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The Impact of Control-Display Gain on User Performance in Pointing Tasks

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ABSTRACT

We theoretically and empirically examine the impact of control display (CD) gain on mouse pointing performance. Two techniques for modifying CD gain are considered: constant gain (CG) where CD gain is uniformly adjusted by a constant multiplier, and pointer acceleration (PA) where CD gain is adjusted using a nonuniform function depending on movement characteristics.

Géry Casiez is a computer scientist with interests in empirical evaluation of user interfaces including associated metrics and predictive models of human performance; he is an Assistant Professor in the Department of Computer Science of the University of Lille, France. This work was conducted while he was a postdoctoral fellow at the University of Toronto. **Daniel Vogel** is a graduate student in the Department of Computer Science, University of Toronto. **Ravin Balakrishnan** is an Associate Professor of Computer Science and Canada Research Chair in Human-Centred Interfaces at the Department of Computer Science, University of Toronto. **Andy Cockburn** is a computer scientist with interests in modeling and empirically measuring human performance with interactive systems; he is an Associate Professor in the Department of Computer Science of the University of Canterbury, Christchurch, New Zealand.

CONTENTS

Both CG and PA are evaluated at various levels of relationship between mouse and cursor movement: from low levels, which have a near one-to-one mapping, through to high levels that aggressively amplify mouse movement. We further derive a model predicting the modification in motor-space caused by pointer acceleration. Experiments are then conducted on a standard desktop display and on a very large high-resolution display, allowing us to measure performance in high index of difficulty tasks where the effect of clutching may be pronounced. The evaluation apparatus was designed to minimize device quantization effects and used accurate 3D motion tracking equipment to analyze users' limb movements.

On both displays, and in both gain techniques, we found that low levels of CD gain had a marked negative effect on performance, largely because of increased clutching and maximum limb speeds. High gain levels had relatively little impact on performance, with only a slight increase in time when selecting very small targets at high levels of constant gain. On the standard desktop display, pointer acceleration resulted in 3.3% faster pointing than constant gain and up to 5.6% faster with small targets. This supported the theoretical prediction of motor-space modification but fell short of the theoretical potential, possibly because PA caused an increase in target overshooting. Both techniques were accurately modeled by Fitts' law in all gain settings except for when there was a significant amount of clutching. From our results, we derive a usable range of CD gain settings between thresholds of speed and accuracy given the capabilities of a pointing device, display, and the expected range of target widths and distances.

1. INTRODUCTION

Pointing at a target is a fundamental and frequent task in graphical user interfaces (GUIs), so even a marginal improvement in pointing performance can have a large effect on a user's productivity. Commensurate with its importance, pointing and methods to improve it are among the most mature areas of research in human–computer interaction. It is therefore somewhat surprising that pointer acceleration—the widely deployed and simple technique that governs a dynamic relationship between mouse and pointer movement—has not been thoroughly studied.

Pointer acceleration (PA) is the default behavior on the Microsoft Windows XP/Vista and Apple Mac OS X operating systems. It dynamically manipulates the *Control-Display* (CD) gain between the input device and the display pointer as a function of the device velocity: when the velocity of the control device is high, CD gain is high (typically well above 1) and when the control device moves slowly, the CD gain is low (in some cases less than 1). The assumption is that fast device movement implies a great distance must be covered to reach the intended target, so pointer movement can be amplified to quickly cover that distance. Conversely, slow device movement implies that the target is close, so pointer movement should be slow to support accurate adjustments. *Constant gain* (CG) is the simpler method for manipulating CD gain via a constant multiplier regardless of device movement characteristics.

Previous research comparing pointer acceleration with constant CD gain has found that it either harms performance (Graham, 1996; Trankle & Deutschmann, 1991) or it makes little difference (Jellinek & Card, 1990). Unfortunately, these studies evaluated mapping functions that were noncontinuous or conservative, and consequently dissimilar to the continuous and more aggressive functions that are widely used today. Prior research on the effect of constant CD gain is more extensive, but there are no definitive results. Some researchers have shown experimental evidence that performance follows a U-shaped curve with optimal performance at moderate levels (Gibbs, 1962; Zhai, Milgram, & Buxton, 1996), whereas others have found no effect at all (Accot & Zhai, 2001; Arnaut & Greenstein, 1990; Buck, 1980; Jellinek & Card, 1990; Johnsgard, 1994; Langolf, Chaffin, & Foulke, 1976). Jellinek and Card even suggest that CD gain can have no effect or it would violate Fitts' law. Yet intuitively there would seem to be performance barriers such as increased clutching and muscle coordination at low levels of CD gain and limits of fine muscle control at very high levels.

This article investigates and compares the effects of constant CD gain and PA in two experiments. Unlike previous work, we use an aggressive and continuous PA function taken from a modern operating system, evaluate a broad range of constant gain levels, essentially eliminate mouse quantization problems, accurately motion track users' limb movements, and evaluate pointing at very high index of difficulty targets on both a normal desktop display and a 5-m wide, high-resolution display. We also propose a model for target acquisition with pointer acceleration, which adapts the Fitts' law index of difficulty to accommodate the effective motor-space changes created by the PA function. Finally, to aid future pointing research, we propose a model identifying boundary constant CD gain levels to account for quantization effects.

Our empirical results show that the performance of constant CD gain follows an "L-shape" with performance decreasing rapidly at low gain levels but with little degradation at very high levels of gain. We attribute the decrease in performance at low gain levels to increased device clutching and limitations of user limb velocity. We also found that pointing acceleration has a small performance advantage over constant CD gain when selecting small targets or covering long distances.

2. Related Work

2.1. Fitts' Law

Fitts' law (Fitts, 1954) is a highly successful model for predicting the movement time of a pointing task. Originally used to model direct pointing where the hand taps physical objects, Fitts' law is also robust for indirect pointing where the control device and display pointer are decoupled (Card, English, & Burr, 1978; MacKenzie, 1992). The decoupling of control and display creates two different *spaces*: the *display space,* where we view a representation of the pointing action, and the *motor space,* where we manipulate the control device. Given the intended target's width W and distance D, the total movement time T is predicted with the following equation using MacKenzie's (1992) Shannon formulation:

$$T = a + b\log_2\left(\frac{D}{W} + 1\right) \tag{1}$$

The constants a and b are empirically determined for the pointing technique and/or device being used. The logarithmic term is the pointing task's index of difficulty (ID) measured in bits. Intuitively it shows that tasks become more difficult as a target moves farther away, or as a target becomes smaller.

2.2. Constant CD Gain

CD gain (Gibbs, 1962) is a unit free coefficient that maps the movement of the pointing device to the movement of the display pointer (the reciprocal is called the CD ratio; McCormik, 1976). If CD gain is 1, the display pointer moves at exactly the same distance and speed as the control device; when CD gain is greater than 1, the display pointer moves proportionality farther and faster than the control device; and when CD gain is less than 1, the display pointer moves slower, covering less distance than the control device. The CD gain can be computed by taking the ratio of the pointer velocity to device velocity (see equation 2)

$$CDgain = \frac{V_{pointer}}{V_{device}} \tag{2}$$

Quantization can become a problem if the maximum resolution of the control device together with a high CD gain prevents every pixel from being addressable on the display. The maximum CD gain that can be used without quantization problems is calculated by dividing the resolution of the pointing device by the resolution of the display using the same unit of measurement (e.g., DPI).

When CD gain is very low and/or the physical device movement area is constrained, the device may need to be *clutched* to move the display pointer over a long distance. Clutching is when a device is repositioned in motor space without affecting the display pointer. The device movement area constraint may be a well-defined characteristic of the device, such as the limited input area on laptop track pads, or less defined, such as the comfortable range of arm movement or unobstructed surface space. We call the maximum area of unconstrained physical movement the *operating range* of the device. Note that Jellinek and Card (1990) use the term *device footprint*, but this can be confusing because it also refers to the static area occupied by the physical device.

As noted by Jellinek and Card (1990), there is no term for CD gain in Fitts' law. Considering that it was originally formulated for direct pointing, where CD gain is always equal to 1, this is not surprising. Also, manipulations of CD gain on one device can be accommodated by considering each CD gain level as a different device with different values for *a* and *b* constants. However, this does not mean that Fitts' law is necessarily independent of CD gain, and an enhanced formulation of Fitts' law that included CD gain as a parameter would be useful. Furthermore, including a term related to CD gain may become necessary if the CD gain levels are dynamically manipulated during a pointing task, as is the case in pointer acceleration.

2.3. Prior Studies

CD gain has been studied extensively in the context of physical and virtual control devices, but unfortunately these studies do not provide a definitive picture of the impact of CD gain on user performance.

Gibbs (1962) found that high CD gains improved pointing performance with position and rate control systems. For experimental stimuli, he used a one-dimensional pointing task with a single target distance (22.5 mm) and single target width (3 mm) resulting in a single ID of 3. Error rate was not a reported factor because each pointing task had to be completed successfully (i.e., any errors had to be corrected and this correction cost is included in the trial time). He tested six CD gain (G) levels ranging from 0.15 to 0.90 and five artificial exponential lag (L) times ranging from 0 to 2 sec. His results for position control systems are summarized in the following empirically derived equation:

$$T = 0.91 - \frac{0.02}{G} + 1.212L - \frac{0.106L}{G} - 0.4L^2 + \frac{0.032L}{G^2} - \frac{0.003L^2}{G} \tag{3}$$

It is evident from this model that higher lag times decrease performance, however if we set L equal to an ideal amount of zero, Gibbs's equation simplifies to $T = 0.91 - 0.02/CD$. This predicts movement time based solely on CD gain, with movement times increasing with CD gain level.

