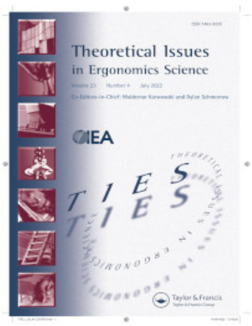

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Pinaki Chakraborty & Savita Yadav

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REVIEW

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Applicability of Fitts' law to interaction with touchscreen: review of experimental results

Pinaki Chakraborty and Savita Yadav

Department of Computer Science and Engineering, Netaji Subhas University of Technology, New Delhi, India

ABSTRACT

Fitts' law models human psychomotor behaviour and can be used to predict the time required to complete a movement task. Although originally proposed for physical apparatus, Fitts' law has been adopted to study how human beings use various computer input devices to perform onscreen pointing tasks. Touchscreens are now used in smartphones, tablets and other digital devices. The applicability of Fitts' law to the interaction with touchscreen has been studied for both stationary computers and mobile devices. Researchers have been studying this problem for about forty years, but the body of work remains small and there is no consensus on whether Fitts' law is valid for touch-based interaction. This paper reviews studies reporting positive-, null- and negative results on the applicability of Fitts' law to interaction with touchscreen and proposing modifications to Fitts' law especially for modelling interaction with touchscreen.

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Fitts' law; touchscreen; onscreen target acquisition; smartphone; tablet

Relevance to human factors/ergonomics theory

Touchscreen devices like tablets and smartphones are now used by a large number of people on a daily basis and hence quantitative studies on interaction with touchscreen are of interest to software developers. Fitts' law is a well known model in ergonomics for predicting the time required to complete a movement task. Several researchers have conducted experiments to ascertain the applicability of Fitts' law to interaction with touchscreen. This paper summarizes their results and comments on how their findings can help in designing software for touchscreen devices.

> Many pointing devices are available for use with computers, but none are as natural to use as the touchscreen. – Sears and Shneiderman (1991)

1. Introduction

Human-computer interaction is the science of how human beings interact with computers and other digital devices. Computers are highly sophisticated devices and used for an extremely wide range of purposes. Therefore, interaction between human beings and

CONTACT Pinaki Chakraborty pinaki_chakraborty_163@yahoo.com Department of Computer Science and Engineering, Netaji Subhas University of Technology, New Delhi, 110078, India

computers should be open ended just like interaction between human beings. The objective of human–computer interaction is to develop hardware and software that can help human beings to interact more effectively with computers. To fulfil this objective, it is necessary to study how human beings work in natural settings and understand their physical and cognitive capabilities. It is necessary to identify the skills required by human beings to solve various tasks using computer. It is highly beneficial when measures of human capability are developed. Modelling human behaviour and predicting human performance mathematically can help in planning interactions of human beings with computers. Well-planned interactions between human beings and computers improve the usability, and in turn the usefulness, of computer-based systems (Karray et al. 2008).

Fitts' law is a model of human psychomotor behaviour (MacKenzie 1992) developed with a cross-disciplinary analogy to information theory. The law quantifies the difficulty of movement tasks using an index that is measured in bits. When human beings complete such movement tasks in measurable duration of time, the throughput is expressed in bits/s.

Fitts' law is widely used in human–computer interaction to model interaction of human beings with different types of input device. The law is typically used to predict the time required by human beings for completing various onscreen movement tasks, and this prior knowledge can help in designing friendlier user interface.

Tablets and smartphones became popular in the 2000s. These devices have hardware and operating system similar to those of computers and can execute application software like computers do. They are typically less expensive and easier to carry than computers. Tablets and smartphones have a touchscreen which acts as their primary input and output device. Touch-based interaction is often easier than using other input devices (Gustafsson et al. 2018). Consequently, many people who have little or no experience of using computer can use tablets and smartphones with ease (Haan, Lugtig, and Toepoel 2019). Touchscreen plays a crucial role in increasing the usability of tablets and smartphones (Kostyrka-Allchorne, Cooper, and

