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Pen pressure, tilt, and azimuth in pen-based interfaces: human capability and utilization

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Abstract

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Pen is favoured in many user environments due to portability, outdoor accessibility, short learning curve, and ease of manipulation. Pen interfaces have been implemented in several ways such as pointing input, handwriting/gesture recognition, and direct manipulation. Particularly, for individuals with physical disabilities or unfamiliar with computers, the pen interface is a more natural approach.

However, compared with that of other input devices such as keyboards and mice, the input throughput capacity of pens is less because the pen input channel is restricted to x-y coordinate data. Inherent pen input modalities (pressure, tilt, and azimuth) provide possible ways to enhance the input throughput. However, rational use of these inherent pen input modalities is still an open question because little is known to rationally, naturally, and comfortably utilize pen input modalities according to human characteristics.

Therefore, there is an urgent need to systematically investigate human ability to control pen pressure, tilt and azimuth and interrelated design factors that influence human performance. In this light, this paper quantitatively investigates the pen input modalities using empirical methodology.

This paper firstly investigates pen input modality natural use profiles both in static and dynamic conditions, and the covariations between pen input modalities with different input contents, input sizes, and input positions. After discovering that pen modality values fit Gaussian distribution, this paper proposed a pen pressure discretization method based on personal use profile that increased the discernable number of pressure levels from 6 to 8. This paper also systematically investigates the human ability to control tilt through three experiments which are tilt acquirement, tilt pointing, and tilt steering, which provides a tested foundation for pen tilt user interface designs both in static and dynamic situations. For azimuth, this paper investigates the human ability to control pen azimuth through two experiments along with quantitative and qualitative analysis, which is by far the first study to systematically investigate the pen azimuth. Moreover, the verifications of Fitts' Law in tilt pointing tasks spread its dedication to pen tilt utilization aspects.

In real applications, two or more pen input modalities may often be used in tandem. In order to compare pen input modalities during a given trajectory tasks, this paper uses a specially designed concrete widget and conducts experiment to evaluate these modalities. The advantages and disadvantages of the pen modalities are comprehensively discussed. In addition, this paper also proposes several novel pen modality based techniques such as Pressure Palette, Fan Menu, and Granularity Widget, which are completely original and considered promising for pen-based interface designs.

This paper provides pen-based interface designers with a general understanding of pen input modality in HCI (human computer interaction) field.

key words Pen computing, pen pressure, pen tilt, pen azimuth, input modalities, human ability, pen based interaction.

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Glossary

ANOVA: In statistics, analysis of variance (ANOVA) is a collection of statistical models, and their associated procedures, in which the observed variance is partitioned into components due to different explanatory variables.

Block: In order to investigate the learning effect, trials were grouped in “blocks”. Each subject was asked to perform several blocks of trials so that the performance of each block can be evaluated.

Fitts’ law: Fitts’ law is a model of human movement in human-computer interaction and ergonomics which predicts that the time required to rapidly move to a target area is a function of the distance and the size of the target. Fitts’s law is used to model the act of pointing, either by physically touching an object with a hand or finger, or virtually, by pointing to an object on a computer display using a pointing device. It was proposed by Paul Fitts in 1954.

GUI: A graphical user interface (GUI) is a type of user interface item that allows people to interact with programs in more ways than typing such as computers, hand-held devices, Gaming devices, household appliances and office equipment. A GUI offers graphical icons, and visual indicators, as opposed to text-based interfaces, typed command labels or text navigation to fully represent the information and actions available to a user.

HCI: HumanCcomputer interaction (HCI) is the study of interaction between people (users) and computers. It is often regarded as the intersection of computer science, behavioral sciences, design and several other fields of study. Due to the multidisciplinary nature of HCI, people with different backgrounds contribute to its success. HCI is also sometimes referred to as manCmachine interaction (MMI) or computerChuman interaction (CHI).

ID: Index of Difficulty (ID) is a measurement of the theoretical difficulty of performing an aiming movement. It is based on Fitt's law, and is expressed as $\log_2(\frac{A}{W}+1)$, where A is the amplitude of the movement required and W is the width of the target. It indicates that the difficulty of a movement is jointly related to the distance a limb moves and the narrowness of the target at which it is aimed.

