

A Study of Model Iterations of Fitts' Law and Its Application to Human–Computer Interactions

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Abstract: Fitts' law, a predictive model for motor task completion time, is widely utilized in human–computer interaction (HCI) research. While its formulas in two dimensions have achieved consensus over the decades, research diverges on its application in three dimensions. This paper synthesizes practical applications across touchscreens, virtual reality (VR), pedals, handheld devices, etc., with a specific emphasis on enhancing interaction experiences for vulnerable populations. This review studies Fitts' law's applicability in diverse interaction scenarios, highlighting design considerations for touchscreens and handheld/foot-held devices. This article underscores the need for future research to explore three-dimensional applications and consider user age, with potential expansions into medical and sports domains. This systematic review aims to empower designers in crafting more ergonomic products and improving HCI experiences.

Keywords: Fitts' law; human–computer interaction; human motor behavior; ergonomics



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1. Introduction

Fitts' research in 1954 extended information theory to human motor systems. Based on information theory, he formulated the original model of Fitts' law, which quantifies the difficulty of human motor tasks. The difficulty index (ID) of a motor task is defined as follows:

$$ID = -\log_2 \frac{W}{2A} = \log_2 \frac{2A}{W} \quad (1)$$

W represents the width of the motor task's acquisition goal, and A denotes the magnitude of the task. The difficulty index (ID) is measured in bits. Essentially, the formula can be succinctly described as follows: the farther and smaller the target, the more challenging it is to acquire it. Additionally, Fitts defines a performance metric for a motor task completed within time t seconds, formulated as follows below in Equation (2).

$$IP = -\frac{1}{t} \log_2 \frac{W}{2A} \quad (2)$$

The index of performance (IP), measured in bits/s, is the full name of the term “IP”. Some later HCI researchers refer to it as throughput (TP) [1,2]. Fitts hypothesized that, for a motor task, the IP remains constant over a wide range of values for A and W. In his experiments involving three different motor tasks, the IP values were not exactly constant but exhibited minimal variation [3]. By substituting Equation (1) into Equation (2), the following form can be written:

$$t = \frac{ID}{IP} \quad (3)$$

The formula suggests that the time needed to complete a motor task is proportional to the motor difficulty index (ID). When applying Fitts' law to HCIs, we need to find ways to

reduce the value of the ID. We need to make the target as large as possible and as close as possible to the limb with which we are performing the interactive behavior.

In Fitts' 1964 article, he proposed a formula for predicting the time required to complete a sport based on the difficulty index:

$$MT = a + b \cdot ID \quad (4)$$

The formula referred to is the well-established Fitts' law model, where MT represents movement time. The parameters *a* and *b* denote the intercept and slope, respectively, which vary depending on the specific application [4]. Fitts' law asserts a linear correlation between task complexity and movement time (MT), and it has evolved into a fundamental principle of interaction design in contemporary practice.

Subsequent researchers have built upon and refined Fitts' ideas and findings, introducing modified versions of Fitts' law to meet the increasing demands of real-world interactions [5–7]. Initially, the vectors defining motion from the starting point to the target were confined to a two-dimensional plane, limiting the applicability of the original Fitts' law model to simpler movements. In everyday scenarios, translational motion within a plane is less common, with rotations and other forms of movements predominating, necessitating models in three-dimensional space to address these complexities. Regrettably, the diversity of variables and scenarios in three-dimensional motion precludes the existence of a universally accepted model capable of perfectly simulating motion behaviors in such environments. Current adaptations of Fitts' law to the three-dimensional domain are tailored to specific applications where they can effectively resolve the challenges. Nevertheless, the foundational principles of the original Fitts' law persist in these variants, shaping ongoing research and application in this field.

Since Fitts' law was first proposed about 70 years ago, researchers have worked hard to connect it to everyday interactions and HCIs. This fundamental idea is widely used in simulating the interaction between people and various input devices in HCIs. Scholars have investigated how to apply Fitts' law to various user demographics and interaction patterns, with a focus on examining its applicability to handheld devices, treadle devices and a range of HCI applications. Fitts' law's implications for exceptional groups have also received recent attention, indicating a developing area of research interest. Scholars have expanded their research beyond interactive environments, examining Fitts' law theories and real-world applications in fields including sports and healthcare.

We utilized the Web of Science database to identify the relevant literature on Fitts' law, focusing on HCI and human motor behavior. Chapter 4 of this paper categorizes these findings, distinguishing between valid and flawed studies. We review the current state of the research on Fitts' law across five distinct domains: touch screens, VR devices, handheld devices, pedals, and interactions involving vulnerable groups. By addressing each domain separately, we summarize their contributions to interactive design and highlight potential applications in human movement. We aim to provide accessible insights to designers, aiding them in creating more ergonomically sound industrial products.

This study summarizes the developments in Fitts' law model iterations and its wide range of applications in many settings since its origin. Through providing an extensive synopsis of Fitts' law's development and application, this paper hopes to stimulate scholars' curiosity about further research into this fundamental idea. By combining Fitts' law's historical development with its modern uses, this paper aims to stimulate additional academic research and promote a more sophisticated comprehension of its importance in various fields.

2. Physiological Basis of Fitts' Law

A basic idea is expressed by Fitts' law, which states that a target's size and closeness affect how quickly and correctly it may be reached. Larger, closer targets are typically reached more quickly than farther, smaller ones. Fitts' law's fundamentals are being studied

in greater detail by experts, who are discovering fascinating linkages to the neural system that encourage more investigation into this complex relationship [8].

