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The Application of Fitts' Law to the Research and Development of Assistive Technology: A Brief Examination on Relevant Intervening Variables

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ABSTRACT

This study aimed to examine three intervening variables (i.e., muscular trait, limb mobilization, and device weight) which were supposed to have influence on the prediction of Fitts' law. The researcher sampled 46 college students from the Special Education Department of National Taitung University and treated them with three experiments. The results manifested as follows:

1. Muscular trait and limb mobilization could be viewed as the intervening variables which affected the prediction of Fitts' law.
2. For muscular trait, the body action of operating assistive aids should fit its demanded muscular trait, namely, the operation in need of gross (fine) muscles should better be performed by gross (fine) muscles.
3. As to limb mobilization, the users' conditions of physical disability could affect their own performances of operating assistive aids, thus emphasized the concept of universal design in the production of assistive devices.
4. Muscular trait and limb mobilization were both not the major factors of typewriting errors. For the subjects' opinions, the major factor affecting the typewriting errors was supposed to be the subjects' keyboard familiarity.
5. Device weight, as the data shown in this study, revealed not robust enough to be an intervening variable for Fitts' law.

Keywords: Fitts' Law, Intervening Variables, Assistive Technology

INTRODUCTION

1. Background

Human factors, also called "ergonomics" in Europe, initiated since World War I in Britain (Shackel & Richardson, 1991), has increasingly played a more essential role in the research and development of assistive technology (AT). Of all these human factors principles, Fitts' law, developed in 1954, is supposed to be the most famous and important theorem which, based on time and distance, enables the prediction of human movement and human motion based on rapid, aimed movement, not drawing or writing (Fitts' Law Group, 1996). Fitts' law was pretty important for the research and development of assistive technology. Thus, it's quite essential for the engineers and the users of assistive technology to recognize the mathematical rationale and application potential of Fitts' law (King, 1999). Fitts' law applies only to the kinds of motions we make when we are using most human-machine interfaces (Raskin, 2000). And it has described that movement time could be the function of distance and target width (King, 1999). Thus, Fitts' law affords to explain, for example, why it is much faster to move the cursor to an Apple Macintosh-style menu that is on the edge of a display than to a Microsoft Windows-style menu that floats away from an edge (Raskin, 2000). According to the fundamental rationale of Fitts' law, the further a target is from the user's current position or the smaller the target is, the longer it will take the user to move the cursor to the target (Raskin, 2000; Washburn, 1996). In its simplest, most elegant mathematical form, Fitts' law is expressed as

$$MT = a + b \bullet \log_2(\frac{2D}{W})$$

wherein:

MT = movement time of any given control site (body part) from initiation of movement to touching the targeted activation site (switch or control surface).

a and b = empirically derived constants.

D = the distance of control site movement from start to center of the targeted activation site.

W = the width of the targeted switch or control activation site (King, 1999).

The application of Fitts' law to real human-machine interface has been shown valid and able to predict and describe relationships in human interactions with switches and controls (Kantowitz & Sorkin, 1983). Fitts' law is an effective method of modeling rapid, aimed movements, where one appendage (like a hand) starts at rest at a specific start position, and moves to rest within a target area, but there still are specific situations, however, in which Fitts' law cannot be easily applied, such as

(1)Multi-dimensional target acquisition tasks. Fitts' law is one-dimensional, so his interpretation of target width cannot be used.

(2)Unequal measures of performance index for similar devices. Another problem arises when researchers attempt to use equations predicted by Fitts' law for various input devices. Different index of performance (IP) measures have been found for the same input device. The problem arises as to which value should be used (Fitts' Law Group, 1996).