JND: In psychophysics, a just noticeable difference, customarily abbreviated with lowercase letters as JND, is the smallest detectable difference between a starting and secondary level of a particular sensory stimulus. It is also known as the difference limen or the differential threshold.

Likert scales: A Likert scale is a psychometric scale commonly used in questionnaires, and is the most widely used scale in survey research, such that the term is often used interchangably with rating scale even though the they are not synonomous.

MT: Movement Time (MT) is the time that it takes to complete the movements of a particular action, from its initiation to its termination. In this paper, Movement Time sometimes is replaced with Selection Time.

NC: Number of crossings (NC) is defined as the number of times subjects crossed the target inside or outside a target in a particular trial, minus 1.

ONPL: The optimal number of pen pressure levels (ONPL) is defined as the maximum number of pressure levels that users are able to manipulate with optimum performance.

PC: A personal computer (PC) is any general-purpose computer whose size, capabilities, and original sales price make it useful for individuals, and which is intended to be operated directly by an end user, with no intervening computer operator.

PDA: A personal digital assistant (PDA) is a mobile device, also known as a palmtop computer. PDAs are used to organize a person's life by taking notes, holding contacts, and connecting to the Internet.

Pen and stylus: In computing, a stylus (or stylus pen) is a small pen-shaped instrument that is used to input commands to a computer screen or mobile device. The user places the stylus on the surface of the screen to draw or make selections by tapping the stylus on the screen.

Pen azimuth: Azimuth is the angle from the north direction on the tablet surface to the vertical projection of the pen on the tablet surface.

Pen pressure: Pen pressure means the pressure exerted on the stylus pen tip by the user.

Pen rolling: Rolling means the angle the user rolls the pen around its longitudinal axis.

Pen tilt: Pen tilt means the angle between the tablet surface and the pen body.

PIM: Pen input modalities. In this paper, PIM mainly refers to pen pressure, tilt, azimuth, and rolling input modalities.

Steering law: The steering law is a predictive model of how quickly one may navigate, or steer, through a 2-dimensional tunnel. The tunnel can be thought of as a path or trajectory on a plane that has an associated thickness or width, where the width can vary along the tunnel. The steering law has been independently discovered and studied three times (Rashevsky, 1959; Drury, 1971; Accot and Zhai, 1997).

Target: A virtual object that the subjects need to select it as fast as accurate as possible.

User experience: User experience encompasses all aspects of the end-user's interaction with the company, its services, and its products. User experience design is a subset of the field of experience design that pertains to the creation of the architecture and interaction models that impact a user's perception of a device or system.

Weber-Fechner law: also called Weber's law which states that the ratio of the increment threshold to the background intensity is a constant. So when you are in a noisy environment you must shout to be heard while a whisper works in a quiet room. And when you measure increment thresholds on various intensity backgrounds, the thresholds increase in proportion to the background.

Chapter 1

Introduction

1.1 Research Motivation

The stylus-pen which possesses both physical properties of real pens and digital characteristics of electronic pens is taken more seriously than other input devices such as keyboards and mice in many user environments due to pen's portability, outdoor availability, short learning curve, and ease of manipulation. Moreover, the pen lets a user draw on his computer screen and create unique shapes and contours just as if he were drawing with some sort of virtual, electronic ink. Many pen-based devices such as wireless tablet PCs, PDAs and GPS receivers are equipped with stylus pens.

Pen-based interfaces are designed on the pen-paper metaphor which is a universal and fundamental way for capturing daily experience, communicating ideas, recording important events, conducting deep thinking and visual descriptions. With the advances of hardware technology, off-the-desktop computing in the forms of hand-held devices and tablets has made pen-based interfaces increasingly more relevant to mainstream applications. And user interfaces for pen computing have been implemented in several ways such as pointing/locater input, handwriting recognition, direct manipulation, and gesture recognition. Particularly, for individuals who are unable to use a keyboard and/or mouse, such as people with physical disabilities or individuals who are not familiar with computers, the pen interface is a more natural approach.

