Modeling the Effect of Gain on Mid-air Pointing

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ABSTRACT

We test a theoretical model of mid-air pointing performance for very large wall displays that uses the Welford two-part formulation of Fitts's law. This allows for an independent contribution of movement amplitude A and target width W to movement time. We demonstrate how the relative contributions of A and W can be mathematically captured in an exponent k. We then provide new experimental data that suggests that the exponent k increases monotonically as control-display gain increases, and that it appears to increase linearly. We conclude that to accurately model pointing performance on interactive displays more robust models, such as the Welford two-part formulation, should be adopted that take into account control-display gain.

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INTRODUCTION

The Fitts's law model of pointing performance [6] has proven to be extremely robust. As Pratt et al. [24] point out, it has been applied to physical pointing underwater [15], in near-zero gravity [9], with microscopic targets [18], and even pointing with one's feet [13]. Fitts's law has found a home in the field of Human Computer Interaction, with a nearly thirty-year legacy [26]. When evaluating new pointing devices or new display form factors one of the first research tasks is often to perform a Fitts's law evaluation to produce a predictive model of performance and determine throughput for the particular approach.

However there are exceptions to Fitts's law. Not long after Fitts's original paper, Welford observed [27] that some Fitts-like tasks result in data that does not follow Fitts's model. Welford proposed an alternate two-part formulation of performance to take into account this deviation from expected performance. The Welford formulation allows for independent contributions to movement time of movement amplitude A and target width W, rather than only considering the ratio of A and W captured in Fitts's "index of difficulty." We discuss this at length in the next section.

More recently there have been other indications that Fitts's law has limitations. Pratt et al. [24] discovered that allocentric spatial information can modulate pointing performance, with the result that pointing to a farther target can in some cases take less time than pointing to a closer target. As Pratt et al. conclude: "it now seems unlikely that a single equation will be able to accurately capture all aspects of speed-accuracy trade-offs." From these two examples it is clear that Fitts's law, while widely useful and validated, should not be taken as gospel. Alternate explanations should be considered when appropriate. One such situation is when the size of the display varies significantly from those traditionally studied, or when dramatically different values of the control/display gain ratio are employed.

Until recently, a single nearly universal form factor dominated computing interaction. The ubiquitous keyboard and mouse paired with a relatively modest-sized display required that a user sit stationary at a desk, working in isolation. In the last few years new form factors have grown in popularity. As a result new interaction techniques have become widespread. Handheld devices such as the iPhone allow users to interact with very small displays at a moment's notice while walking down the street, while shopping, or when meeting with friends. At the other extreme, very large displays embedded in the environment also hold potential to support users in completing certain kinds of tasks. Large wall and tabletop displays support natural collaborative interactions, they support brainstorming and shared data storage, and they allow for interaction in public spaces.

With the introduction of these new display form factors it is important that we develop an understanding of low-level human interaction tasks such as pointing. Models of interaction performance assist system designers in a number of ways. They can help to determine which devices are appropriate for use. They can also guide designers in the implementation of specific interaction techniques and inform the positioning and sizing of on-screen display elements.

In this paper we explore how display-control gain in mid-air pointing performance on very large wall displays can be explained using the two-part Welford formulation of Fitts's

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law. We present results from a new experiment that investigated distance pointing on a very large wall display. These results indicate that the Welford two-part formulation models pointing performance much better than does the original Fitts formulation, and that pointing performance does indeed vary with gain.

VARIANTS OF FITTS'S LAW

Fitts's law [6] was originally developed as a tool for modelling the performance of human physical pointing. It was later applied to pointing on a computer display by Card et al. [2]. The empirically determined parameters of a Fitts model for computer pointing depend largely on the device used. Researchers have performed numerous evaluations of devices, including investigations into traditional mouse, pad, and trackball devices [5], stylus input [7], direct touch on tables [8], and pointing with a laser pointer [22]. Researchers have also extended Fitts's law to special cases. Variations on Fitts's model have been developed for 2-D pointing [19], 3-D pointing [11], pointing to expanding targets [21], and pointing to dynamically revealed targets [1], among others. Researchers have even investigated such subtle points as the impact of cursor orientation on performance [23], and the independence of throughput on the speed/accuracy tradeoff [20].