For the potential deficiencies of Fitts' law, revised equations were therefore developed. Meyer's law, for example, corrected Fitts' law into the simplified form

$$T = A + B \bullet \sqrt{\frac{D}{W}}$$

wherein:

T = movement time,

D = distance,

W = target width,

A and B = empirical constants (Meyer, Abrams, Kornblum, Wright, & Smith, 1988)。

Nevertheless, most human factors theorems were derived from non-handicapped subjects, the potential deficiencies of these theorems might then manifest when it is applied to the development and research of assistive technology. Besides, the disability conditions of handicapped people, which could be viewed as potential intervening variables, are also supposed to alter the prediction of Fitts' law. What variables could intervene then? And how do they influence the prediction of Fitts' law? To find out the answers, the researcher performed a brief examination on three hypothesized intervening variables.

2. Goals

Focused on three potential intervening variables, muscular trait, device weight, and limb mobilization, this study aimed to examine if there were significant differences between various conditions while the width and distance of targeted button were controlled as constants. Three hypotheses were given as follows:

(1) The movement time of Fitts' law can be affected significantly by various muscular traits (e.g., gross versus fine muscles).

(2) The movement time of Fitts' law can be affected significantly by various limb mobilizations (e.g., handicapped versus non-handicapped hands).

(3) The movement time of Fitts' law can be affected significantly by various device weights (e.g., original device weight versus those plus weight appendixes).

3. Definition of Terms

(1) Muscular Trait

The body sites which controlled the assistive devices (e.g., mouthsticks and headsticks) were categorized into two major muscular traits, namely, gross muscles and fine muscles.

(2) Limb Mobilization

Limb mobilization in this study was defined as two conditions, namely, handicapped hands (simulated by restricted hands) versus non-handicapped hands (simulated by non-restricted hands). For simulating handicapped hands, both hands of the subjects were bound and restricted by keyboard wrist rests, thus their hands could just move horizontally, not vertically.

(3) Device Weight

Different assistive devices manufactured with various materials differed from each other in weights. To simulate such differences, the researcher used 10-NT-dollar coins as weight appendixes to increase the device weights, and by doing so to explore the effects of various device weights on both typewriting time and typewriting errors.

LITERATURE REVIEW

Human disability and aging are perceived as two major reasons why people need assistive technology. For human disability, a common misconception is that the population is small. Although there are many different types of disabilities, some of which represent smaller number of individuals, cumulatively people with disabilities represent around a fifth of the population (Vanderheiden, 1997). On the other hand for human aging, as far as the developed world is concerned, one of the strongest trends is towards older societies

(Coleman, 2001). By the year 2000, the World Bank estimated that 20% of the population in countries with market economies will be over 60 years of age (Worden, Walker, Bharat, & Hudson, 1997). Approximately 72% of those who live beyond age 75 will have functional limitations, and 41% of them will have severe functional limitations (Kraus & Stoddard, 1989). These functional limitations caused by human disability and aging could then become barriers reducing people's performance in daily lives and thus make them need assistive technologies. Almost all of the consumer base will have employees with disabilities (Vanderheiden, 1997). Some argued that disability is the inability to accommodate poor design (Caplan, 1992), so from this perspective disability is a consequence, not a condition (Vanderheiden, 1997). Thus, if Fitts' law is employed for the research and development of assistive technology, the researchers or the developers should not ignore the intervening variables which could be derived from human disability and aging and finally alter the prediction of Fitts' law in return. For our clinical observations, three potential intervening variables, listed as follows, are considered extremely essential.

(1) Muscular Trait

The muscular trait mainly related with the resolution of movement effectors. As described by Cook & Hussey (2002), 'resolution' is used to define the degree of fine control, and it describes the smallest separation between two objects that the effector can reliably control. Namely, the higher resolution between two switches, the better fine control that we need. All the components of effector use contribute to the generation of high-resolution fine movements, so that the effector resolutions could be listed, form high to low, in such a sequence: fingers (high resolution), eyes (high), hand (moderate), head (moderate), foot (moderate), arm (low), and leg (low) (Cook & Hussey, 2002). The human control sites with different effector resolutions could be generally classified into two categories of muscular trait, namely, fine muscles and gross muscles. When the interaction between a person with a disability and an assistive device involves relatively fine control, the hand and the fingers are the preferred control site because they are typically used for manipulative tasks (Cook & Hussey, 2002). But the users might encounter the disabilities in the upper extremity. If the hand is not controllable, the use of the head as an interface site is preferred; with pointers of various types as control enhancers (e.g., a head pointer), it is possible to obtain relatively precise control using the head (Cook & Hussey, 2002).