2.1. Various Formulations and Studies on Fitts' Law as It Relates to Human Motor Behavior

The human body transmits signals in phases as people respond to tasks, so information is not processed instantly and actions take time to complete [8]. Longer distances impair the accuracy of faster actions, as this delay impacts both movement speed and accuracy. Based on these factors, the Fitts formula was created to forecast movement time. Fitts' law was first proposed fifty years ago, and since then, a great deal of study has been conducted on the physiological mechanisms behind movement, demonstrating the law's wide application. Fitts' law has so established itself as a common tool in the field of HCI studies [5].

Woodworth first proposed in 1899 that a basic component of athletic conduct is a trade-off between accuracy and speed [9]. Expanding on this idea, Fitts suggested that the average amount of information (measured in bits) needed to carry out a movement corresponds with the amount of time needed to finish a task. This theory affirms that the trade-off between speed and accuracy is a fundamental characteristic of human motor activity and highlights the crucial role that this trade-off plays in human motor behavior.

2.2. Connection between Fitts' Law and Nerves

The rate at which afferent signals from the hand's muscles travel to the cerebral cortex is similar to the rate at which corticospinal efferent signals travel to the hand's muscles. The range of efferent conduction velocities is 11–18 m/s. There is a minor delay of around 10 ms when signals are transmitted from the cerebral cortex to the intercostal muscles as opposed to the hand muscles via corticomotor signals [10]. Fascinatingly, the cerebral connection pattern shown in the hand muscles is at odds with this delay. Reduced conduction speed inside the central nervous system or delayed peripheral conduction of intercostal muscle afferents may be the cause of the disparity in afferent and efferent cortical transmission times [11].

Fitts' law accurately predicted human movement, so Beamish et al. wondered if the target's size and distance would affect the body's ability to react quickly and accurately, as well as the rate at which electrical signals from the internal nervous system are transmitted. Based on Beamish et al.'s experiments to estimate Fitts' law coefficients by modeling brain currents with motor currents, we hypothesize that Fitts' law does affect psychomotor latency in humans [12]. This hypothesis was supported by Bullock and Grossberg's 1988 demonstration of the invariance of motion using endpoint vector integral circuit modeling and the transformation of distance differences into changes in muscle contraction to produce synergies [13].

2.3. Connection between Fitts' Law and Muscle

Fitts' law's formula is a technique used in movement time (MT) analysis to assess variations in the effects of exercise. When performing exercises, electromyography is frequently used to measure static muscle loading [14]. Muscle workouts are often classified as light when the load is under one kilogram and as heavy when the weight is greater than one kilogram [15,16]. This categorization is based on the force that is applied.

Light movement analysis showed that while muscles vary, there are consistent patterns in all thirteen directions. Interestingly, there is a noticeable decrease in performance in the 150° direction [15]. On the other hand, large exercise studies have shown that the directions that have a greater impact on the muscles are, in order, left–right, up–down, and front–back directions. While other directions tend to have an upward parabolic shape, the horizontal direction exhibits parabolic fluctuations. Long-term activity lengthens the time it takes for muscles to tire out. Push and pull actions require different amounts of force and sensitivity from muscles, with pulling exercises making muscles more sensitive. There is a chance that this heightened sensitivity will result in a shorter finishing time. Exercise duration,

difficulty, and muscle status have a nonlinear relationship that is modified by the body's spatial location.

3. The Origin of the Fitts' Law Formula and How It Was Developed

We explore the widely accepted application of Fitts' law in this section. Through a review of Fitts' law's extensive application, we hope to evaluate its development and boundedness across a range of fields.

3.1. Original Formula

The original formulation of Fitts' law for motion time (MT) is presented in Equation (4), while the coefficient of difficulty (ID) is depicted in Equation (1). Fitts' original experiment solely encompassed fundamental one-dimensional linear motion; however, the formula is also applicable to motion behavior within two dimensions.

3.2. Further Studies in the 2D Plane

Fitts' law's application has been greatly expanded by researchers; one major development is about how it is integrated with probability theory. Through the integration of probability theory, scholars have aimed to enhance the model's relevance and capacity for prediction in a variety of settings and assignments. A series of traditional augmentation equations have been carefully selected in Table 1 to represent the evolving results of Fitts' law in the modern research.

Table 1. The classical study of Fitts' law in two-dimensional domains.

Name of Proposer	Time	ID Composition	Usage Scenario
Fitts	1954	$ID = \log_2\left(\frac{2A}{W}\right)$	1/2D
Welford	1960	$ID = \log_2\left(\frac{A}{W} + 0.5\right)$	2D
MacKenzie	1989	$ID = \log_2\left(\frac{A}{W} + 1\right)$	2D
Hoffmann	1995	$ID = \log_2\left(\frac{2A}{W+F}\right)$	2D

Welford made improvements to the original formula by removing the double distance term and introducing a constant term of 0.5 to the difficulty index [17]. MacKenzie, on the other hand, questioned Fitts' formula's deviation from the original formula in information theory. He proposed defining the coefficient of difficulty (ID) based on Shannon's work. MacKenzie applied his formula to replot the data from Fitts' 1954 experiments and found that it provided a better fit than Fitts' formula [18]. MacKenzie's formula is similar to Welford's, with the exception that the constant term is set to 1. MacKenzie argued that the cursor must reach the center of the target to be considered touching it, rather than merely touching the target and considering it complete, as Welford did. Both formulas yielded positive results in corresponding experiments. Hoffmann's study incorporated the influence of the size of the index finger's pad into the equation. His formula introduced finger width (F) as an additional factor, along with target width (W) and distance (A), recognizing the importance of this factor. In the case of the inverted Fitts task, the formula that accounts for finger width demonstrated better results. Hoffmann's research on Fitts' law expanded into the three-dimensional realm by considering the effect of target depth [6].