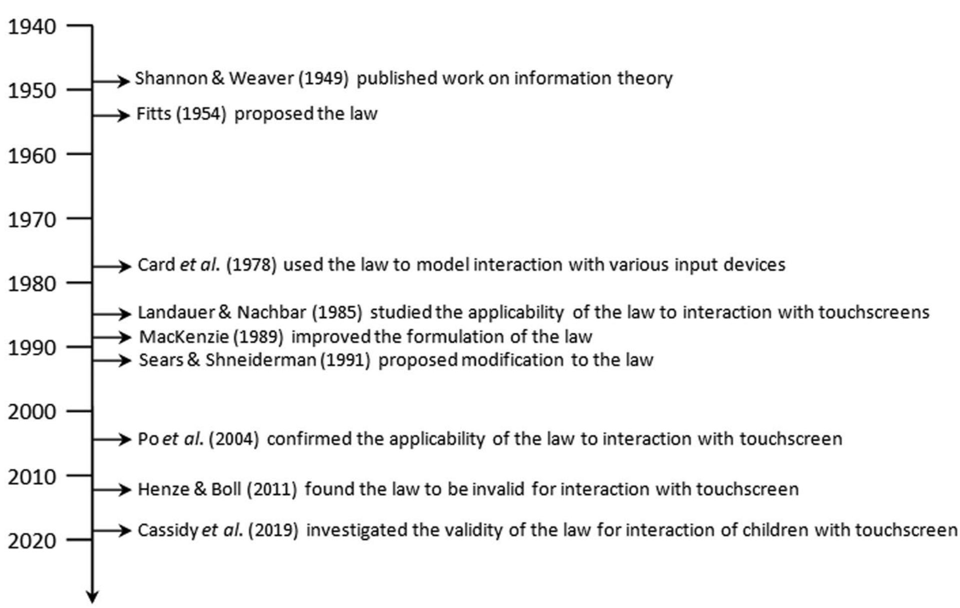

Figure 1. Timeline of research on the applicability of Fitts' law to interaction with touchscreen.

Simpson 2017). Touchscreens were developed long ago but became common only with such mobile devices (Lovato and Waxman 2016).

The statement by Sears and Shneiderman (1991) quoted at the beginning of this paper holds true even after more than thirty years, and this is something rare in computer science. Touchscreen devices are now used by a majority of people in the world. Application programs are specially developed for such devices. So, it is necessary to understand how people interact with touchscreen and, more specifically, if their interaction with touchscreen follows Fitts' law. Researchers have been investigating the validity of Fitts' law for interaction with touchscreen since the 1980s (Figure 1). Several researchers have demonstrated the applicability of Fitts' law to interaction with touchscreen, while at least two studies have found otherwise. Researchers have also proposed modifications to Fitts' law especially for touchscreen. This paper reviews the work done so far on the applicability of Fitts' law to interaction of human beings with touchscreen. Studies reporting positive-, null- and negative results and proposing modifications have been included in this review. Given the importance of the problem, the volume of work done so far on the applicability of Fitts' law to interaction with touchscreen is small. We hope that this paper will attract more researchers to investigate interaction of human beings with touchscreen devices.

2. Fitts' thesis

Fitts was strongly influenced by information theory especially the then recent work of Shannon and Weaver (1949). Fitts (1954) wanted to extend information theory to the human motor system. He designed movement tasks in which a subject has to perform repetitive back and forth movement over a distance A to acquire targets of width W. Apart from the motor system, the movement tasks involved the visual and proprioceptive feedback loops that enabled the subject to monitor her/his own activities. Fitts defined index of difficulty of a movement task as follows:

$$I_d = -log_2 \frac{W}{2A} \tag{1}$$

I_d is measured in bits. Further, Fitts defined index of performance of a movement task completed in t time as follows:

$$I_p = -\frac{1}{t} log_2 \frac{W}{2A} \tag{2}$$

I_p is measured in bits/s. From Equations (1) and (2), I_p can also be written as follows:

$$I_p = \frac{I_d}{t} \tag{3}$$

Fitts hypothesised that I_p to be constant for a movement task for a wide range of values of A and W. In terms of information theory, the channel capacity of the motor system for a particular movement task is expected to be independent of A and W. He conducted three experiments with different movement tasks to validate the hypothesis.

2.1. Fitts' first experiment

In the first experiment, Fitts studied the performance of sixteen subjects in a reciprocal tapping task. The subjects were made to sit in front of a purpose-designed apparatus and perform the task one at a time. The apparatus consisted of two identical metal plates and the subjects were asked to tap on them alternately with a metal-tipped stylus (Figure 2a). The subjects were made to perform the task for sixteen different combinations of width of the plates (W) and distance between the plates (A). Plates of width $\frac{1}{4}$ inch, $\frac{1}{2}$ inch, 1 inch and 2 inches were used in the experiment.[1] The distance between the plates, measured between their centre, was varied among 2 inches, 4 inches, 8 inches and 16 inches. The length of all the plates used in the experiment was 6 inches. Further, the task was repeated with two styli weighing 1 ounce (=28.35 grams) and 1 pound (=453.59 grams). Each trial was of 15 seconds during which the subjects had to tap on the plates as many times they could. The number of times they could tap on the plates was recorded and the average time between two successive taps and the index of performance were calculated for each combination of width of the plates, distance between them and weight of the stylus. The task primarily involved movement of the lower arm of the subjects.