However, compared with that of other input devices such as keyboards and mice, the input throughput capacity of pens is less because the pen input channel is restricted to x-y coordinate data. Concurrent pen manipulation, e.g. to use the pen to adjust both a parameter and the granularity without other input modalities, is not easily accomplished in devices using only a pen tip. Moreover, this inferior of input throughput capacity also makes some pen-based designs such as mode switching and command combinations very difficult to operate. Fortunately however, besides x-y coordinate information, the pen has other inherent input modalities that can be used such as pressure, tilt, and azimuth which can be detected in many pen devices (see Fig. 1.1). These input modalities provide possible ways to input more information concurrently using a pen.

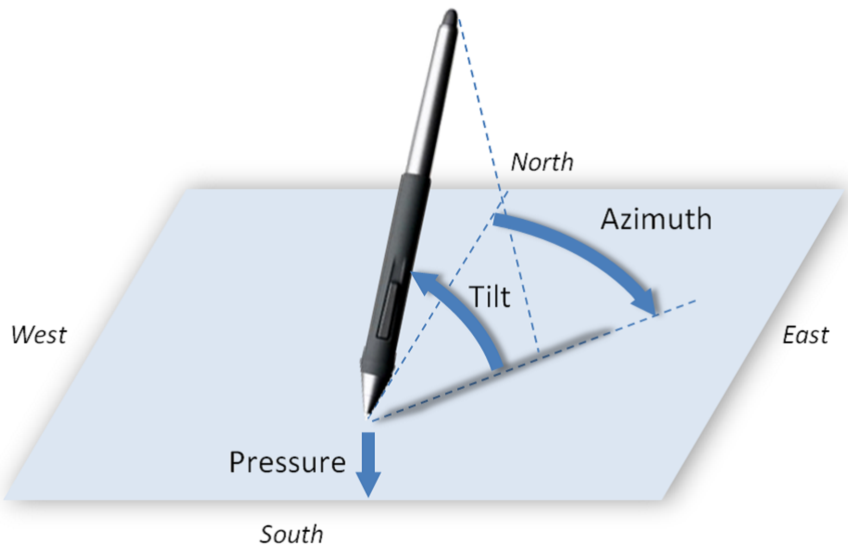

Fig. 1.1 Pen input modalities: pressure, tilt, azimuth, and so on.

Nevertheless, rationally use of these inherent pen input modalities is still an open question because there are still a number of challenges that need to be addressed before pen interface designs: Although pens have their spaces of pressure, tilt and azimuth, not all space values can be easily controlled by users because of the structural limitations of the human hand and personal pen use habits; Natural pen pressure, tilt, and azimuth use profiles are still unexplored and common/rare pen pressure, tilt, and azimuth ranges are unknown; Most importantly, the human ability to control pen pressure, tilt, and azimuth are still far from complete. In general, we have little idea to rationally, naturally, and comfortably utilize pen input modalities according to human characteristics.

On the other hand, in real applications, two or more pen input modalities may be often used in tandem. However, very little literature is available that provides us with a theoretical and practical basis showing whether covariations exist between these pen input modalities. Moreover, in a given trajectory-based application, which pen input modality is more excellent and optimal than other modalities is also unexplored.

The problems mentioned above are very critical for pen-based technique designs. Knowing them can help us to design more satisfactory and efficient interfaces and provide pen-based interface designers with a tested foundation. Although many researchers were broadly attracted to investigate pen techniques in recent years, little research explored the utilization of pen input modalities: (1) No literature quantitatively investigated natural pen pressure, tilt, and azimuth use profiles, which resulted in inefficiency in concrete pen modality based designs; (2) Most studies investigated only one pen modality. Few comprehensively investigated all three modalities; (3) No evaluations of the covariations between modalities, which are essential if combined uses of multiple modalities are to be fully exploited, have ever been investigated; (4) No literature systematically compared the pen input modalities during a given trajectory tasks; (5) No literature proposes natural discretization method for pen input modalities.