Currently, the most widely used formula for use in the two-dimensional plane is MacKenzie's formula. The formula has been thoroughly studied, and it is more flexible and efficient than other formulas [19–21].

3.3. Research in 3D Space and VR

Researchers are progressively shifting their focus to the three-dimensional domain as Fitts' law develops, freeing them from the limitations of two-dimensional investigations. However, moving from two-dimensional motion analysis to three-dimensional motion

analysis has special difficulties since user actions are less predictable due to their complex movement and spatial navigation [22].

3.3.1. Research in Three-Dimensional Fields of Varying Forms

Target thickness could have a major influence on prediction time, which led to a move from limited two-dimensional studies to three-dimensional research. Hoffmann's seminal work provided the basis for the three-dimensional formulation of Fitts' law in this expanded area [6]. Due to the greatly increased complexity of human motion in three dimensions, modifications to the Fitts formula are not only required for the coefficient of difficulty but also for the motion time formula as well. Building on this foundation, studies conducted in the past ten years have explored Fitts' law's applications in three dimensions, yielding important new understandings and findings. To provide an overview of the state of Fitts' law research in the field of three-dimensional studies, a representative summary of the most important discoveries is assembled in Table 2.

Table 2. Classical formulas for Fitts' law in three dimensions.

Name of Proposer	Time	MT Composition	ID Composition	Usage Scenario
Fitts	1954	$MT = a + b \cdot ID$	$ID = \log_2 \left(\frac{2A}{W} \right)$	1/2D
Murata	2001	$MT = a + b \cdot ID$	$ID = \log_2 \left(\frac{d}{s} + 1 \right) + c \cdot \sin \theta$	3D
Myung	2013	$MT = a + b\theta_1 + c \sin \theta_2 + d \cdot ID$	$ID = \log_2 \left(\frac{2D}{W+F} \right)$	3D
Machuca	2019	$MT = a + b \cdot ID + c \cdot CTD$	$ID = \log_2 \left(\frac{A}{W} + 1 \right)$	3D/VR

Murata's team proposed an early formulation of Fitts' law in three dimensions, which involved similar modifications to the coefficient of difficulty (ID). In MacKenzie's formula, a sine function was introduced to account for the angle of motion (θ), where θ represents the angle pointing towards the motion. Additionally, an arbitrary constant c was incorporated through linear regression. This formula outperformed the traditional Fitts formula in predicting motion time, although the improvement in fit was not significant [23]. Myung's team also presented their formula for predicting motion time by Fitts' law in three dimensions. This formula considered the inclination angle (α), which refers to the angle between the target and the horizontal plane, as well as the orientation angle (β), representing the angle of position after establishing a coordinate system centered on one's hand. By enhancing the spherical coordinate system, this formula aimed to more accurately model motion in all directions within three dimensions. However, the addition of $\sin(\theta)$ to the formula did not significantly contribute to movement time prediction [7]. Machuca's team conducted research using VR equipment and discovered that display defects had unexpected effects, specifically related to the change of target depth (CTD). It was observed that prediction time was not solely influenced by the difficulty factor but also by display defects during virtual presentations. Their formula exhibited greater effectiveness in predicting motion time. This work holds significant implications for VR and augmented reality technologies [24].

There is no complete system for comparing the advantages and disadvantages of each 3D model, and each formula has good experimental results within its experimental range. Despite the continuous efforts of researchers, it is still difficult to create a generalized formula to describe reaction time. Many scholars have proposed various ideas and models for different research questions [25–27]. Nowadays, as virtual devices become more commonplace, there is an increasing interest in studying 3D Fitts' law further. Researchers are using these cutting-edge technologies to learn more about how humans interact with computers [28–30]. To properly traverse this changing landscape, it becomes critical to recognize and understand the particular circumstances in which these new gadgets are employed. Researchers can effectively meet the varied issues offered by 3D Fitts' law by tailoring their findings and applying pertinent formulas by recognizing the subtleties of usage circumstances [31–33].

3.3.2. Multifactorial Influences in Three-Dimensional Studies

Human movement behavior in three-dimensional space encounters many disturbing factors, so some researchers have conducted in-depth studies on these disturbing factors [34,35]. Prediction times are influenced by device performance; problems like head motion may have an impact on display quality, and device content may have an impact on experimental results [28]. Empirical research by Batmaz et al. showed that VR devices could display differences from reality, which would affect prediction times [28,34,36]. People who are looking for information frequently rely on three-dimensional visual signals, which means that to obtain the best visual performance, our eyes' sensory processes must be actively adjusted. However, such modifications may deviate from the real intention [37]. Fitts' law requires participants to click and target with their arms, which encourages ongoing experimentation that may potentially incorporate shoulder joint movements that impact muscle effort [3,15,16]. Despite the multiple influencing factors, these parameters can inform practical applications within a reasonable margin of error [31,36,38].

3.4. Impact of Uncontrollable Factors on Forecasting Time

When choosing targets with and without influence, Keulen's team observed differences in the subjects' performance. Target selection took much less time when there was no interference than when there was, but it took much longer when interference was present. This increase was even more pronounced when the interference moved constantly [39]. Interestingly, the amount of time needed to choose the final target reduced slightly when participants clicked on a predetermined number of successive targets [40]. Moreover, changing the spacing between targets resulted in an overall time increase. Yet, a recurring pattern was noticed, demonstrating a notable reduction in time upon clicking the final object in the set sequence.

