Virtual Pointing on a Computer Display: Non-Linear Control-Display Mappings

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Abstract

Subjects' 3-D pointing movements were mapped to a 2-D computer display in three conditions as a function of hand speed: constant gain, discrete gain increase, and continuous gain increase. Analysis of hand and cursor kinematics demonstrated that discrete gain change provided no real advantage, and performance suffered with continuous gain change as movement profiles were disrupted. Reduced footprint was traded for increased difficulty in decelerating to the targets. A detailed analysis of movement time as a function of distance and target width suggests that a better strategy for improving pointing performance is to improve device resolution, and use higher constant control-display gain.

Keywords: Analysis methods, Fitts' law, human performance modelling, input devices, pointing, virtual environments.

1. Introduction

Using an input device to indicate a location on a computer monitor is an elemental gesture in many forms of human-computer interaction (HCI). A number of studies (for a summary see [10]) have suggested that theories and models from motor control research on natural pointing movements, when humans interact with the physical world, may be brought to bear on the study of more abstract interactions with a 2-D or 3-D graphical interface mediated by a pointing device. This paper describes an experiment in which hand movements, rather than an intermediary physical device, directly controlled a pointer to select targets on a graphics display. We examined how humans adapted when the mapping (control-display gain) between hand motion and the motion of the pointer on the display was changed while a movement was ongoing, and whether such a strategy offers an advantage in terms of improved performance.

Goal-directed pointing movements have been studied since Woodworth [14] proposed that they be understood in terms of two movement phases: an initial planned impulse, followed by a deceleration to the goal position under current control. Fitts [2] modelled movement time (MT), and speed accuracy tradeoffs with regard to the index of difficulty (ID) of a positioning task, based on the ratio between the movement amplitude (A) and target width (W):

$$MT = a + b\ ID, \quad \text{where } ID = \log_2(2A/W) \qquad (1)$$

Note that scaling or magnification of both A and W in equal proportion does not affect ID or predicted movement time.

More recent studies [8,9,11] have examined kinematics along movement trajectories, and described characteristic features of the velocity profile and their possible relation to underlying perceptual-motor processes for movement planning and control. In a previous study [5] we demonstrated two separable effects of A and W on pointing movement kinematics: first, that timing and magnitude of the first velocity peak were a function of distance to be covered by the hand regardless of target width; and second, that the proportion of time decelerating to the target was a function of target width as an accuracy constraint for the hand regardless of the distance covered. These results supported a base trajectory representation [9] for hand movement in terms of a velocity profile with a skewed shape determined by target width (precision effect), and scaled in size to reflect movement distance. Figure 1 illustrates a typical skewed velocity profile from a pointing movement, key kinematic features, and a schematic base trajectory representation which captures these features.

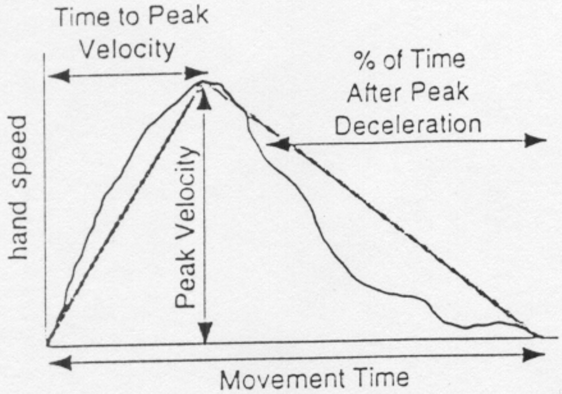

Figure 1. Typical velocity profile (black line) for a pointing movement, and its base trajectory representation (grey line). The initial phase of the movement is characterised by the timing and magnitude of the velocity peak. Proportion of time in the deceleration phase is related to the accuracy constraint of the target.

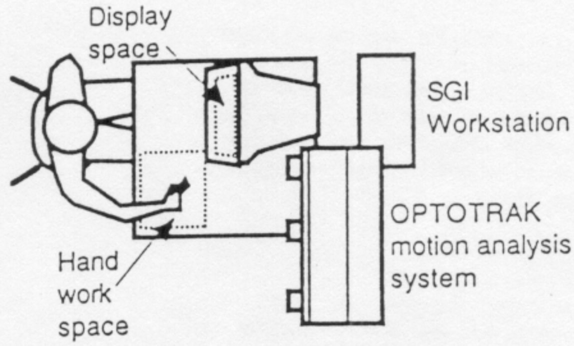

Figure 2. Top view of the of the experimental setup. Hand motions over the work space are monitored by an OPTOTRAK system and used to control the graphics display in real time. Total system lag from sensing hand position to updating the display was determined to be approximately 25 ms.

