Scale Effects in Steering Law Tasks

Johnny Accot

Centre d'Études de la Navigation Aérienne
7 avenue Edouard Belin
31055 Toulouse cedex, France

accot@cena.fr

Shumin Zhai

IBM Almaden Research Center
650 Harry Road
San Jose, CA 95120, USA

zhai@almaden.ibm.com

ABSTRACT

Interaction tasks on a computer screen can technically be scaled to a much larger or much smaller sized input control area by adjusting the input device's control gain or the control-display (C-D) ratio. However, human performance as a function of movement scale is not a well concluded topic. This study introduces a new task paradigm to study the scale effect in the framework of the steering law. The results confirmed a U-shaped performance-scale function and rejected straight-line or no-effect hypotheses in the literature. We found a significant scale effect in path steering performance, although its impact was less than that of the steering law's index of difficulty. We analyzed the scale effects in two plausible causes: movement joints shift and motor precision limitation. The theoretical implications of the scale effects to the validity of the steering law, and the practical implications of input device size and zooming functions are discussed in the paper.

Keywords

Movement scale, steering law, motor control, input device, control gain, C-D ratio, limb, joints, finger, wrist, arm, elbow, hand, device size.

INTRODUCTION

This research addresses the following questions: Can we successfully accomplish the two steering tasks in Figure 1 in the same amount of time? Can a large input device be substituted with a small one without significantly impacting user performance? Does size matter to input control quality? Can a small-sized input area be compensated by higher control gain (i.e. control-display ratio)? What are the scale effects in movement control, if any? How sensitive are the scale effects?

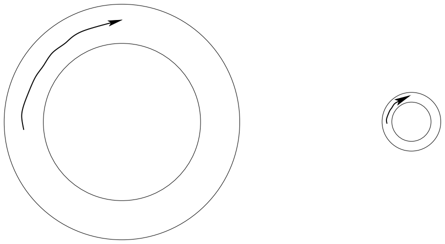


Figure 1: The two circular tunnels are equivalent in steering law difficulty but they differ in movement scale. Does it take the same amount of time to steer through the two tunnels?

There are many practical reasons to ask these questions. One concerns the miniaturization of the computing devices. We are indeed stepping into the long-awaited era of inexpensive, powerful and portable computers. In the rush towards miniaturization, input devices are expected to adapt to the system physical constraints: trackballs now come in a much smaller diameter than before and touchpads are designed with a fairly small contact surface, for instance. It is not clear whether these reduced-size input devices still maintain the same level of performance as their predecessors.

If we push the question of scale to the extreme, the answer is obvious: of course size matters. Humans can not do well in movement scales that are either greater than their arm's reach or smaller than their absolute motor precision tolerance. Within these extremes, however, the question is much more difficult to answer.

RELATED WORK AND LITERATURE

One might imagine that the scale effects in input control should be a well documented topic in the human-machine system literature. In reality, however, the results were scattered and controversial. The scale effects were often studied and reported under two related concepts: control gain and control-display (CD) ratio. When the display (output) size is fixed, these two concepts correspond to control movement scale. Major handbooks [5, 6, 15] tend to suggest that human performance is an inverted U-shaped function of control gain or CD ratio: it reaches the highest point in a medium range of the control gain and deteriorates in both directions away from this range. Such a U function was usually found in studies that involved control systems with higher order dynamics (e.g. rate control system, or systems with inertia or lag).

Hess [11] is a common source regarding the U-shaped function. In his experiment, subjects performed tracking tasks by manipulating a near-isometric joystick in rate control. A U-shaped function was found between participants' subjective rating and the system control gain[1].

Gibbs [9] provided the most comprehensive set of data on control gain. He studied control gain in both positional and rate control systems and found that the target acquisition time follows the function:

$$\frac{}{G} \qquad 6\frac{}{G} \qquad 3\quad\frac{}{G} \qquad 3\frac{}{G} \tag{1}$$

where G is the control gain and is the system lag. The function produced U-shaped curve when was greater than zero. When was zero (no system lag), the performance-gain function produces a straight line — the greater the gain was (which means the smaller the movement scale was), the worse the performance was.

Buck [7] called into question the views on the significance of CD gain. Based on results from a target alignment experiment, he argued that target width on both the control device and the display were important, but their ratio was not.

Arnaut and Greenstein [3] conducted a rather convoluted study in which control input magnitude (movement scale), display output magnitude, display target width, control target width and Fitts' index of difficult were varied in two experiments. They found that a greater movement scale increased gross movement time but decreased fine adjustment time. Gross and fine movements were defined by the initial entry point in the target. The total completion time, in the case of a tablet, was a U-shaped function. In the case of a trackball, however, the greater movement scale increased the total completion time monotonically. They concluded that a combination of gain and Fitts' index of difficulty could be a more useful predictor than either of them alone.

Jellinek and Card studied users' performance as a function of the control gain in a computer mouse [12]. They found a U-shaped performance-gain function, but argued against its status as a basic human performance characteristic. They believed the performance loss in case of a large control gain was due to the loss of relative measurement resolution (i.e. a quantization effect). If there were not a resolution limit, and as long as the control gain was in a "moderate" range, a user's performance should have stayed constant, so they argued.