4. Some Studies of Fitts' Law in HCI Scenes

Fitts' law, which was first developed for physical devices, is today used as a foundational framework to comprehend how people interact with a wide range of computer input devices [41]. The law's use has broadened to include screens on electronic devices, including those used in vehicles used for transportation, such as airplanes [42]. The ideas of the law have also been applied to foot-operated and handheld devices, demonstrating the law's adaptability in capturing human behavior across many interfaces. Fitts' law has been adopted more recently in the research of VR device interaction design, indicating its continuous applicability and flexibility in assessing user experiences in developing technologies [43].

4.1. Touchscreen Scenes

Touchscreen technology has become pervasive in entertainment, education, and industrial applications, catering to diverse needs in daily life [44,45]. Touchscreens are typically classified into small and large screens based on size and handling convenience: small screens, like those on cell phones and smartwatches, allowing for one-handed operation; or larger screens, such as those on tablet PCs and large touchscreen displays, usually requiring two-handed operation or additional support like a stand. Notably, touchscreens integrated into vehicles present a unique case due to their large size and the inherent safety concerns associated with driver distraction. Design considerations for automotive touchscreens prioritize user safety by minimizing distractions, as tapping on the screen while driving could compromise the driver's focus and lead to unsafe behavior.

4.1.1. Small Touchscreen

Our contact with restricted display areas has expanded substantially with the advent of small-screen devices, including smartphones [46]. User interface buttons are frequently resized to accommodate smaller screens, which presents design issues and calls for optimization for efficient finger interactions. Song et al. improved Soukoreff's initial model

by extending Fitts' law to small-size targets [2,47]. Additionally, by utilizing probabilistic insights, researchers such as Bi et al. have dug deeper into assessments of finger-touch input. Bi et al. introduced the Fitts law, a revision of Fitts' law that analyzes the movement endpoint distribution as a mix of speed-accuracy control and the finger touch distribution. This sophisticated model delivers greater accuracy in simulating finger-touch inputs compared to the classic Fitts' law approach [48].

On small-screen devices, the majority of users prefer one-handed touch interactions. Fitts' law was utilized by Trudeau et al. to evaluate thumb motor performance during one-handed touch interactions. They observed that thumb performance can be improved by smaller phone sizes [49]. The natural thumb position was defined by Lee et al., who also showed that one-handed movement within 45 mm of this location preserves optimal task performance [50]. Smaller buttons cause users to make more mistakes and take longer to move (MT), while larger buttons result in lower error rates and less finger strength being used [51,52]. Wu et al. offered particular quantitative insights, demonstrating a considerable increase in movement time when the icon size was less than 110 response pixels. Additionally, participants stated that when the icon's size increased to 140 response pixels, clicking became easier [53]. Multi-touch actions including pinching, turning, and dragging are frequently used when using smartphones. Based on Fitts' law, Park et al. created a model that provides useful guidance for designing products with multi-touch interfaces [54].

Variations in handheld posture, hand tremors, and surrounding noise can all have a big impact on how well cell phones function when used in motion [55]. A study by Conradi et al. showed that using a button size of 14×14 mm reduced error rates when standing and walking, emphasizing the importance of this size for cell phone screen design [56]. Music et al. reported a drop in click accuracy when users engaged in walking, with distinct gait phases impacting operation precision. It is interesting to see that utilizing the index finger instead of the thumb produced better results when using the phone. According to the study, walking at a pace equivalent to 75% of one's normal pace while using a phone can also improve the accuracy of the offset model [57].

A few things that affect interactive performance on small-screen interfaces are button size, device size, walking distractions, and operating mode selection. When creating interfaces for small-screen devices, designers must take all of these factors into account to maximize user experiences.

4.1.2. Large Touchscreen

Users frequently face fixed usage scenarios while using large touchscreens, which necessitates that they take into account both the width and length dimensions while interacting. The angle of motion between the first touch point and the target object is important in 2D target acquisition, and it needs to be carefully assessed for best results.

Motion angle had a major effect on user performance in a 2D pointing task on big touchscreens, according to Vetter et al. They combined motion time, angle, amplitude, and target width to create a nonlinear sinusoidal model [58]. Building on these findings, Bützler et al. improved Fitts' law for these kinds of tasks by adding variables like motion angle and target width, demonstrating how effective this method is in considering motion time differences [59]. Furthermore, studies indicate that faster movements in horizontal and vertical directions than in diagonal ones are associated with positioning effects, which are important in touchscreen pointing activities [60]. Ge et al. investigated how beginning and ending positions affected pointing tasks and showed how important they are for task completion [42]. Because of the size of the screens, the size of the icons becomes less important when designing large-screen interfaces. In the two-dimensional plane, designers give priority to elements including target width, motion distance, angle, and positional effects. Designers may efficiently create interactive interfaces that are suited for large touchscreens by integrating these variables.

4.1.3. Screens in Vehicles

The use of in-vehicle information systems (IVIS) by drivers has increased significantly in the past few years, with touchscreens acting as the main user interface [41]. Drivers naturally gravitate toward touchscreen technology because of its natural user-friendliness and intuitive engagement. Touchscreen interactivity is playing a bigger part in driving experiences as electric vehicles continue to gain popularity. Driving is the main priority when operating a vehicle, leaving little time for intricate device interactions. Touchscreen interfaces are therefore the favored option for drivers due to their ease of use and simplicity [61]. For a driving experience to be pleasant, touchscreen activities must be seamlessly integrated with driving movements.

