Fitts' Law with a Virtual Reality Glove and a Mouse: Effects of Gain

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Abstract

The effects of gain on target acquisition using the classic Fitts' law paradigm with a mouse and a virtual reality glove were tested. The mouse was significantly faster and had significantly lower error rates. For both devices, increased gain decreased movement times. Errors and movement times increased for both devices as the index of difficulty increased. Target entries were found to be significantly higher for the mouse. A model is proposed whereby gain has an inverse multiplicative effect upon Fitts' index of difficulty. The model accounts for 81% of the mouse's variance and 48% of the glove's variance. The lower number for the glove shows that Fitts' law has difficulties predicting its performance. The glove appeared not to operate at Fitts' law's predictions when gain was greater than one. The implications for the design of cyberspaces are discussed.

Résumé

Les conséquences du changement de vitesse de réaction du pointeur pour accéder à un objet cible ont été testées par le biais d'une souris et d'un gant électronique, conformément à un modèle respectant la loi de Fitts. La souris s'est avérée non seulement plus rapide que le gant, mais a également généré beaucoup moins d'erreurs. L'essai de ces deux types de dispositifs a confirmé qu'une vitesse de réaction supérieure diminue la durée du mouvement de l'opérateur. En outre, le taux d'erreurs et la durée du mouvement augmentent avec le niveau de difficulté. Néanmoins, la souris a continué à être plus précise que le gant. Nous proposons donc une formule mathématique démontrant qu'augmenter la vitesse de réaction du pointeur produit un effet multiplicatif inverse sur l'index de difficulté de Fitts. Cette formule tient compte de 81% de la variance de la souris et de 48% de celle du gant. Le pourcentage inférieur du gant indique que la loi de Fitts n'est peut-être pas le meilleur modèle pour évaluer la performance de ce dispositif. Lorsque le facteur de vitesse de réaction du pointeur excède 1, les prédictions de la loi de Fitts sont irrégulières. Les résultats de cette expérience intéresseront certainement les concepteurs d'espaces de réalité virtuelle.

Keywords: virtual reality, Fitts' law, gain, glove, mouse

Introduction

In the areas of human factors and human motor behavior one of the most studied relationships is Fitts' law [6]. This law predicts that the movement time (MT) to acquire a target is logarithmically related to the distance, or amplitude, of the move (A) and the target width (W). Mathematically, this relationship was derived from Shannon's Theorem 17 which expresses the effective information capacity of a communications channel [14, 20]. Fitts' law can be expressed as:

$$MT = a + b \log_2(2A/W) \quad (1)$$

where *a* (the intercept) and *b* (the slope) are empirical constants determined through linear regression. As amplitude increases it takes longer to move to a target. Similarly, as target width becomes smaller it also takes longer to strike a target. Thus, to measure the difficulty of a task scenario mathematically, Fitts defined an "index of difficulty" (ID) as:

$$ID = \log_2(2A/W) \quad (2)$$

ID is a simple number measured in bits that allows Fitts' law to be restated as:

$$MT = a + b\, ID \quad (3)$$

The unit for the slope is time/bit. The reciprocal of the slope is bits/second, an index of channel capacity. Thus, the slope measures channel capacity for the movement generating system [12]. Fitts described this movement generating system relationship as the "index of performance" (IP), which is defined as:

$$IP = -1/t \log_2(W/2A) = 1/b \quad (4)$$

where t is the average time in seconds per movement. Welford [21] proposed a modification to Fitts' law that generally provides a better fit to observed data of:

$$MT = a + b \log_2(A/W + 0.5) \quad (5)$$

However, by using an exact adaptation of Shannon's theorem, one can obtain an even better fit of empirical data and always get a positive ID using a further modification proposed by MacKenzie [14]:

$$MT = a + b \log_2(A/W + 1) \quad (6)$$

Using equations (1) or (5) produce a negative ID when the A:W ratio drops below 1:2. A negative index is theoretically unsound and diminishes some of the potential benefits of a model [15].

Fitts' law has no term present for the gain of a device. This suggests that changing the gain of the device should not improve its performance [9]. This was presumed since a device like the mouse has finite resolution (typically between 100 to 400 dpi). Jellinek and Card [9] stated that increasing the gain could prove detrimental to the mouse's performance because of quantization effects. Gain is defined as the amount of cursor movement on the display in response to a unit amount of movement of the control [1]. For example, if the mouse is moved one inch and in return the cursor moves three inches, the gain is three. Systems in which small inputs are magnified to produce large outputs are economical regarding effort -- yet not without cost. With such systems initial target acquisition may be rapid, but oscillation around the target will result since small corrections are magnified therefore "steadying time" will be prolonged [22]. The alternate strategy of approaching the target at a slow constant rate is time consuming [18].