It is necessary to clarify that the most basic construct, in our view, should be the "control movement scale". Other variables, such as control gain and CD ratio, are derivative or secondary. We think the concept of C-D ratio (or gain) in itself is partially responsible for the contradictions in the literature. By definition, C-D ratio is a compound variable between the display scale and the control movement scale. The same relative C-D ratio could have very different implications on input control, depending on the display size. Control movement scale, on the other hand, is absolute and can be compared to human body measurements. Furthermore, between the display and the control movement scale, the former is more relevant to perception and the latter is more directly relevant to control performance.

One implication of movement scale is the limb segments (or motor joints) involved in executing a task. Although limb segments rarely work in isolation, a large movement (e.g. m), tends to be carried out primarily by the arm (shoulder and elbow joints), a medium range by the hand (wrist joint), a small range (e.g. mm) by the fingers. Langolf et al. [13] demonstrated that Fitts' law gave different slopes and intercepts in finger, wrist, and forearm scales [2]. They came to the conclusion that the smaller the scale, the greater the aiming performance, which in terms of primary limb segments means that:

$$\text{fingers} > \text{wrist} > \text{forearm} \tag{2}$$

This performance order was confirmed by Balakrishnan et al. [4], who found that a combined use of multiple fingers resulted in higher performance than other limb segments. However they noted that "the finger(s) do not necessarily perform better than the other segments of the upper limb" when a single finger was involved[3].

In a six degrees of freedom docking task, Zhai et al. [16] showed that relative performance of 6-DOF devices did depend on the muscle groups used. More specifically, they demonstrated that the user performance was superior with the fingers involved (together with the wrist and the arm) in operating the control device than without (wrist and arm only).

It is natural to ask the question of scale in light of the well-known Fitts' law [8, 14]), which predicts that the time to select a target of width W that lies at distance A is:

$$a \qquad b\ \mathrm{l}\ \ \mathrm{g}\left(\frac{A}{W}\qquad\right) \tag{3}$$

where a and b are empirically determined constants. The logarithmic transformation of the ratio between A and W is called the index of difficulty of the task. Some researchers argue that control scale should not matter in view of Fitts' law [12]. If a reaching task is scaled by a factor of two, both the distance A and the width W will be twice as large and hence cancel each other in the index of difficulty measure. On the other hand, the impact of scale could be reflected in a and b, as shown in [13].

The validity of index of difficulty as the sole determinant of aimed movement has been recently called into question by Guiard [10]. He argued that the way Fitts' law was studied and applied in the past was problematic; both difficulty and scale should be viewed as the basic dimensions of aimed movement.

---

[1] Note that the notion of control gain is related but not always interchangeable with movement scale or C-D ratio. Control gain, a term originated in feedback control theory, exists in both zero order (position control) and higher order systems. Control display ratio and movement scale only exist in position control systems. For example, since a force joystick was used, there was no control movement scale *per se* in Hess' study [11].

[2] Some objections have been raised about this study, suggesting a faulty experimental design [4]. But the finding that the index of performance varies with movement scale is widely accepted.

[3] Note that in the Balakrishnan study, however, the finger movement was controlled in the lateral direction, which does not occur frequently in natural movement

We recently established a movement law that models human performance in a different class of tasks: trajectory-based tunnel steering [1]. It is both theoretically and practically necessary to study the scale effects in relation to the steering law. Theoretically, it is important to investigate how the steering law prediction is affected by movement scale. Practically, the steering law may serve as a platform based on a new class of tasks for studying the control movement scale effects, which may guide the design and selection of interaction devices and techniques. Some input devices, such as tablet, are primarily designed for trajectory-based tasks.

THE STEERING LAW AND MOVEMENT SCALES

To move a stylus tip or a cursor through a tunnel or path (see Figure 1 for examples) without crossing the boundaries is a steering task. One common steering task in HCI is traversing multi-layered menus. In a recent study [1], we proposed and validated a theoretical model for the successful completion of steering tasks. This model, called the steering law, comes in both an integral and a local form.

Integral form

The integral form of the steering law states that the difficulty for steering through a generic tunnel $\mathcal{C}$ can be determined by integrating the inverse of the path width along the tunnel (see [1] for details). Formally, we define the index of difficulty $_{\mathcal{C}}$ for steering though $\mathcal{C}$ by:

$$_{\mathcal{C}} \quad \int_{\mathcal{C}} \frac{ds}{W(s)} \tag{4}$$

where the integration variable s stands for the curvilinear abscissa along the path. As in Fitts' law, the steering task difficulty $_{\mathcal{C}}$ predicts the time needed to steer through tunnel $\mathcal{C}$ in a simple linear form:

$$_{\mathcal{C}} \quad a \quad b \times \quad _{\mathcal{C}} \tag{5}$$

where a and b are constants. Finally, by analogy to Fitts' law, we define the index of performance P in a steering task by $P \quad /b$. This quantity is usually used for comparing steering performance between experimental conditions.