Buck (1980) studied the effect of CD gain using a joystick for input. He used a one-dimensional pointing task with a range of target distance and width combinations selected to produce a consistent ID of 4.2. Like Gibbs's experiment, error rates were not reported because each pointing task had to be completed successfully. Target widths ranged from 0.85 mm to 1.7 mm and distances from 15 mm to 30 mm. He tested rather low CD gain levels of 0.5, 1.0, and 2.0 and found that varying CD gain had no effect on movement time, although he noted that acquisition time (time at which the pointer first crosses the edge of the target) increased as the motor space target width decreased and were independent of the display target width.

Arnaut and Greenstein (1990) evaluated the effect of CD gain on performance using a trackball and touch tablet. Their experimental design used pointing tasks with a single ID of 3.16 and five different CD gain levels ranging from 1 to 3, but results showed no significant effect across CD gain levels (no error rates were reported). In spite of this, they argue that a combination of CD gain and ID should be used to predict movement time, but they do not provide an equation or model.

Johnsgard (1994) found that higher CD gains decreased selection time when using a mouse and a virtual reality glove with mean error rates of 6.5% for the mouse. However, this experiment used low IDs (1 to 4) and low CD gain levels (1, 2, and 3) so any conclusion should be taken within this context. He proposed an equation to model the result and demonstrated that it explained 81% of the variance of his data:

$$T = a + b\log\left(\frac{D}{W}\frac{1}{G} + 1\right) \tag{4}$$

The equation reduces to Fitts' law when CD gain equals 1 (G = 1). However, changing the CD gain divides both the distance and width of the target in motor space and thus should not change the motor space ID. This equation predicts that movement time decreases as CD gain is increased.

Jellinek and Card (1990) found that plotting mean selection times against CD gain resulted in a U-shape, with the best performance when CD gain was near 2 (no error rates were reported). They attributed the effect to increased clutching at low CD gain and to quantization at high gain. They tested CD gain levels of 1, 2, 4, 8, 16, 32, and their IDs ranged from 1.6 to 5.0, with a maximum target distance of 223 mm and a minimum target width of 7 mm. Considering the resolution of their equipment—a 73 DPI display and 200 DPI mouse—any CD gain above 2.7 would cause quantization preventing the user from selecting every pixel. They also observed that a CD gain of 1 required frequent clutching. So in effect, their experiment only allowed accurate testing of a single gain factor (2).

Accot and Zhai (2001) studied a graphics tablet steering task at four CD gain levels from 1 to 16. Like Jellinek and Card (1990), they also found a U-shape relationship between performance and CD gain with error rates increasing with higher CD gain. They observed that different muscle groups were used at different CD gain levels and suggested that this may be the reason for the performance degradation. However, these are qualitative observations with no empirical measurements, so it is difficult to draw definitive conclusions.

Bohan, Thompson, and Samuelson (2003) found that a CD gain of 1 was significantly slower than CD gains of 2, 4, or 8 in a mouse pointing task (no error rates were reported). Like Accot and Zhai (2001), they also attributed this effect to the difference in muscle groups used at a CD gain of 1 compared to the other levels, but this is also based on qualitative observation rather than empirical measurement.

Langolf et al. (1976) studied movement amplitude with varying levels of microscope magnifications, giving a similar effect to CD gain between motor control and visual display through the microscope eyepiece. Error rate was not reported because each trial had to be completed successfully. They found that magnification does not affect performance until it approaches 20× magnification, at which point performance deteriorates because of finger tremor. They also conducted Fitts' law analyses for different limbs (fingers, wrist, and forearm), with results showing that the limbs with a small range of movement had greater aiming performance. Balakrishnan and MacKenzie (1997) found a similar trend in which the combined use of multiple fingers outperformed other limb segments but that a single finger in isolation did not necessarily perform better. Zhai et al. (1996) also found that user performance increased when coordinated fingers where used to control 6 DOF docking tasks.

These results are summarized in Figure 1, which shows that there is no clear result governing the effect of CD gain. Accot and Zhai (2001) and Jellinek and Card (1990) found that very low and very high CD gains reduced performance creating a U-shaped profile for movement time versus CD gain. Gibbs (1962) found that performance decreased with high CD gain, but Johnsgard (1994) found the inverse. Langolf et al. (1976) found that performance decreased sharply at a certain CD gain threshold, but Buck (1980) found no effect at all. In all of these studies, the range of CD gain evaluated was either small or had quantization problems. Also, the target distances and widths were conservative (see Figure 1).

2.4. Dynamic Gain: PA

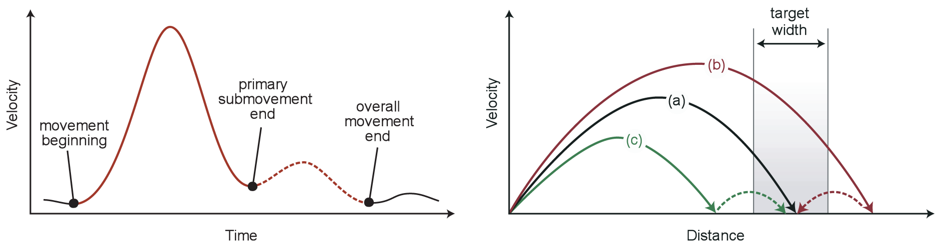
PA dynamically increases CD gain as the velocity of the control device increases. This behavior is motivated by the hybrid *optimized initial impulse* motor control model[1] for human pointing motions (Meyer, Smith, Kornblum, Abrams, & Wright, 1988, 1990). It works as follows: an initial high-velocity *ballistic movement* is made in the direction of the target. If the ballistic movement ends on the target, the task is complete, but if the movement under- or

1. Note that there are other models proposed for human pointing motion: Balakrishnan (2004) gave a brief summary; Rosenbaum (1991) provided more detail.

Figure 1. **Summary of Prior Work Evaluating the Effect of Control Display Gain.**

Study	Device	CD Gain	ID	Display W (mm)	Display D (mm)	Result
Gibbs (1962)	joystick	0.15–0.90	3	3	22.5	Effect Found: time increases with increased gain
Buck (1980)	joystick	0.5–2.0	4.2	0.85, 1.7	15, 30	No effect of gain
Arnaut and Greenstein (1990)	trackball & touch tablet	1–3	3.16	5–15	40–120	CD gain is not an adequate specification for performance. Optimization of performance requires an optimal combination of control input amplitude, display output amplitude, and display target width.
Johnsgard (1994)	mouse	1– 3	1–4	13–51	50–203	Effect Found: time decreases with increased gain
Jellinek and Card (1990)	mouse	1–32	1.6–5.0	7–28	56–223	Effect Found: U-shape with best gain of 2, but they dismiss results. Also, quantization present for gains greater than 2.7
Langolf, Chaffin, and Foulke (1976)	hand (tapping task)	1	1.7–7.4	0.076–50.8	2.5–305	Performance varies between the different limbs used (finger > wrist > arm)
Accot and Zhai (2001)	graphics tablet	1–16	4–33 (steering task)	7.6–17.8	63–254	Effect Found: U-Shape, best time between CD gain 2 and 4
Bohan, Thompson, and Samuelson (2003)	mouse	1–8	1.4–7.6	1.5–12	18.75–300	Effect Found: Longer movement times with movements involving proximal joints (forearm) compared to those involving distal joints (wrist, fingers)

Figure 2. **(left) Decomposition of a pointing movement into the ballistic and corrective phases (adapted from Meyer et al., 1988). (right) (a) Is the case where a single movement reaches the target. (b) and (c) are the more likely cases where the initial movement under or over shoots the target, requiring subsequent corrective movements.**



overshoots the target, a second lower velocity *corrective movement* is used in the direction of the target. Successively slower corrective movements are reapplied until the target is acquired (see Figure 2).

PA is one of many techniques that influence the motor-space through which the device travels during target acquisition: High gain reduces the motor distance during ballistic movement, and low gain increases the motor size of the target during corrective action. Other successful examples of motor-space adaptation include McGuffin and Balakrishnan's (2002) expanding targets; Grossman and Balakrishnan's (2005) bubble cursor; and Blanch, Guiard, and Beaudouin-Lafon's (2004) semantic pointing, all of which dynamically adjust motor-space to reduce the target distance, increase the width, or both. These techniques, fully reviewed in Balakrishnan (2004), are all target oriented: The CD gain or the target/cursor area is dynamically adjusted as a result of the cursor's proximity to the target. PA, in contrast, is more general because it is independent of the semantics of the target environment.

A PA function f produces a CD gain G from the device motor space velocity v (the function may map motor-space velocity directly to display space velocity, but this is equivalent).

$$G = f(v) \tag{5}$$

Most previous work has investigated variants of discrete two-level threshold functions (Jellinek & Card, 1990). These are easy to implement and were

2. Linux distributions still use the two-level threshold functions. The X server controls the PA using the threshold velocity and the second level of the functions which are set in the mouse configuration panel. The XChangePointerControl function is an alternative way of configuring these settings from within a software application.