According to Vollrath et al., performance on both primary and secondary tasks may suffer when attention is divided between them [62]. Inadequate touch key design in the context of in-car touchscreens might worsen interface issues and possibly intensify driving disturbances [41]. Although it would be ideal to avoid using screens while driving, this may not be possible due to the increasing integration of in-car screens [63]. The impact of button size on movement time was highlighted in Kim et al.'s examination of task completion times and error rates while driving at different speeds, suggesting that larger buttons can enhance interaction efficiency [41]. Furthermore, Dooddd et al.'s findings from aviation settings showed that particular cockpit postures and touchscreens during turbulent conditions led to longer job execution times, higher error rates, and a perception of workload [64].

While driving, drivers need to visually engage with the information displayed on screens, adding to the cognitive load. In a study by Large et al., they investigated the visual requirements of HCIs and developed predictive equations to estimate the visual demands associated with using these interfaces while driving [65]. Additionally, the application of Fitts' law in designing and evaluating icons for in-car screens provides valuable insights into optimizing user interactions. Although the study by Large et al. was primarily focused on single-finger touch-pointing tasks with touchscreens in driving scenarios, the findings are broadly applicable beyond driving environments. The results offer guidance for interface design and decision-making interactions across diverse settings where users interact with interfaces to make choices.

4.2. VR Scenes

Although VR devices provide a novel means of engagement, they are not yet able to offer tactile input that sets them apart from touchscreens. On the other hand, VR devices are widely used for a variety of visual experiences in various settings [43]. Even though VR provides immersive digital experiences, problems have surfaced. Variations in the size of objects in virtual space can impact our capacity to target and interact with them more quickly [66]. Furthermore, compared to a hand-tracking system, a head-tracking system's lag has a greater influence on performance prediction in the use of VR devices. Since most VR device interactions are hand-based, even modest delays can significantly reduce performance, especially when aiming at small objects [67].

Apart from its size, a target's shape is a major factor in estimating our reaction time. To describe the selection of targets with different shapes in VR environments, Liu et al. presented a prediction approach that makes use of probabilistic fitting principles [68]. Expanding upon this methodology, a motion target selection prediction model was created by integrating probability fitting laws and a decision tree [69]. This model aims to improve the precision of target selection predictions, ultimately producing a more lifelike VR experience. Auditory signals influence our performance forecasts in VR environments as well. High-pitched error feedback has been shown in studies by Batmaz to negatively impact user performance in terms of throughput and time. On the other hand, the research discovered that adaptive audio feedback lowers the mistake rate connected with performing activities at top speed without sacrificing task completion time [70]. These research findings on VR can help with the development and design of various VR systems.

4.3. Handheld Devices

A mouse's main purpose is to give users a tangible way to enter data into a computer by enabling them to click and move the cursor across the screen. The mouse gain, which is the ratio of the distance on the screen to the distance the mouse moves, affects the sensitivity and speed of the pointer. To improve the efficiency of HCIs, a great deal of research is being conducted to find the ideal mouse gain and integrate Fitts' law. Cursor behavior is affected differently by varying gains; a high gain allows for faster but less accurate cursor placement, whereas a low gain allows for regulated accuracy but slower cursor movement. It is imperative to strike the ideal balance between precision and speed, which calls for a trade-off between high and low gain settings [71]. Pang et al.'s study looked at the relationship between movement time (MT) and different gains and found that the optimal gain depends on the size of the movement [72]. Whisenand et al. also found that, in addition to target size and distance, the angle of approach has a major impact on target selection when using a mouse, which is consistent with the results of touchscreen pointing tasks [73]. Fitts' law, which takes into account the angle of approach as well as the best mouse gain data—which has been demonstrated through research—can be used in computer interface design to facilitate effective mouse operation.

4.4. Foot Pedals

In addition to hand-machine interactions, foot-machine interactions are common. Situations where leg movements cannot be continuously observed with the naked eye lead to ballistic movements with no chance for mid-course corrections. In these situations, visual feedback has no bearing on the movement's ultimate precision [74]. Drury's research indicates that foot pedal tasks follow a Fitts'-law-like pattern [75]. Hoffmann investigated the lengths of hand and foot movements in visually guided and ballistic activities and found that foot motions usually take twice as long to execute as equivalent hand movements [76]. Hoffmann's square root amplitude equation, which was developed for arm movements, can be extended to ballistic foot motions, and Welford et al.'s improved Fitts' law provides a useful framework for characterizing movement time for visually directed foot motions [77,78]. Hoffmann and Chan's later studies investigate the effects of the direction of foot motion and sitting versus standing postures on the length of a movement. Their results show that the movement time correlates with the square root of the movement amplitude when there is no continuous visual control. On the other hand, actions performed with constant visual guidance can show a more complex relationship between movement amplitude and time [79]. Even though foot interactions are important, there is not much research on the subject. It is proposed that, in contrast to hand movements, foot activities are subject to temporal deviations because of interference from shoe design, highlighting the need for more thorough research in this area.

4.5. Groups with Poor Interaction

Not everyone is equally adept at using digital gadgets. Children, for example, frequently have difficulty in acquiring small targets since their fine motor skills are not as developed as those of adults. Designing user-friendly programs for children requires an understanding of their dexterity on touchscreens [80–82]. On the other end of the age spectrum, physical aging and declining sensory capacities in the elderly can hinder their ability to respond effectively and receive information quickly, making it more difficult for them to interact with various interactive gadgets. The elderly population often has diminished haptic feedback sensitivity, which can be a hindrance while using smart gadgets [83]. Furthermore, vision impairments make HCI problems worse, which makes using devices more difficult. The distinct obstacles presented by age and visual impairments highlight how crucial it is to modify interactive interfaces to suit a wide range of users. In this regard, the study of Fitts' law offers insightful information from three different angles: young people, the elderly, and people with visual impairments. Through investigating target acquisition and fine motor skills in these populations, scientists want to improve

the usability and design of interactive systems that serve people with different needs and capacities [84].