Local form

The steering law also has a local formulation, which states that the instantaneous speed at any point in a steering movement is proportional to the permitted variability at that point:

$$v(s) \quad \frac{W(s)}{\tau} \tag{6}$$

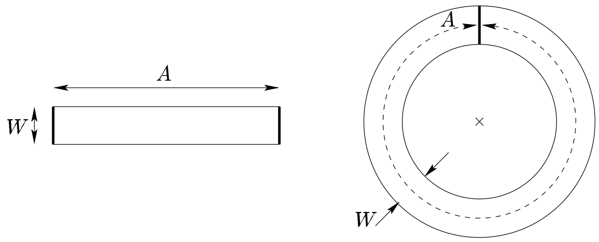
where $v(s)$ is the velocity of the limb at the point of curvilinear abscissa s, $W(s)$ is the width of the path at the same point, and τ is an empirically determined time constant.

Types of tunnels

Equation 4 allows the calculation of steering difficulty for a wide range of tunnel shapes. In [1], three shapes were tested: straight, narrowing and spiral tunnels. It was suggested [2] that the properties of a great variety of tunnel shapes could be captured by two common tunnel shapes: a linear tunnel and a circular one (Figure 2). For both of the two steering tasks, the steering law can be reduced to the following simple form:

$$a \quad b\,\frac{A}{W} \tag{7}$$

where A is the tunnel length in the case of linear tunnels and the perimeter of the center circle in the case of circular tunnels (Figure 2). In both cases W stands for the path width. a and b are experimentally determined constants. They were found to be different for linear and circular tunnels, due to the very different nature of steering in the two cases.



(a) Linear tunnel (b) Circular tunnel

Figure 2: Two steering tasks

Influence of scale

One will notice from Equation 7 that the argument against scale effects based on Fitts' law can also be found here: in both the linear circular path, the steering difficulty depends on the length/width ratio, such that dividing both the length and the width of the steering path by a factor k gives the same index of difficulty. In other words, although the speed in a tunnel of width $\frac{W}{k}$ will be k times slower than in a tunnel of width W, this decrease in speed should be fully compensated by the shortened steering length by the same ratio, such that the movement time remains the same.

It is thus pertinent to ask whether the steering law still holds over very different scales and, if not, how significant the scale impact is.

EXPERIMENT

The experimental task was steering through linear and circular tunnels at five different scales. The scales were chosen to cover a broad range of movement amplitudes so as to guarantee that different combinations of motor joints were tested. The input device used in the experiment was a graphics tablet, which, in comparison to other input devices, provided the most direct interaction, hence allowing us to focus on more fundamental human performance characteristics. Depending on the movement scale the movement of a tablet stylus may be controlled by the fingers, the wrist, or the arm joints. When operating the stylus, multiple fingers work in conjunction, which should be much better than a single finger working in isolation [4].

Ten volunteers participated in the experiment. All were right-handed and had no or little experience using graphics tablets.

Apparatus

The experiment was conducted on a PC running Linux, with a 24-inch GW900 Sony monitor ($\times$ p els resolution), and equipped with a Wacom UD-1218E tablet ($55\times$ $3\ \ 3\,\mathrm{mm}$ active area, $76\times$ $77\,\mathrm{dp}$ resolution). The computer system was sufficiently fast that the input or feedback lag was not perceptible. The size of the active view of the monitor was set exactly equal to the size of the active area of the tablet, which gives an approximate $7\times$ dp screen resolution. Different portions of the tablet area were mapped onto the screen depending on the movement scale currently being tested (mappings are detailed in the design section). All experiments were done in full-screen mode, with the background color set to black.

Procedure

Subjects performed two types of steering tasks: linear tunnel and circular tunnel steering (Figure 2). At the beginning of each trial, the path to be steered was presented on the screen, in green color. After placing the stylus on the tablet (to the left of the start segment) and applying pressure to the stylus tip, the subject began to draw a blue line on a screen, showing the stylus trajectory. When the cursor crossed the start segment, left to right, the line turned red, as a signal that the task had begun and the time was being recorded. When the cursor crossed the end segment, also left to right, all drawings turned yellow, signaling the end of the trial. Crossing the borders of the path resulted in the cancellation of the trial and an error being recorded. Releasing pressure on the stylus after crossing the start segment and before crossing the second, but without crossing the tunnel border, resulted in an invalid trial, but no error was recorded[4]. Subjects were asked to minimize errors. Finally, linear tunnels were all oriented horizontally and were to be steered left to right; as for circular steering, it had to be done clockwise.

Design

A fully-crossed, within-subject factorial design with repeated measures was used. Independent variables were movement scale (S , , , 8, 6; detailed below), test phase (P first and second block), task type (linear and circular tunnels), tunnel length (A 5 , p els) and tunnel width on the screen (W 3 , , 7 p els). The tunnel lengths and widths define 6 different s, ranging from to 33. The order of testing of the five scales (S conditions) was balanced between five groups of subjects according to a Latin square pattern. Within each S condition, subjects performed a practice session, consisting of 1 trial in each of the 6 conditions, in both linear and circular steering. The practice session was followed by two identical sets of the 12 -A-W conditions presented in random order, during which data was actually collected. Subjects performed 3 trials in each S-P- -A-W condition.