In summary, there is an urgent need to systematically investigate human ability to control pen pressure, tilt and azimuth. Moreover, the way to rationally utilize pen pressure, tilt, and azimuth are also ripe for systematic exploration. Since pen technique is still at the initial stage of development, these basic insights on pen pressure, tilt, and azimuth could help designers design more efficient interfaces. In this light, we quantitatively investigates natural pen input modalities use profiles, the covariations between pen input modalities, human ability to control pen pressure, tilt, and azimuth, utilization of pen pressure, tilt, and azimuth, and the performance comparisons between these modalities.

The findings of this study have implications for human-oriented pen use in pen based user interface design. This chapter provides pen-based interface designers with a general understanding of pen input modality in HCI (human computer interaction) field.

1.2 Background Knowledge

1.2.1 Pen Computing and Pen-based Interaction

Pen computing refers to a computer user-interface using a pen (or stylus) and tablet, rather than devices such as a keyboard and a mouse. Pen computing is also used to refer to the usage of mobile devices such as wireless tablet PCs, PDAs and GPS receivers. The term has been used to refer to the usage of any product allowing for mobile communication. An indication of such a device is a stylus, generally used to press upon a graphics tablet or touch screen, as opposed to using a more traditional interface such as a keyboard, keypad, mouse or touchpad.

Pen computing has very deep historical roots. Pen computing starts with the Stylator [26] and RAND tablet [38] systems of the 1950s and early 1960s. Benefit to pen computing, the direct manipulation interface, where visible objects on the screen are directly manipulated with a light-pen, was first demonstrated by Ivan Sutherland in Sketchpad [94], which was his PhD thesis. SketchPad supported the manipulation of objects using a light-pen, including grabbing objects, moving them, changing size, and using constraints. It contained the seeds of myriad important interface ideas. The system was built at Lincoln Labs with support from the Air Force and NSF. William Newman's Reaction Handler [70], created at Imperial College, London (1966-67) provided direct manipulation of graphics, and introduced "Light Handles," a form of graphical potentiometer, that was probably the first "widget." Another early system was AMBIT/G (implemented at MIT's Lincoln Labs, 1968, ARPA funded). It employed, among other interface techniques, iconic representations, gesture recognition, dynamic menus with items selected using a pointing device, selection of icons by pointing, and mode-free styles of interaction. David Canfield Smith coined the term "icons" in his 1975 Stanford PhD thesis on Pygmalion [93] (funded by ARPA and NIMH) and Smith later popularized icons as one of the chief designers of the Xerox Star [92]. Many of the interaction techniques popular in direct manipulation interfaces, such as how objects and text are selected, opened, and manipulated, were researched at Xerox PARC in the 1970's. In particular, the idea of "WYSIWYG" (what you see is what you get) originated there with systems such as the Bravo text editor and the Draw drawing program [35] The concept of direct manipulation interfaces for everyone was envisioned by Alan Kay of Xerox PARC in a 1977 article about the "Dynabook" [52]. The first commercial systems to make extensive use of Direct Manipulation were the Xerox Star (1981) [92], the Apple Lisa (1982) [103] and Macintosh (1984) [104]. Ben Shneiderman at the University of Maryland coined the term "Direct Manipulation" in 1982 and identified the components and gave psychological foundations [90].

Early attempts to use pen input were limited by the touch screen technologies. The first patent for an electronic tablet used for handwriting was granted in 1888 [36]. And the first patent for a system that recognized handwritten characters by analyzing the handwriting motion was granted in 1915 [37]. In the late 1980s, early pen computer systems generated a lot of excitement and there was a time when it was thought they might eventually replace conventional computers with keyboards. Pen computers, as envisioned in the 1980s, were built around handwriting recognition. In the early 1980s, handwriting recognition was seen as an important future technology. In 1991, the pen computing hype was at a peak. The pen was seen as a challenge to the mouse, and pen computers as a replacement for desktops. Microsoft, seeing slates as a potentially serious competition to Windows computers, announced Pen Extensions for Windows 3.1 and called them Windows for Pen Computing. However, pen computers did not sell well. Most of users found pen tablets difficult to use. A critical problem is the limited input capacity and difficulty to achieve natural and comfortable pen manipulation. As a result, a comprehensive understanding of pen input modalities has implication for designers to develop friendly pen interface both in increasing the input capacity and achieving natural and effective pen interaction.