A surprising result of our previous study was that the amplitude and width effects were not equal in magnitude, and that performance to targets of equal IDs improved when movements were scaled down in size. This result has application to a design issue in HCI: the proper selection of control-display gain for a particular configuration of input device, graphics display, and tasks [1]. For devices which transduce motion or position, higher gain offers the advantage of a reduced footprint; a smaller work space is required to reach all available locations on a display. With higher gain hand tremor, limited device resolution, granularity, and accuracy and stability of the motion and position sensors all compromise our ability to reliably select a target as small as a single pixel.

A common solution to these problems, used in most commercial systems, is a two-step gain or so-called "powermouse". Jellinek & Card [7] suggested the real advantage of powermouse is reduced footprint, as they demonstrated no overall advantage in pointing speed with various powermouse settings. There is some support for the idea that varying the gain as a function of movement speed would improve performance, given our understanding of pointing movement phases. The powermouse could reduce the total distance travelled by the hand (high gain), while relaxing the accuracy constraint of the target for the hand (low gain). Compared to a constant gain device, decreasing effective A and increasing effective W could reduce the effective ID for a given target. A possible drawback is ·' iscrete gain changes amount to a perturbation, and have been shown to disrupt the characteristic smooth velocity profile of a pointing movement [6], increasing time to reach a target.

We decided to test two non-linear control-display mappings (a discrete gain change, and a continuous gain change) which offered to reduce the size of the work space for the hand. Movement kinematics of both the hand and cursor were analysed to understand how subjects adapted to distorted relationships between hand and cursor motions. For non-linear mappings, we predicted that characteristics of the movement trajectory which result from the movement plan should stay the same for the hand, but be distorted for the cursor. Similarly, features governed by visual comparison of the target and cursor position should stay the same for the cursor, but be distorted for the hand in non-linear mappings.

2. Method

2.1 Subjects

Six subjects with normal or corrected vision were paid to participate in the experiment. All had experience using computer systems with pointing devices, and preferred to use their right hand in this context. The subjects were naive as to the purpose of the experiment.

2.2 Apparatus

The experimental setup is illustrated in Figure 2. A subject viewed an RGB monitor (1280 by 1024 pixels) placed directly in front, while pointing with the index finger in a region of the table surface in front of, and to

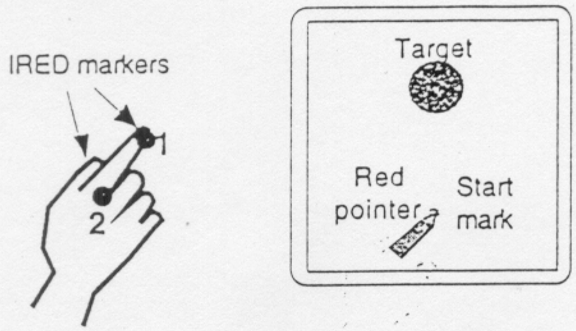

Figure 3. The positions of markers (IREDs), placed on the hand and index finger (left), over the workspace were mapped to the display, allowing the hand to control the position and orientation of a red pointer.

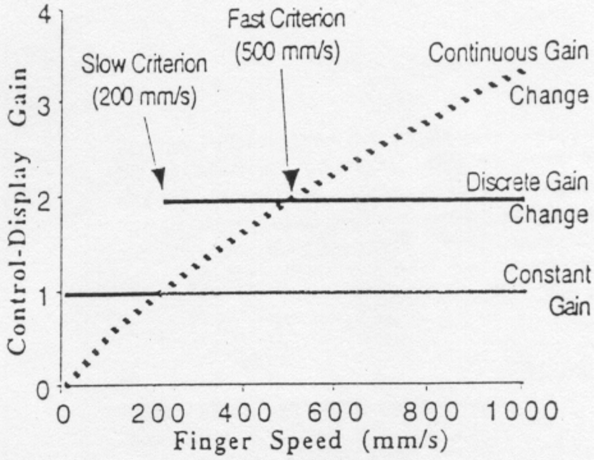

Figure 4. Constant gain (grey horizontal line), discrete gain change (two black lines), and continuous gain change (dashed line) mappings as a function of hand speed.

the right of the body midline, imitating the configuration typically used with pointing devices.