2.2. Fitts' second experiment

In the second experiment, Fitts studied the performance of another sixteen subjects in a task to transfer small plastic discs pegged on one pin to another pin (Figure 2b). The pins

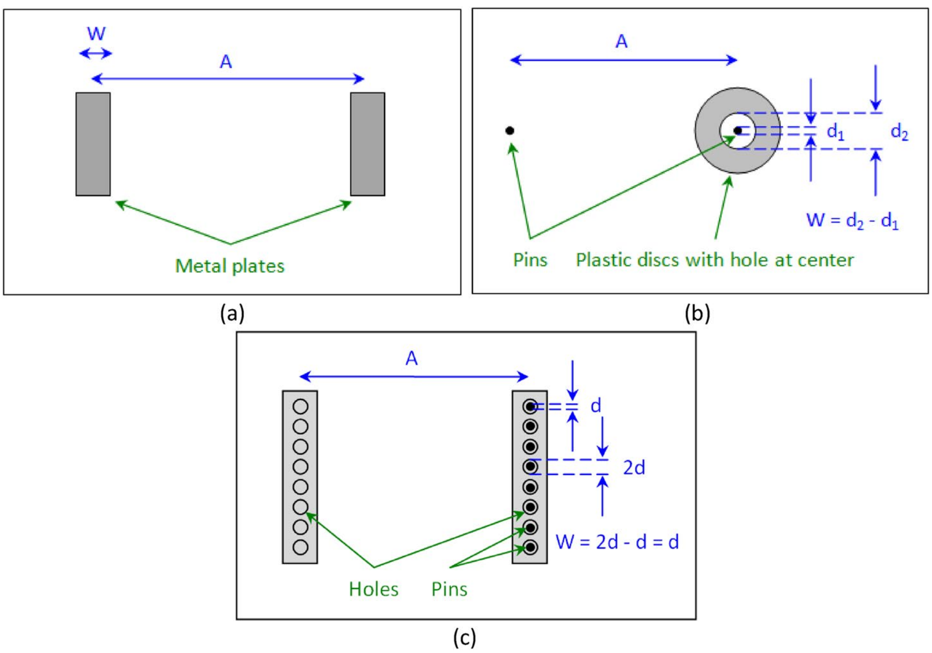

Figure 2. Simplified schematic diagram of Fitts' experiments. (a) In the first experiment, a subject had to alternately tap with a stylus on two metal plates of width W separated by a distance A. (b) In the second experiment, a subject had to transfer eight discs with a hole of diameter d_2 at the centre from a pin of diameter d_1 to another similar pin at a distance A. (c) In the third experiment, a subject had to transfer eight pins of diameter d from one set of holes with diameter $2d$ to another set of similar holes at a distance A.

used in the experiment had a diameter of $\frac{1}{8}$ inch. The distance between the pins (A) was varied among 4 inches, 8 inches, 16 inches and 32 inches. The discs used in the experiment had a diameter of 1.5 inches and thickness of $\frac{1}{8}$ inch. A hole was drilled at the centre of each disc. The difference between the diameter of the pins and the diameter of the hole at the centre of the disc (W) was varied among $\frac{1}{2}$ inch, $\frac{1}{4}$ inch, $\frac{1}{8}$ inch and $\frac{1}{16}$ inch. The subjects were asked to transfer eight discs with hole of the same diameter at the centre from one pin to another one at a time. The time taken to transfer the discs was noted and the index of performance was calculated for all the sixteen combinations of distance between the pins and difference between the diameters of the pins and the hole at the centre of the discs. The task involved movement of the lower arm and some finger activity of the subjects.

2.3. Fitts' third experiment

In the third experiment, Fitts studied the performance of twenty subjects in transferring pins from one set of holes to another set of holes (Figure 2c). The diameter of the pins was varied among $\frac{1}{4}$ inch, $\frac{1}{8}$ inch, $\frac{1}{16}$ inch and $\frac{1}{32}$ inch. The diameter of the holes was twice that of the corresponding pins. The difference between the diameters of the pins and the holes was considered as W. The distance between the holes from where the pins had to be picked up and the holes where the pins had to be released (A) was varied among 1 inch, 2 inches, 4 inches, 8 inches and 16 inches. The subjects had to transfer eight identical pins from one set of holes to another set of holes one at a time and then transfer them back to their original position again one at a time. The time taken to transfer the pins was noted and the index of performance was calculated for all the twenty combinations of distance between the holes and diameter of the pins. The task involved movement of the lower arm and substantial finger activity of the subjects.

