing path shapes in (Accot & Zhai, 2001). It has been shown in hand steering movement that a circular path took longer time than its straight counter part. We expect this is true for locomotion as well.

In order to test if there is any difference due to the direction of turning, clockwise (right turn) and counter-clockwise (left turn) driving on the circular path were treated as separate tasks. Hence

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[1] The dictionary definition of locomotion is "The act of moving from place to place". Some researchers use the term more restrictively to movement that involves gait (Hollerbach, 2002). We use the term in the more common sense. An alternative term for movements studied in this section is "navigation" that, however, also connotes "way finding".

there were a total of three types of paths in the experiment: straight, right circular and left circular driving.

Figure 5. Driving in virtual world

The length *D* of the driving path was always set at 1885 m (300 m in radius for the circular path). The width of the "vehicle" was 1.80 m. The width *W* of the path was set at 1.80 m plus one to six 0.5 m increments, i.e. 2.3, 2.8, 3.3, 3.8, 4.3, 4.8 m. The range of the width was so chosen in a pilot testing that it was as wide as possible without saturating the limit of the simulated engine power.

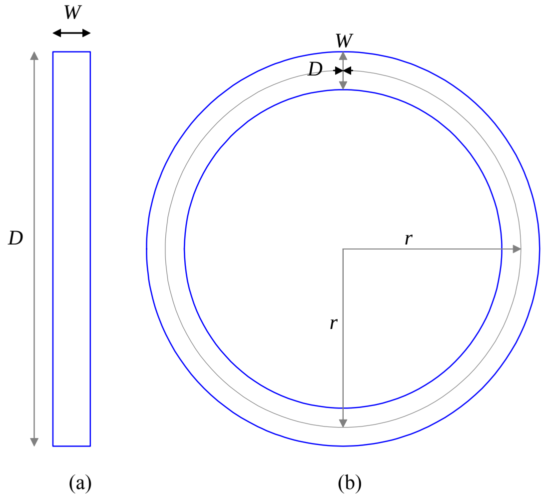

Figure 6. Two types of paths used in the experiment

In order to enable the participant to judge the car position in relation to the road, we first graphically represented the vehicle's hood at a height similar to a regular car on the screen. Pilot testing showed that with this display it was too difficult to judge precisely the relative distance between the vehicle and the road boundary due to visual parallax (the hood obscured the path). In order not to let the participants drive in uncertainty, we eventually represented the front of the vehicle as a flat plate 1 cm above the ground level, giving the driver a clear and direct visual comparison between the vehicle and the path boundary (Figure 7).

The participant's task was to drive the vehicle to a clearly marked finishing point (Figure 7 lower left picture) as quickly as possible without going out of the path's boundary. The path was clearly marked with white boundary and enhanced with poles placed every 10 meters (Figure 7). Whenever the vehicle was out of the boundary, a car crash sound was played and the trial had to be restarted from the beginning point. Time and speed reported later were all based on the completed trials. The numbers of failed trials (error rate) were also recorded.

The power of the simulated car was adjustable. In a pilot experiment we found the engine power had to be set according to a speed-accuracy trade-off. If the power were too high, it would be too difficult to control the car to a steady slow speed. If the power were not high enough, the car would not reach driver's desired speed even if the gas pedal were pressed all the way down. The power of the simulated vehicle was eventually set at 5 times of a normal sedan so it was not over sensitive for the narrowest path but still not saturated for the widest path based on pilots' experience.