There are still some open questions, however, regarding how Fitts's law should be applied in HCI. Guiard [12] raised the question of consistency in the design of Fitts's law experiments and introduced a new interpretation, form and scale, for Fitts's law experimentation. Outside of the field of HCI, questions have also been raised regarding the applicability of Fitts's law. Pratt et al. [24] discovered that allocentric information can modulate pointing performance, suggesting that there is more to pointing than the low-level motor movement modelled by Fitts's law. These explorations, combined with Keulen et al.'s [16] identification of multiple reference frames used for reaching, suggest that our understanding of pointing performance and Fitts's law is far from complete, and that we should continue to re-evaluate our understanding and use of Fitts's law.

One-part and two-part models of pointing performance

Fitts established a theoretical model of physical pointing performance [6] that has proven to be robust, as well as flexible enough to be applied to other domains. Several formulations of Fitts's law have been posited. We discuss here four important variants.

$$MT = a + b\log_2\left(\frac{2A}{W}\right) \quad (1)$$

$$MT = a + b\log_2\left(\frac{A}{W}+1\right) \quad (2)$$

$$MT = a + b\log_2\left(\frac{A}{W}+0.5\right) \quad (3)$$

$$MT = a + b_1\log_2 A - b_2\log_2 W \quad (4)$$

The original version due to Fitts (eq. 1) defines movement time as depending on the distance (amplitude) between targets (A) and the size (width) of the targets (W), as well as two experimentally determined constants. The $\log_2\left(\frac{2A}{W}\right)$ term is known as the index of difficulty (ID). In the Fitts formulation it is this dimensionless ratio of A and W that matters; the individual values of A and W are not in isolation important.

Soukoreff and MacKenzie [26] have promoted the use of a formulation (eq. 2) where ID is more consistent with a Shannon-inspired information-theoretic interpretation of Fitts's law. This is similar to what we refer to as the Welford one-part formulation (eq. 3). Both have an additive constant within the logarithmic term.

The fourth important variation, and the one we will focus on, is the Welford two-part formulation (eq. 4), which allows for separable contributions of A and W to movement time. By separable, we mean that the individual values of A and W are of significance, rather than just the ratio A/W. Welford introduced his two-part formulation to account for deviations from Fitts's law that he observed in data collected from a reproduction of Fitts's original experiments [27, page 158]. The Welford two-part formulation seems to have been largely overlooked in the HCI literature, but we think it is potentially powerful in its generality, especially when applied to interaction with large displays.

Several properties of large display interaction techniques differentiate them from the direct touch motor movement that was originally studies by Fitts. First, interaction and feedback are often located in different spaces. For example, a user may manipulate an input device (e.g. a mouse) in one space while visual feedback, including a visual cursor, is shown on a display in a separate space. Second, there is not necessarily a one-to-one correspondence between input movements and resultant feedback. The control-display gain (CD gain) can be manipulated in different ways, and motion can be either relative or absolute. Third, manipulation can be performed outside of a person's physical reach, using devices such as laser pointers. It is known that humans use different cognitive mechanisms to operate inside and outside of physical reach [14], and these different mechanisms may result in different performance profiles. Because of this, a single model, such as Fitts's law, may not be adequate in describing a task with many influencing variables.

In order to understand the performance properties of different interaction techniques for very large wall displays, it is necessary to determine whether Fitts's law applies and how it might need to be generalized. Important questions include: does the original Fitts formulation (or alternately one of the Shannon-inspired formulations) apply to distance pointing on a large display? If not, does an alternate model, such as the Welford two-part formulation, better explain performance? Are conclusions generalizeable across multiple interaction techniques? To answer these questions it helps to first develop a clearer understanding of existing work involving the different formulations, and different interaction scenarios.

Kopper et al. [17] examined distance pointing with a laser pointer on large displays. They developed a model of performance based on angular measurements α for movement amplitude and ω for target width (eq. 5).

$$MT = a + b\log_2\left(\frac{\alpha}{\omega^k} + 1\right) \tag{5}$$

The use of angular measurements is consistent with their technique, where rotation of the input devices, rather than translation, results in cursor motion. The exponent k they introduce allows α and ω to have separate degrees of impact on movement time.