The five scales were chosen considering the maximum movement amplitude for each arm segment and in order to cover the maximum number of motor “strategies”. They were:

- very large scale (S): the whole active area of the tablet ($55\times 3\ \ 3\,\mathrm{mm}$) was used, which corresponded to standard A3 format. This scale involves movement amplitudes typically around cm, which require mainly forearm movements.
- large scale (S): the active tablet area was $7\times\ 5$ mm, which was one half of the tablet in both dimensions. This was equivalent to a A5-sized tablet. In this scale, movement amplitudes are typically around cm, which require mainly wrist movements but involve to a certain extent the use of the forearm.
- medium scale (S): with an active area of $\times 76\,\mathrm{mm}$ ($^1/_4$ of the tablet), movement amplitudes in this scale condition are around $5\,\mathrm{cm}$, which require mainly finger and wrist movements and prevent the use of the forearm. This scale was somewhat equivalent to a A6-format tablet.
- small scale (S 8): the tablet active area size was $57\times 38\,\mathrm{mm}$ ($^1/_8$ of the tablet). Typical movement amplitudes in that condition are $\simeq$ cm, which require finger movements and to some extent wrist movements. This was the size of a touchpad used in some notebook computers.
- very small scale (S 6): a $8\times$ mm active area of the tablet ($^1/_{16}$ of the tablet) implied very small movements amplitudes, around cm, which require finger movements exclusively, with the wrist and forearm joints stabilized on the tablet surface. Note that this smallest scale tested was still orders of magnitude above the tablet resolution, hence preventing the possible machinery quantization effect in previous studies.

Figure 3 illustrates the relative size of active areas of the tablet for the different movement scales. The outermost box, labeled S , corresponds to the whole tablet active area.

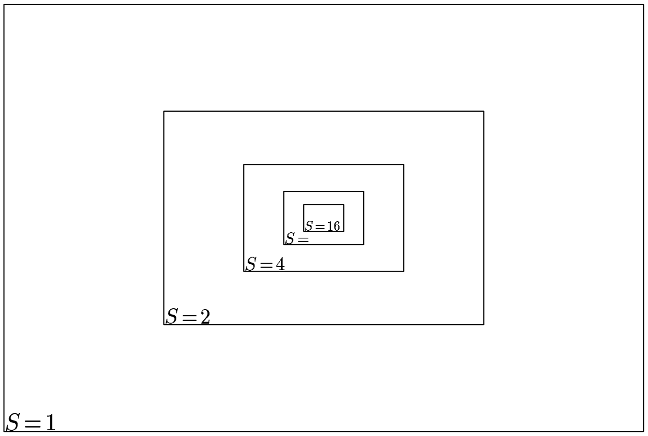


Figure 3: Relative active tablet sizes at different scales

Table 1 shows the movement amplitudes and path widths in input space for each scale condition: for instance, the tunnel to be steered on the graphics tablet when S , W 6 and A 5 has a width of $5\,\mathrm{mm}$ and a length of $8\,\mathrm{mm}$.

Finally, in light of the movement scale vs. C-D ratio and display scale discussion, the visual stimuli were kept in the same size over all five movement scales, so that no visual perception effect could influence the results. The experimental software was identical for all scales; only the tablet scale settings were changed.

---

[4] Subjects sometimes released the pressure by mistake, but this could not be attributed to the constraints imposed on movement variability.

	S	S	S	S 8	S 6
W_1 3		5	5	3	6
W	3 5	6 7	3	7	8
W_3 6			5	5	3
A_1 5	5	6	8	7	3 7
A	37	8 5	5	6	8

Table 1: Movement amplitudes and path widths in input space for each scale condition (in millimeters).

RESULTS

The results of the experiment include steering time, steering speed and error rates.

Steering time

As expected, movement amplitude and tunnel width significantly influenced steering time ($_{1\ 9}$ $8\ 6$, $p <$, and $_{18}$ 5, $p <$ respectively); there was also a strong interaction between movement amplitude and tunnel width ($_{18}$ 3, $p <$), which is consistent with the fact that the steering time depends on the ratio of amplitude and width. As in [2], steering type (linear vs. circular) proved to be also a significant factor influencing steering time ($_{18}$ $678, p<$). As for the studied variable, movement scale, it had a significant influence on steering performance ($_{4\ 36}$ 3 , $p<$). While the significant impact of test phase ($_{1\ 9}$ 3 , $p<$) shows a strong learning effect, the non-significant interaction between test phase and movement scale ($_{4\ 36}$ 8, $p >\ 5$) suggests that the influence of scale is likely not to vary much with practice.