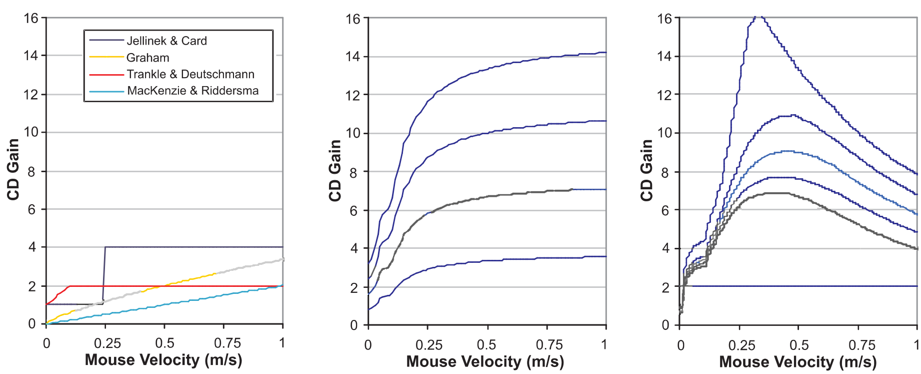
once common in commercial operating systems,[2] but they cause discontinuities where the pointer suddenly accelerates or decelerates, potentially reducing performance. The functions used in contemporary operating systems are continuous to smooth out changes in CD gain (see Figure 3).

Like constant CD gain, previous experiments investigating the effects of PA have produced divergent results. This is likely because of the inconsistent or poor quality of the PA function used, or the limited range of IDs, target distances, and widths. All evaluations used a mouse as the input device.

Jellinek and Card (1990) found that a two-level discrete threshold PA function did not improve user performance compared to constant CD gain of 2, and they claim that PA cannot improve performance or it would violate Fitts' law. However, their results need to be considered in light of their experimental conditions and apparatus, which used a discrete acceleration function with conservative upper CD gain levels (4 or 8), IDs below 5 bits, and a maximum display distance of 223 mm.

Graham (1996) found that a two-level discrete threshold function for 3D hand movement in virtual reality pointing tasks provided no advantage but that a continuous function impaired performance compared to a constant CD gain of 1. Like Jellinek and Card (1990), he used conservative functions in comparison to contemporary ones (Figure 2b and 2c). His two-level function

Figure 3. **Plotting the control device velocity against Control Display gain shows the characteristic curve of pointer acceleration functions. In previous research, conservative and discrete two-level pointer acceleration functions have been used (a) when compared with pointer acceleration functions used by modern operating systems (b, c) (calculated from the registry and source code; see Appendix).**



(a) Previous research (only one discrete function has been represented)

(b) Windows XP/Vista levels 0.25 to 1.0 corresponding to positions on preference slider

(c) Mac OSX levels 0.0 to 0.875 corresponding to positions on preference slider had a CD gain of 1 until a control velocity of 200 mm/sec, at which the CD gain became 2, and his continuous function set $Gain = (velocity/200)^p$, where p =.756, which is likely to produce gain values below 1. The experiment evaluated IDs from 1.4 to 6.6 with a maximum target distance of 300 mm and a minimum width of 3 mm.

Trankle and Deutschmann (1991) found no difference between a continuous PA function and constant CD gain settings of 1 or 2. Their function linearly increased CD gain from 1 to a maximum of 2 when control device velocity reached 100 mm/sec. Their experiment evaluated IDs from 2.6 to 4.4 with a maximum target distance of 100 mm and a minimum width of 2.5 mm. Although not statistically significant, they noted mean movement times for PA were almost 10% higher.

Finally, MacKenzie and Riddersma (1994) tested three different scales of a continuous PA function found in the Apple Macintosh OS6 operating system, showing the medium scale setting to be significantly faster. The Macintosh function mapped control device velocity to CD gain as the product of squared control device velocity and a constant parameter. The experiment evaluated only a single ID of 3.2 with a target distance of 94 mm and a minimum width of 12 mm. They attribute the slower performance with the low setting to the observed predominant use of the forearm for device movement, whereas participants primarily used their wrist with the medium and high settings. They also found significantly lower error rates for the lower CD gain.

3. PA PERFORMANCE MODEL

PA causes dynamic modification to the target's distance and width in motor-space. This modification can be modeled to predict the extent to which the Fitts' law index of difficulty changes in motor space for each target. This section derives the motor space index of difficulty (ID_{mot}) formula for PA.

When constant CD gain is increased by a factor k, the distance and width of the target in motor-space are both reduced equally by a factor of k. Trivially, the ID in motor space equals the ID in display space so the difficulty of the pointing task has not changed. If we also assume unchanged constants for the intercept a and slope b (a reasonable assumption because the device has not changed), then Fitts' law predicts the exact same movement time regardless of the change in CD gain.

Recall that with PA, the mapping function is designed to produce high CD gain levels at high velocities and low CD gain levels at low velocities. Recall also that according to the optimized initial impulse motor control model, high velocities are used in the ballistic phase which attempts to get as close as possible to the target and low velocities are used during the subsequent corrective movements.

For the sake of illustration, assume we have constructed an ideal PA function, which instantly produces a high CD gain G_D for the duration of the ballistic phase (which mostly affects the distance to target, hence the subscript $_D$ for G_D), and a low CD gain G_W for the duration of the corrective phase (which mostly affects the target width, hence the subscript $_W$). Let G_D be k times greater than some baseline CD gain level and G_W be j times greater than the same baseline. By definition, $j < k$. Now, unlike the constant CD gain case, the distance and width of the target in motor space are not reduced equally; the distance is reduced by a factor of k and the width by a factor of j. The ID in motor space is now smaller than the ID in display space by a factor of j/k. According to Blanch et al.'s (2004) work with Semantic Pointing (which in some ways approximates the ideal pointer acceleration constructed for this argument) users are able to take advantage of a reduction of ID in motor-space and improve performance.

Of course, PA functions are not able to reliably produce a single high CD gain during exactly the duration of the entire ballistic phase. Because CD gain continuously changes with the velocity of the pointing device, we can compute the mean CD gain used to cover the distance (CD_D) and the mean CD gain used when near the target (CD_W). If a function is continuous, the mean of the function in an interval is the integral divided by the interval length. We approximate the ballistic phase as the movement occurring before the pointer crosses the target boundary at time T_1. CD_D is then the mean CD gain used in the interval T_1 and CD_W is then the mean CD gain used in the interval $T - T_1$, where T is the total time for the movement.

$$CD_D = \frac{1}{T_1}\int_0^{T_1} Gain(t)\,dt \qquad CD_W = \frac{1}{T - T_1}\int_{T_1}^{T} Gain(t)\,dt \tag{6}$$

From Fitts' law (equation 1), we find the ID in motor space ID_{mot}:

$$ID_{mot} = \log_2\left(\frac{\dfrac{D - W/2}{CD_D}}{\dfrac{W}{CD_W}} + 1\right) \tag{7}$$

Let the ratio of CD_W/CD_D be r and assume $D >> W$, then:

$$ID_{mot} = \log_2\left(\frac{D}{W} + \frac{1}{r}\right) + \log_2(r) \tag{8}$$

If $1/r << D/W$, then:

$$ID_{mot} \approx ID + \log_2(r) \tag{9}$$

By definition $CD_W < CD_D$, so we can deduce that the index of difficulty in visual space (ID) is reduced in motor space by a quantity equal to the log of the ratio between mean CD gain used to cover the distance (CD_D) and the mean CD gain used when near the target (CD_W).

4. EXPERIMENT 1: DESKTOP SIZE DISPLAY

Our goal is to explore the effect of constant CD gain and PA on user performance. Because previous research comparing different levels of constant CD gain has been inconclusive, we want to confirm or refute any effect. If there is an effect we want to test previous hypotheses proposing that it is because of different limbs being used or the limits of fine motor control. Similarly, because previous research on PA has used noncontinuous mapping functions, and given that our theoretical analysis of PA using Fitts' law suggests that there should be a positive effect, we want to examine the effectiveness of a contemporary continuous PA function in comparison to constant CD gain. We used the default Microsoft Windows XP/Vista PA function (Microsoft, 2002), as it is arguably the most widely used.

4.1. Apparatus

We used a 20-in. 1600 × 1200 resolution 100 DPI LCD monitor and a 1600 DPI mouse (Logitech MX518 Gaming-Grade Optical Mouse). With our mouse and display configuration, this provided a maximum CD gain of 16 with no quantization problems (each pixel on the display is selectable). Our Windows C++/OpenGL application bypassed the standard mouse driver and read directly from the mouse hardware to get raw, real numbered coordinates at 60Hz, and updated the display at a regular 60FPS. To measure clutching time we mounted a feather weight switch under the mouse which recorded clutching events when the mouse was lifted off the surface. We also used a Vicon optical motion tracking system (http://www.vicon.com) to capture the absolute positions of the arm, hand, and mouse at 120Hz with submillimetre accuracy for limb movement analysis. Because the system is vision based and uses a custom predictive filter to smooth trajectories, it can be susceptible to tracking errors from marker occlusion or markers outside the calibrated tracking volume. However, with the small movement area in this experiment, tracking error was extremely low.