A formulation analogous to the Kopper angular formulation can be constructed using linear units (eq. 6).

$$MT = a + b\log_2\left(\frac{A}{W^k} + 1\right) \tag{6}$$

In this formulation, linear amplitidue A replaces angular α, and linear width W replaces angular ω. A second formulation is also possible (eq. 7), where we omit the Shannon-inspired "$+1$" term. We will use it to analyze new experimental data.

$$MT = a + b\log_2\left(\frac{A}{W^k}\right) \tag{7}$$

The linear analog of Kopper et al.'s formulation (eq. 7) can be derived directly from the Welford two-part formulation (eq. 8). They are mathematically equivalent. The k and b values in the linear version of the Kopper formulation are equal to b_2/b_1 and b_1 from the Welford formulation, respectively. We therefore have a second means of expressing the Welford two-part formulation, this time with just a single multiplicative constant b_1 but with another constant k that appears as an exponent.

$$\begin{aligned} MT &= a + b_1\log_2(A) - b_2\log_2(W) \\ &= a + b_1\left[log_2 A - \frac{b_2}{b_1} log_2(W)\right] \\ &= a + b_1\left[log_2(A) - log_2(W^{b_2/b_1})\right] \\ &= a + b_1 log_2\left(\frac{A}{W^{b_2/b_1}}\right) \\ &= a + b_1 log_2\left(\frac{A}{W^k}\right) \end{aligned} \tag{8}$$

The exponent k is a single constant that conveniently encapsulates the relative magnitude of the separable contributions of the independent variables A and W to the overall movement time. If experimental results determine that $k = 1$ the model is simply Fitts's law (without the factor of 2 multiplying A, an inconsequential detail), and Fitts's law will accurately model the experimental data. However, in cases where experimental data dictate that k deviate significantly from unity, the Fitts formulation will do a poor job of modelling results. Thus the exponent k is useful not only for gauging the relative contributions of A and W, but is also a good indicator of the applicability of the original Fitts formulation. We adopt the use of the exponent k for much of the remaining paper to illuminate the separable contributions of A and W.

This glosses over an important point. Both A and W appear within logarithms. This is not mathematically valid because the logarithm of whatever dimensions are involved (space in this case) is not really an admissable quantity. As Graham explains [10], Welford anticipated this objection and postulated nominal values A_0 and W_0 that "normalize" A and W respectively and eliminate the problem of logarithmic dimensions.

$$MT = a + b_1\log_2\left(\frac{A}{A_0}\right) + b_2\log_2\left(\frac{W}{A_0}\right) \tag{9}$$

We will assume that suitable constants A_0 and W_0 are used as in eq. 9, and will simply write eq. 4.

MID-AIR POINTING PERFORMANCE ON LARGE DISPLAYS

To test a model of mid-air relative pointing performance for very large wall displays with separable contributions of A and W to pointing time we examined a wide range of gain values and to using multiple pairs of A and W values. The general design of our experiment is inspired by those of Casiez et al. and Tsukitani et al.

Apparatus

Users viewed a large vertical glass screen approximately 5m×3m in size. The screen was rear-projected by a 4×3 array of 800×600 resolution projectors (Figure). The images of neighbouring projectors overlapped 160 pixels with a blending function to minimize discontinuities due to possible misalignment. Overall resolution was 2720×1480 pixels.

Click events were performed using the thumb (A) button on a Nintendo Wii Remote ("Wiimote"). Tracking of the Wiiemote was performed using a Vicon motion capture system because the native Wiimote sensing capabilities were not accurate enough for our needs. The Wiimote was outfitted with reflective markers for this purpose (Figure).

The software ran on a computer running the Windows XP operating system and was written in C# using the Microsoft XNA Game Studio library and .NET 3.5. The WiimoteLib library was used to communicate with the Wii remote device. The same computer ran the Vicon tracking software. Logging of events was performed in real time and stored on the machine.

Figure 1. A participant interacting with the experimental system.

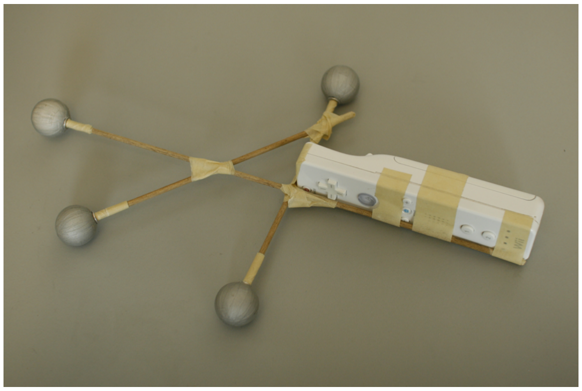

Figure 2. The Wiimote mounted with reflective Vicon tracking markers.