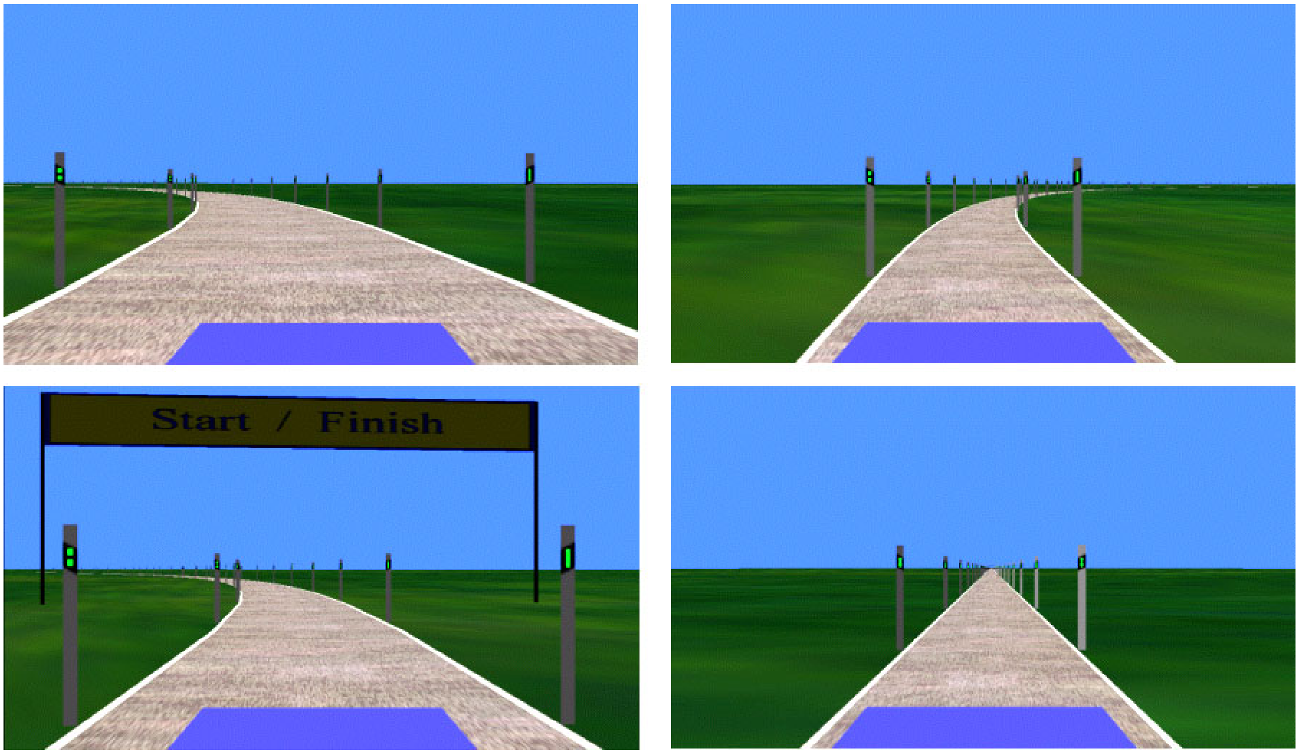

Figure 7. Screen shots of the simulator's central screen. Top left: wide width left turning circular path. Top right: narrow right turning path. Bottom left: medium width straight path approaching finishing line. Bottom right: narrow straight path.

12 paid volunteers participated in a within participant experiment. Each participant performed in all three (3) tasks (left turning, right turning and straight driving) with all six (6) widths. The testing order of these 3 x 6 paths was random. Six warm up trials, two widths from each shape, were given to each participant before the two complete testing blocks of trials. The participants were incidentally all male who had participated in a simulation study investigating a nighttime driving aid several weeks before this experiment. Their age ranged from 25 to 42, with an average of 30.5 years. They had a driving license for an average of 12.2 years and in the past year they drove on average 17208 km. Their experience with computer racing games ranged from zero to very extensive.

4. Results

Participants' driving behavior was recorded every tenth of a second throughout the experiment, including vehicle's X and Y coordinates, heading, gas pedal amplitude, brake pedal amplitude, steering wheel amplitude, speed, deviation from middle line, and collisions.

A salient aspect of the data is the large variance both between and within individual, which was much larger than path steering behavior previously observed in hand movement (Accot & Zhai, 1997; 1999; 2001). Participants used varied strategies from conservative-steady to risky-jerky extremes in order to be as fast as possible but not to crash (out of the path). A set of trials is shown in Figure 8.