The three-dimensional positions of infrared markers (IREDS) placed on the hand (Figure 3) were sampled at 60 Hz by an OPTOTRAK motion analysis system, recorded in computer files for subsequent kinematic analysis, and also used by a computer (Silicon Graphics Indigo Extreme) in real time to generate a display. The planar projection of the finger IREDS on a work space for the hand (the same size as the monitor) allowed the subject's index finger to control the position and orientation of a red pointer on the display (Figure 3).

Three control-display mappings (shown in Figure 4) characterised by gain as a function of hand speed in the plane of the table top were contrasted:

1) Constant Gain of 1 - the position of the finger over the work space was mapped directly to a corresponding position on the monitor screen.

2) Discrete Gain Change - gain of 1 when the finger moved slowly and gain of 2 when the finger moved quickly (the powermouse).

3) Continuous Gain Change - gain varied as a function of finger speed in mm/s:

$$\text{gain} = (\text{finger speed}/200)^p$$

The exponent p was adjusted so that gain was 2 at the fast movement criterion.

The slow (200 mm/s) movement criterion was chosen to represens a maximum speed during deceleration. The fast movement criterion (500 mm/s) was chosen to represent a typical peak velocity for the task, based on experience from previous studies.

2.3 Procedure

For a trial, the subject rested the hand on the table, positioning the index finger so that the tip of the red pointer was held inside a start mark (5 mm diameter white circle). The experimenter caused a white circular target to be presented. While looking at the monitor screen, the subject lifted the hand and quickly pointed with the index finger to a place on the table, causing the tip of the red pointer to land anywhere inside the target on the display. Four movement amplitudes on the display (A = 37.5, 75, 150, 300 mm) were combined with four target diameters (W = 3, 6, 12, 24 mm) for to produce IDs varying from 1.6 to 6.6 bits.

Data for each subject were collected during a single session lasting about one and one half hours. For each of the three control-display mappings, the subject performed a block of up to 64 practice trials to different amplitude-width combinations. After practice, the subject performed a block of 192 trials to all A and W combinations in random order, for a total of twelve trials in each combination. This was repeated for each control-display mapping, with the order of presentation counterbalanced across subjects.

2.4 Data analysis

Three-dimensional position data from the hand IREDS for each trial were rotated and translated so that the x-axis represented the principal direction of movement away from the subject's body. Two-dimensional position data from the pointer on the display were rotated so that the x-axis represented the principal direction of movement, upwards on the screen. We refer to the latter as cursor data; note that the letter C is used as a prefix on all kinematic measures derived from the motion of the pointer. Both the hand and cursor trajectories were smoothed, differentiated to produce velocity profiles, and the resultant of the velocity profiles (speed along the movement path) further differentiated to produce acceleration profiles. Various computer programs were used to calculate the following dependent measures:

MT - Movement time determined from the velocity profiles (refer to Figure 1).

PV and CPV - Magnitude of the first velocity peak for the hand and the cursor (refer to Figure 1).

TPV and CTPV - Timing of the first velocity peak, relative to the start of the movement, for the hand and the cursor (refer to Figure 1).

%TAPD and C%TAPD - Per cent time, relative to total movement time, after the first deceleration peak for the hand and the cursor (refer to Figure 1).

We - Effective target width, 4.13 times the variable error of the cursor position along the axis of movement [10].

SUBM - The number of corrective submovements was counted from the first negative peak in the hand acceleration profile, using a method similar to that in [12].

DIST - Straight-line distance from the start position to final position for the hand.

Within-subject means for all dependent measures were calculated from the last ten good trials for each combination of mapping, amplitude and width. For each dependent variable, ANOVA with repeated measures was performed on a subjects x mapping x amplitude x width design. In addition, multiple regression was performed on Welford's two-part model [5,13] giving movement times as a function of A and W .

3. Results

The main effects from the ANOVAs on all dependent measures for control-display mapping, movement amplitude, and target width are summarised in Tables 1, 2, and 3 respectively. F and p values are also given for each effect; these will not be included in the text. This analysis contrasted the control condition (constant gain) with the two non-linear mappings (discrete gain change, continuous gain change).