4.5.1. Children

When developing interactive platforms, designers of children's software have typically relied on inherent experience rather than using actual data on young children's motor skills to influence interface design. This traditional method has frequently disregarded the complex requirements and skills of younger users, which may have limited the usefulness and accessibility of kid-friendly software. In an attempt to close this gap, new studies have looked at how kids of different ages engage with different computer input devices. To shed light on the nuances of children's involvement with technology, researchers hope to analyze and comprehend the dynamics of these interactions by utilizing Fitts' law's predictive capacity. Researchers may improve children's software interfaces by using data-driven insights and empirical research to gain a better understanding of young users' motor capabilities and interaction patterns. Designers can optimize the usability and effectiveness of software intended for young children by incorporating empirical evidence and utilizing theoretical frameworks such as Fitts' law to create more intuitive and user-centric interfaces that cater to the diverse needs and abilities of young children [85,86].

Chang et al.'s study, which looked at how kids ten years old and up interacted with touchscreen devices, found a fit with Fitts' law [87]. The study demonstrates the usefulness of this predictive model in predicting kids' behavior. Similarly, Jones's study highlighted the progressive nature of motor abilities in young users by showing an age-related improvement in children's performance on Fitts' law tasks using computerized input devices [88]. In contrast, Woodward et al. found that the Shannon formula performed better in this situation than the conventional Fitts' law while comparing several models to predict children's finger movement times on touchscreens [5,89].

Gestural engagement is more user-friendly and intuitive than conventional methods such as a mouse and keyboard [90]. Taking this choice into account, the question of how using gesture interaction might enhance kids' computer engagement is raised. Fitts' law was employed by Lyu et al. to assess children's effectiveness in using aerial gesture exchanges under a variety of spatial restrictions, including distances and orientations, to explore this issue [91]. Their research demonstrated the value of gesture direction and target size in improving kids' performance, which prompted the creation of interaction schemes designed to maximize menu navigation through half-empty interactions, resulting in younger users' experiences being quicker and more seamless.

Research has shown that the original Fitts' law may not fully match children's interacting behaviors, requiring adjustments to better accommodate their cognitive and physical dynamics. For example, Hourcade et al. measured movement times during various phases of an encounter utilizing a mouse interface. According to their research, Fitts' law correctly anticipated when a youngster would first approach the target, but it did not fully account for later activities, including pressing and releasing buttons [85]. Similar to this, Yadav et al. created a typical two-dimensional task application for kids and discovered differences between the observed data from thirty participants of different age groups and Fitts' law predictions [92]. The limitations of Fitts' law in directing the creation of kid-friendly smartphone interfaces are brought to light by their research. These results highlight the necessity of customized approaches in child-centric interface design and advise against leaning too heavily on Fitts' law. Still, there is a lack of study on children under the age of ten, which adds to the ongoing discussion about the applicability of Fitts' law to the design of interactive interfaces for young users.

4.5.2. Seniors

Because of their cognitive and physical deterioration, older persons find it difficult to use various interactive gadgets, which causes delays in processing some haptic signals [83]. Fitts' law was used by Hwangbo et al. to investigate senior pointing performance, and the

results showed that older users have a preference for larger target sizes [93]. Remarkably, when aural input was included, elders performed better when pointing. Moreover, it has been demonstrated that adding vibration feedback enhances pointing accuracy on real keyboards [94]. The usability and overall user experience of smart device designs for seniors can be improved by incorporating haptic and aural feedback, taking into account elements such as location effects, target size, and motion angle.

Fitts' law has also been applied to the field of senior physical fitness, specifically in assessing how aging affects myoelectric amplitude control, which is crucial for muscle coordination. Studies show that when seniors are given more difficult activities, their ability to regulate their muscles noticeably declines [95]. In many older persons, age-related issues such as neurological diseases, including chronic stroke, can lead to a reduction in muscular grip strength. In their investigation into the rehabilitation of patients with chronic stroke, Wininger et al. found a relationship between grip distance and the loss of muscle strength following a stroke, suggesting the possibility of recovery. Their work demonstrated potential insights by emphasizing the relevance of Fitts' law in evaluating dynamic force application in stroke patients [96]. Fitts' law measures exercise duration, which is a useful statistic for monitoring older patients' recovery from activity-related diseases that are common in the geriatric population.

4.5.3. Visually Impaired Groups

While graphical user interfaces (GUIs) have long been a common way for people to engage with information devices, people who are fully or partially visually impaired may find it difficult to use the spatial arrangement of GUIs [84]. For visually impaired users, navigating graphical interfaces can be time-consuming; nonetheless, the application of Fitts' law has proven useful in anticipating their motor patterns. Fitts' law was applied to predict visually impaired people's performance in a study by Charoenchaimonkon et al., even though their mean time to movement (MT) was longer than the usual duration for quick aim motions [97]. It has been demonstrated that providing abrupt bump feedback as the mouse pointer crosses target borders helps participants more effectively than altering friction on the target surface to precisely localize and contact smaller targets [98,99]. Expanding upon these findings, Fitts EVAL is an experimental framework designed by Lahib et al. to investigate shape-specific accessibility on vibrating touchscreens [100]. Blind users improved their pointing operations by varying parameters such as target size, angle of attack, and distance [101,102]. The findings showed that Fitts' law is still a reliable predictive model for blind users of vibrating touchscreens, especially when differences in target size and distance are incorporated.