Fitts' law has no term for gain since it was originally developed for direct pointing -- not indirect pointing. Similarly, Fitts' law has no term for the weight of the input device. Is there a connection between Fitts' use of a one ounce and a one pound stylus and gain? It would seem that gain and the weight of the stylus would have similar effects upon movement time and proportion of errors. In direct pointing the control and the display are inseparable. When using indirect pointing and the gain is doubled, the same force on the controller will produce twice the movement of the cursor relative to the initial gain. For direct pointing when the weight of the stylus is increased more force will be required to make an equal sized movement. Another similarity of gain to stylus weight is that as gain decreases and stylus weight increases target acquisition errors increase. Finally, as gain and stylus weight decrease time to initially enter the target decreases.

Studies involving manipulation of gains have yielded a variety of results. Most positioning experiments [8, 9, 11] find that movement time increases as gain increases (from zero to ∞). These studies have found no main effect for gain for zero-order controls (a zero-order system has no integrations between input and output; position input produces position output as an example). However, Buck [3] found movement time to decrease as gain increased with an isotonic controller (joystick).

Although, a gain term is absent from Fitts' law, it is still an important design variable. Optimal, or nearly optimal performance can be obtained across a wide range of gain values, particularly for zero-order control devices [22] Since it is impossible to minimize travel time and adjustment time with the same control-display ratio, one should instead minimize the sum of these two times by selecting a gain that is a compromise between optimal travel and adjustment times [12]. An "optimal" gain must be determined individually for different control-display combinations by taking into account the task, hardware, etc.

The purpose of the present experiment was to examine the performance of two continuous movement devices: a virtual reality glove (namely, the Mattel PowerGlove Nintendo game controller) and a mouse. The present study is similar to experiment number one conducted by Jellinek and Card [9] in that amplitude, target width, and gain were all manipulated. It differs from the Jellinek and Card [9] study in that the present study contained only one target, and target selection errors were not permitted. This experiment is similar to studies performed by MacKenzie et al. [16] and MacKenzie and Buxton [17], differing in the devices used, the manipulation of gain and not permitting target selection errors.

Method

Subjects

Eighteen right-handed subjects served as volunteers. None were familiar with the Mattel PowerGlove Nintendo game controller nor a mouse and all had little or no experience with computers.

Apparatus

Two input devices, a standard Apple mouse and a Mattel PowerGlove ultrasonic Nintendo game controller, connected to an Apple Macintosh IIci through a Transfinite Systems Gold Brick (model 1, release 2) served as the apparatus.

The Mattel PowerGlove ultrasonic Nintendo controller senses the X, Y, Z location and three axes of rotary orientation of one's hand. The output display was a 13 inch color CRT (used in monochrome) with a resolution of 640 by 480 pixels.

Software for the PowerGlove controller was included with the Gold Brick hardware that permitted variations in the gain for that device. The experiment was conducted using Apple's system software version 7.0.1. Additionally, the Kensington Turbo Mouse 4.01 control panel was used to achieve the various values of gain for the mouse.

The stimuli were presented on the computer screen and the data were collected using the HyperCard application (version 2.1). Timing from HyperCard was collected in 1/60 second and was converted to milliseconds. HyperCard's timing was verified with a separate program that determined that other programs were not interfering with HyperCard's ability to record accurate times.

Procedure

PowerGlove: Subjects were seated facing the computer with the Mattel PowerGlove ultrasonic Nintendo game controller on their right hand. Subjects bent the first finger on their right hand to indicate when the user had selected a target.

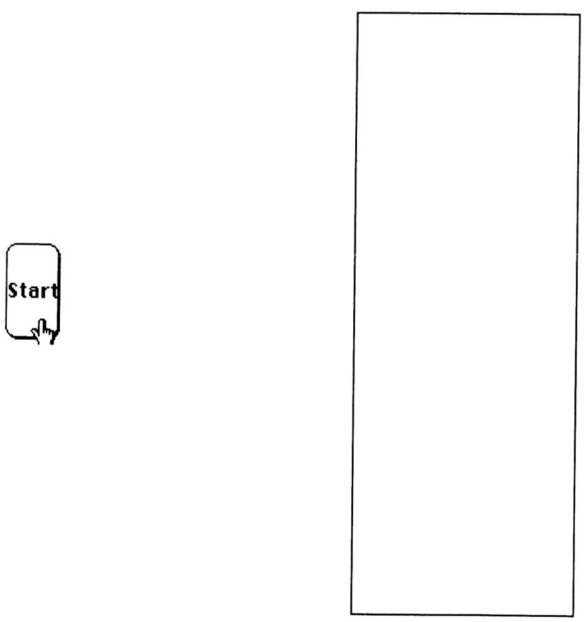

Figure 1. Sample experimental condition.