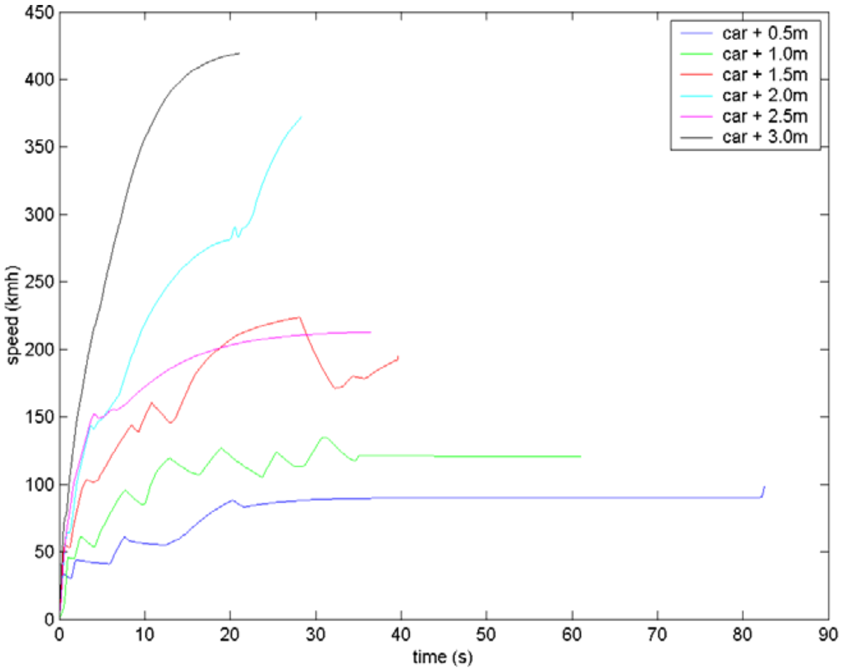

Figure 8. Sample speed-time trajectories (one participant, Block 2, Right turning path)

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Recording of the gas pedal position showed that some participants used all the power available by pressing the gas pedal all the way down in some trials. This shows that the individual variance in this type of tasks was greater than we anticipated based on our pilot testing. Figure 9 shows such cases for the straight path in one block of trials. When the power of the vehicle is saturated, driving speed would be limited by the power of the simulated vehicle rather than by driver's ability to stay with the specified path boundary. Clearly these participants' data could not be used for analyzing path effect. Note that if a participant used the maximum power in any of the path width, his data were excluded in the analysis of the rest of the path conditions as well. Otherwise the participants ability would not be consistent across all width tested.

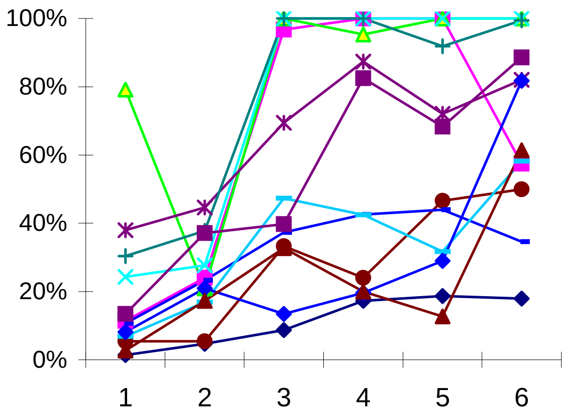

Figure 9. Gas pedal maximum magnitude of all participants in 6 path widths (from the narrowest on the left to the widest on the right) in one block

It was evident that driving involves much stronger dynamics than hand drawing movement. We therefore cannot expect the speed of driving be determined by the width of the path instantaneously. However, it was also evident in the data that path width affected speed. To investigate this effect, we examined two measures of driving performance: total time (equivalent to mean speed) across each entire trial and maximum speed in a trial. Total time is more reliable due to the filtering effect of aggregation, but it should also be more biased against wider path. The wider a path is, the greater portion of the trial is in acceleration toward the desired speed (Figure 8). On the other hand, the maximum speed in a trial could be a closer estimate of the steady state mean speed, but it might also be noisier since it is taken at one point of a trial.

4.1 Trial Completion Time

Straight Path.