1.2.2 Pen Input Modalities

The pen stylus is a wireless, pen-like device, and is activated by pressing its tip to the tablet. Being an input device, the pen has several different input modalities. The most basic input is the x-y coordinate position information of the pen tip. The tip points to a particular location on the active area of the tablet, and triggers the transmission of the X-Y coordinate data from the tablet to the application. This x-y coordinate information can support the common pen functions such as pointing, clicking, selecting, dragging, writing, drawing, gesturing, signing.

Besides, most of electronic stylus pens provide barrel buttons, with which user can realize click functions similar to mouse buttons. Some pens also provide eraser at the other end of the pen so that the eraser-aware applications can be supported.

The pen has also it specific input. For example, most of the pens have the function of hovering that the pen tip position information can be detected when the pen tip is out contact with the tablet surface. Thus, the pen click functions can be performed without touching the pen tip to the tablet surface.

In particular, some inherent input modalities such as pressure, tilt, and azimuth can be detected by most of pens. These additional input modalities could serve to increase the human-computer communication bandwidth, particularly when pen-based devices are used as pure slates with no keyboard.

We emphasize that a successful pen-based application must also include pen-based interaction techniques which are apt to pen characteristics. In views of computer operation pen-based interaction techniques have not been paid much attention on by researchers yet. Therefore, there is an urgent need to explore pen-based interactions coupling with pen devices characteristics and multiple input modalities, which enable the user to interact with pen-based devices in a natural way.

1.2.3 Models of Human Performance

A model is a simplification of reality. In human-computer interaction (HCI), models allow metrics of human performance to be determined analytically without undertaking time-consuming and resource-intensive experiments. Predictions of models allow a design scenario to be explored hypothetically without implementing a real system and gathering the same performance metrics through direct observation on real users. Therefore, models help in designing, evaluating, or otherwise providing a basis for understanding the behaviour of a complex artifact such as a computer system. Fitts' law, Steering law, and Weber-Fechner law are three fundamental models which are used in our researches. As these elements are used in the dissertation, it's necessary to understand these three models in the following sections.

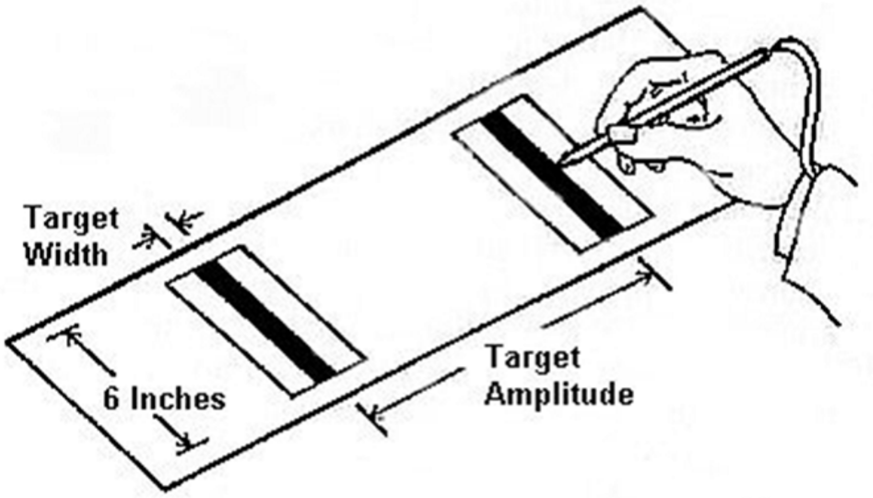

Fig. 1.2 The serial tapping task used by Fitts (1954) [30].

Fitts' law

Fitts' law is a model of human movement in human-computer interaction and ergonomics which predicts that the time required to rapidly move to a target area is a function of the distance and the size of the target [30]. Extending Shannon's theorem in information theory (a formulation of effective information capacity of a communication channel), Fitts discovered a formal relationship that models speed/accuracy tradeoffs in rapid, aimed movement (not drawing or writing). Fig. 1.2 shows one of Fitts' experiments to investigate human performance.