A START button appeared on the left-hand side of the screen, centered vertically. The subject first positioned the cursor over the START button. Then the subject selected the START button (by bending their first finger) which caused a rectangular bar to appear at a designated amplitude toward the right side of the screen (see Figure 1). The subject then moved the cursor from the START button to the rectangular bar and bent their first finger. Once correctly selected, the rectangular bar disappeared and they selected the START button again to initiate the next trial. Subjects were allowed to take breaks between trials, as needed.

Mouse: The procedure for the mouse was identical to the PowerGlove device except that subjects initiated a trial by pressing the mouse button over the START button, then moved the cursor to the rectangular bar and clicked the mouse button again once the target was reached. As with the PowerGlove, once the target bar was correctly selected it disappeared and subjects selected the START button again to continue onto the next trial.

Design

A fully within-subjects repeated measures design was used. Both input devices used three target amplitudes (distance from the starting point to the center of the target) (A = 2, 4, and 8 inches) fully crossed with three target widths (W = 1/2, 1, and 2 inches) and with three gain values (1, 2, and 3). Target height was kept constant at 6".

The independent factor of device type was also within-subjects. Ordering of the devices was counterbalanced.

The first dependent variable was task completion time. Task completion time was recorded with the three components below:

1. <u>reaction time (RT):</u> time from when the target appeared until the subject began moving the cursor
2. <u>movement time (MT):</u> time from first cursor movement until the cursor first entered the target area
3. <u>final acquisition time (AT):</u> time from first entry of the target by the cursor until the subject correctly selected the target

Subjects were prevented from making errors in the selection of the target -- they had to continue each trial until they successfully selected the target. Errors are defined as responses that did not strike the target. This procedure was more realistic and did not detract from the time analyses because the individual components were recorded. The second dependent measure was the number of errors per trial. Since subjects were required to successfully complete each trial, the multiple errors that were possible per trial were collected. In line with the number of errors being collected, the third dependent variable was the number of times, per trial, that a subject entered the target. The more entries into the target before confirmation, the more difficult the target selection was considered.

Before beginning to use a device, subjects were given one block of 81 warm-up trials. A block consisted of a random presentation of each of the nine A-W combinations each being given nine times. Following the practice block there were three blocks of 81 trials administered. Each block was given under a different, and counterbalanced, gain setting. Short breaks were allowed between sessions. Subjects completed all four blocks in a single sitting. On the subsequent day, each subject completed one practice and three other blocks for the remaining input device.

Results and Discussion

Movement Times

The mouse mean task completion times appear in Table 1.

	ID					
Gain	1	2	3	4	5	Mean
1	501	638	925	1164	1531	935
2	461	530	697	852	1082	711
3	483	540	685	805	979	690
Mean	482	570	769	940	1197	778

Table 1. Mean mouse task completion times (in ms.).

Comparative data from the glove is contained in Table 2. As with the mouse data, the glove data displays task completion times that increase with increasing ID's and decrease with increasing gains.

	ID					
Gain	1	2	3	4	5	Mean
1	1642	2289	3310	4242	5520	3350
2	1391	2044	2670	3470	3798	2692
3	1420	1888	2515	3081	3934	2537
Mean	1484	2074	2831	3598	4417	2860

Table 2. Mean glove task completion times (in ms.).