4.2. Task and Stimuli

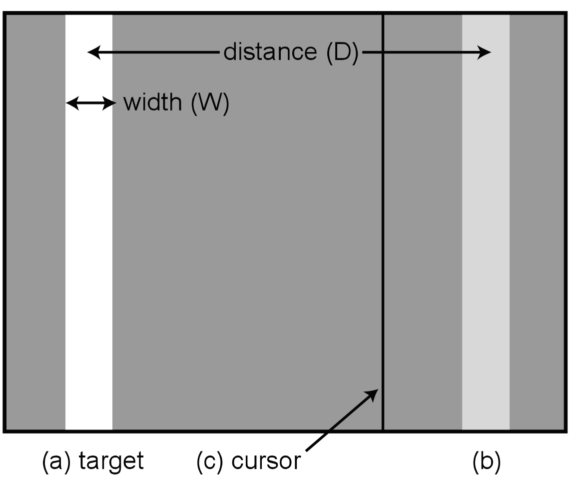
The task was a reciprocal one-dimensional pointing task, requiring participants to select two fixed-sized targets back and forth in succession (see

Figure 4). When participants correctly selected a target, the targets would swap colors, indicating the next target to select. If they missed a target, a sound was heard and the error logged. Participants had to successfully select the current target before moving to the next, even if it required multiple clicks. This design encourages participants to do the task to the best of their ability, rather than "racing through the experiment just to get done," as going too fast incurs errors that have to be corrected. After each block of trials, a cumulative error rate was displayed and a message encouraged participants to conform to an approximately 4% error rate by speeding up or slowing down. The pointer was not constrained to the bounds of the display to prevent using the edges to assist in target acquisition. Participants were encouraged to take breaks between blocks.

4.3. Participants

Eight volunteers (all male) with a mean age of 24.5 ($SD = 6.3$) participated. Compensation was in the form of credit for "experiment participation" in an undergraduate HCI course. We prescreened participants to form two groups of four: those that used Windows XP/Vista pointing acceleration on their own computer and those that did not.

Figure 4. **Experimental display. The targets were rendered as solid vertical bars, equidistant from the center of the display in opposite directions along the horizontal axis. The target to be selected was colored white (a), and the last target, which was the starting position, light gray (b). The cursor was represented by a one-pixel-thick vertical black line (c).**



4.4. Design

A within-subjects design was used. The independent variables were *Technique* (*CG* for Constant Gain and *PA* for Pointer Acceleration), *Level* (6 CD gain levels for *CG* and 6 scale factors for *PA*), distance between targets *D* ($D_L = 360$ mm, $D_M = 180$ mm, $D_S = 90$ mm), and target width *W* ($W_L = 8$ mm, $W_M = 4$ mm, $W_S = 2$ mm). *D-W* combinations were fully crossed with the exception of the combination D_M, W_M, which was excluded to reduce experiment completion time because it had the same ID as D_L W_L and D_S W_S. The eight *D-W* combinations gave five task IDs: 3.6, 4.5, 5.5, 6.5, and 7.5. The CD gain *Levels* for the *CG* technique were 1, 2, 4, 6, 8, and 12 (left hand column of Figure 5); the scale *Levels* for the *PA* technique were 0.1, 0.25, 0.5, 0.75, 1.0, and 1.25, which span the scale factors available in the default "Mouse Properties" panel in Windows XP/Vista. Figure 5 summarizes and compares the six *CG* gain levels and *PA* scale levels—columns 3 and 4 show the minimum and maximum gain settings attainable with the *PA* levels, and columns 5 and 6 show the maximum and average gain levels used by the participants across all trials in the experiment. Our aim in supporting these settings for factor *Level* is to provide good coverage of settings for the *CG* and *PA* techniques. The analyses of results explicitly address the issues of conflating *Technique* and *Level*.

The presentation of the two techniques was fully counterbalanced across the participants in each PA usage group. Presentation of *Level* was counterbalanced between ascending or descending order. In that way we expect to lower the effect of learning between the different levels. For each technique and level, five blocks of trials were performed. Each block had each of the 8 *D-W* combinations presented in ascending order of ID, with 12 trials each. The presentation of the *D-W* combinations in ascending order of ID rather than randomly was an attempt to reduce drastic changes in the difficulty of trials from one set of 12 trials to the next. When each level was completed, the participant was asked to rate their performance in comparison to the previ-

Figure 5. **Comparison of Constant Gain and Pointer Acceleration Levels.**

CG Level (CD Gain)	PA Level (Scale)	Min CD Gain	Max CD Gain	Max CD Gain Used	Average CD Gain Used
1	0.1	0.31	1.46	1.4	0.7
2	0.25	0.79	3.66	3.1	1.4
4	0.5	1.59	7.32	5.7	2.2
6	0.75	2.38	10.98	7.8	3.0
8	1.0	3.18	14.65	9.6	3.6
12	1.25	3.98	18.31	11.1	4.2

ously completed level using a 5-point Likert scale. Because of the number of conditions and trials, the experiment was split across 2 days with each technique completed on 1 day (90 min per day).

In summary, the experimental design was:

8 participants ×
2 *Techniques* ×
6 *Levels* ×
5 *Blocks* ×
8 *D-W* combinations ×
12 trials
= 46,080 total trials

4.5. Results and Discussion

Error Rate

There is a significant effect of *W*, $F(2, 14) = 14.3$, $p < .0001$, on error rate. Error rate increases with small widths. A pairwise comparison[3] shows significant differences between each width: 6.8% for W = 2 mm, 4.5% for W = 4 mm, and 3.9% for W = 8 mm. The overall mean error rate was 5.0%. No other factors or interactions showed significant effects for error rate.

Movement Time

Movement time is the main dependent measure and is defined as the time taken to move from the previous target until the first click. Targets that were not selected on the first attempt were marked as errors but still included in the timing analysis. (We did the analysis with and without the errors removed and the same significant effects were found with comparable F and p values.)

Repeated measures analysis of variance (ANOVA) showed that the presentation order of techniques or levels had no significant effect on movement time (all $p > .3$), indicating that a within-subjects design is appropriate. We also found no significant effect or interaction for *Block* (all $p > .15$), indicating no learning effect was present, which is not surprising given the elemental nature of the task. We found no significant effect for PA usage group (whether the participant used Windows XP/Vista acceleration on their own computer or did not), $F(1, 6) = 1.2$, $p = .31$.

---

3. All post hoc pairwise analyses for all tests were performed using Bonferroni correction.

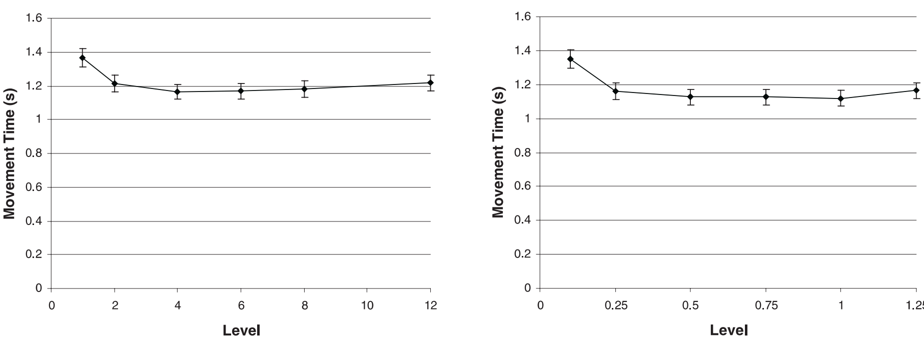
Although we found significant main effects for *Technique*, *D*, and *W,* we have to be cautious before drawing any conclusions because of the different meaning of the *Level* variable in each *Technique.* Thus, we proceed with an analysis of *Level.*

There was a significant main effect for *Level,* $F(5, 35) = 13.5$, $p < .001$. Post hoc pairwise comparisons found a significant difference between *CG Level* = 1 and *CG Levels* up to 8 ($p < .03$) with an 11% improvement between *CG Level* 1 and 2 (all $p < .05$). A significant difference was also found between *PA Level* = 0.1 and the other *PA Levels* (all $p < .05$) with a 14% improvement between 0.1 and 0.25 (Figure 6; recall that a *PA Level* of 0.1 corresponds to an effective CD gain range of 0.31 to 1.46, see Figure 5). No significant differences were found among the other *CG* or *PA Levels.* This shows that low CD gain does indeed have a negative effect on performance.

To see if the slower times observed for *CG Level* 1 and *PA Level* 0.1 are because of fatigue, we analyzed the variation of movement time across the blocks. We found that the time does not increase with *Block* for these levels (all $p > .1$) so we can reject this hypothesis. We also looked at clutching time and found it remained under 0.4% of the movement time, so it cannot be held responsible for the difference: Participants preferred to increase the operating range over which they operated the mouse rather than clutching.

To ensure that *CG* and *PA* are compared within their calibration "sweet spots," we removed *CG* levels 1, 2 and 12 (see Figure 4a) and *PA* levels 0.1, 0.25 and 1.25 (see Figure 6b) from further movement time analysis. We then find a marginal effect of *Technique* on movement time, $F(1, 7) = 4.8$, $p = .065$, with the *PA* mean of 1.16 sec ($SD = 0.3$) 3.3% faster than the *CG* mean of 1.2 sec ($SD = 0.3$).