TABLE 1
Main effects for Control-Display Mapping on Cursor and Hand Kinematics

Mapping	Constant	Discrete	Continuous	$F_{2,10}$	$p<$
MT (ms)	696	683	782	17.0	.001
CPV (mm/s)	474	535	535	2.7	.110
CTPV (ms)	194	170	165	19.9	.001
C%TAPD	56.8	62.1	70.5	42.7	.001
We (mm)	9.27	11.11	10.95	19.5	.001
PV (mm/s)	514	325	250	114.4	.001
TPV (ms)	180	153	137	41.4	.001
%TAPD	62.6	68.8	75.3	76.4	.001
SUBM	.59	.71	1.06	11.7	.002
DIST (mm)	141.0	71.4	55.5	1493.8	.001

3.1 Control-display Mapping Effects

Table 1 indicates that there were statistically significant and pronounced effects of control-display mapping an all dependent measures. Movement times in the constant and discrete gain change conditions were similar, but were significantly greater for the continuous gain change mapping. The first velocity peak for the cursor (CTPV) and the hand (TPV) occurred earlier with the non-linear mappings. The magnitude of the first peak for the hand (PV) was dramatically reduced with non-linear mappings, the cursor peak (CPV) was not significantly different across mappings. The earlier peaks for the non-linear mapping conditions suggest that movements were not simply slowed down in order to adapt to the increased gain. The invariance of CPV across conditions suggests that one element of the movement plan is to achieve an ideal, visually determined speed for the cursor.

The extra movement time for the non-linear conditions was accounted for by significant differences in the proportion of time spent decelerating to the target for both the cursor (C%TAPD) and hand (%TAPD). The increase in deceleration time was not the result of smoothly extending this phase of the movement. The average number of corrective submovements (SUBM) increased significantly for the non-linear mappings, compared to constant gain. Increased difficulty of homing in on targets with non-linear mappings was also evidenced by increases in effective target width (We) compared to the constant gain condition.

As expected, the actual distance covered by the hand (DIST) was significantly reduced for the non-linear

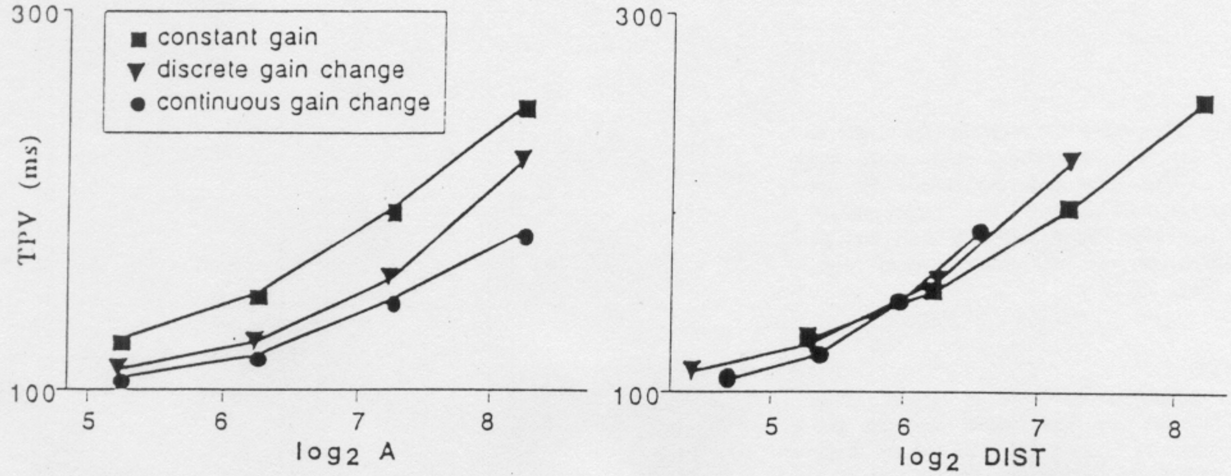

Figure 5. Time to the first velocity peak for the hand increased more rapidly in the constant and discrete gain change conditions than in the continuous gain change condition, when considered as a function of A on the display (left). Plotting the same data in terms of DIST, shows that the timing of the peak is strongly related to the actual distance covered by the hand.