A within-subjects ANOVA with repeated measures (using task completion time for the dependent measure) for device, gain, amplitude, and width was conducted. Significant main effects for device $F(1,17) = 99.64$, $p < .0001$, gain, $F(2,34) = 11.98$, $p < .001$, amplitude, $F(2,34) = 510.0$, $p < .0001$, and width, $F(2,34) = 26.24$, $p < .0001$, were found. A significant interaction between device and amplitude, $F(2,34) = 182.00$, $p < .0001$, was found. This interaction is evident by task completion times increasing for the glove versus the mouse and for both devices as target amplitude increased. This shows that both the glove consumed more time as did larger amplitudes upon both input devices. The significant two-way interaction of device and width was, $F(2,34) = 8.38$, $p < .01$. Again, this interaction is portrayed by task completion times increasing for the glove over the mouse and for both devices as target width decreased. Thereby, subjects using the glove took longer as did smaller target widths. The interaction between gain and amplitude was also significant, $F(4,68) = 25.71$, $p < .0001$. In this interaction as gain increased and amplitude increased, there was an increase in task completion time. Additionally, the interaction between gain and width was found to be significant, $F(4,68) = 3.34$, $p < .05$. Here this interaction demonstrates that decreases in both gain and target width yielded an increased task completion time. The three-way interaction between device, gain, and amplitude was significant, $F(4,68) = 5.05$, $p < .01$. Verbally this interaction can be delineated as decreases in gain combined with increases in amplitude caused increased task completion times with the glove having higher task completion times than the mouse. Finally, the three-way interaction of device, gain, and width was significant, $F(4,68) = 3.32$, $p < .05$. This interaction can be described as decreased gain and target width resulted in increased task completion times with the glove having higher task completion times than did the mouse. There were no other significant interactions found.

Selection Errors

The mean error rates for the mouse appear in Table 3.

	ID					
Gain	1	2	3	4	5	Mean
1	3.1%	8.0%	9.5%	9.3%	12.4%	8.7%
2	0.6%	4.6%	4.7%	7.1%	7.4%	5.1%
3	1.9%	4.6%	6.8%	6.5%	8.0%	5.8%
Mean	1.9%	5.8%	7.0%	7.6%	9.3%	6.5%

Table 3. Mean error rate percentages for the mouse.

Similarly, the error rate data for the glove appears in Table 4.

	ID					
Gain	1	2	3	4	5	Mean
1	16.1%	17.9%	31.5%	44.8%	43.2%	31.0%
2	11.1%	21.6%	29.0%	37.7%	31.5%	27.6%
3	12.4%	16.4%	28.0%	36.7%	46.3%	27.6%
Mean	13.2%	18.6%	29.5%	39.7%	40.3%	28.7%

Table 4. Mean error rate percentages for the glove.

For both devices the errors increase as ID increases. It is important to realize that subjects were not permitted to complete a trial until they successfully selected the target. Thus, the data also reflects cases where more than one error was made per trial. This viewpoint gives one a truer look at the data -- rather than coding each trial as an error or as error-free. Indeed, the magnitude of the errors rose for the glove and with gain increases.

A within-subjects ANOVA with repeated measures (using target selection errors as the dependent variable) for device, gain, amplitude, and width was performed. Significant main effects for device, $F(1,17) = 19.98, p < .001$, amplitude, $F(2,34) = 8.52, p < .01$, and width, $F(2,34) = 17.36, p < .0001$, were found. A significant interaction between device and amplitude, $F(2,34) = 8.54, p < .001$, was also found. This interaction is evident by target selection errors increasing for the glove over the mouse and for both devices as target amplitude increased. This indicates that the glove took longer as did larger amplitudes upon both input devices. Finally, a significant interaction between device and width, $F(2,34) = 11.70, p < .001$, was discovered. Again, this interaction is portrayed by target selection errors increasing for the glove over the mouse and for both devices as target width decreased. Thereby, subjects using the glove took longer as did smaller target widths. There were no other significant main effects or interactions.

Target Entries

The mean number of target entries for the mouse are shown in Table 5.

	ID					
Gain	1	2	3	4	5	Mean
1	1.02	1.04	1.05	1.02	1.04	1.04
2	1.04	1.08	1.10	1.07	1.07	1.08
3	1.09	1.15	1.10	1.12	1.14	1.11
Mean	1.08	1.08	1.08	1.06	1.09	1.08

Table 5. Mean number of target entries for the mouse.

For comparison, equivalent data for the glove are displayed in Table 6. Both tables containing information on the number of target entries display a trend of increasing entries as gain increases.

	ID					
Gain	1	2	3	4	5	Mean
1	1.00	1.00	1.01	1.01	1.01	1.01
2	1.00	1.01	1.02	1.03	1.03	1.02
3	1.00	1.00	1.02	1.01	1.01	1.02
Mean	1.00	1.00	1.02	1.02	1.02	1.01

Table 6. Mean number of target entries for the glove.