(2) Limb Mobilization

The human operator controls the assistive technology through his various effectors, and they enable manipulation of the environment in a variety of ways, but the presence of disability dramatically alters the use of effectors (Cook & Hussey, 2002). This is why human factors play an important role in the design of supportive products and environments, because human factors are defined as systematic approaches to improving the fit between the user and the environment (Jones, 2002). As we know, two primary factors underlying the use of effectors are automatic movements and muscle tone (Cook & Hussey, 2002). The performance of limb mobilization is closely related with muscle tone. Muscle tone varies with ages, level of activity, stress, and other factors. As we age, the amount of tone generally decreases for many reasons, including changes in muscle fibers, sensory receptors, and central nervous system (CNS) function (Farber, 1991). On the other hand, the function of effector movements, reflecting in limb mobilization, could be defined in resolution, range, strength, endurance, and versatility for an anatomical site (Cook & Hussey, 2002). Trauma or diseases to the CNS that results in abnormal muscle tone, the presence of primitive reflexes, or abnormal righting or equilibrium reactions affect the individual's ability to maintain a stable upright posture and perform smooth, coordinated movements, so as to affect the handicapped users' operation performance of assistive devices. Thus, the physical agility, namely, the limb mobilization, also affects the use of assistive devices, and might therefore alter the prediction of Fitts' law.

(3) Device Weight

As shown in Baker's Basic Ergonomic Equation (BBEE), AT success occurs if the upper part of the equation, user motivation, exceeds the sum of all of the load or effort factors in the lower part of the equation (King, 1999).

$$\frac{Motivation\ \ of\ \ AT\ \ User\ \ to\ \ Pursue\ \ and\ \ Complete\ \ a\ \ Given\ \ Task}{Physical\ \ Effort + Cognitive\ \ Effort + Linguistic\ \ Effort + Time\ \ Load} = Successful\ \ AT\ \ Use$$

Thus, physical effort, related with the device weight, has been considered as an important human factor in AT design. Besides, according to the 6th principle of "universal design", low physical effort, the design can be used efficiently and comfortably and with minimal fatigue if fitting the following guidelines:

A.Allow the user to maintain a neutral body position.

B.Use reasonable operating forces.

C.Minimize repetitive actions.

D.Minimize sustained physical effort (The Center for Universal Design, 1996).

All the above four guidelines focus altogether on the same factor, namely, device weight, which could increase the users' load and finally reduce the possibility of AT success in return. Thus, device weight should be viewed as an essential factor in AT design and human factors, since one AT item made with various materials may differ from each other in device weights. Being the most famous and important theorem in human factors, Fitts' law predicts the consequence of human operation, but which might be altered by the variable of device weight.

METHOD

1.Design

As shown in Figure 1, the independent variables involved in this study were muscular trait, limb mobilization, and device weight, and the dependent variables including total typewriting time and typewriting errors.

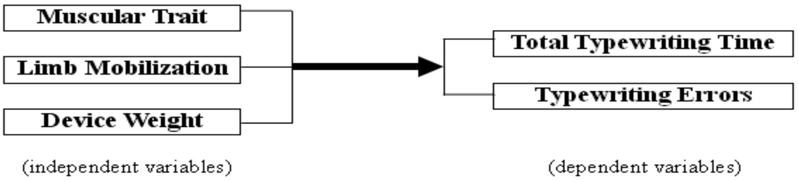

Figure 1. Research Design

2. Instruments

The instruments employed in this study are listed as follows:

(1) Headstick: The headstick (Model No.IOU016) this study employed was manufactured by Assistive Technology Engineering Lab.