2.4. Validation of Fitts' thesis

The movement task used in the three experiments was different and 16 to 20 combinations of values of A and W were used in each experiment. Although I_p was not precisely constant in any of the experiments, the variation in the same was low (Table 1). This validated Fitts' hypothesis.

Equation (3) can be rewritten as follows:

$$t = \frac{I_d}{I_p} \tag{4}$$

Since I_p can be assumed to be constant for a movement task, the time required to complete the task is expected to be proportional to I_d. Over the years, researchers have used

Table 1. Number of combinations of A and W used in the three experiments by Fitts.

	Number of values of A	Number of values of W	Number of values of I_d	Range of I_p
First experiment	4	4	4×4=16	5.56–11.54 bits/s (for the lighter stylus) 5.49–10.99 bits/s (for the heavier stylus)
Second experiment	4	4	4×4=16	7.47–10.38 bits/s
Third experiment	5	4	5×4=20	8.92–12.57 bits/s

Equation (4) to predict the time required to complete various types of movement tasks by human beings. This linear relationship between the index of difficulty of a movement task and the time required to complete it is colloquially known as the Fitts' law.

Scientific laws are generally based on facts which are further developed using mathematical derivation and can be used to describe a range of phenomenon. Fitts' law differs slightly from other scientific laws. Fitts' law was not developed mathematically from facts related to human motor system but adopted from information theory. The similarities between information theory and human motor system are coincidental. This means that the applicability of Fitts' law to interaction between human beings and an apparatus can be verified experimentally only, and not theoretically.

3. Adoption in human–computer interaction

Card, English, and Burr (1978) were perhaps the first to adopt Fitts' law in computer science. They were influenced by two schools of thought. First, they appreciated the work done by English, Engelbart, and Berman (1967) and later researchers on measuring the mean pointing time for various input devices. Second, they realised the importance of studying the effects of the distance and width of targets in movement tasks as done by Fitts (1954).

Card, English, and Burr (1978) performed an experiment with four subjects and studied their performance in a text selection task using four different input devices, *viz.* mouse, joystick, step keys[2] and text keys.[3] The subjects were made to sit in front of a computer with a CRT display unit. The subjects were asked to select a portion of text on the screen using the different input devices. The distance from the starting position on the screen to the target (A) was varied among 1 cm, 2 cm, 4 cm, 8 cm and 16 cm. The length of the target text (W) was varied among 1, 2, 4 or 10 characters.[4] The time taken by the subjects to point the target text on the screen using the different devices was measured.

A movement task in the physical domain needs a subject to touch and manipulate targets with a limb. Alternatively, an onscreen movement task needs her/him to touch and manipulate an input device and the effect of the same is visible on the screen. Accordingly, Card, English, and Burr (1978) divided the time required to complete a movement task into two components as follows.

$$t = t_{hom} + t_{pos} \tag{5}$$

The time required by a subject to move her/his hand to the input device is called the homing time (t_{hom}) and the time required after that to move to the target text is called the positioning time (t_{pos}). Among the four input devices, the mouse had the maximum t_{hom} but minimum t_{pos} and t.

Card, English, and Burr (1978) found that the interaction of the subjects with the mouse and the joystick followed Fitts' law. Card, English, and Burr (1978) actually used a version of Fitts' law suggested by Welford (1968) as given below.

$$t_{pos} = K_0 + K log_2\left(\frac{A}{W} + 0.5\right) \tag{6}$$

Here, K_0 and K are constants. Card, English, and Burr (1978) could determine the values of K_0 and K for mouse and joystick, and thus verify the linear relationship between index of difficulty and positioning time. Additionally, with a value of K almost equal to 0.1 s/bits, the mouse was found to have nearly maximal information processing capability for an eye-hand guidance-based system. Card, English, and Burr (1978) remarked that mouse-based interaction is close to, but slightly slower than, finger-based interaction much before touch-screens became popular. It is also worth mentioning that t_{pos} was found to be proportional to the number of keystrokes required to complete the movement task for the step keys and text keys. Most importantly, Card, English, and Burr (1978) was able to introduce a theoretical justification to the assessment of performance of input devices.