A within-subjects ANOVA with repeated measures was not possible for target entries since there was insufficient variance in this dependent measure to conduct such an analysis. In order to assess differences in the mean number of target entries for the glove and the mouse by subject, the data was collapsed across amplitude, gain, and width. A Wilcoxon signed ranks test on this data was found to be significant, $p < .001$. This test is the same as conducting a repeated measures ANOVA testing for a main effect of device type.

Fit of the Models

A goal of this experiment was to compare the performance of Fitt's information processing model and two of its variations. Since the MacKenzie [14] formulation,

$$MT = a + b \log_2(A/W + 1) \quad (6)$$

always provided the best fit to the data it will be the sole formula discussed and displayed in the following tables.

Table 7 displays the results of linear regression analyses whereby equations are classified according to device type and gain. Note since gain is not accounted for in these equations that the correlations decrease as gain increases. The index of performance increases with increases in gain.

Device	Gain	Model (times in ms.)	r^2
Mouse	1	$TCT=140 + 333 \log_2(A/W + 1)$	0.83
Mouse	2	$TCT=232 + 202 \log_2(A/W + 1)$	0.80
Mouse	3	$TCT=304 + 162 \log_2(A/W + 1)$	0.76
Glove	1	$TCT=363 + 1245 \log_2(A/W + 1)$	0.67
Glove	2	$TCT=746 + 791 \log_2(A/W + 1)$	0.31
Glove	3	$TCT=621 + 798 \log_2(A/W + 1)$	0.36

Table 7. Results of linear regression analyses.

As a result of the degradation of fit following gain increases an extensive effort was made to develop a new formula that incorporated a term for gain. The best predictive formula was:

$$TCT = a + b \log_2((A/W) * (1/GAIN) + 1) \quad (7)$$

where TCT equals task completion time (RT + MT + AT). After linear regression analyses were conducted using this new equation the results are shown in Table 8. For a comparison, MacKenzie's formula (with no term for gain) is also shown. Thereby, it is evident that this new formula provides improved data predictability.

Device	Model (times in ms.)	r^2
Mouse	TCT=285+274 $\log_2$((A/W) * (1/Gain)+1)	0.81
Mouse	TCT=225+232 $\log_2$(A/W+1)	0.65
Glove	TCT=911+1065 $\log_2$((A/W)*(1/Gain)+1)	0.48
Glove	TCT=577+944 $\log_2$(A/W+1)	0.42

Table 8. Results of linear regression analyses using gain equation.

Conclusions

The mouse was found to be superior (faster) to the virtual reality glove. The reaction time component was insignificant between devices. The mouse continues to be the best input device (as measured with a Fitts' law task). This finding is consistent with past research [4, 5, 10, 17]. The mouse has been found to be equal to the human arm performing the reciprocal tapping task [4].

The mouse has the advantage of a mouse pad and table top, upon which one is able to rest one's arm. Input devices such as a glove or touch screen lack such a method for reducing arm fatigue [13, 19]. Since the glove was very light weight and the cord length was adequate for the task -- neither of those design aspects are believed to account for the significantly poor performance of the glove. Another possible solution to this problem is to have a number of different control devices and be able to choose any of them [1]. For, as much as working on a two-dimensional screen requires a mouse, working in three-dimensional cyberspaces requires some type of three-dimensional input device.

The adherence of the glove input device to Fitts' law was found (within certain gain parameters). However, the indices of performance were always highest for the mouse. The performance indices rose across both devices as gain increased. Overall, IP for the mouse ranged from 3.0 to 6.2 bits/sec, somewhat less than the values reported by Card et al. [4], but comparable to other studies' values. The glove's IP's ranged from 0.8 to 1.3 bits/sec -- very low as compared to input devices from other studies. These low IP values and the low linear regression r^2 values at gains of two and three depict a deterioration of Fitts' laws ability to predict the gloves performance.

Therefore, it is believed that the glove doesn't operate at Fitts' law at gains greater than one and in reality gain is always one. The glove was designed to act like a natural extension of one's hand. Conversely, the mouse was invented as an input device with no real world referents. Yet, subjects have no difficulty acclimating to, and improving their performance with the mouse as gain increases. The mouse is an alien attachment to the human body while the outward appearance of the glove shows it as a more natural extension. However, with real world interactions with one's hand always being at a gain of one a person may have difficulty adjusting to one's arm (or any glove-like attachment) moving at gains greater than one. This unnatural movement may catch us by surprise, and an individual may require practice to adjust to the benefits of changes in gain.