(2) Mouthstick: The mouthstick (Model No. 5376-01-09) this study employed was manufactured by Ever Prosperous Instrument, INC.

(3) Keyboard Wrist Rest: The keyboard wrist rest (Flagship Version) this study employed was manufactured by T. C. Star Electronic Co., LTD.

(4) Weight Appendix: The researcher used 10-NT-dollar coins as the weight appendixes to increase the weights of both headsticks and mouthsticks, so as to simulate different materials (reflecting in different device weights) of assistive aids.

(5) Personal Computer: The personal computers employed in this study were packed up with components including Pentium 586 CPU, 30 GB of hard disk, standard 104-keyboard, standard mouse, LCD monitor, and the operating system of Windows XP.

3. Subjects

In order to prevent inter-variable interferences from the influence of the variable 'disability', the researcher recruited 46 non-handicapped college students (aged 18-19, 6 males and 40 females) from the Special Education Department of National Taitung University.

4. Data Analysis

The data were analyzed respectively by *t*-test, chi square, or one-way ANOVA, and the statistical significance level was set at $\alpha = .05$. The statistical software used in this study was SPSS-version 10.0.

5. Procedure

The subjects used headsticks, mouthsticks, or keyboard wrist rests, respectively according to the experimental manipulations designed in light of three independent variables, to typewrite the alphabets from A to Z, so as to measure typewriting time and errors. The experiment schedule was sequenced in three sections: (1) muscular trait, (2) limb mobilization, and (3) device weight. For counter-balance design, the subjects were divided into seven experiment groups. These seven groups executed their own experiments with mutually different sequences, so as to prevent from the interferences with similar experimental sequences. The interval between every two experimental sections was controlled more than one month at least in order to eliminate mutual interferences.

RESULTS

1. Statistics

(1) Muscular Trait

The total time and the errors of typewriting alphabets with various muscular traits (i.e., headstick for gross muscles versus mouthstick for fine muscles) revealed significant differences (see Table 1), wherein the subjects spent more time in typewriting by headstick (M=38.56) than that by mouthstick (M=35.21). As shown in Table 1, the chi square results revealed no significant differences among typewriting errors made by gross and fine muscles.

Table 1. The tests of typewriting time and errors among gross and fine muscles

	Headstick	Mouthstick	df	N	Comparison
Total typewriting time	38.56	35.21	45	46	t = 2.85**
Typewriting errors	107	97	1	46	χ^2 = .49

** p<.01

(2) Limb Mobilization

The total time and the errors of typewriting alphabets with various limb mobilizations of control part (i.e., non-restricted hands simulated as non-handicapped hands versus restricted hands simulated as handicapped hands) revealed significant differences (see Table 2), wherein the total typewriting time spent by handicapped hands (M=15.22) was more than that by non-handicapped hands (M=13.99). As shown in Table 2, the chi square results revealed no significant differences among typewriting errors made by handicapped and non-handicapped hands.

Table 2. The tests of typewriting time and errors among handicapped and non-handicapped hands

	Handicapped hands	Non-handicapped hands	df	N	Comparison
Total typewriting time	15.22	13.99	43	44	t = -2.61*
Typewriting errors	12	17	1	44	χ^2 = .86

* p<.05

(3) Device Weight

A. Total typewriting time

The total time of typewriting alphabets with various headstick weights (i.e., a single headstick weight plus 0~5 coins, whereas 7.443 grams per coin in average) presented in Table 3.

Table 3. The *t*-test of typewriting time between various headstick weights (N=43)

t value	+0 coin	+1 coin	+2 coins	+3 coins	+4 coins
+1 coin	2.53*				
+2 coins	2.34*	.06			
+3 coins	2.49*	.41	.41		
+4 coins	2.44*	.05	.02	-.42	
+5 coins	2.66*	.46	.53	.21	.92

*p<.05

The total time of typewriting alphabets with various mouthstick weights (i.e., a single mouthstick weight plus 0~5 coins, whereas 7.443 grams per coin in average) presented in Table 4.