Task and Stimuli

The experimental task was a serial 1-D tapping task between two targets of variable amplitude and width, modelled closely after tasks used by Casiez et al. [3] and Fitts [6]. It was decided to use a traditional 1-D task similar to what was originally used by Fitts, rather than a 2-D task such as that defined by ISO 9241-9 [4] because we were concerned with the fundamental applicability of Fitts's law.

For each target pair a participant first clicked the start target and then performed a sequence of 8 reciprocal taps between the two targets. The current target was always blue, and the current non-target was always grey. One target was directly in front of the participant, while the other target was to the right of the participant at the given amplitude. This arrangement was chosen to avoid any possible impact of cross-lateral inhibition, which is a difficulty in motions where the hand crosses the body's midline [25]. The participant was required to correctly click the first target to initiate the trial. Missed clicks for the following eight taps were recorded. There was no requirement to correct errors. After a click the target briefly flashed green to indicate success, or red to indicate an error.

Participants

Nineteen participants (two female) were recruited through on-campus advertising. All were right-handed, a requirement for participation in the experiment. Ages ranged from 20 to 42, mean 26.4, SD 5.7. All participants were regular computer users (9+ hours per week). They were compensated $10 for participating, and the half with the best performance were later compensated an extra $10. The additional compensation was intended to be an incentive to participants to perform well.

Design

A within-subjects design was used. The independent variables were gain (2, 5, 8, 12, 16, 20), target size (5cm, 10cm, 20cm), target amplitude (25cm, 50cm, 100cm, 250cm), and trial block (1, 2, 3). A and W combinations were fully crossed, except the 250cm amplitude was only used at gains 16 and 20, because it was not reachable at lower gains.

Each gain level was presented during each block of trials. Gain levels were randomly ordered during each block. Within each gain level each A and W pair was presented. A and W pairs were randomly ordered during each gain level. 8 trials were performed for each A and W pair.

In summary, the experimental design was:

19 participants ×
3 blocks ×
(4 gains × 9 A and W combinations) + (2 gains × 12 A and W combinations) ×
8 trials
= 27,360 total trials

Procedure

Each participant performed the experiment in a single session of approximately 50 minutes. Participants arrived and filled out a pre-questionnaire gathering demographic information. They were introduced to the system and the pointing task was explained. Particpants were told to complete the task as quickly as possible with a goal of 95% accuracy. They each practiced at least five trials, and were invited to practice more if they felt the need.

Participants then completed the three experimental blocks. Whenever the gain level was changed a practice A and W pair was presented to the participant. The purpose was to allow the participant to grow accustomed to the new gain level. The participant was not informed that the A and W pair was a practice pair. It was presented in the flow of the experiment, but the data for these pairs were not analyzed.

Between each block the participants sat at a table and played a distractor puzzle task for three minutes. They were invited to take extra time to rest, but none did so. After all conditions were completed a participant filled out a post-questionnaire that gathered qualitative feedback on particular aspects of the experiment.

Measures

Factor	F-ratio	Significance	Partial η^2
$gain$	$F_{3.0,53.8} = 36.9^*$	$p < 0.001$	0.672
A	$F_{1.1,20.4} = 778.5^*$	$p < 0.001$	0.977
W	$F_{1.1,20.1} = 408.3^*$	$p < 0.001$	0.958
$gain \times A$	$F_{10,180} = 4.3$	$p < 0.001$	0.194
$gain \times W$	$F_{4.3,77.6} = 15.0^*$	$p < 0.001$	0.455
$A \times W$	$F_{2.5,45.8} = 18.5^*$	$p < 0.001$	0.506

*A Greenhouse-Geisser correction was applied.

Table 1. Significant ANOVA results for movement time in Experiment 2.