Paired t-tests between scale levels classified the scales into three groups. The first group includes scales and , the second includes scales and 8, and the last one is only composed of scale 6. The differences were insignificant between the two scales of the first group ($p >\ 8$) and the scales of the second group ($p >\ 3$). The scales of the first group outperformed significantly the scales of the second group (with $p<$ for all compared pairs), while the last group is outperformed by both the first group ($p<$) and the second one ($p<$). The ranking between movement scales in terms of time performance is:

$$\{\ ,\ \} \underset{(p<.0001)}{<} \{\ ,8\} \underset{(p<.0001)}{<} \{\ 6\} \qquad (8)$$

This grouping of scales and the ranking between groups held in both linear and circular steering. Figure 4 summarizes the average steering time depending on the movement scale and steering task.

There was also a strong interaction between movement scale and tunnel type ($_{4\ 36}$, $p<$), which suggests that the circular tasks were more sensitive to changes in movement scale than the linear ones (see Figure 4). We also found a significant interaction between scale and amplitude ($_{4\ 36}$ 3 , $p<$), as well as between scale and width ($_{8\ 7}$ $3\ 3$, $p <$). The movement scale effects was greater when the movement amplitude was greater or the tunnel width was smaller (Figure 5). This was especially true for the scale-16 conditions: very long amplitudes or very narrow tunnels in this case were very difficult to steer, such that often subjects could achieve the trial only after a couple of attempts (see error rates analysis further). However, a significant interaction between test phase and movement amplitude ($_{1\ 9}$ 7 , $p<$) suggests that subjects tend to deal with long amplitudes much better with practice.

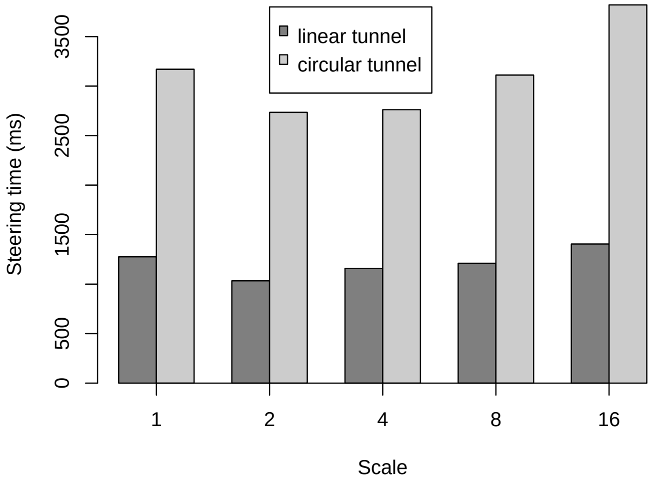


Figure 4: Steering time as a function of scale

As for the fitness to the steering law model, the integral form of the steering law [1] proved to hold at all studied scales with very good regression fitness (see Figure 6). The models of steering time were, for linear steering (in ms):

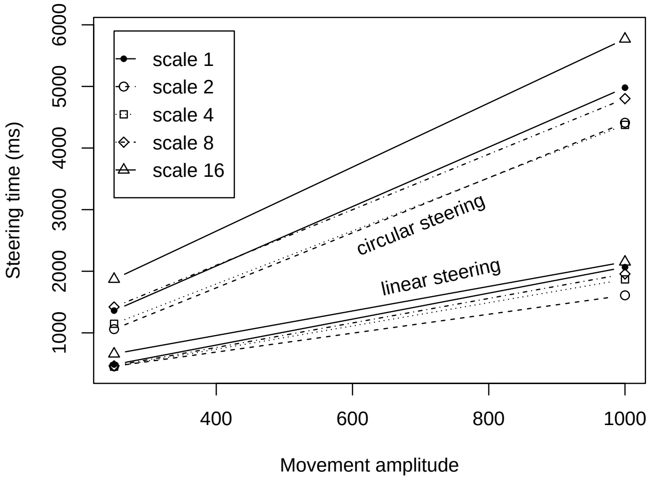
$$S\ : \quad 83 \times \quad r \quad 8 \qquad (9)$$
$$S\ : \quad 6\ \ 6 \times \quad r \quad 6 \qquad (10)$$
$$S\ : \quad 7 \times \quad r \quad 6 \qquad (11)$$
$$S\ 8: \quad 53\ \ 8 \times \quad r \quad 6 \qquad (12)$$
$$S\ 6: \quad 78\ \ 85 \times \quad r \quad 77 \qquad (13)$$

and for circular steering:

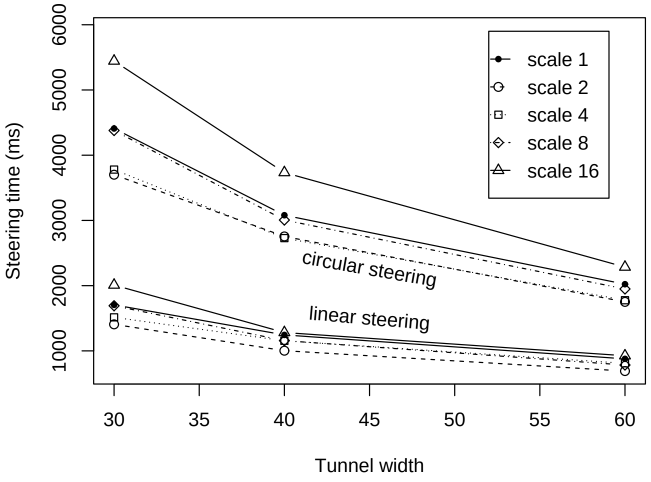
$$S\ : \quad 37 \quad \times \quad r \qquad (14)$$
$$S\ : \quad 68\ \ 7 \times \quad r \quad 8 \qquad (15)$$
$$S\ : \quad 8\ \ 7 \times \quad r \quad 7 \qquad (16)$$
$$S\ 8: \quad \times \quad r \quad 86 \qquad (17)$$
$$S\ 6: \quad 77\ \ 7 \times \quad r \quad 7 \qquad (18)$$

The slope of linear regressions was significantly influenced by tunnel type ($_{1\ 9}$, $p<$) and movement scale ($_{4\ 36}$ 5, $p <\ 5$). The intercept was not significantly affected by tunnel type ($_{1\ 9}$ 6, $p >\ 8$) or by movement scales ($_{4\ 36}$, $p >\ 3$); furthermore, all intercepts were rather small comparing to the total times involved, which is consistent with previous results [1, 2].

Similar to the results found on steering times, the relationship between the steering law index of performance and the movement scale was an (inverted) U-shaped function (Figure 7), with the best performance in the medium scale and



(a) Interaction between movement amplitude and movement scale

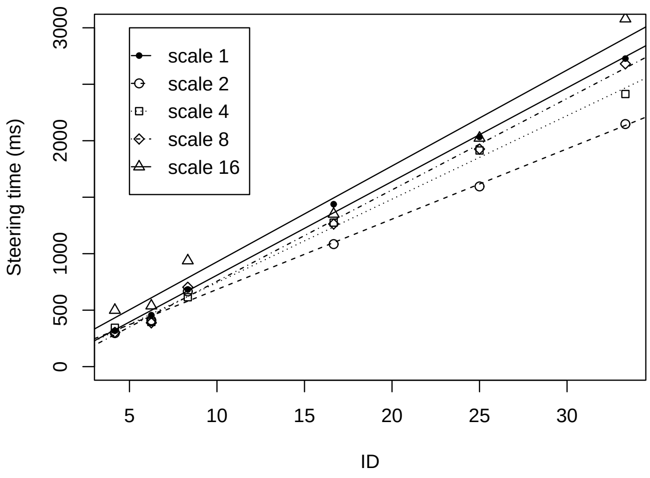


(b) Interaction between tunnel width and movement scale

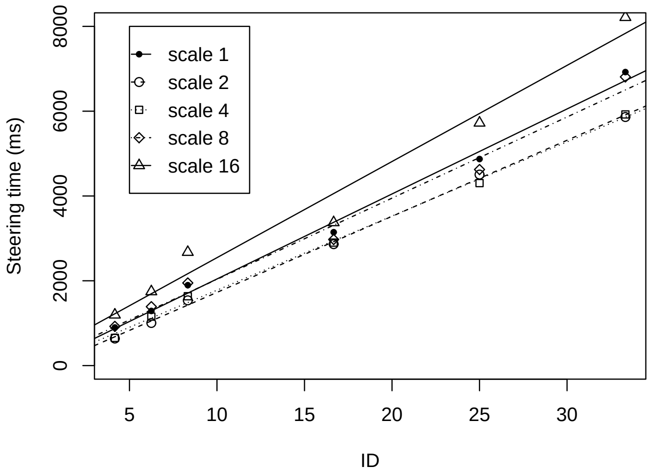
Figure 5: Steering time against scale depending on movement amplitude and tunnel width

(scale was slightly higher than scale 4 in linear steering) and lower performance in scale and 8, and lowest in scale 6. All scales resulted in almost equivalent performance for very easy tasks, but significant differences appeared for very difficult tasks; this was characterized by the statistical interaction between scale and index of difficulty of the tasks ($_{4\;36}$, $p <$ 5).

In conclusion, the time performance was the highest when the movement scale was between scale and scale . In terms of tablet size, this corresponds to A4/A5-sized tablets. In terms of motor joints involved, it was when the wrist and the fingers were the primary movement carriers. A3-sized tablets seemed to be too large and require too much movement efforts, while tablets smaller than A6 format were likely to amplify noise beyond reasonable rates.



(a) Linear steering



(b) Circular steering

Figure 6: Steering time against

Errors

Besides the expected main effects on error rates of movement amplitude ($_{1\;9}$ 8 , $p <$) and tunnel width ($_{18}$ 38, $p <$), scale had a strong influence on error occurrence ($_{4\;36}$ 36, $p <$). Like in [2], circular steering resulted in more errors than linear steering ($_{1\;9}$ 5, $p <$). A significant interaction between scale and tunnel type ($_{4\;36}$, $p <$) shows that the number of errors increases much faster for circular steering than for linear steering when the movement scale decreases (see Figure 8). Finally interactions between movement scale and width ($_{8\;7}$ 6, $p <$), and between movement scale and movement amplitude ($_{4\;36}$ 3 8, $p <$ 5) indicates that it is more likely to make errors in long or narrow tunnels when the tablet is very small: in the scale-16 conditions, natural tremor and biomechanical noise was greatly amplified such that subjects systematically made a few failed trials in a sequence, even though they did their best.