Figure 6. **Effect of level on movement time for constant gain and pointer acceleration (error bars 95% confidence interval).**



(a) Constant Gain

(b) Pointer Acceleration

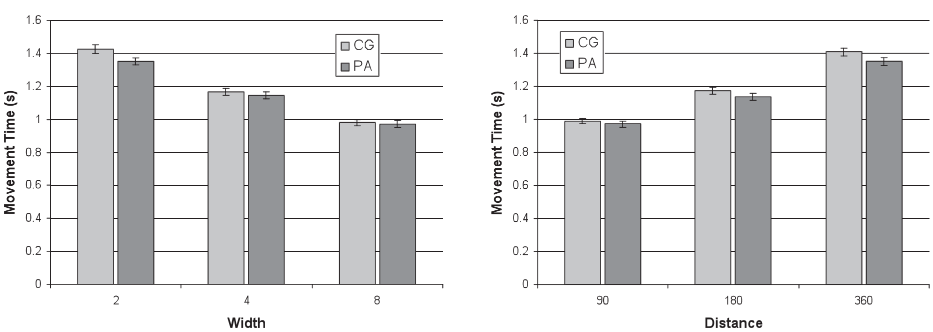
As predicted by Fitts' law, we found significant main effects for *D*, *W*, and *D-W*. We also found significant interactions with *Technique*. The *Technique* × *D-W* interaction, $F(4, 28) = 5.6$, $p < .01$, shows that performance with *PA* technique deteriorates less rapidly with increasingly difficult tasks than with the *CG* technique (further discussed in the Fitts' Law Analysis section later). The *Technique* × *W* interaction, $F(2, 14) = 6.8$, $p < .01$, depicted in Figure 7 (left), shows that *PA* has a 5.6% advantage over *CG* at small widths (pairwise significant, $W_S = 2$ mm, *PA* = 1.35 sec, *CG* = 1.43 sec, $p < .01$). This suggests that users encounter accuracy problems with *CG* because of the small motor space available for the target, particularly at high gain levels (also noted by Buck, 1980). With *PA*, however, users can maintain accuracy because of the low CD gains available at low device speeds. Finally, the *Technique* × *D* interaction, $F(2, 14) = 7.4$, $p < .01$, shown in Figure 7 (right), is caused by a similar effect, with *PA* allowing comparatively faster movement time as the target distance increases. *PA* has a 3.5% advantage over *CG* at large distances (pairwise significant, $D_L = 360$ mm, *PA* = 1.36 sec, *CG* = 1.41 sec, $p < .01$).

Mouse Operating Range and Limb Use

We define the mouse operating range as the maximum area on the desk traversed by the mouse. We calculated the operating range from motion tracking data, but because we are evaluating a one-dimensional task, we consider only the corresponding horizontal dimension.

There was a significant main effect for *Technique* on operating range, $F(1, 7) = 27.7$, $p < .005$, with a mean of 74 mm for the *CG* technique and 67 mm for the *PA* technique. Pairwise comparisons found significant differences between all *Levels* for each technique. As expected, the operating range decreases proportionally with increasing CD gain for *CG Levels*, with mean operating range

Figure 7. **Mean movement time for the two techniques, by width and distance (error bars 95% confidence interval).**



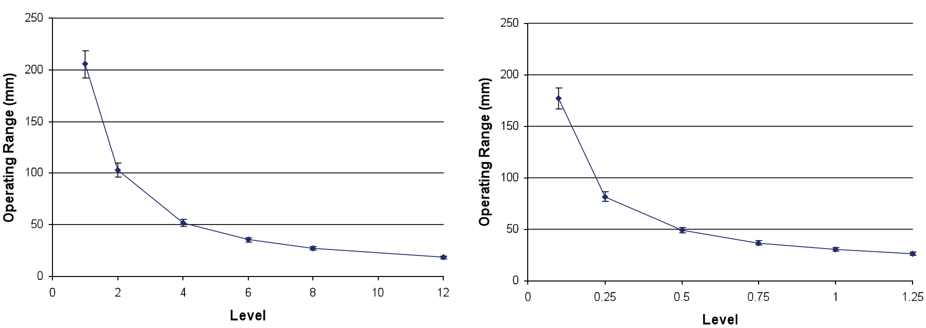
decreasing from 205 mm at *CG Level* = 1 to 18 mm at *CG Level* = 12 (Figure 8a). In contrast, the operating range decreased less dramatically across *PA Levels*, from 177 mm at *PA Level* = 0.1 to 26 mm at *PA Level* = 1.25 (Figure 8b).

Using the motion tracking data we also calculated the amount of forearm, hand, and finger movement in each frame within the parent limb's coordinate frame. We found a limb movement threshold based on the mean percentage of time in which the mouse velocity was zero during a trial. With this threshold, we calculated *limb usage profiles*: the percentage of time limbs or combinations of limbs moved in each frame during a trial (Figure 9).

For both techniques across *Levels*, limbs are rarely used in isolation. As the effective CD gain for each *Level* increases, there is progression from using all limbs together to using the hand and fingers in combination to using the hand or fingers individually. For example, to avoid clutching at a low CD gain of 1, users need to move the mouse a distance of 360 mm, equivalent to the on-screen target distance which is much too far for the hands or fingers alone. The arm is rarely used alone and fingers seem to play a role in maintaining accuracy at high CD gain levels.

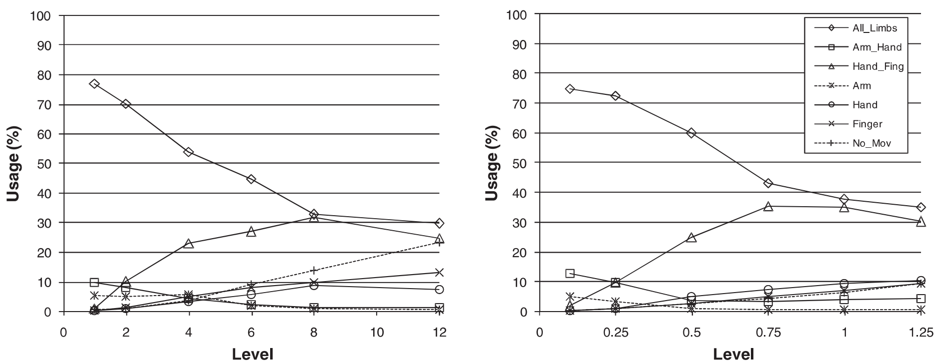
Previous work by Langolf et al. (1976) and Balakrishnan and MacKenzie (1997) found that finger throughput exceeds that of the arm in pointing tasks, so we anticipated that arm use would explain slow performance times at low CD gain levels. However the limb usage profiles do not have a strong correspondence to the movement time profile. For example, the differences in limb usage between *CG Level* = 1 and *CG Level* = 2 do not appear great enough to explain the 11% movement time difference. In fact, there is a larger

Figure 8. **Mean mouse operating range across levels with the two techniques (error bars 95% CI).**



(a) Constant Gain **(b) Pointer Acceleration**

Figure 9. **Limb usage profiles across all target distances.**



(a) Constant gain

(b) Pointer acceleration

difference in limb usage between *CG Level* = 2 and *CG Level* = 4, yet the movement time difference in these two levels is smaller.

Overshooting

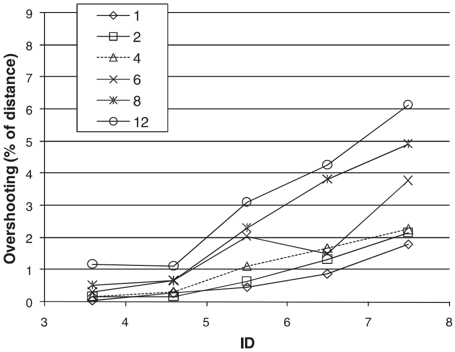
We define overshooting as the ratio of distance traveled past the extent of the target to the theoretical mean distance required for selection, which we define as $D + W / 2$. A repeated measures ANOVA found a learning effect across *Blocks*, $F(4, 28) = 7.7$, $p < .01$, and pairwise analysis showed higher values for the first two blocks compared to the last three. As a result, we used only the last three blocks for overshooting analysis.

There was a significant effect of *Technique* on overshooting, $F(1, 7) = 6.3$, $p < .05$, with a *PA* mean of 2.2%, compared to *CG* with 1.6% . We also found significant main effects for *D-W*, $F(4, 28) = 10$, $p < .01$; *D*, $F(2, 14) = 9.9$, $p < .01$; and *W*, $F(2, 14) = 8.3$, $p < .01$, with more pronounced overshooting in high difficulty selections (more distant or smaller targets). Overshooting also increased with *Level*, $F(5, 35) = 8.8$, $p < .01$. Finally, there was a significant *Level* × *D-W* interaction, $F(20, 140) = 4.1$, $p < .01$, with high levels of CD gain causing more overshooting on difficult targets (Figure 10).

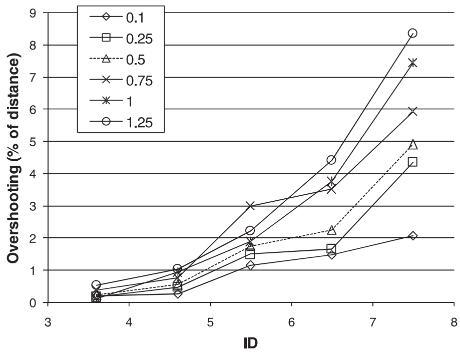
Peak Velocity in Motor and Display Space

Peak motor-space velocity (PMV) is the maximum velocity of the mouse during a trial and the peak display-space velocity (PDV) is the peak velocity of

Figure 10. **Overshooting across level and ID (D-W combination) for the two techniques.**



(a) Constant gain



(b) Pointer acceleration

the on-screen pointer. These two measures are related by the function mapping motor movement to CD gain—constant for the *CG* technique and dynamic for the *PA* technique. Thus, for the *CG* technique, PDV is always a constant multiple of PMV depending on *CG Level*, but this not the case for the *PA* technique.