	Fitts			Welford				
Gain	a	b	R^2	a	b_1	b_2	k	R^2
2	0.070	0.23	0.99	0.27	0.24	0.23	0.97	0.99
5	0.089	0.20	0.99	0.34	0.20	0.21	1.05	0.99
8	0.076	0.21	0.98	0.39	0.20	0.22	1.12	0.99
12	0.032	0.24	0.98	0.40	0.23	0.26	1.13	0.98
16	0.022	0.26	0.97	0.52	0.24	0.30	1.24	0.98
20	0.035	0.28	0.96	0.65	0.25	0.33	1.32	0.98
2-20	0.012	0.25	0.94	0.34	0.25	0.26	1.08	0.94

Table 2. Linear regression constants determined when using both the Fitts formulation and the Welford two-part formulation. Movement times were averaged over all participants. Actual movement amplitude A and actual target width W were used.

Performance was measured as the time taken to perform each individual click action. Timing began for each A and W pairing when the participant clicked the first target. Errors were measured as click events that occurred outside of the current target. The locations of each click were also recorded.

Hypotheses

We had the following hypotheses for our experiment.

H1 The Fitts formulation will not accurately model pointing performance at all gain levels.

H2 The Welford two-part formulation will accurately model pointing performance at each individual gain level.

H3 The exponent k will vary linearly with gain.

RESULTS

We were concerned with the possible impact of learning effects. Before our main analysis we performed a repeated measures ANOVA to determine if there was an effect of block. We found no effect of block on either movement time ($F_{2,36} = 0.943$, $p = 0.399$) or error rate ($F_{1.382,24.873} = 0.117$, $p = 0.814$, with a Greenhouse-Geisser correction for violation of sphericity). We therefore combined all of the blocks in our subsequent ANOVAs.

Movement Time

Significant main effects of gain, a, w were found. Significant interactions of $gain \times A$, $gain \times W$, and $A \times W$ were also found. Results are summarized in Table 1.

We performed a linear regression using data aggregated from all participants. Regression constants calculated using both a Fitts's model ($MT = a + b\log_2(2A/W)$) and Welford two-part formulation ($MT = a + b_1 logA - b_2 logW$) are shown in Table 2. In order to adjust for accuracy we performed a second analysis of the results, this time using effective target width (W_e), in the manner suggested by Soukoreff and MacKenzie [26]. These results are presented in Table 3.

	Fitts			Welford				
Gain	a	b	R^2	a	b_1	b_2	k	R^2
2	0.133	0.223	0.989	0.214	0.240	0.210	0.875	0.993
5	0.041	0.228	0.982	0.274	0.227	0.228	1.00	0.982
8	-0.002	0.241	0.973	0.358	0.229	0.260	1.14	0.978
12	-0.050	0.278	0.937	0.613	0.264	0.365	1.38	0.961
16	-0.028	0.292	0.910	0.985	0.273	0.457	1.67	0.970
20	0.013	0.314	0.891	1.275	0.290	0.529	1.82	0.975
2-20	-0.017	0.278	0.861	0.332	0.274	0.291	1.06	0.862

Table 3. Linear regression constants determined when using both the Fitts formulation and the Welford two-part formulation. Movement times were averaged over all participants. Actual movement amplitude A and effective target width W_e values were used.

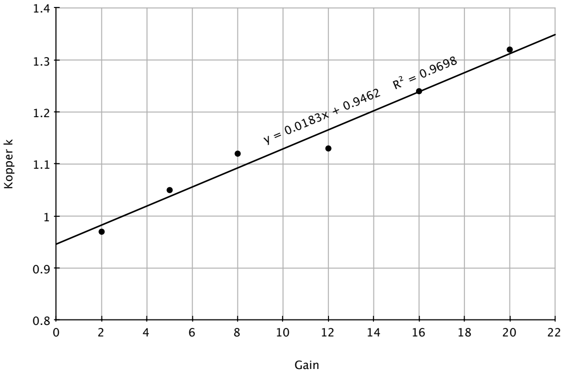

Figure 3. Actual movement amplitude A and actual target width W

To test the hypothesis that the exponent k will vary based on gain we performed a linear regression analysis on the exponent k computed for each gain level (Figure 3). The linear function of best fit was found to be $k = 0.95 + 0.018 \times gain$, with a fit of $R^2 = 0.97$. Because effective target width is often considered to be a better descriptor of performance for pointing tasks, we computed a second linear regression using effective target width instead of actual targe width (Figure 4). The linear function of best fit was found to be $k = 0.735 + 0.055 \times gain$, with a fit of $R^2 = 0.99$

Although k conveniently captures the *relative* contributions of A and W on performance, it can still be useful to investigate the *individual* contributions of A and W to movement time. Towards this goal we examined how both b_1 and b_2 from the Welford formulation varied with gain. These results are shown in Fig. 5 and Fig. 6. What is revealed is that as gain changes b_2 varies much more than does b_1.