The cited work creatively applied Fitts' law in a non-visual setting by carefully modifying several parameters to incorporate haptic input and reference points by experimental results. This study emphasizes the value of adding tactile features to improve usability for those with visual impairments in addition to discussing the practical implementation of Fitts' law in settings with limited visual signals. Through the optimization of Fitts' law's parameters to conform to tactile feedback systems, this research significantly contributes to the advancement of visually handicapped individuals' access to visual information in modern computerized environments. Moreover, the discoveries drawn from these studies provide an important direction for the creation of interfaces that are specially designed to accommodate the requirements of people with visual impairments, thereby advancing inclusivity and usability in contemporary technology environments.

5. Conclusions

5.1. Summary

Since its conception, Fitts' law has been thoroughly examined and improved upon by a large number of scholars whose studies have explored the complexities of motion systems related to muscles and nerves. As a result of these efforts, the original model has been updated to fit various applications and scenarios. Notably, studies have looked

into how Fitts' law is widely used in the context of touchscreens in daily life. This adaptation emphasizes Fitts' law's applicability and practicality in contemporary technology surroundings by highlighting how it may be used to inform interactive touch interface design and usability. In addition, we have compiled Fitts' law's guidelines for designing various hand and foot devices. Furthermore, we have examined the challenges faced by vulnerable groups in terms of interaction inconvenience and have organized Fitts' law's contributions in addressing these issues.

5.2. Future Research Direction

Although Fitts' law has been extensively researched in two dimensions, its application in three dimensions is still in its early stages of investigation. The construction of a comprehensive model remains an issue that has not yet been fully solved due to the intrinsically complicated nature of 3D interactions. As a result, the complexities of three-dimensional HCI still present technological challenges that need to be overcome. Furthermore, there are still gaps in our knowledge of Fitts' law, especially when it comes to how it applies to people who do not fit the typical adult demographic. Disparities in the ways that disadvantaged groups interact highlight the need for specialized research to clarify their particular dynamics. Notably, Fitts' law's analysis in interactions involving children, the elderly, and other marginalized groups is impeded by insufficient sample sizes in previous studies. To develop thorough and dependable interaction design concepts, researchers must step up their investigation of these unexplored areas.

Future research on the expansion of the Fitts' law formulation should be focused within the three-dimensional domain, and the establishment of some more adaptable formulas with better guidance performance is highly desirable. In addition, the optimal solution for interaction design varies for people of different ages. For researchers, it is necessary to increase the sample size in different age intervals as a way to provide more accurate data.

5.3. Discuss

Fitts' law provides a robust model for motion in two dimensions and is widely recognized in that context. However, MacKenzie's modification of the original Fitts formula, proposing a modified version, has gained greater acceptance. On the other hand, motion within three dimensions is more intricate, resulting in a diverse range of proposed formulas. Each formula has its specific conditions of applicability, necessitating a meticulous comparison of the usage conditions for each formula. In general, Fitts' law should not be mechanically applied in HCIs, but should be considered in practical situations. The formula highlights the importance of target size and distance. However, when different interaction devices are involved, factors such as movement direction, target thickness, position effect, interference, user age, and user psychology combine randomly with the previous factors. Designers must carefully select the original or modified versions of Fitts' law that correspond to the scope of their study when designing related products.

Certain aspects warrant special attention when applying Fitts' law. One such consideration arises when modeling motion for pointing at small targets, particularly on small-screen devices. In these cases, the traditional Fitts' law becomes less accurate. This poses challenges when using Fitts' law to assess pointing performance on mobile touchscreen devices, as the accuracy of finger input is typically lower compared to mouse pointing (commonly known as the "fat finger problem") [89]. In such scenarios, alternative models that deviate from Fitts' law demonstrate better predictive performance. Furthermore, traditional Fitts' law studies have not adequately addressed the impact of age on movement time and should be given more serious consideration. As individuals age, their motor skills and ability to achieve goals through physical movement change. Consequently, the time required to accomplish a given task may vary with age. Therefore, future experiments related to Fitts' law must devote more attention to understanding the effects of age differences on users' movement behaviors.

Unlike other scientific laws, Fitts' law was not developed mathematically from the principles of human movement systems but is instead derived from information theory. However, the similarities between information theory and human movement systems are coincidental. This implies that Fitts' law applies to interactions between humans and various devices and can only be validated experimentally, rather than theoretically [103]. The various variants proposed by different researchers may yield different results under different experimental conditions, making it extremely challenging to compare the validity of the individual formulations.

In the two-dimensional context, Fitts' law is generally recognized through the motion time formula given in Equation (4), where the definition of the index of difficulty (ID) is crucial for the rewriting of variant formulas. The individual intra-two-dimensional formulas in Table 1 are the currently recognized formulas, as well as the original formulas. Among the formulas that consider only target width and distance, Fitts' original formula and MacKenzie's formula are the most widely recognized and applied. Welford's formula is similar to MacKenzie's; however, using the bullseye as the target endpoint is more reliable than using the edges. Both Fitts' and MacKenzie's formulas were developed based on information theory, with MacKenzie's formula being more aligned with the principles of information theory. In addition, Fitts' original Formula (1), in which A is multiplied by two to ensure that the ID is positive, differs from MacKenzie's definition of A . This modification was confirmed by Mackenzie's experiments as a better fit than the original formula, and the later widely adopted ID was Mackenzie's formula. Hoffmann's formula, which incorporates finger widths into the ID, is appropriate for inverse Fitts tasks that take finger widths into account. Hoffmann's formula considered more factors than Fitts' and Mackenzie's, and his research provided inspiration for subsequent formulations for various situations. Yet, the formula itself is not widely used.