Based on data collected in both blocks of the straight path condition, Figure 10 shows the regression result between mean completion time and the index of difficulty (*ID*) of the law of steering (equation 7). *ID* was calculated by the ratio between path length (D) and width (W). W was the path width effectively available for maneuvering, hence excluding the vehicle width. Mean completion time was based on valid data only, excluding Participant # 2, 3, 4, 7, 9, and 11 who reached the maximum gas pedal amplitude.

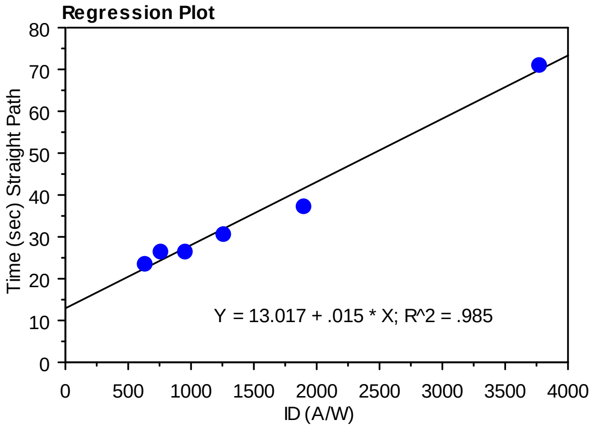

Figure 10. Trial completion time vs. index of difficulty in the straight path condition

Despite the greater complexity of driving as opposed to the hand movement without any external dynamics as previously studied (Accot & Zhai, 1997), there was a strong linear relationship between the mean time and ID ($r^2 = 0.985$), indicating the law of steering also holds for locomotion.

Right Circular Path

The procedure here was identical to the straight path condition. The "disqualified" were Participant # 4, 7, and 11. Figure 11 shows the results.

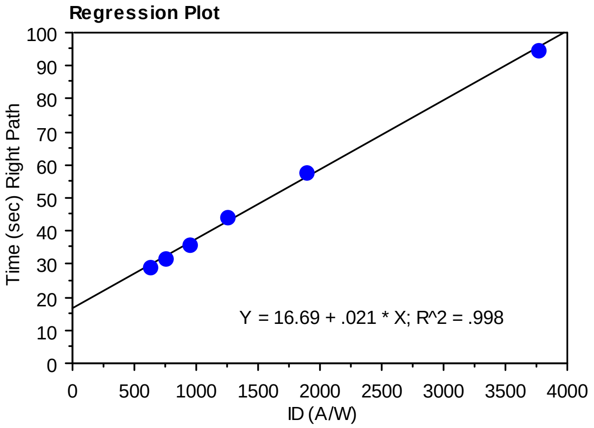

Figure 11. Trial completion time vs. index of difficulty in the right circular path condition

Left Circular Path

Figure 12 shows mean trial completion times for the left circular path condition. Invalid and excluded participants were # 2, 3, 4, and 7.

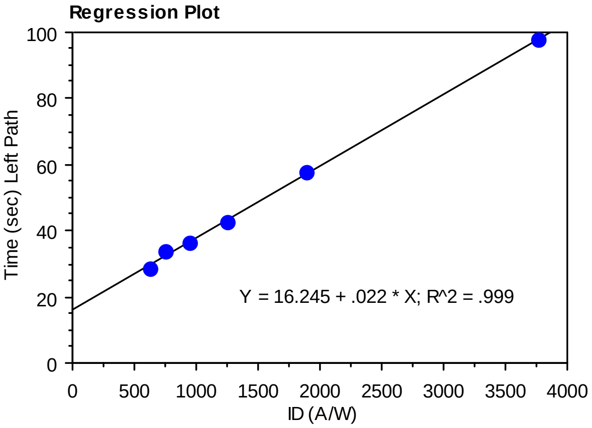

Figure 12. Trial completion time vs. index of difficulty in the left circular path condition

Taken together, the law of steering in its global form held extremely well for this locomotion task in all three path shapes (straight, left or right circular). The performance in the straight path steering was higher than the circular paths, both in terms of slope (less time increase per unit of ID) and intercept. Note that more (fast) participants reached the maximum gas pedal position in the straight path condition hence could not be included in the analysis. If there were more speed control amplitude available, the straight path could outperform the circular paths by a larger extent. Little difference could be detected between the left and right circular path in the time performance.