Error Rate

Mean error rates were found to be XXX. An ANOVA found significant main effects of $gain$, A, and W. The interaction

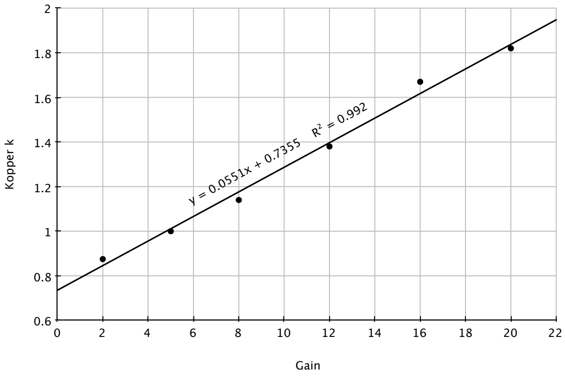

Figure 4. Exponent k values for Experiment 2.

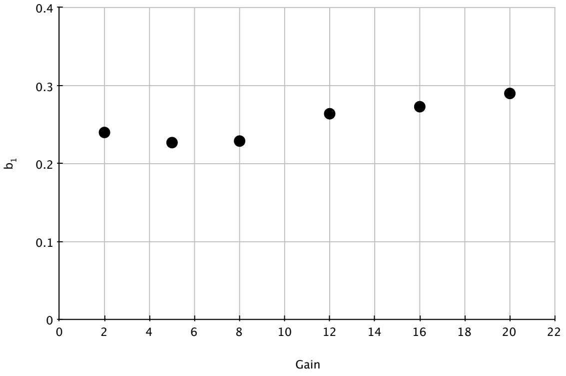

Figure 5. Dependence of b_1 on gain.

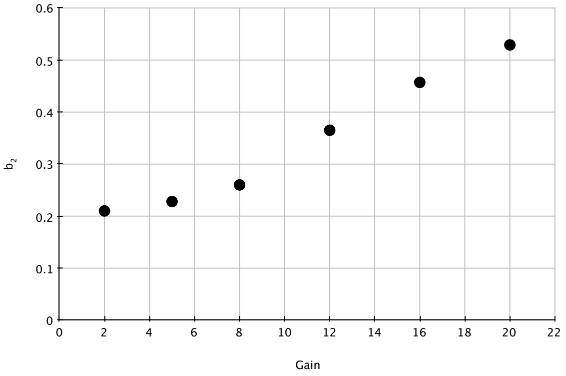

Figure 6. Dependence of b_2 on gain.

Factor	F-ratio	Significance	Partial η^2
gain	$F_{2.9,52.8} = 28.5^*$	$p < 0.001$	0.613
a	$F_{2,36} = 13.6$	$p < 0.001$	0.431
w	$F_{1.4,24.3} = 96.0^*$	$p < 0.001$	0.842
gain×w	$F_{4.2,75.8} = 16.6^*$	$p < 0.001$	0.480

*A Greenhouse-Geisser correction was applied.

Table 4. Significant ANOVA results for error rate in Experiment 2.

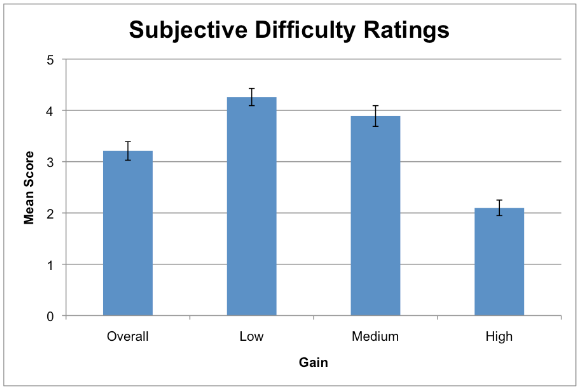

Figure 7. Mean scores of task difficulty overall, at low (2, 5), medium (8, 12) and high (16, 20) gain levels, with standard error. Ratings on a scale of one (impossible) to five (easy). N=19

of $gain \times W$ was also significant. Results are summarized in Table 4.