With the progression of research, the original formulation of Fitts' law needs to be appropriately adapted to different interaction scenarios. In touchscreen interactions, most target acquisition tasks are two-dimensional, making the two-dimensional formula well-suited for addressing these tasks. Mackenzie's formula has been validated by researchers in the context of touchscreen interaction [104]. Ljubic et al. tested the validity of Mackenzie's adaptation of Fitts' law for smartphone and tablet touchscreen interactions, establishing a linear relationship between the index of difficulty and movement time [105]. Currently, for the interactive aspects of touchscreens, MacKenzie's formula is considered appropriate. When dealing with small touchscreens, Bi et al.'s Fitts' law is recommended for small target acquisition tasks. This new adjustment addresses the inaccuracies of the original formula under extreme conditions and serves as a model for small target acquisition on touchscreens [89]. Touchscreen human-machine interfaces (HMIs) are often used as the primary control interface in vehicles. Touchscreens for in-vehicle deployment often necessitate time-consuming and costly experiential testing and user trials. Large et al. proposed a model combining Fitts' law with Hick-Hyman's law. This model provides an effective design and evaluation tool capable of making valuable predictions about visual requirements and performance limitations associated with in-vehicle HMIs much earlier in the design cycle than traditional design evaluation techniques. This model holds significant reference value for the design of touchscreen interfaces under driving tasks [65]. The interaction of handheld devices such as mice also occurs on a two-dimensional plane, and such interaction behavior can be explained by Fitts' law. Pang et al. modified the original Fitts' law to present a formula applicable to mouse devices, offering guidance for the design of these devices [72]. For the application of Fitts' law in pedaling, the effects of leg movement and footwear should be considered. Chan et al. summarize the use of the original formula of Fitts' law in foot motion and propose a modification that accounts for both visually controlled and non-visually controlled motion. Their research provides important guidance for the application of Fitts' law in pedal equipment [79].

In the two-dimensional context, several formulas are primarily used for developing touchscreen interfaces. Among the more well-known formulas, MacKenzie's formula has

gained significant recognition and is widely used in the design of touchscreen interactive interfaces. For other applications, modifications of the formula by later researchers can better meet specific needs.

In contrast to 2D formulas, several formulas within the 3D context do not have widely recognized, appropriate counterparts and must rely on those proposed for specific experimental scenarios. Due to the different use situations, it is impossible to compare the formulas. Several of the three-dimensional formulas in Table 2 are presented in different contexts and have different scopes of application. The definitions for both movement time (MT) and index of difficulty (ID) in these three-dimensional variants differ significantly. Formulas that consider the three dimensions of length, width, and height are more effective in guiding in-space motion than the original Fitts formulas. For target acquisition in 3D space, Murata's formulation is particularly noteworthy [23]. The extended model in the spherical coordinate system proposed by Myung can be utilized during the design and evaluation phases of development, aiding designers and developers [7]. Machuca's formulation, which accounts for target depth variations, serves as a valuable reference for virtual reality and augmented reality devices [34]. There is no similar formula in three-dimensional space to that of Mackenzie in two-dimensional space, and the complexity of the situation challenges the comparison of various modified formulas. It is hoped that this field will receive the continued attention of future researchers.

5.4. Remark

Fitts' law finds extensive application in the field of HCI, particularly in the design of touchscreen interfaces. The parameters and formulation of the formula may undergo subtle changes in different interaction scenarios. However, the fundamental concept remains the same: motion involves a trade-off between speed and accuracy. Therefore, Fitts' law can be used to guide the design of various devices, including mice, pedals, and more. Any motor behavior that involves target acquisition can be designed and analyzed using the principles of Fitts' law. Moreover, we have discovered that Fitts' law is not limited to the field of HCI. It also holds potential in other domains such as medicine and sports, although these applications are still in the developmental stage. The idea of utilizing movement time as a metric plays a significant role in these fields. Therefore, we have intentionally compiled the relevant literature in this area and organized it in the subsequent chapter, aiming to provide insights and ideas for the advancement of these domains.

6. Prospects

Fitts' law has applications in a variety of industries, including sports and medicine, while being traditionally linked to domains such as HCI. During treatments and diagnostic testing, patients in medical practices frequently come across graphical representations. Fitts' law is useful for measuring and evaluating patient performance in comprehending and utilizing these kinds of visual features objectively [106]. The law's usefulness also extends to research involving patients who have neurological abnormalities and arm tremors, as it makes it easier to create linear regression models that assess treatment outcomes. This modeling technique has the potential to help healthcare providers evaluate patient progress and improve treatment plans, and this potential is growing as it continues to develop. The usefulness of this assessment technique may eventually spread to smaller healthcare settings thanks to improved model refinement, enabling physicians in a greater variety of medical scenarios and streamlining the treatment of patient diseases [96,107].

Fitts' law has produced insightful results when used in conjunction with training in sports such as handball, fencing, golf, and soccer [38,108–110]. A recurring theme appears in all of these different sports: applying Fitts' law to tasks involving deft hand and foot movements can improve the creation of more successful execution plans. This shows that Fitts' law may be applied to sports training as a useful tool, providing a mathematical framework to estimate the amount of time required to move from a starting place to a desired position. By intentionally adjusting the target's width and distance

characteristics, athletes can improve their speed and accuracy when performing motions that are specific to their sport. Athletes can improve their performance by refining their movements and creating specialized methods to advance their skill level by using this mathematical approach.

Given Fitts' law's adaptability outside of the conventional interface design domain, there is an increasing expectation that it will be applied in other domains. Fitts' law has a significant impact on fields other than interaction design, such as athletic training and ergonomics in healthcare. Fitts' law can provide insightful analysis and useful applications that can boost output, optimize training regimens, and enhance user experiences by expanding its application to diverse fields such as healthcare and sports development.

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