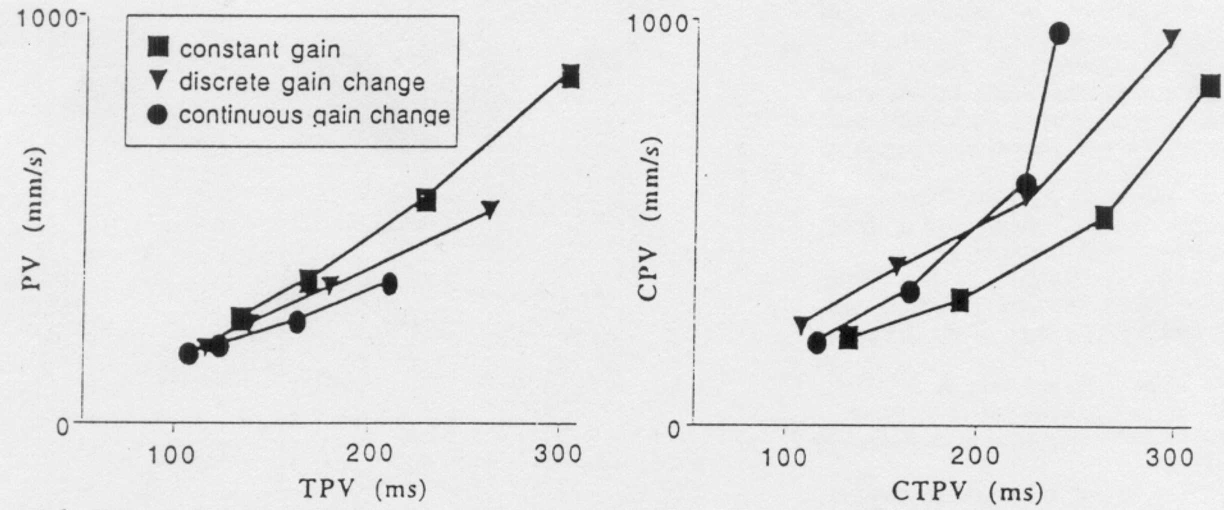

Figure 6. The relationship of the magnitude and timing of the first velocity peak for the hand (left) and cursor (right) for different control-display mappings. Measures for the hand show a strong linear relationship. Measures for the cursor trajectory are also highly correlated, but the linear relationship is not as evident.

mappings. With constant gain, the mean was 141 mm, essentially identical to the predicted value of 140.6 mm. Actual distance was almost half for the discrete gain change condition, and almost one third for the continuous gain change mapping, indicating that subjects were taking advantage of much higher gains for distance-covering in these conditions.

Significant two-way interactions between control-display mapping and amplitude for both CTPV and TPV were found. On the left in Figure 5, the systematic increase in time to the first velocity peak for the hand (TPV) with increased A is illustrated. The increase was less for the continuous gain change mapping than for the other conditions. The same data is plotted on the right of Figure 5, but as a function of the log of actual distance moved by the hand. Note that the spread of the curves due to control-display mapping is reduced. This suggests that actual distance to be covered by the hand is used to form the movement plan for the initial phase, rather than the visually perceived distance (A) on the display.

A base trajectory representation for the velocity

TABLE 2
Main Effects for Movement Amplitude (A) on Cursor and Hand Kinematics

A (mm)	37.5	75	150	300	$F_{3,15}$	p<
MT (ms)	533	630	755	965	376.3	.001
CPV (mm/s)	231	333	565	931	197.5	.001
CTPV (ms)	116	150	202	236	139.0	.001
C%TAPD	65.1	63.5	60.1	63.7	4.1	.026
We (mm)	9.3	10.1	11.5	11.0	6.3	.005
PV (mm/s)	214	269	386	583	463.1	.001
TPV (ms)	114	130	166	217	69.2	.001
%TAPD	69.6	70.3	68.2	67.6	1.3	.312
SUBM	.68	.69	.78	.99	10.2	.001
DIST (mm)	27.9	51.1	95.8	181.1	4712.9	.001