4.2. Maximum Speed

In this section we analyze the relationship between the maximum speed and the effectively available path width W (the total path width minus the car width) as prescribed by the local form of the law of steering (Equation 8). The mean value of all participants' maximum speed in both blocks was regressed against the W values. Those disqualified participants for time analyses were not included in this analysis for the same reason. Figure 13, 14, and 15 show regression results for the straight, right circular, and left circular conditions respectively.

The results show that maximum driving speed and the effective path width followed the local form of the steering law quite well, particularly for the more difficult circular path ($r^2 \geq 0.97$). The straight path fit the linear relationship less well, but still with $r^2 = 0.91$.

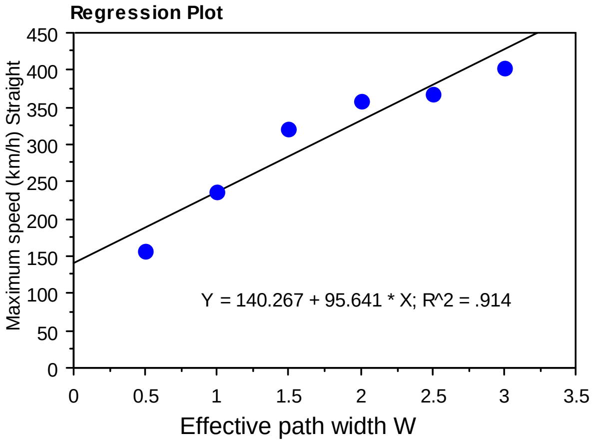

Figure 13. Mean maximum speed vs. path width, straight path

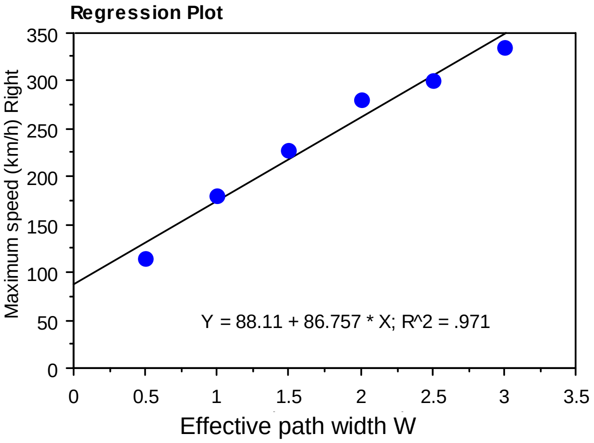

Figure 14. Mean maximum speed vs. path width, right circular path

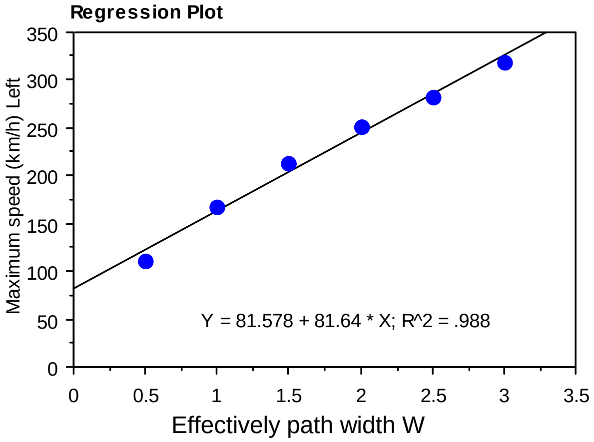

Figure 15. Mean maximum speed vs. path width, left circular path

4.3. Error Rate

Inevitably participants sometimes drove beyond the specified boundaries in pursuit of the maximum possible speed. Repeated measure variance analysis on the number of failed attempts per success trial (from all participants) showed that the error rate depended on the path width ($F_{5, 55} = 6.66$, $p < .0001$) with the narrowest path significantly more error prone than others (Fisher PLSD post hoc, $p < .0001$). There was a significant interaction between the path conditions (straight, left, right) and the path width ($F_{10, 110} = 2.95$, $p = .0026$). None of the other effects (block, condition, other interactions) or post hoc comparison were significant (Figure 16).