According to Fitts' law, the time to move and point to a target of width W at a distance A is a logarithmic function of the spatial relative error ($\frac{A}{W}$), that is:

$$MT = a + b\log_2(\frac{A}{W} + 1) \tag{1.1}$$

where MT is the movement time. a and b are empirically determined constants, that are device dependent. A is the distance (or amplitude) of movement from start to target center. W is the width of the target, which corresponds to "accuracy".

The term $\log_2(\frac{A}{W}+1)$ is called the index of difficulty (ID). It describes the difficulty of the motor tasks. 1/b is also called the index of performance (IP), and measures the information capacity of the human motor system. Mathematically interpreted, Fitts' Law is a linear regression model.

Fitts' law is an effective quantitative method of modeling user performance in rapid, aimed movements, where one appendage (like a hand) starts at a specific start position, and moves to rest within a target area. Card et al. [19] reported the first comparative evaluation of the mouse, and also the first use of Fitts' law in Human-Computer Interaction. MacKenzie [64] surveyed six studies and discussed the Fitts' law as a research and design tool in Human-Computer Interaction. In the same year, MacKenzie and Buxton [62] investigated the feasibility of extending Fitts' law to two-dimensional tasks.

Balakrishnan [11] surveyed research into new techniques for artificially facilitating pointing at targets in graphical user interfaces and gave suggestions that pointing in the virtual world did not necessarily have to abide by the constraints of Fitts' law, opening the possibility for "beating" Fitts' law with the aid of the computer by artificially reducing the target distance, increasing the target width, or both. McGuffin and Balakrishnan [65] reported research into using target expansion for facilitating selection and gave an examination of the issues involved in both untiled and tiled multiple expanding targets and present various design strategies for improving their performance. In recent years, Fitts' law becomes an intensively used theory in Human-Computer Interaction [50]. It has been used in assisting interface designs and in interface evaluation such as [13], [14], [15], and [21].

Steering law

The steering law is a predictive model of how quickly one may navigate, or steer, through a 2-dimensional tunnel. The tunnel can be thought of as a path or trajectory on a plane that has an associated thickness or width, where the width can vary along the tunnel. The goal of a steering task is to navigate from one end of the tunnel to the other as quickly as possible, without touching the boundaries of the tunnel. A real world example that approximates this task is driving a car down a road that may have twists and turns, where the car must navigate the road as quickly as possible without touching the sides of the road. The steering law predicts both the instantaneous speed at which we may navigate the tunnel, and the total time required to navigate the entire tunnel.

The steering law has been independently discovered and studied three times (Rashevsky in 1959 [82], Drury in 1971 [27], and Accot and Zhai in 1997 [1]). Its most recent discovery has been within the human-computer interaction community, which has resulted in the most general mathematical formulation of the law.

Within human-computer interaction, the law was rediscovered by Johnny Accot and Shumin Zhai [1], who mathematically derived it in a novel way from Fitts' law using integral calculus, experimentally verified it for a class of tasks, and developed the most general mathematical statement of it. The steering law has been verified with several input devices, such as the stylus, mouse, touchpad, and trackball in [119] and [2], and it has been verified in different scales [3]. Some studies such as [23], [75], and [100] also investigated the steering law in a variety of settings. Some researchers within this community have sometimes refer to the law as the Accot-Zhai steering law. In this context, the steering law is a predictive model of human movement, concerning the speed and total time with which a user may steer a pointing device (such as a mouse or stylus) through a 2D tunnel presented on a screen (i.e. with a bird's eye view of the tunnel), where the user must travel from one end of the path to the other as quickly as possible, while staying within the confines of the path. One potential practical application of this law is in modelling a user's performance in navigating a hierarchical cascading menu.

Many researchers in human-computer interaction, including Accot himself, find it surprising or even amazing that the steering law model predicts performance as well as it does, given the almost purely mathematical way in which it was derived. Some consider this a testament to the robustness of Fitts' law.

In its general form, the steering law can be expressed as

$$T = a + b \int_C \frac{ds}{W(s)} \tag{1.2}$$

where T is the average time to navigate through the path, C is the path parameterized by s, $W(s)$ is the width of the path at s, and a and b are experimentally fitted constants. In general, the path may have a complicated curvilinear shape (such as a spiral) with variable thickness $W(s)$.