4. Mackenzie's formulation

By the end of the 1980s, several versions of Fitts' law were in use. Although Fitts (1954) was influenced by information theory, his equation (Equation (2)) deviated from Shannon's Theorem 17 (MacKenzie 1989). MacKenzie (1989) tried to simplify and standardise the equations. He simplified Equation (1) as follows:

$$ID = log_2 \frac{2A}{W} \tag{7}$$

However, he advocated defining index of difficulty in line of Shannon's work as follows:

$$ID = log_2 \left(\frac{A}{W} + 1 \right) \tag{8}$$

Further, MacKenzie (1989) rewrote Fitts' law as follows:

$$MT = a + b\, ID \tag{9}$$

This was an interesting shift in the narrative with movement time (MT) being presented as a predicted variable in a slope-intercept formulation. The index of performance of a movement task could be calculated as $\frac{1}{b}$, but the value would be slightly different from that calculated using Equation (2) which has no intercept. MacKenzie (1991) compared three versions of Fitts' law, *viz.* an adaptation of Shannon's Theorem 17, Fitts' version and Welford's version, for modelling the interaction of subjects with three pointing devices, *viz.* mouse, touchpad[5] and trackball, and found that the three versions produced somewhat different results. Equation (9) has been used widely by later researchers as Fitts' law.

It may be noted that Fitts (1954) multiplied A by 2 in the definition of I_d in Equation (1) to ensure that I_d has a positive value for all conditions in his experiments. Several later researchers continued to use this adjustment and both Equations (7) and (8) continue to be in use to calculate index of difficulty. Equation (8) is also used in ISO standards (ISO 2000; ISO 2012).

5. Preliminary studies

Some researchers investigated the applicability of Fitts' law to interaction with touchscreen in the 1980s. Landauer and Nachbar (1985) conducted an experiment in which eight subjects were asked to select items from tree menus displayed on a touchscreen by touching at appropriate places on the screen with a finger. The time required by the subjects to select the desired items in the menus was found to be proportional to *log b* where *b* was the number of alternatives at each level of the menus. Landauer and Nachbar (1985) interpreted the results to be following Hick's law and Fitts' law simultaneously. However, they did not explicitly show the existence of a linear relationship between index of difficulty and movement time as expected in a study related to Fitts' law. Nevertheless, Landauer and Nachbar (1985) deserve credit for being the first to discuss the applicability of Fitts' law to interaction of human beings with touchscreen.

A few years later, Sears and Shneiderman (1991) conducted three experiments to compare the performance of a mouse and a touchscreen, and to determine how the use of stabilisation software can improve the performance of touchscreen. The first experiment is of our interest. In this experiment, thirty-six subjects were asked to select rectangular targets using a mouse and a touchscreen. The size of the targets (W) varied among 0.4 mm × 0.6 mm, 1.7 mm × 2.2 mm, 6.9 mm × 9.0 mm and 13.8 mm × 17.9 mm. Sears and Shneiderman (1991) observed that the subjects required lesser time to acquire targets of the three larger sizes when using the touchscreen than when using the mouse. For acquiring targets of the smallest size, i.e. 0.4 mm × 0.6 mm, the subjects required more time when using the touchscreen than when using the mouse. Further, it was observed that the time required by the subjects to acquire the targets decreased with their width for both mouse and touchscreen. However, Sears and Shneiderman (1991) could not precisely measure the distance from the current location to the target (A) and worked with only four target sizes. Consequently, the results were inconclusive to verify if Fitts' law is applicable to interaction of human beings with touchscreen.

6. Confirming studies

Several researchers could confirm the applicability of Fitts' law to interaction with touchscreens in the 2000s and 2010s. Po, Fisher, and Booth (2004) were the first to confirm the applicability of Fitts' law to interaction of human beings with touchscreens. They conducted an experiment with eight subjects. They used an LCD touchscreen of 136 cm × 102 cm size and 1024 × 768 pixel resolution. (We deduce that a pixel was of 0.13 cm.) The subjects were asked to acquire targets displayed on the screen using mouse and touch. The width of the targets (W) was varied among 1.04 cm, 2.08 cm, 4.16 cm and 8.32 cm. The distance of the targets from the starting position (A) was varied among 4.16 cm, 8.32 cm, 16.64 cm and 33.28 cm. Po, Fisher, and Booth (2004) observed that Fitts' law was valid, i.e. there existed a linear relationship between index of difficulty and movement time, for the interaction with both mouse and touchscreen. Po, Fisher, and Booth (2004) determined the slope and the intercept as in Equation (9) for the upper and lower visual fields separately for the two input devices.

Sasangohar, MacKenzie, and Scott (2009) emulated the Fitts' first experiment on a tabletop display with a touch-sensitive screen of 32 inches. They used 'plates' of four different widths (W) and four different values of distance between the plates (A). The index of difficulty varied from 1.00 bits to 6.02 bits. Twelve subjects participated in the study and were asked to 'tap' on the plates using mouse and touch-based interaction. Sasangohar, MacKenzie, and Scott (2009) observed a linear relationship between index of difficulty and movement time for both mouse and touch-based interaction. However, the movement time was significantly lower for touch-based interaction than for interaction with mouse.