Table 4. The *t*-test of typewriting time between various mouthstick weights (N=43)

t value	+0 coin	+1 coin	+2 coins	+3 coins	+4 coins
+1 coin	2.19*				
+2 coins	1.30	-.21			
+3 coins	2.77**	1.24	1.17		
+4 coins	3.17**	1.64	1.52	.49	
+5 coins	1.66	.26	.40	-.84	-2.29*

**p*<.05 ***p*<.01

B. Typewriting errors

The errors of typewriting alphabets with various headstick weights (i.e., a single headstick weight plus 0~5 coins respectively, whereas 7.443 grams per coin in average) presented in Table 5.

Table 5. The χ^2 test of typewriting errors between various headstick weights (N=43)

χ^2 value	+0 coin	+1 coin	+2 coins	+3 coins	+4 coins
+1 coin	.20				
+2 coins	.56	.09			
+3 coins	.82	.21	.03		
+4 coins	2.04	.97	.47	.27	
+5 coins	.33	.02	.03	.11	.74

The errors of typewriting alphabets with various mouthstick weights (i.e., a single mouthstick weight plus 0~5 coins respectively, whereas 7.443 grams per coin in average) presented in Table 6.

Table 6. The χ^2 test of typewriting errors between various mouthstick weights (N=43)

χ^2 value	+0 coin	+1 coin	+2 coins	+3 coins	+4 coins
+1 coin	2.15				
+2 coins	.72	.39			
+3 coins	1.52	.06	.15		
+4 coins	3.91*	.27	1.31	.57	
+5 coins	4.06*	.31	1.40	.63	.0001

**p*<.05

2. Discussions

(1) Muscular Trait

The headstick spent significantly more time in typewriting than the mouthstick did, namely, fine muscles controlled the assistive devices to typewrite faster than gross muscles, but errors made by these two kinds of muscular traits revealed no significant differences. Basically, typewriting was a certain kind of fine control, and was supposed to be performed better by fine muscles. On the contrary, it would take more time in typewriting by gross muscles. Thus, the movement time (MT) mentioned in Fitts' law was obviously altered by various muscular traits while distance (D) and target width (W) being simultaneously kept constant. Besides, as the data shown in this section, muscular trait couldn't be viewed as the major factor of typewriting errors. For the opinions collected from the interviews with all subjects, the major factor affecting typewriting errors was the subjects' keyboard familiarity.

(2) Limb Mobilization

The restricted hands spent significantly more time in typewriting than the non-restricted hands did, namely, non-handicapped hands controlled the assistive devices faster than the restricted hands, but errors made by these two kinds of hands revealed no significant differences. Thus, the MT mentioned in Fitts' law was obviously altered by various limb mobilizations while D and W were simultaneously kept constant. Also, as the data shown in this section, limb mobilization couldn't be viewed as the major factor of typewriting errors. Like the discussion above, the major factor affecting typewriting errors was the subjects' keyboard familiarity.

(3) Device Weight

The data shown in this section were so fuzzy and obscure that 'device weight' couldn't be viewed as a significant intervening variable for Fitts' law. The researcher interviewed and discussed with all subjects in order to figure out the possible reasons, which were inferred as follows:

Reason 1: Unequal weight per coin

In order to confirm the subjects' inference, the researcher randomly weighed ten 10-NT-dollar coins with an electronic scale, and finally obtained the data as 7.42, 7.31, 7.47, 7.42, 7.72, 7.30, 7.50, 7.47, 7.44, and 7.38, wherein the average weight was 7.443 grams per coin. The weight differences between every two coins ranged from .01 (=7.31-7.30) to .42 (=7.72-7.30) grams, so that unequal weight per coin really existed. In this study, the subjects were divided into seven groups, but each group didn't use the same 10-NT-dollar coins of equal weight. Therefore, the maximum appendix weight differences (i.e., the original device weight plus five additional coins) these seven groups encountered maybe ranged from .05 to 2.10 grams, which seemed weighty enough to exaggerate the experimental errors.