Simpler paths allow for mathematical simplifications of the general form of the law. For example, if the path is a straight tunnel of constant width W, the equation reduces to

$$T = a + b\frac{A}{W} \tag{1.3}$$

where A is the length of the path. We see, especially in this simplified form, a speed-accuracy tradeoff, somewhat similar to that in Fitts' law.

We can also differentiate both sides of the integral equation with respect to s to obtain the local, or instantaneous, form of the law:

$$\frac{ds}{dT} = \frac{W(s)}{b} \tag{1.4}$$

which says that the instantaneous speed of the user is proportional to the width of the tunnel. This makes intuitive sense if we consider the analogous task of driving a car down a road: the wider the road, the faster we can drive and still stay on the road, even if there are curves in the road.

Weber-Fechner law

The Weber-Fechner law attempts to describe the relationship between the physical magnitudes of stimuli and the perceived intensity of the stimuli. Ernst Heinrich Weber (1795-1878) was one of the first people to approach the study of the human response to a physical stimulus in a quantitative fashion. Gustav Theodor Fechner (1801-1887) later offered an elaborate theoretical interpretation of Weber's findings, which he called simply Weber's law.

E. H. Weber (1795-1878) described the relationship between the physical magnitude of stimuli and the perceived (subjective) intensity of the sensation. Given the difficulties inherent in estimating the absolute strength of sensations, Weber operationalized the perception of stimulus change in intensity by mental comparison of two or more sensations. These sensations include the perception of weight, vision, sound, and numerical cognition. Perceptual comparison allows one to discern the minimal physical difference in stimulus intensity that produces a detectable change in sensation (i.e., the difference threshold [101]).

Weber's law states that the ratio between the difference threshold and the background stimulus intensity is a constant. Or, the change in a stimulus that will be just noticeable is a constant ratio of the original stimulus. For example, when you are in a noisy environment you must shout to be heard while a whisper works in a quiet room. And when you measure increment thresholds on various intensity backgrounds, the thresholds increase in proportion to the background. In its general form, the Weber's law can be expressed as

$$K = \frac{\Delta I}{I} \tag{1.5}$$

The fraction ΔI/I is known as the Weber fraction. If we rearrange the equation to ΔI=I × K, Weber's Law predicts a linear relationship between the increment threshold and the background intensity.

The law was originally postulated to describe researches on weight lifting by Weber in 1834 and was later applied to the measurement of sensation by Fechner, who went on to develop from the law the science of psychophysics. The combined work of Weber and Fechner has been useful, especially in hearing and vision research, and has had an impact on attitude scaling and other testing and theoretical developments such as [57], [113], and [22].

1.3 Research Objectives

This research attempts to comprehensively understand the pen input modalities with empirical methodology.

The primary problem of the research is to investigate the pen pressure, tilt, and azimuth use profiles when human naturally writes. This investigation can provide pen-based interface designers a practical foundation on which pen input modalities ranges human feel comfortable and natural to manipulate the pen, with which more friendly user interface could be designed. Thus, the natural pen modalities distributions should be investigated both in static and in dynamic conditions. Moreover, the influence of input contents, input size, and input position on pen modalities use profiles will be explored. Besides, in real applications, two or more pen input modalities are often used in tandem. Whether there exist covariations between these input modalities will also be explored. Chapter 2 is seeking to settle these questions.

The number of levels into which the pen pressure space is divided determines the number of states in the multi-state widgets. Traditionally, the whole pen pressure space is divided into equal levels and the optimal number of pen pressure division is 6. However, even division will not likely afford optimal usability because human ability to control different levels of pen pressure varies over all levels. To increase the optimal number of divisions of the pen pressure space and achieve greater pen pressure usability, we will propose a new discretization method. This will be addressed in chapter 3.

Pen tilt and azimuth are seldom investigated modalities. The human ability to control these modalities remains unknown. Moreover, whether Fitts' law and steering law are still valid in pen tilt and azimuth manipulation is still unexplored. These issues will be handled in chapter 4 and 5.

Up to now, no literature comparatively investigated the performance of all three input modalities (pressure, tilt, and azimuth). Particularly, for a trajectory task, which modality works better is known. This comparative study will be conducted in chapter 6 with a concrete application using these modalities.