In the 2010s, touchscreens became common in mobile devices and some researchers studied the applicability of Fitts' law to interaction with such devices. Ljubic, Glavinic, and Kukec (2015) conducted an experiment to check the validity of Fitts' law for interaction with the touchscreen of smartphones and tablets. They used four devices in the experiment with screen size varying from 3.27 inches to 10.10 inches. They studied three methods of target acquisition that are common among users of mobile devices, *viz*. single-handed thumb-based target acquisition with the device held in portrait orientation in the same hand, target acquisition using the index finger with the device held in portrait orientation in the other hand, and target acquisition using the index finger with the device held in landscape orientation in the other hand. They developed software to randomly generate targets with different combinations of width and distance from the starting position. The index of difficulty of the tasks varied from 1.0 bits to 5.5 bits. They performed the experiment with thirty-five subjects. Ljubic, Glavinic, and Kukec (2015) could establish a linear relationship between index of difficulty and movement time, and hence the validity of Fitts' law, for all devices and methods of target acquisition.

MacKenzie (2015) experimented with the applicability of Fitts' law to interaction of human beings with smartphones. He used a smartphone with screen size of 2.4 inches × 4.0 inches. He performed the experiment with four different values of distance between the targets (A) and two different values of width of the targets (W), and index of difficulty varying from 1.14 bits to 3.17 bits. Sixteen subjects participated in the experiment. MacKenzie (2015) performed the experiment for one-dimensional as well as two-dimensional arrangements of targets (Figure 3). In the one-dimensional variant, the subjects had to move back and forth horizontally to acquire the targets twenty times. Alternatively, in the two-dimensional variant, twenty targets were arranged in a circle and the subjects required selecting diametrically almost opposite targets successively. MacKenzie (2015) performed the experiment with the smartphone kept on the desktop and also with the subjects holding it in their non-dominant hand. He found that Fitts' law was valid for all combinations of the relevant factors. Movement time was significantly higher for the two-dimensional variant than for the one-dimensional variant. However, no significant difference in movement time was observed when the smartphone was kept on the desktop and when the subjects held it in their hand.

7. A repudiating study

Henze and Boll (2011) performed a crowd-supported experiment in which they developed and distributed an app that measured the time required to acquire onscreen targets. The app displayed targets of different size (W) and at different distance (A). The app was downloaded by people and installed on 63,154 smartphones of different specifications. The app allowed Henze and Boll (2011) to collect data at a much larger scale than other researchers. They observed that there was only a weak correlation between index of difficulty and movement time. They also did not find any strong correlation of D, W, $\log_2 D$ or $\log_2 \frac{1}{W}$ with movement time.

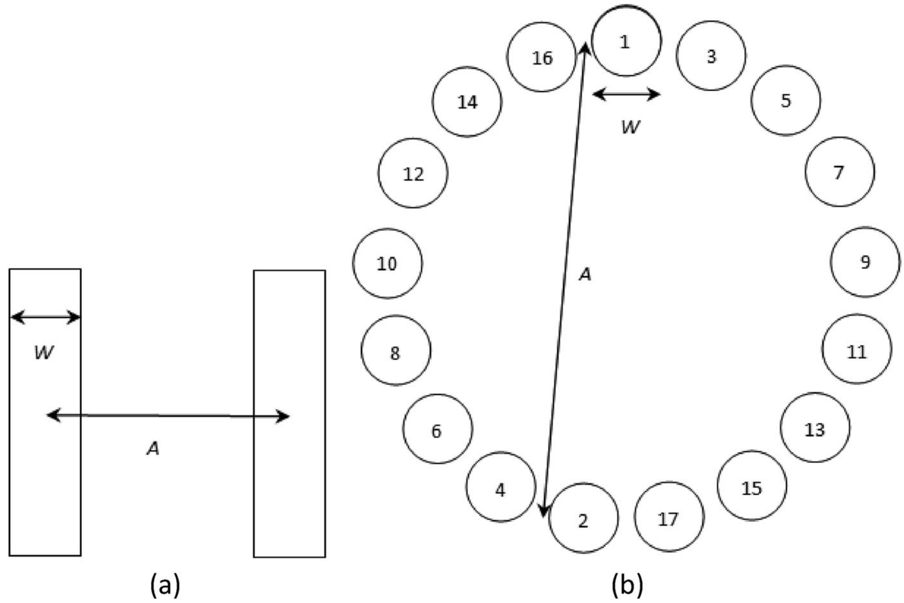

Figure 3. Typical layout of the targets in (a) one-dimensional and (b) two-dimensional arrangements for studying Fitts' law.