Reason 2: Fatigue factor

The subjects entirely manipulated three sections of experiment in this study, and 'device weight' was scheduled to be the third section. Having already been fatigued in the earlier two sections, the subjects had to perform 15 more typewriting measurements respectively for mouthstick and headstick, with totally up to 30 measurements in the third section. The fatigue factor could easily happen in the third section.

CONCLUSIONS

1. Major Findings

(1) The subjects with various functional levels in muscular trait and limb mobilization revealed significant differences in total typewriting time, so that muscular trait and limb mobilization could be viewed as the intervening variables which could affect the prediction of Fitts' law.

(2) For muscular trait, the body action of operating assistive aids should fit its demanded muscular trait, namely, the operation in need of gross (fine) muscles should better be performed by gross (fine) muscles.

(3) As to limb mobilization, the users' conditions of physical disability could alter their own performances of operating assistive aids, thus emphasized the concept of universal design in the production of assistive devices.

(4) Muscular trait and limb mobilization were both not the major factors of typewriting errors. For the subjects' opinions, the major factor affecting the typewriting errors was supposed to be the subjects' keyboard familiarity.

(5) Device weight, as the data shown in this study, revealed not robust enough to be an intervening variable for Fitts' law.

2. Suggestions

(1) Different functional levels of muscular traits could influence the performance of operating assistive aids. In assistive technology, some operations originally based on fine muscles were alternatively operated by gross muscles, simply because of the users' functional limitations. But the performance qualities among find and gross muscles are essentially different. Some foot-manipulated steering wheels, for example, were adapted for the special needs of people with functional limitations in upper extremities, but the muscular traits of upper and lower extremities differ from each other. Basically, the hand is more versatile than the foot, and the higher the versatility, the more options provided for the use of the effector to control an assistive device (Cook & Hussey, 2002). Thus, it could make a lower level of driving security while the actions originally based on both fine and gross muscles alternatively employing gross muscles instead. To solve this problem, some additional designs (e.g., fatigue reduction, slip-proof interface, and motor assistance) must be considered as well.

(2) Different functional levels of limb mobilizations could also affect the performance of using assistive aids, so that handicapped and non-handicapped hands couldn't make equal performance level with the same device. Thus, the concept of universal design, advocated by The North Carolina State University Center for Universal Design, was highly emphasized in the research and development of assistive technology (The Center for Universal Design, 1996). The researcher strongly suggested that, in next amendment of Taiwan's Special Education Act, it should be extremely important to push the legislation of universal design and to enforce its application to all market products.

(3) For the sake of inappropriate weight control in appendices (coins) and unpredicted fatigue factor happened in this study, device weight, in the future study, should be confirmed again, as so to make sure if it is really robust enough to be an intervening variable of Fitts' law. All subject groups in the future study should better use the same coins of equal weights during the entire experiment course in order to improve the weight control of appendices.

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費慈定理在輔助科技研發之應用：相關中介變項之初探

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摘要

本研究旨在探討足以影響費慈定理之預測結果的三個中介變項，此即：肌肉特性、肢體靈活度、以及設備重量。研究者抽取 46 位國立台東大學特殊教育系學生進行三項實驗。其結果如下：

1.肌肉特性與肢體靈活度可視為影響費慈定理之預測結果的中介變項。

2.就肌肉特性而言，操作輔具之動作特性應配合其所需之肌肉特性，亦即：屬於大（小）肌肉之操作動作宜以相對應之大（小）肌肉為之。

3.就肢體靈活度而言，使用者之肢體障礙狀態可影響其操作輔具之表現，此突顯生產輔具之通用設計概念的重要性。

4.肌肉特性與肢體靈活度並非為影響打字錯誤之主要因素，依據受試者之見解：其主要因素應為受試者之鍵盤熟悉度。

5.本研究結果並無法支持輔具之設備重量可視為費慈定理之中介變項。

關鍵詞：費慈定理、中介變項、輔助性科技