TABLE 3
Main Effects for Target Width (W) on Cursor and Hand Kinematics

W (mm)	3	6	12	24	$F_{3,15}$	p<
MT (ms)	837	766	690	590	168.1	.001
CPV (mm/s)	492	514	521	533	4.9	.014
CTPV (ms)	172	178	179	175	4.1	.028
C%TAPD	69.2	65.7	62.0	55.6	98.6	.001
We (mm)	5.0	6.2	11.5	19.5	345.2	.001
PV (mm/s)	351	361	366	375	20.6	.001
TPV (ms)	156	159	155	156	0.9	.442
%TAPD	73.8	70.9	68.4	62.6	79.0	.001
SUBM	1.04	.82	.75	.54	25.9	.001
DIST (mm)	89.7	89.6	89.2	87.6	7.3	.003

profile (refer to Figure 1) predicts that the timing and magnitude of the initial velocity peak will be highly correlated. This is evident in Figure 6, where a strong linear relationship is illustrated between these measures for the hand (PV and TPV on the left), but less so for the cursor (CPV and CTPV on the right). For the hand, the correlations are almost perfect, with $r^2 > .99$ for all control-display mappings. For the cursor, the correlations are also strong, with r^2 ranging from .85 to .96. We suggest that Figures 5 and 6 reveal how subjects adapt their distance-covering strategy to the different control-display mappings: the base trajectory is always scaled to the actual distance they expect to move, given their experience with a particular mapping. The height (PV) and the width (TPV) of the initial portion of the profile covary because overall size of the velocity profile is determined as a function of the distance the hand is required to move. The ratio between height (PV) and width (TPV) is altered somewhat to adapt to different control-display mappings, but the relationship is strongly linear within each mapping condition.

3.2 Amplitude Effects

The main effects for movement amplitude on all kinematic measures are summarised in Table 2 . As predicted by Fitts' law, movement time increased for larger amplitudes and for smaller targets. Systematic A effects were evident in the timing and magnitude of the initial velocity peaks for both the cursor (CPV and CTPV) and the hand (PV and TPV). Amplitude showed no significant effect on the proportion of time decelerating to the target for the hand (%TAPD), but did show a significant small effect for the cursor (C%TAPD). Effective target width (We) varied slightly with movement amplitude about the actual mean target width of 11.25 mm. The number of corrective submovements (SUBM) increased for longer distances.

3.3 Width Effects

The main effects for target width are outlined in Table 3. W did not affect the timing of the first velocity peak for cursor and the hand. The magnitude of the peak showed an increase for larger targets for both the cursor and the hand, but this effect was small. In contrast, proportion of time spent decelerating to targets increased systematically as target width decreased, both for the cursor (C%TAPD) and the hand (%TAPD). Effective target width (We) ranged from 5 to 19.5 mm, demonstrating a slight range effect; actual W ranged from 3 to 24 mm). The number of corrective submovements (SUBM) increased for smaller targets. Note that the magnitude of this effect was similar to that for movement amplitude, suggesting that SUBM increased with higher IDs.

3.4 Two-part Model of Movement Time

It is evident from the movement time (MT) data in Tables 2 and 3 that the effect for changes in amplitude was much more pronounced than for width, even though the ratio of the largest to smallest A, and largest to smallest W was identical (3 bits). This result is consistent with our previous studies [4,5], where we captured the effects of A and W in a two-part model from Welford [13]:

$$MT = a + b_1 \log_2 A - b_2 \log_2 W \quad (2)$$

The coefficient b_1 gives the sensitivity of MT to changes in amplitude, and the b_2 to changes in width for a particular task and configuration of input device and display. For the three control-display mappings in the present experiment, the models explain at least 97 per cent of the variance in movement time:

Constant
$$MT = -105 + 153 \log_2 A - 77 \log_2 W, \quad R^2 = .97 \ (3)$$

Discrete
$$MT = 9 + 131 \log_2 A - 73 \log_2 W, \quad R^2 = .97 \ (4)$$

Continuous
$$MT = 149 + 138 \log_2 A - 101 \log_2 W, \quad R^2 = .98 \ (5)$$

Note that in each case, MT is more sensitive to changes in amplitude than width. One explanation would be that subjects were failing to take advantage of the relaxed accuracy constraint of a larger target to speed up their movement. To answer this question, we modelled MT based on effective target width (We) rather than actual width, giving:

Constant
$$MT = -72 + 162 \log_2 A - 111 \log_2 We, \quad R^2 = .97 \ (6)$$

Discrete
$$MT = 97 + 136 \log_2 A - 107 \log_2 We, \quad R^2 = .97 \ (7)$$

Continuous
$$MT = 133 + 147 \log_2 A - 113 \log_2 We, \quad R^2 = .94 \ (8)$$

Although in this case MT is somewhat more sensitive to We, the pattern of coefficients is similar to the models based on W, indicating that subjects were taking advantage of larger targets. For predicting performance, a model based on the actual target dimensions is preferable as long as it effectively describes the subjects' performance in a task. For this reason, we continue to discuss the results for MT with respect to W on the display.