8. Studies on children

Children form the largest class of non-expert users of digital technologies and a few researchers have recently investigated if the interaction of children with touchscreen follows Fitts' law. Cassidy, Read, and MacKenzie (2019) performed an experiment with twenty-eight children aged eight and nine years. They used a tablet with a screen size of 7 inches. They used three different values of distance between the targets (A) and two different values of width of the targets (W), with index of difficulty varying from 1.34 bits to 3.41 bits. The subjects were asked to acquire fifteen targets arranged in a two-dimensional circular arrangement using drag and drop touchscreen gesture with a stylus and touch-based interaction. Cassidy, Read, and MacKenzie (2019) observed that the interaction of the children with the stylus and also their touch-based interaction obeyed Fitts' law. Further, the difference in movement time was insignificant for touch and stylus.

Later, Yadav et al. (2021) performed an experiment with children of three age groups, *viz*. four to six years, seven and eight years, and nine and ten years. Each age group was represented in the experiment by ten children. Yadav et al. (2021) used a smartphone with screen size of 7.2 cm × 12.7 cm. The width of the targets (A) was varied among 1.30 cm, 1.06 cm and 0.82 cm, and the distance between the targets (W) was varied among 5.4 cm, 4.4 cm and 3.4 cm. Thirteen targets were arranged in a two-dimensional circular arrangement (Figure 3b) and the subjects were asked to acquire the targets using the tap gesture and the drag and drop gesture. Yadav et al. (2021) did not observe any strong correlation between index of difficulty and movement time, and inferred that Fitts' law was not valid for interaction of children with touchscreen. The results of Yadav et al. (2021) are comparable to those of Henze and Boll (2011). However, Yadav et al. (2021) found that movement time decreased significantly with age for both touchscreen gestures. Movement time was significantly higher for the drag and drop gesture than for the tap gesture for the four to six year old children. However, movement time for the two touchscreen gestures was not significantly different for seven to ten year old children.

9. Proposed modifications

Two interesting modifications have been proposed to Fitts' law in context of interaction with touchscreen. Sears and Shneiderman (1991) remarked that cursor positioning with touchscreen is inherently different from that with most other devices. Sears and Shneiderman (1991) hypothesised that when using a touchscreen a person first lands a finger near the target and then drags the finger to the target. The time taken to land the finger on the touchscreen is a function of the width of the target (W) and the distance moved by the finger in the three-dimensional space before landing on the screen (A). Alternatively, the time taken to drag the finger to the target is a function of the width of the target (W) only. Accordingly, movement time can be calculated as follows.

$$MT = a + b\ log_2 \frac{cA}{W} + d\ log_2 \frac{e}{W} \tag{10}$$

This modification is comparable to the concept of homing time and positioning time proposed by Card, English, and Burr (1978) vide Equation (6).

A finger lacks the precision of interaction with a stylus or a mouse. Bi, Li, and Zhai (2013) proposed Fitts' law for finger input, abbreviated as FFitts law, as a modification of Fitts' law for modelling acquisition of small targets on a touchscreen. According to FFitts law, index of difficulty is calculated as follows.

$$ID = log_2 \left(\frac{A}{\sqrt{2\pi e\left(\sigma^2 - \sigma_a^2\right)}} + 1 \right) \tag{11}$$

Here, σ is the standard deviation of the distribution of the endpoints and depends on the particular task, while σ_a is the absolute precision of the finger of a person and independent of the task.

10. Discussion

10.1. Technological factors

We have three observations on the technological factors related to the studies included in this review as follows. First, the applicability of Fitts' law to interaction with touchscreen was initially studied for stationary computer systems. In the last two decades, smartphones and tablets have become common, and recent studies typically investigate the validity of Fitts' law for interaction with such devices (Table 2). Second, the screen size of smartphones is typically much less than those of computers and tablets. In fact, devices with a wide range of screen size have been used in the studies included in this review. Third, all three of Fitts' experiments used one-dimensional movement tasks (Figure 2). However, target acquisition on a touchscreen is typically a two-dimensional task and accordingly most researchers have used two-dimensional target arrangements in their experiments. On the basis of these observations, we recommend future researchers on this topic to investigate the effects of mobility of the device, screen size and various arrangements of targets on user performance.

Langolf, Chaffin, and Foulke (1976) experimented with several movement tasks with physical apparatus and found that the value of b in Equation (9) is lesser for movement tasks involving finger movement only than for tasks requiring movement of wrist and arm. People typically use only a finger to acquire targets on the screen of smartphones and tablets. Hence, the value of b is expected to be low for these devices.