A repeated measures ANOVA showed significant main effects for *D* on PMV, $F(2, 14) = 220$, $p < .0001$, and *D* on PDV, $F(2, 14) = 383$, $p < .0001$, with PMV and PDV increasing with increased *D*. This confirms that the intensity of a ballistic movement is dependent on the distance to be covered (Plamondon & Alimi, 1997). A significant effect was also found for *Level* on PMV, $F(5, 30) = 160$, $p < .0001$, and on PDV, $F(5, 35) = 165$, $p < .0001$, with PMV decreasing with *Level,* and PDV increasing with *Level.*

We found no significant effect for *Technique* on PMV (*CG* mean 296 mm/sec, *PA* mean 279 mm/sec), but there was an effect for *Technique* on PDV, $F(1, 7) = 60.1$, $p < .0001$, with *CG* slower than *PA* (1031 mm/sec and 1314 mm/sec, respectively). This suggests that *PA*'s dynamic function provides a more pronounced ballistic movement in display space.

To estimate the maximum usable limb speed during pointing tasks we analyzed the peak velocity in motor space for the *CG* technique at *Level* 1.0. The maximum logged limb speed was 2441mm/s, with a 97th percentile value of 1536 mm/sec.

User Preference

After completing each set of blocks for a *Level*, the participants were asked if they found the current *Level* easier or more difficult to the previous *Level* using a 5-point Likert scale. On average, participants preferred *CG Level* 4 and *PA Level* 1 for the two techniques.

Fitts' Law Analysis and Relationship to the Model

Fitts' law models described here are based on regression analysis of the eight D-W combinations, rather than aggregate performance for each of the five IDs. This analysis allows independent effects of D and W to be exposed.

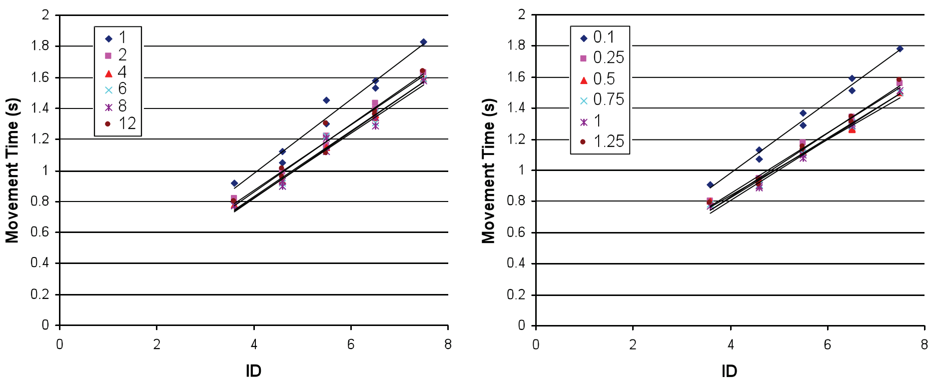
Regression analysis shows that both techniques closely adhere to Fitts' law (Figure 11 and Figure 12), refuting Jellinek and Card's (1990) claim that pointer acceleration would not.

From Equation 9 of our pointer acceleration performance model (see Section 3), we expect the index of difficulty in visual space (ID) to be reduced in motor space by a quantity equal to the log of the ratio between the mean CD

Figure 11. **Fitts' law regression across *Level*. The columns a and b are the standard constants from Fitts' law (equation 1).**

CG Level	a	b	r^2	PA Level	a	b	r^2
1	0.026	0.239	0.966	0.10	0.076	0.227	0.984
2	–0.011	0.218	0.982	0.25	0.059	0.197	0.987
4	–0.026	0.213	0.994	0.50	0.181	0.111	0.985
6	–0.042	0.215	0.975	0.75	0.055	0.191	0.990
8	–0.002	0.207	0.973	1.00	0.014	0.197	0.989
12	0.027	0.211	0.956	1.25	0.011	0.204	0.986
4–8	–0.023	0.212	0.984	0.5–1.0	0.060	0.190	0.991

Figure 12. **Fitts' law regression.**



(a) Constant gain **(b) Pointer acceleration**

gain used to cover the distance (CD_D) and the mean CD gain used when near the target (CD_W). As a first approximation, the time T_1 defined in our model (see Section 3) is taken as the time until the cursor crosses the border of the target. We computed the ratio CD_W/CD_D from the participants' performance data, finding it to be close to constant for all *PA Levels*, with a mean value of 0.5 ($SD = 0.14$). As a result, we can expect to decrease the ID in motor space (ID_{mot}) by approximately $\log_2(0.5) = 1$bit.

Computing the linear regression for ID_{mot} versus ID, we obtain good regression fitness for all PA Levels (with slopes and intercepts being close) revealing that the index of difficulty in motor space (ID_{mot}) is reduced at the same extent for all index of difficulty in visual space (ID). Using aggregated *PA Levels*, we obtain the following:

$$ID_{mot} = 0.93 * ID - 0.62 \quad r^2 = 0.931 \tag{10}$$

Although the slope follows our model's prediction because it is close to 1, we found that participants did not take full advantage of the 0.6 bit of ID reduction in motor space—there should have been an overall 10% time improvement compared to constant gain. The discrepancy between the theoretical prediction and the empirical data reveals the limitation of the PA technique. Although the theory is based on optimal performance without overshooting, the experimental data showed that the high CD gains used during the ballistic movement increased the amount of overshooting. Having overshot the target, the user must make corrective movements during which the device is likely to move slowly, resulting in low CD gains, and consequently time-consuming large motor distances. Although the theoretical model suggests that the index of difficulty in motor space can be reduced to zero with an ideal acceleration function which perfectly interprets the user's actions, in practice this is difficult to achieve. The increased overshooting and increased corrective movement time is symptomatic of the acceleration function incorrectly interpreting the user's actions preventing the user from reaching the full potential of pointer acceleration. Further work to tune the shape of pointer acceleration curves to match human performance might be a worthwhile endeavor.

5. EXPERIMENT 2: VERY LARGE, HIGH-RESOLUTION DISPLAY

Our goal with the second experiment is to explore the effect of high constant CD gain levels and high Micrsoft Windows XP/Vista PA scales on a very large, high-resolution display. With such a display, we can evaluate performance with very high index of difficulty pointing tasks, higher than those conventionally studied in previous Fitts' law studies and in our first experiment. The high ID tasks should also induce enough clutching at low CD gain levels to allow us to inspect its impact on Fitts' law models.

5.1. Apparatus, Task, and Stimuli

The same apparatus, task, and stimuli were used as in Experiment 1, except the display was 4.7 m × 1.7 m and 25 DPI. With our 1600 DPI mouse, this provided a maximum CD gain of 64 with no quantization problems (each pixel on the display is selectable). Participants were seated at a large desk 3 m from the display at its center. They were free to use the entire desktop to operate the mouse. Although we used the same Vicon motion tracking setup as Experiment 1, the high amount of clutching resulted in large arm and forearm movements, which reduced the reliability of our tracking data.

5.2. Participants

Eight volunteers (6 male and 2 female) with mean age of 23.5 ($SD = 1.6$) participated; none had participated in Experiment 1. Compensation was in the form of credit for "experiment participation" in an undergraduate HCI course. Seven of the participants used Microsoft Windows XP/Vista PA on their own computer.

5.3. Design

The experiment design was similar to Experiment 1. A within-subjects design was used. The independent variables were *Technique* (*CG* for Constant Gain and *PA* for Pointer Acceleration), *Level* (6 CD gain levels for *CG* and 6 scale factors for *PA*), distance between targets D ($D_L = 4500$ mm, $D_M = 2250$ mm, $D_S = 1125$ mm), and target width W ($W_L = 36$ mm, $W_M = 18$ mm, $W_S = 9$ mm). The minimum width of 9 mm was chosen because people with 20/40 vision can read an 8.6 mm symbol from a distance of 3 m[4] (Millodot, 1997). As in Experiment 1, D-W combinations were fully crossed with the exception of the combination D_M, W_M which was excluded. The eight D-W combinations gave five task IDs: 5, 6, 7, 8, and 9. The CD gain *Levels* for the *CG* technique were 2, 5, 8, 12, 16, and 20. The scale *Levels* for the *PA* technique were 0.25, 0.5, 1.0, 1.25, 1.5, and 2.0.

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4. The min decipherable symbol height h given distance d: $h = 2\, d \tan(\Theta/2)$, $\Theta = 5'$ of arc for 20/20 vision. With $d = 3$ m, $h = 4.36$ mm or 8.73 mm for 20/40 vision (Millodot, 1997).

As in Experiment 1, the presentation of the two techniques was fully counterbalanced across participants and presentation of *Level* was counterbalanced between ascending or descending order. To reduce total task completion time, and because there was no significant learning effect on movement time in Experiment 1, only three *Blocks* of trials were administered. Each block had each of the 8 *D-W* combinations presented in ascending order of ID, with six trials each. The experiment duration was between 75 and 90 min.

In summary, the experimental design was:

8 participants ×
2 *Techniques* ×
6 *Levels* ×
3 *Blocks* ×
8 *D-W* combinations ×
6 trials
= 13,824 total trials

5.4. Results and Discussion

Error Rate

The mean error rate was 4% with no significant difference across independent variables.