In Figure 7 we illustrate how the models of equations 3, 4, and 5 can be visualised in a parameter space. In this space, points for data well characterised by Fitts' law will fall on the the line $b_1 = b_2$. Points above the line indicate tasks for which movement time is more sensitive to changes in target width than movement amplitude. For these tasks, performance can be improved by increasing the scale of hand movements. Points from the present study fall below the Fitts' law line, indicating increased performance when the scale of hand movements is reduced. The point for the discrete gain change mapping falls very close to point for constant gain, indicating that the "powermouse" strategy provides no obvious advantage in terms of sensitivity of MT to changes in A or W. The point for continuous gain change falls above the others, indicating this mapping is more sensitive to changes in W, probably due to increased difficulty in locating smaller targets.

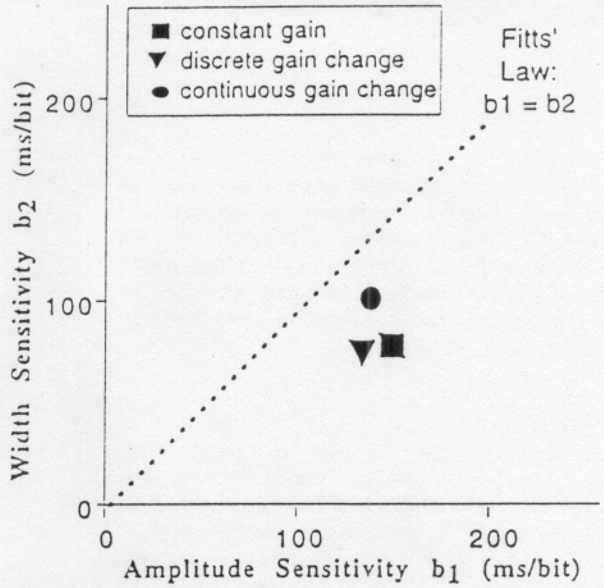

Figure 7. Parameter-space description for the two-part model relating changes in movement time to changes in amplitude and width for the three control-display mappings in the experiment. Points fall below the Fitts' law line, indicating that performance for a given index of difficulty will be faster for shorter distances. The vertical displacement of the continuous gain change condition relative to the other points indicates increased difficulty in controlling deceleration to the target, compared to the other mappings.

4. Discussion

In general, the non-linear mappings seem to be disruptive in terms of movement control, with any distance-covering advantage paid for with increased time, and presumably difficulty, decelerating to the target.

The strong systematic relationship between actual movement distance for the hand and the timing and magnitude of initial velocity peaks indicates that the ballistic phase of a pointing movement is stereotypic, and based on a plan with simple features. Our results suggest that peak velocity for the hand is selected to limit the speed of the visual representation of the movement, whereas timing of the first velocity peak is simply a function of distance to be covered by the hand. This strategy is effective with natural, three-dimensional pointing movements to physical targets, but may generate more variability when gain is changed during the initial phase of the movement; the resulting error must be dealt with in the deceleration phase. We intend to address this question through further analysis of the variability of kinematic features in the different control-display conditions. The results support a base trajectory representation of the velocity profile for the hand for a particular control-display mapping, but the shape is dramatically affected by the type of mapping. Contrary to our predictions, it seems that the features of the initial phase of the movement are determined both visually (from the display) and kinesthetically (from the hand), and that deceleration characteristics are distorted for both the hand and cursor for non-linear mappings.

Although they reduced distance covered by the hand, neither non-linear mapping demonstrated any significant advantage in performance in our pointing task. The slight increase in performance for the discrete gain change mapping over constant gain (13 ms) was not as great as would have been achieved by simply using a constant gain of two. We can estimate this effect from equation 3 by reducing both A and W by one bit; the predicted improvement would be 153 - 77 = 76 ms. This emphasises an important point illustrated by the position of the models in the parameter space of Figure 7: for this task in all conditions performance will benefit from reducing the scale of hand movements, or equivalently, from increasing control-display gain. Given the difficulties our subjects had in adapting to the non-linear control-display mappings, and the disruption of their ability to decelerate to targets, we would recommend increasing pointing device resolution to allow the use of higher (constant) gain as a strategy to improve performance, rather than altering the relationship between hand and cursor dynamics.

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