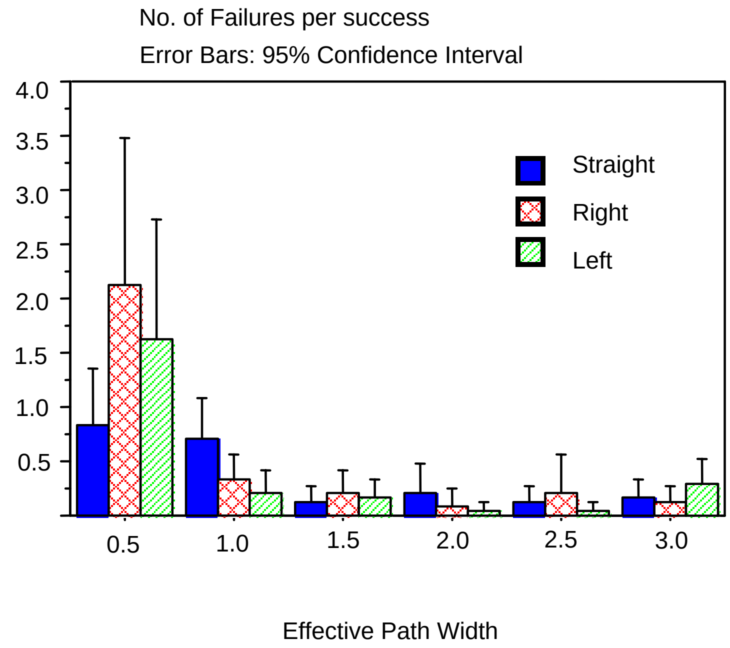

Figure 16. Number of failed attempts per success trial

4.4. Lateral Deviation

The participants exhibited a general tread to deviate from the centerline towards the side the path turns to. On average this deviation was about 10% of the effective path width, independent of the width value (Figure 17).

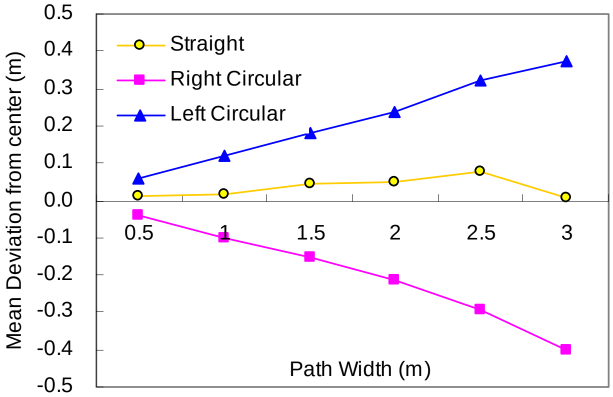

Figure 17. Deviation from the centerline, negative = right

4.5. Attention behavior

Participants were interviewed on various aspects of their experience. In particular, they were given an opportunity to indicate where they pay visual attention to when performing the task. The answers were not always consistent. Without statistical analysis based on reliable eye-gaze tracking, it is difficult to quantify visual attention. Nonetheless, participants' subjective indication revealed some trends: they looked further ahead when driving on wide roads (up to at the horizon) and more close to the "hood" on narrow roads (sometime between the blue indicator and the road edge), 10 of the 12 participants reported this pattern. Half of these participants reported to look at the inner side of the corner, the other half reported to look at both sides or the middle. 2 of the 12 participants always looked straight ahead towards the horizon. Figure 18 shows the overall tendency of visual attention focus.

5. Discussion, Conclusion and Application

Our study has confirmed that the law of steering is also valid for locomotion in electronic virtual worlds. We choose virtual driving to represent human locomotion tasks. Although driving is more complex than hand movement due to the vehicle dynamics and indeed showed large momentary change in speed, we found that people's mean performance was fundamentally constrained by path properties as quantified by the law of steering.