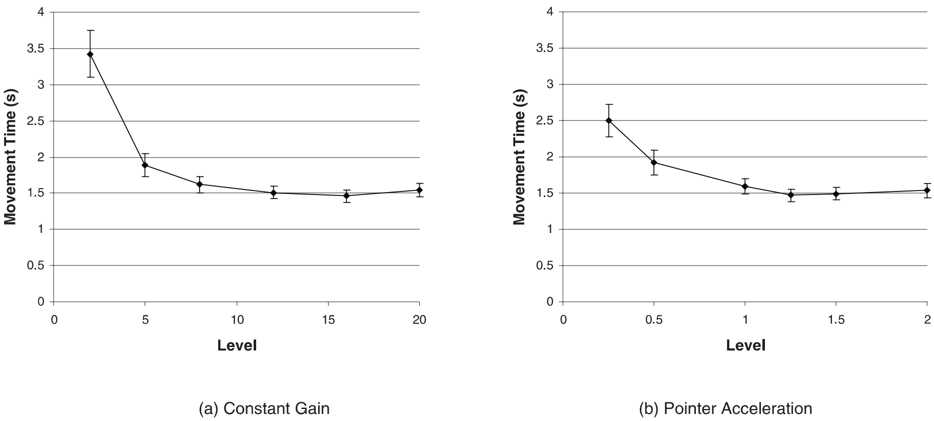
Movement Time

A repeated measures ANOVA showed a significant main effect for *Block,* $F(2, 14) = 23.4$, $p < .001$, caused by slower performance in Block 1 suggesting a learning effect; as we wished to study expert performance, we removed Block 1 data from further analysis. Subsequent analysis showed a significant main effect for *Technique,* $F(1, 7) = 18.6$, $p = .004$, with *PA* 10% faster than *CG* (*M*s = 1.697 sec and 1.882 sec, respectively). However, before drawing any conclusions, we must study the effect of *Level* for both *Techniques.*

There was a significant main effect of *Level,* $F(5, 35) = 159$, $p < .0001$, and pairwise comparison showed significant differences between the first two *CG* and *PA Levels* and all others. There was also a significant difference between the first *CG Level* and the first *PA Level* that can explain the difference observed between the two techniques. As a result, we removed the two first *CG Levels* and the two first *PA Levels* to fairly compare the two techniques within their "sweet spots" of calibration (Figure 13).

Subsequent analysis showed no significant difference between the two techniques, $F(1, 7) = 0.22$, $p = .653$. Unlike Experiment 1, where *PA* had a 6% advantage over *CG* for the smallest targets, there was no *Technique* × *W* inter-

Figure 13. **Effect of *Level* on movement time for the two techniques (error bars 95% confidence interval).**



action—even with a *CG Level* of 20, accuracy was maintained with small targets. We suspect that W_S was too large to replicate the accuracy problem.

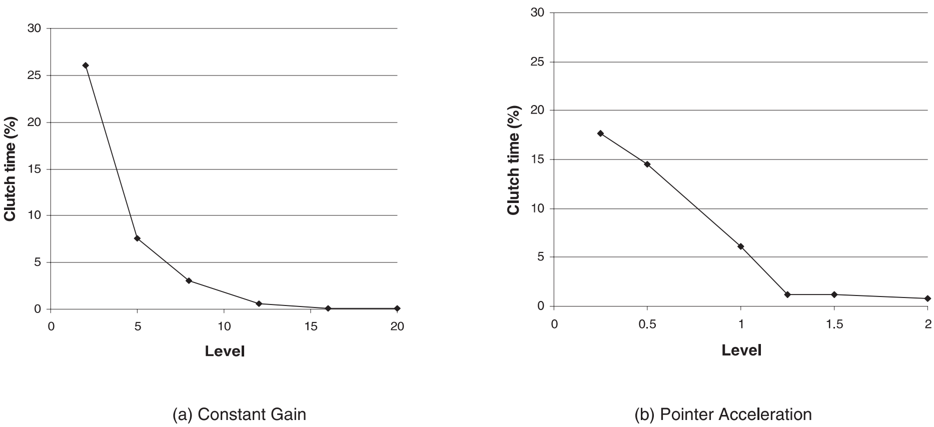
Clutching Time

There was a significant main effect for *Level* on clutching time, $F(5, 35) = 20.9$, $p < .001$. Pairwise comparison showed that clutching decreased significantly after the first two *CG* and *PA Levels* (Figure 14). *CG* Levels 2 and 5 had 26% and 7% clutching time, whereas both *PA* Levels 0.25 and 0.5 had 17% and 14%. As anticipated, increased clutching time also increased movement time, for example, by 124% with 24% clutching (Figure 13). This empirically confirms the assumptions of prior work (Jellinek & Card, 1990). We anticipated a significant effect of *D* on clutching, but the data did not confirm it—possibly because the participants formed a clutching strategy for high *D* tasks and maintained it for all levels of *D*.

Note that although the lowest level of *PA* had less clutching compared to the lowest level of CG, for other PA levels clutching was higher. For example, the amount of clutching for *CG Levels* above 8 is nearly zero, but with *PA Levels* above 1 clutching remained close to 1%. With the PA function, users need to accelerate through the low CD gain zones to get the benefit of high CD gain.

Because of the high amount of clutching that involved both arm and forearm in some conditions, we were not able to perform an analysis of limb usage like we did in Experiment 1 with the desktop-sized display. Unfortunately, we had not anticipated this behavior and our tracking equipment was

Figure 14. **Clutching time as percentage of the total movement time.**



not set up to track such large-scale movements. As a result, we are unable to infer reliable results on the limb usage.

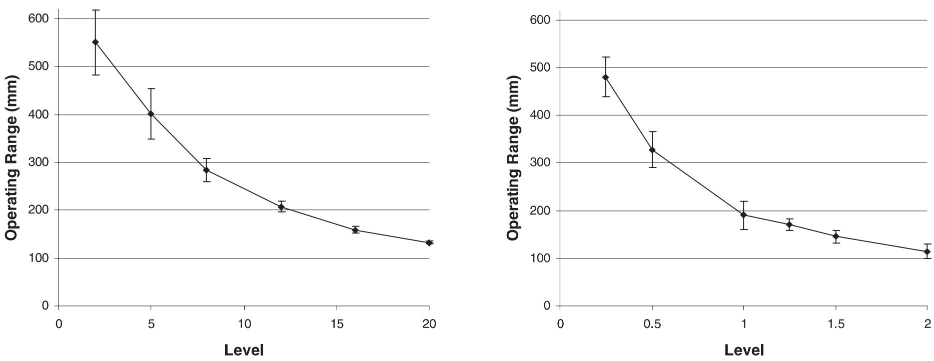
Mouse Operating Range

Analysis of the mouse operating range data showed significant main effects for *Technique,* $F(1, 7) = 65.5$, $p < .0001$; *Level,* $F(5, 35) = 140.8$, $p < .0001$; *D-W,* $F(7, 49) = 177.5$, $p < .0001$; and significant interactions between *Technique* × *Level,* $F(5, 35) = 4.3$, $p = .046$, and *Technique* × *W,* $F(2, 14) = 44.3$, $p < .0001$. The mean operating range is 335 mm for *CG* and 271 mm for *PA.* The significant effect of *Level* shows that the operating range decreases with increased *Level* (Figure 15). Pairwise comparison shows significant differences between all the *CG Levels* ($p < .035$) and all *PA Levels* ($p < .001$) expect for scales 1.0, 1.25 and 1.5.

Overshooting

Supporting the result of Experiment 1, overshooting is significantly more pronounced with *PA* ($M = 1.44\%$) than with *CG* (0.78%): $F(1, 7) = 16.8$, $p < .01$. There are also significant main effects for *Level,* $F(5, 35) = 6.5$, $p < .05$; *D,* $F(2, 14) = 11.12$, $p < .005$; and W, $F(2, 14) = 8.3$, $p < .01$. Overshooting increases with *Level* and *Distance.* Unlike Experiment 1, however, the significant effect of *Width* is not caused by increased overshooting on small targets ($W_S = 0.84\%$, $W_M = 0.73\%$, and $W_L = 1.06\%$). It seems that the participants remained accurate and confident with the small (9 mm) targets, using higher speeds to acquire them, resulting in higher overshooting.

Figure 15. **Mean mouse operating range at different levels (error bars 95% confidence interval).**



(a) Constant Gain

(b) Pointer Acceleration

User Preference

After completing each set of blocks for a *Level*, participants were asked if they found the current *Level* easier or more difficult to the previous *Level* using a 5-point Likert scale. On average, participants preferred *CG Level* 16 and a *PA Level* 1.5 for the two techniques.

Fitts' Law

As in Experiment 1, Fitts' models are based on regression analysis of the eight D-W combinations. Except for those Levels with significant clutching (*CG Level* 2 & 5 and *PA Level* 0.25), we found that performance followed Fitts' law (Figure 16 and Figure 13). This is a result that, to our knowledge, has not been shown before. The regression equations show a large negative intercept and relatively high slope, comparable to those previously observed with the touchpad (Epps, 1986), which also requires extensive clutching. We hypothesise that clutching accounts for the negative intercepts. Figure 17 shows the high slope (and hence low index of performance) for the two *Levels* with clutching.