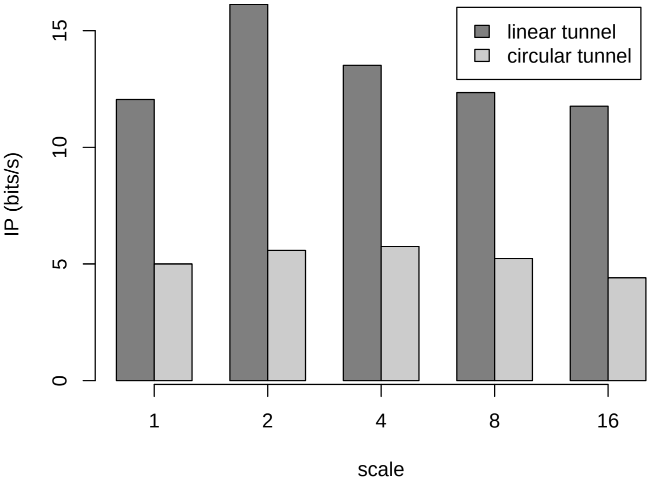


Figure 7: Index of performance against scale

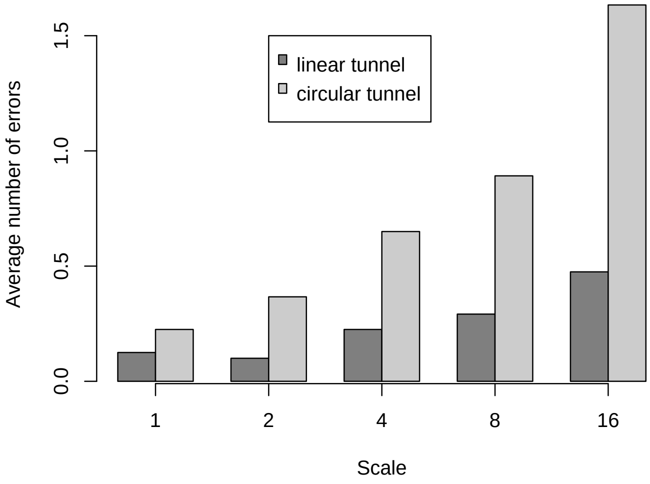


Figure 8: Average number of errors in each scale

To conclude, the smaller the scale, the higher the error rates. Considering that the optimal scales were and for time performance, it appeared that the scale-2 condition had the best overall performance while considering both time performance and error rate.

DISCUSSION AND CONCLUSION

Movement scale, control gain, control-display ratio and motor joints performance differences, are a set of related concepts in input control literature without consistent conclusions. In terms of movement scale or control gain effects, some researchers found a U-shaped function [11, 3]; others straight linear function [9], and yet others did not believe gain or scale should matter much [12, 7]. Traditionally these issues have been studied in the framework of target acquisition tasks. We have conducted a systematic study on these issues in a new paradigm — the steering law. Furthermore, we focused on the most fundamental concept of them all — control movement scale.

Our results supported the U-shaped performance-scale function: scale does matter. The U-shaped function is easily plausible in the two extrema: too large a scale is beyond the arm's reach and too small a scale is beyond motor control precision. But even within the "moderate" range we tested, the U shape was still clearly demonstrated. The cause for the U-shaped function in this range is likely to be twofold: motor joints shift and the human motor precision limitation.

The best performance appeared in the middle range (scale and), when the movements were carried out by all parts of the upper limb (arm, hand, and finger), although the arm's role might be lesser than the hand and finger. In this range, the steering P was (in $\mathrm{b\ \ s/ms}$) $/6$ and $/7$ for linear steering; and $/\ 7$ and $/\ 7$ for circular steering. On the larger scale side, when the movements were primarily carried out by the arm movement, steering performance dropped to $/8$ for linear and $/$ for circular steering.

On the smaller scale side (scale 8 and 6), when the movements were carried out mostly by fingers, the performance also dropped (to $/85$ and $/\ \ 7$ for scale 6). However, we can not make a conclusion that the fingers are inferior, because the other factor, motor control precision limitation, was increasingly more limiting as the movement scale decreased. This was clearly demonstrated by the number of errors (failed attempts to complete the entire steering path) shown in Figure 6: participants increasingly "accidentally" moved out of the tunnel. Note that because we maintained the same visual display size for all scale conditions, the error had to be on the motor precision side.

The more theoretical implication of the results pertains the validity of the steering law [1]. Similar to Fitts' law, the steering law states that the difficulty of movement lies in relative accuracy. The two steering tasks in Figure 1 are exactly the same in steering law terms. This study shows that while the fitness of the steering law held very well in all levels tested, the movement scale does have an impact on steering law's index of performance. A steering law model with strictly the same index of performance is only valid if the scale does not vary so widely that the motor joint combination shift fundamentally or the control precision becomes the primary limiting factor.