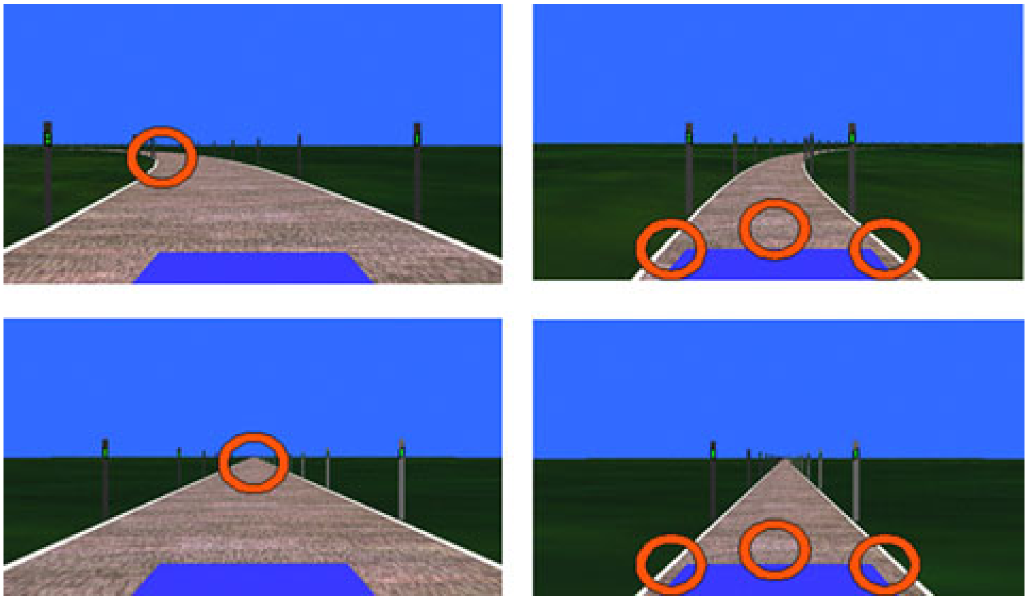

Figure 18. Subjective visual attention tendency

However, the validity of the law of steering only applies to a limited range of path width. We varied the path width (and hence the steering index of difficulty) by a factor of 6 in this study. Although this is much wider than what could be studied in real world driving due to safety concerns (for example, Defazio, Wittman, & Drury (1992) varied the effective width by less than 60%), the law of steering did start to saturate for the wider paths. In previous research on steering law in the hand movement paradigm (Accot & Zhai, 2002a), it had been consistently found that the law leveled off at certain maximum width beyond which the speed of steering was limited by the arm's physical power rather than by the human capacity in information processing and control. This was still true in our locomotion experiment, although the power limitation in driving simulation was not physiological. Some participants reached the maximum available control amplitude in the gas pedal whose limited range had to be mapped to accommodate both high and low speed. Would a longer range control handle possibly operated by hand enable the linear relationship be valid in a wider ranger of path width? This has to be tested in the future but the control range of any system is likely to be bounded.

The strong regularity in human steering performance in fact is quite plausible. The most basic theoretical underpinning of the law of steering lies in the limited human information processing and control capacity (Accot & Zhai, 2002a). Specifically, due to random noise either in the human perception-action channel or in the vehicle system and environment, the locomotion direction tends to deviate from that of the path. Such a deviation, if uncorrected, will eventually bring the movement out of the path boundary. Due to the limited human information processing capacity, it takes a certain amount of time to process the deviation information and form control action according to the vehicle dynamics. Over this time interval, the directional deviation results in a lateral deviation from the center of the path that is proportional to the locomotion speed. The greater the speed, the greater the lateral deviation, the less time it takes for such a lateral deviation to bring the locomotion out of the boundary. Conversely to safely stay in the maximum lateral deviation allowed (the path width), one has to keep the speed low enough. Accot and Zhai (Accot & Zhai, 2002a) provide a more formal analysis of this process.