With the arrival of the computer and its various input devices one can adjust gain to a myriad of values. These advances suggest that Fitts' law should be updated to reflect this gain factor. Using data gathered from this experiment the following formula was found to be a good predictor of movement time data where gain was altered:

$$TCT = a + b \log_2((A/W) * (1/GAIN) + 1) \quad (7)$$

Collapsing the data across gain surfaced the fact that MacKenzie's formula had difficulty with the glove (especially at gains greater than one). In terms of the mouse (which was found to conform to Fitts' law at all gains) the added term for gain greatly enhanced the fit to the data. The inverted gain multiplier term is a logical addition to the MacKenzie formula. At gains of one the formula becomes no different from the original formula. This is appropriate since original models did not consider a gain factor and operated at a constant gain of one. As gain increases task completion time was found to decrease (this finding is discussed later). The inverted gain term decreases task completion time in a manner proportional to the gain term.

While this study broke new ground in testing a virtual reality input device and developing a formula accounting for gain, it also demonstrated the classic results of a one dimensional reciprocal tapping task. With both input devices each of the dependent measures (task completion time, number of selection errors, and the number of target entries) increased as ID increased. Trials having the largest amplitude and smallest width were the most difficult (as measured by all the dependent variables).

The other variable of gain had a very significant effect upon most of the collected components of task completion time but gain had no effect upon reaction times. Obviously humans should be unable to change their reaction times with changes in gain. This study's significant effect of gain, whereby performance increased as gain increased, is contrary to other research findings [1, 8, 9, 11]. However, it is consistent with Buck's [3] Fitts' law experiments using joysticks under gain manipulations. Subjects were able to adjust to the increased gains by utilizing them and reducing their movement times without compromising accuracy. It is interesting that the speed improvement from a gain of one to a gain of two was show to be greater than from the gain of two to the gain of three. This suggests that performance may peak at some higher gain value.

Errors increased for the higher ID's and for the glove. These results parallel research findings of Arnaut and Greenstein [1] who conducted a Fitts' law experiment varying gain on a touch tablet. They found a significant effect of gain and target size (a function of target width) upon the dependent measure of errors. The glove performed worse in terms of both errors and times. This result reiterates the inferiority of the glove in direct comparison to the mouse. As the difficulty increased (higher ID values) both input devices showed increased error rates. This result, is expected since as ID increases, errors should also increase.

The number of target entries was higher for the mouse. Additionally, these target entries were predicted to increase as ID increased. Gain was not predicted to have a significant effect upon target entries. These last two predictions were not tested since there was insufficient variance in the number of target entries to conduct these analyses. However, the trends of the data did show that target entries increased with gain increases. This trend was also found for target entries increasing as ID increased. These findings too, are similar to those of Arnaut and Greenstein [1]. Their research showed target entries increased as they increased gain and target size. Since the glove was a novel input device it was believed that this new interaction method might force subjects to enter the target area a minimum number of times. Although all subjects were unfamiliar with both input devices there was more of a novelty to the glove than the mouse. This appears to have lead subjects to be more cautious in their responses and resulted in both positive and negative results for the glove. On the positive side, their caution yielded fewer entries and overshoots of the targets while using the glove. In contradiction, their caution lead to higher task completion times and more target undershoots (error component) for the glove.

Subjects erred more often with the glove by clicking more frequently where there was no target. However, once subjects reached a target while using the glove they were more apt to stay in the target's confines until they "clicked" to successfully complete a trial. Mouse users may have developed a false sense of security with their mastery of that input device and thus found themselves overshooting the target, thereby forcing themselves to re-enter the target. On the contrary the glove users predominantly undershot the target and made more selection errors.

This present study presented a new variation of Fitts' law showing a strong multiplicative effect between the inverse of gain and the index of difficulty. The model explains 81% of the variance in mouse trials however, prediction for the glove dropped to 48%. Both values proved better than the standard Fitts' law equations (as modified by MacKenzie, [14]). Future experiments can evaluate the ability of this new formula to predict pointing tasks' movement times involving gain changes. The current finding of subjects not adapting well to the glove nor to the higher gain values would be unacceptable performance in an actual virtual reality application. One advantage of virtual reality would be making gain values that allow one to accomplish tasks more rapidly than in the real world's gain of one. A major component of the delivery of such a virtual reality system would be attained by overcoming the limitations of current virtual reality input (and output) devices. Certainly, the road will be paved with ineffectual and primitive devices that will quickly be replaced with better ideas, more sophisticated designs, and more advanced technologies [2].

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