10.2. Human factors

We also have three observations on the human factors related to the studies included in this review as follows. First, most studies on the applicability of Fitts' law to interaction with touchscreen had small sample size (Table 2). On the other hand, the only large-scale study by Henze and Boll (2011) did not find Fitts' law to be valid for interaction with touchscreen. Second, the way people interact with touchscreen depends on their age, educational qualification and level of expertise in digital technologies. Cassidy, Read, and MacKenzie (2019) and Yadav et al. (2021) investigated the applicability of Fitts' law to interaction of children with touchscreen. Third, people acquire targets on a touchscreen using either the tap gesture or the drag and drop gesture. Yadav et al. (2021) observed a difference in the performance of users when they used these two touchscreen gestures. On the basis of these observations, we recommend future researchers on this topic to work with large and diverse cohorts, and study the effect of touchscreen gesture on user performance.

10.3. Possible use of Fitts' law in app design

There may be two possible use of Fitts' law in designing apps for touchscreen devices. First, Fitts' law may be used to predict the time required to tap on two keys in a virtual keyboard in quick succession. This information may be used to optimise the layout of the virtual keyboard and placement of the keys to facilitate fast typing. Virtual keyboards have been developed following this technique for use with touchpad (MacKenzie and Zhang 1999) and stylus (Zhai, Hunter, and Smith 2000), and the same may be done for finger-based interaction. Second, apps for touchscreen devices use different types of widgets. An understanding of Fitts' law can help app developers to create widgets of appropriate size and position them in a way on the screen such that they are convenient to use.

Table 2. Summary of studies on the applicability of Fitts' law to interaction with touchscreen.

	Technological factors				Human factors			
Study	Type of device	Screen size	Range of ID (bits)	Target arrangement	Sample size	Subjects	Touchscreen gesture	Applicability of Fitts' law
Landauer and Nachbar (1985)	Touch-sensitive screena	Not specified	Not specified	Two-dimensional	8	High school students	Tap	Inconclusive
Sears and Shneiderman (1991) (First experiment)	Personal computer with touchscreen[a]	27.6 cm × 19.5 cm	Not specified	Two-dimensional	36	University students	Tap	Inconclusive
Po, Fisher, and Booth (2004)	Interactive board[a]	136 cm × 102 cm	Not specified	Two-dimensional	8	Adults	Tap	Confirmed
Sasangohar, MacKenzie, and Scott (2009)	Touch-sensitive surface[a]	32 inch display	1.00–6.02	One-dimensional	12	University students	Tap	Confirmed
Henze and Boll (2011)	Tablets and smartphones[b]	Multiple	Not specified	Two-dimensional	63154 installations	Crowd	Tap	Repudiated
Ljubic, Glavinic, and Kukec (2015)	Tablets and smartphones[b]	3.27 inch–10.10 inch displays	1.0–5.5	Two-dimensional	35	Adults	Tap	Confirmed
MacKenzie (2015)	Smartphone[b]	2.4 inch × 4.0 inch	1.14–3.17	One- and two-dimensional	16	University students	Tap	Confirmed
Cassidy, Read, and MacKenzie (2019)	Tablet[b]	7 inch display	1.34–3.41	Two-dimensional	28	Children	Drag and drop	Confirmed
Yadav et al. (2021)	Smartphone[b]	7.2 cm × 12.7 cm	3.05–3.72	Two-dimensional	30	Children	Tap, and drag and drop	Repudiated

[a]Stationary device.

[b]Mobile device.

11. Conclusion

Fitts' law is an important concept in human–computer interaction. Since the work by Card, English, and Burr (1978), Fitts' law has been used to model interaction of human beings with various input devices in different conditions. Touchscreen is a widely used input device and several researchers have studied the interaction of human beings with touchscreen. However, we call for more Fitts' law based research on interaction with touchscreen. The findings of such studies will help in improving the usability of the software of touchscreen devices.

Notes

1. Some papers included in this review use inch as the unit of length, while the others use cm. We have mentioned the original measures and units.
2. The step keys consisted of five keys. The HOME key took the cursor to the upper left corner of the screen. The four arrow keys moved the cursor one character in the corresponding direction.
3. The text keys also consisted of five keys. The PARAGRAPH key and the WORD key took the cursor to the beginning of the next paragraph and the next word, respectively. The CHARACTER key moved the cursor one character ahead. The LINE key took the cursor to the same position in the next horizontal line. Holding the REVERSE key while pressing any other key moved the cursor in the reverse direction.
4. This and some other papers used D instead of A and S instead of W.
5. The touchpad was called a tablet in this paper.

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ORCID

Pinaki Chakraborty http://orcid.org/0000-0002-2010-8022
Savita Yadav http://orcid.org/0000-0002-4334-1767

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