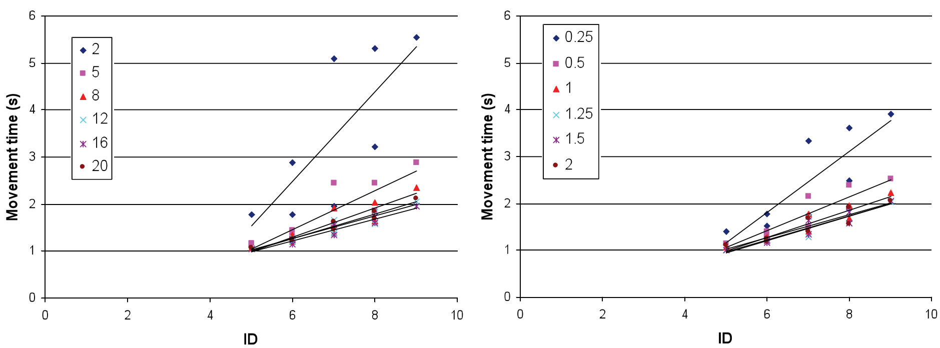
From Equation 9 of our pointer acceleration performance model (see Section 3), we expect the index of difficulty in visual space (ID) to be reduced in motor space by a quantity equal to the log of the ratio of the mean CD gain used to cover the distance (CD_D) and the mean CD gain used when near the target (CD_W). As in the first experiment, the time T_1 defined in our model (see

Figure 16. **Fitts' law regression across *level*. The columns a and b are the standard constants from Fitts' law (equation 1).**

CG Level	a	b	r^2	PA Level	a	b	r^2
2*	–3.207	0.950	0.577	0.25*	–2.079	0.650	0.711
5*	–1.007	0.412	0.734	0.5*	–0.720	0.359	0.810
8	–0.543	0.308	0.805	1.0	–0.438	0.287	0.882
12	–0.196	0.243	0.891	1.25	–0.325	0.258	0.868
16	–0.169	0.232	0.936	1.5	–0.353	0.261	0.909
20	–0.314	0.264	0.959	2.0	–0.212	0.247	0.861
8–20	–0.307	0.262	0.902	1.0–2.0	–0.333	0.263	0.884

*These levels have significant clutching.

Figure 17. **Fitts' law regression. The steep slopes correspond to levels with significant clutching.**



(a) Constant Gain **(b) Pointer Acceleration**

Section 3) is the time before the cursor crosses the border of the target. We computed the ratio CD_W/CD_D from the participants' performance data, finding it to be close to constant for all *PA Levels*, with a mean value of 0.37. As a result, we can expect to decrease the ID in motor space (ID_{mot}) by approximately $\log_2(0.37) = 1.4$ bit.

As in the first experiment, the linear regression for ID_{mot} versus ID has good regression fitness for all *PA Levels* (with slopes and intercepts being close). Using aggregated *PA Levels*, we obtain the following:

$$ID_{mot} = 0.91 * ID - 0.45 \quad r^2 = 0.993 \tag{11}$$

In spite of strong regression fitness, participants could not fully exploit the index of difficulty reduction in motor space. As in the first experiment, this was partly because of increased overshooting and increased correction time.

But here, clutching further eroded the theoretical performance advantage of PA.

6. CONCLUSIONS

We have evaluated mouse pointing performance with varying levels of CG and PA on a desktop display and on a very large, high-resolution display. We evaluated a continuous and mature pointer acceleration function used by the majority of GUI computer users. Our evaluation essentially eliminated any device quantization effects, recorded clutching actions, and used accurate 3D motion tracking equipment to analyze limb movements.

6.1. Gain Level

On both displays, and in both CG and PA techniques, we found that low levels of CD gain had a pronounced negative effect on performance. High levels of gain increased overshooting, indicating an issue with muscle control accuracy because of the reduced distances in motor-space.

Although previous research has suggested that limb bandwidth is responsible for decreased performance at low levels of CD gain (Accot & Zhai, 2001), our findings indicate that maximum limb speed and clutching time are better explanations. In our first experiment on the desktop- sized display we found that participants were limited by a maximum limb speed of about 1.5 m/sec (based on the 97th percentile of logged values with *CG* at Level 1) increasing the mean times at very low CD gain levels by 10% to 14%. In our second experiment on the very large, high-resolution display we found that clutch time was the dominant factor increasing movement time up to 124% with 24% clutching. This empirically confirms Jellinek and Card's (1990) clutching hypothesis. We also found that movement times that included clutching actions did not follow Fitts' law.

We were surprised that the seemingly high levels of CD gain in our experiments did not have a substantial impact on selection time, so we conducted a small three-participant pilot experiment on the large display. We evaluated very high CD gain levels of 8, 16, 20, 30, 40, and 50 with target distances of 4500, 2250, and 1125 mm and widths of 36, 18, and 9 mm. Surprisingly, the movement time appears to remain constant for the CD gain levels above 16. The resulting CD gain versus movement time profile is almost an L-shape, with a slight increase in time with very small targets at high CD gain levels. Essentially CD gain has little effect on pointing performance until human limits of speed and accuracy are approached.

From our results, we can define a usable range of CD gain settings between thresholds of speed and accuracy given the capabilities of a pointing device, display, and the expected range of target widths and distances. These results have particular applications to device and pointer function developers, and future Fitts' law researchers to ensure they are selecting CD gain levels appropriate for the intended hardware, software, and application usage scenario.

To avoid clutching when acquiring distant targets, the user must increase the device operating range. Based on our experimental results, the maximum operating range used in the first experiment was 36 cm with a CD gain of 1, and in the second experiment it was 37 cm with a CD gain of 12 (where participants clutched less than 1%). We also found that device speed increased with larger operating range until a maximum limb speed affects performance. As a result, we make a conservative estimate that the maximum operating range (OR_{max}) should not exceed 30 cm. Using he largest expected target distance (D_{max}), the minimum usable CD gain (CD_{min}) can be calculated:

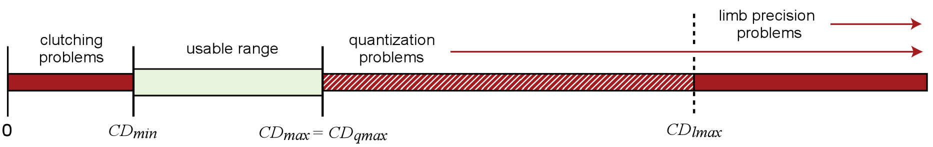
$$CD_{\min} = \frac{D_{\max}}{OR_{\max}} \tag{12}$$

The maximum usable CD gain (CD_{max}) is the lower bound of maximum usable CD gains given human limb precision and device quantization. The maximum CD gain given limb precision (CD_{lmax}) depends on the minimum expected target width (W_{min}) and the precision of the user's limbs. We observed accuracy problems with 2 mm targets and CD gain of 12. Because we used a very high resolution 1600 DPI mouse, these problems must be related to human accuracy rather than device quantization. Thus the minimum resolution of the hand and fingers ($Hand_{res}$) appears to be about 0.2 mm. Device quantization can also affect accuracy before this human threshold is reached, so we must also consider the maximum CD gain given device quantization (CD_{qmax}) which is the ratio of mouse and screen resolution ($Mouse_{res}$ and $Screen_{res}$).

$$CD_{\max} = \min\left(CD_{q\max} = \frac{Mouse_{res}(DPI)}{Screen_{res}(DPI)}, CD_{l\max} = \frac{W_{\min}}{Hand_{res}} \right) \tag{13}$$

A graphical interpretation of the usable range of CD gain is shown in Figure 18. For example, with a 400 DPI mouse, a 20″ display with 100 DPI resolution, a maximum 360 mm target distance, a minimum 2 mm target

Figure 18. **Usable CD gain range.**



width, and a maximum 250 mm operating range, we find $CD_{min} = 1.4$ and $CD_{max} = min\,(CD_{qmax}{=}4,\ CD_{lmax}{=}10) = 4$.

If a researcher calculates that CD_{max} is smaller than CD_{min} for an intended experiment, then the parameters of the experiment must to be changed—for example, the target width can be increased, the maximum distance reduced, or the resolution of the input device increased.

6.2. Pointer Acceleration Versus Constant Gain

On the standard desktop display, we found that pointer acceleration was 3.3% faster overall, and up to 5.6% faster with small targets. This confirmed the advantage predicted by our theoretical analysis; however, the benefit magnitude fell short of the theoretical potential, possibly because *PA* results in increased target overshooting. We also found that pointer acceleration follows Fitts' law with good regression fitness.

Finally we encourage researchers to use pointer acceleration rather than constant gain as a base technique for comparing new pointing technique performance. We found that the aggressive and continuous pointer acceleration functions used in modern operating systems perform better than constant gain, and many people use them already and are proficient with them.

NOTES

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APPENDIX. SOURCE OF WINDOWS XP/VISTA AND MAC OS X POINTER ACCELERATION CURVES

The Windows XP and Mac OS X pointer acceleration curves are defined in a lookup table containing the speed of the cursor and the speed of the mouse. The speed of the cursor is then linearly interpolated. Windows XP pointer acceleration uses a mother curve stored in the registry (HKEY_CURRENT_USER\Control Panel\Mouse). When moving the cursor left and right in the user preference panel with "Enhance pointer precision" enabled, the mother curve is then scaled along the Y axis where the default setting corresponds to a scale of 0.5.

Mac OS X uses different pointer acceleration curves for each position of the slider on the mouse panel setting. The curves were found by analyzing the code for the mouse found on the Darwin Project (http://opensource.apple.com/

darwinsource./10.4/IOHIDFamily-164/IOHIDSystem/IOHIPointing) and using a developer utility on Mac OS X to dump the device tree info to get the HIDPointerAccelerationTable. It is interesting to see that it is possible to use the pointer acceleration technique or constant CD gain of various values on Windows XP but it is only possible to use the pointer acceleration technique on Mac OS X or a constant CD gain of 1.