There can be many types of applications of human performance regularity such as the law of steering. Many may go beyond our current expectation. In the field of virtual reality environments or 3D human machine interfaces, it is conceivable to apply the law of steering in locomotion tasks as a paradigm for systematic performance evaluation of design choice, just as Fitts' law has been applied in traditional input device evaluation (Card et al., 1978). For example, the parameters a, b and τ in equation 6 and 8 of the law of steering may be used as systematic metrics for comparing alternative devices and method for navigation in virtual environment. Past studies on this topic (e.g. (Ware & Slipp, 1991; S. Zhai, Kandogan, Smith, & Selker, 1999)) have lacked a quantitative model as a theoretical foundation. The law of steering in the locomotion paradigm may fill the void.

We have focused on applying the law of steering to model locomotion behavior in VR, because most of the previous law of steering HCI studies are on 2D manual manipulation tasks. It is worth noting that the law of steering can also be applied as a research or design tool for manipulation tasks in 3D VR. For example, the "ring and wire" task, illustrated in Figure 19, is commonly used in VR research and evaluation (e.g. (Ellis, Bréant, Menges, Jacoby, & Adelstein, 1997) (Rose *et al.,* 2000)). However, without a quantitative performance model, evaluation in this paradigm could be only the specific result for a particular task difficulty setting. With the law of steering, we can model the task *systematically* with an index of difficulty calculated from the inner diameter of the ring and the length of the wire (Equation 7 or more generally Equation 6). Once we apply such a model, we would be able to understand the performance difference not only at a specific task setting between two interfaces or conditions differing in either display, or control, or other system characteristics such as lag, but also as a function of the task difficulty, just as Fitts' law index of difficulty has been used to develop systematic studies of VR or teleoperation systems (e.g. (Drascic, 1991) (Watson et al., 2003)).

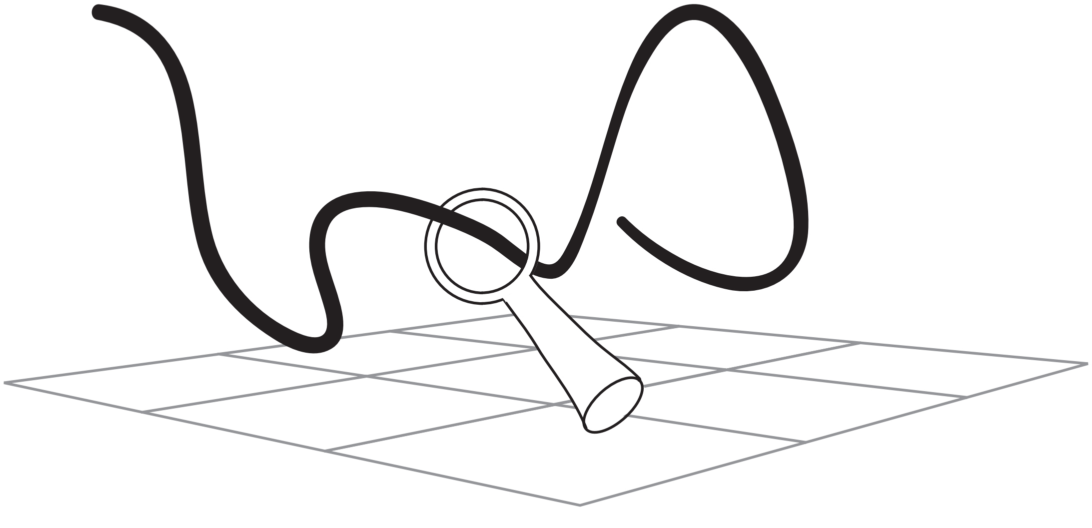

Figure 19. "Ring and Wire" task in VR

In this paper we have reviewed a few simple human performance laws of action for three classes of tasks – pointing, crossing, and steering, with a focus on the steering task that is not widely known. We tested the validity of the law of steering in VR locomotion task in a virtual driving experiment and found that the law of steering relationship between path steering speed and path constraint held in a range of task difficulties that could not be tested in real driving tasks. We also propose to use the law of steering model in VR manipulation tasks such as the "ring and wire" task. We believe that developing and applying quantitative human performance models will continue to play a critical role in advancing interactive technologies including virtual reality and beyond.

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