It is interesting to realize that the impact of scale is much less significant than the steering law's index of difficulty. For example, the range of scale we tested varied by a factor of 16, but the largest steering time difference was only 17% — an impact equivalent to only 17% change of the steering (either 17% longer or 15% narrower tunnel).

There are also many practical implications in our results. For example, the size of a computer input device (tablet or mouse and its pad) should be such that the fingers, wrists and to a lesser extent forearm are all allowed in the operation. Another practical implication lies in the design and use of zooming interface. In fact users often unconsciously make effort to stay at the bottom of the U-shaped scale function by zooming up when their motor precision limits their performance, and zooming down when too much of the movement had to be carried out by large arm movement. How we can deliberately apply the findings in the present study to assist zooming is an interesting future research issue.

Based on the results of this study, we can begin to answer some of the questions we raised at the beginning of this paper on a more scientific ground. First, we found that device size and movement scale indeed affects input control quality: people do not accomplish the two steering tasks in Figure 1 in the same amount of time. Furthermore, small scale tends to be limited by motor precision, large scale limited by the arm dexterity, but scale in the medium range does not significantly influence performance. Consequently, substituting a large input device with a small one will not significantly impact user performance if there is no fundamental change in the muscle groups involved; but it will if the substituted input device is too small that human motor control precision becomes a limiting factor. The scale effects are also not very sensitive in comparison to the steering law index of difficulty effects (e.g. change the tunnel width while keeping the same length). Finally, the question with regard to control gain or control-display ration is ill-posed, because what matters is the control movement scale: for the same movement scale, the appropriate control gain depends on the display size.

In summary, we have 1) introduced a new task paradigm to study scale effect; 2) contributed to the literature of scale effect, confirming the U-shaped function and rejecting straight-line or no-effect hypotheses; 3) improved the understanding of the steering law; 4) provided guidelines to practical input design and selection issues.

ACKNOWLEDGMENTS

We would like to thank Frédéric Lepied of the XFree86 team for his advice on the Wacom tablet configuration.

REFERENCES

1. J. Accot and S. Zhai. Beyond Fitts' law: models for trajectory-based hci tasks. In *Proceedings of ACM CHI'97 Conference on Human Factors in Computing Systems*, pages 295–302, 1997.
2. J. Accot and S. Zhai. Performance evaluation of input devices in trajectory-based tasks: an application of the steering law. In *Proceedings of ACM CHI'99 Conference on Human Factors in Computing Systems*, pages 466–472, 1999.
3. L. Y. Arnaut and J. S. Greenstein. Is display/control gain a useful metric for optimizing an interface? *Human Factors*, 32(6):651–663, 1990.
4. R. Balakrishnan and I. S. MacKenzie. Performance differences in the fingers, wrist, and forearm in computer input control. In *Proceedings of ACM CHI'97 Conference on Human Factors in Computing Systems*, pages 303–310, 1997.
5. K. R. Boff, L. Kaufman, and J. P. Thomas, editors. *Handbook of Perception and Human Performance*. John Wiley & Sons, New York, 1986.
6. K. R. Boff and J. E. Lincoln. Engineering data compendium: Human perception and performance, Harry G. Armstrong Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base, Ohio, 1988.
7. L. Buck. Motor performance in relation to control-display gain and target width. *Ergonomics*, 23(6):579–589, 1980.
8. P. M. Fitts. The information capacity of the human motor system in controlling the amplitude of movement. *Journal of Experimental Psychology*, 47:381–391, 1954.
9. C. B. Gibbs. Controller design: Interactions of controlling limbs, time-lags, and gains in positional and velocity systems. *Ergonomics*, 5:385–402, 1962.
10. Y. Guiard. Difficulty and scale as the basic dimensions of aimed movement. In *Proceedings of the Tenth International Conference on Perception and Action*, page 87, University of Edinburgh, Scotland, 1999.
11. R. A. Hess. Nonadjectival rating scales in human response experiments. *Human Factors*, 13(3):275–280, 1973.
12. H. D. Jellinek and S. K. Card. Powermice and user performance. In *Proceedings of ACM CHI'90 Conference on Human Factors in Computing Systems*, pages 213–220, 1990.
13. G. D. Langolf and D. B. Chaffin. An investigation of Fitts' law using a wide range of movement amplitudes. *Journal of Motor Behavior*, 8:113–128, 1976.
14. I. S. MacKenzie. Fitts' law as a research and design tool in human-computer interaction. *Human-Computer Interaction*, 7:91–139, 1992.
15. W. E. Woodson, B. Tillman, and P. Tillman. *Human Factors Design Handbook*. Second edition. McGraw-Hill, New York, 1992.
16. S. Zhai, P. Milgram, and W. Buxton. The influence of muscle groups on performance of multiple degree-of-freedom input. In *Proceedings of ACM CHI'96 Conference on Human Factors in Computing Systems*, pages 308–315, 1996.