Subjective Measures

A summary of results from participants' subjective ratings of the difficulty of the task is shown in Figure 7. A Friedman test comparing ratings for low (2, 5), medium (8, 12) and high gain levels (16, 20) showed a significant effect of gain on difficulty ($\chi^2_{(2,N=19)} = 30.958, p < 0.001$). Pairwise comparisons using a Wilcoxon Signed Ranks Test showed significant differences between high and low gains ($z = -3.882, p < 0.001$) and between high and medium gains ($z = -3.882, p < 0.001$).

DISCUSSION

We summarize our results according to our hypotheses:

H1 The Fitts formulation will not accurately model pointing performance at all gain levels. *Somewhat supported.*

H2 The Welford two-part formulation will accurately model pointing performance at each individual gain level. *Supported.*

H3 The exponent k will vary linearly with gain. *Supported.*

The Fitts one-part formulation of pointing performance had mixed success in characterizing pointing performance. It seemed to work when target width was used in the analysis, but not nearly so well when effective target width was used.

Using actual W values, Fitts's law gave linear fits ranging in accuracy from a low of $R^2 = 0.964$ to $R^2 = 0.991$ at different levels of gain. For the levels of gain examined these R^2 values are good, surpassing the somewhat arbitrary 0.9 threshold. However, it is clear that the R^2 values decrease as gain increases.

Using effective W, Fitts's law was less successful. Linear fits in this case range from a high of $R^2 = 0.989$ to a low of $R^2 = 0.861$ at different levels of gain, failing to produce acceptable linear fits at some levels of gain.

It is these results that are perhaps most interesting because Soukoreff and Mackenzie [26] suggest that adjusted for accuracy effective target width results are representative of the task actually performed by the user. The reason for the good fits using actual W and the poor fits using effective W is evident from Figures 3 and 4. It is clear that the slope of the dependence of k on gain is much lower for actual target width than for effective target width. Thus, k does not deviate nearly as much from unity for the actual target width analysis as it does for effective target width analysis.

We thus conclude that hypothesis **H1** is somewhat supported. The results were as expected, however in the case of the actual target width analysis the contributions of A and W to performance did not differ enough to result in a poor fit using the original Fitts formulation, at least in the range of gains examined. There is more support for the hypothesis when target effective target width is used.

In sharp contrast to the Fitts one-part formulation, the Welford two-part formulation of pointing performance produced a good fit at each level of gain for both actual target widths and effective target widths. Linear regressions for actual target widths ranged from a low of $R^2 = 0.982$ to a high of $R^2 = 0.992$. For effective target width linear regressions ranged from a low of $R^2 = 0.961$ to a high of $R^2 = 0.993$. Thus, hypothesis **H2** is supported. It is worth noting that Welford's model did not produce a good fit when all data at all levels of gain were analyzed together ($R^2 = 0.862$). This suggests that, even when using Welford's model, each level of gain should be modelled separately.

Exponent k values were observed to vary linearly with gain, supporting hypothesis **H3**. For actual target width results, the k values followed a linear model to an accuracy of $R^2 = 0.970$. For the effective target width results, the k values followed a linear model to an accuracy of $R^2 = 0.992$. Interestingly, the slopes for the two sets of results were noticeably different, with k varying more in the effective target width set of data. The intercept of the slope at $gain = 0$ was also noticeably different, although $gain = 0$ may be meaningless in an interactive setting, suggesting that the intercept might not be of much relevance.

CONCLUSIONS

Fitts's law has been widely used as a tool for analyzing the performance of pointing tasks on computer systems, both for forming predictive models and for determining performance as characterized by throughput. Over the years Fitts's law has become so entrenched that researchers rarely ever question the fundamental assumptions underlying Fitts's law, most significantly whether or not there are limitations to its applicability to modelling pointing on interactive displays where the control-display gain may differ significantly from unity.

Data of our own experiment provide a theoretical model of mid-air pointing on a very large wall display that is more accurate than a standard Fitts's law explanation.

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