In summary, the investigation and exploitation of pen's potential is still in its infancy, particularly the characteristics of inherent input modalities of stylus pens. This dissertation will focus on the investigation of human abilities to control these three pen input modalities and find natural, comfortable, and efficient way to utilize these modalities in pen based interface designs. These investigations will try to establish guidelines for pen based interactions of HCI research and design.

This dissertation will fill the gaps in the world on: 1) investigation of pen modalities distributions; 2) human abilities to control pen tilt and azimuth.

1.4 Dissertation Outline and Structure

This dissertation is concerned with study of three kinds of inherent pen input modalities (pressure, tilt, and azimuth) for pen-based interaction and interrelated design factors that influence human performance. Specific investigations of these three pen input modalities are conducted. Detailed contents are distributed in the various chapters as follows:

Chapter 1 is the general presentation of the research and background knowledge introduction.

Chapter 2 in this dissertation generally explores human natural use profiles of all three pen inherent input modalities: pressure, tilt, and azimuth (PTA below). This chapter systematically investigates natural and non-controlled PTA use. Results show that PTA use profiles fitted Gaussian distribution whereas averages, standard deviations and spans varied. Size and position conditions significantly affected PTA use profiles. Covariations were found between PTA.

Three experiments are reported in Chapter 2. Exp. 1 explored the PTA use profile when users naturally held the pen before starting to write; Exp. 2 explored the PTA use profile when users naturally wrote characters in different sizes; Exp. 3 explored the PTA use profiles and the covariations between PTA when users naturally wrote characters in different positions. Chapter 2 are tested foundation of the following chapters.

Chapter 3 is dedicated to study the pen pressure. Based on the results of chapter 2, a new adaptive pen pressure discretization method based on personal use profile is proposed. This chapter presents four variations of the method: discretization according to personal/aggregation pen pressure use profile with/without visual feedback of uniform level widths and the traditional even discretization method. Experiments are conducted to comparatively evaluate the performance of these methods.

With the new proposed method, the optimal number of divisions of the pen pressure space is 8. However, with traditional even discretization method, the optimal number of divisions of the pen pressure space was 5. It means that more pen pressure levels are discerned with the new method.

Chapter 4 investigates human ability to control pen tilt according to static and dynamic pen tip conditions. Two experiments along with quantitative and qualitative analysis are conducted to investigate tilt acquirement and tilt pointing.

This chapter concludes that (1) the narrower the target tolerance is, the more time subjects need to acquire the target; the tilt pointing tasks fits the Fitts' Law; and (2) human can easily and effectively control pen tilt during tilt acquiring, tilt pointing and tilt steering tasks when tilt interval equals 30°.

Chapter 5 specially investigates the human ability to control pen azimuth. An experiment along with quantitative and qualitative analysis is conducted to investigate pen azimuth acquirement and azimuth stroking respectively. This chapter is by far the first study to systematically investigate the pen azimuth in respect of human control ability.

This chapter concludes that the narrower the target azimuth tolerance is, the more time subjects need to acquire the target; and that the performance of azimuth targets in due directions are much better than in oblique direction; and that south-east is worse because of the occlusion by hand; and that when pen azimuth interval is beyond 60 degrees, it is easy for human to manipulate.

Chapter 6 comprehensively and comparatively investigated each pen input modality for precision parameter manipulations during trajectory tasks. This chapter firstly solves a common problem in pen-based interaction: since pen tip information is confined to x-y coordinate data, concurrent parameter adjustment is not easily accomplished in devices using only a pen tip. Then the performance of inherent pen input modalities and

Key Pressing with the non-preferred hand used for precision parameter manipulation during pen sliding actions are investigated.

In this study, pen pressure enabled the fastest performance along with the lowest error rate, while azimuth exhibited the worst performance. Tilt showed slightly faster performance and achieved a lower error rate. The experimental results afford a general understanding of the performance of inherent pen input modalities in the course of a trajectory task.

Chapter 7 is the general conclusion of the dissertation. Moreover, this chapter prospects the possible future directions of the study.

Fig. 1.3 shows the structure of the dissertation.

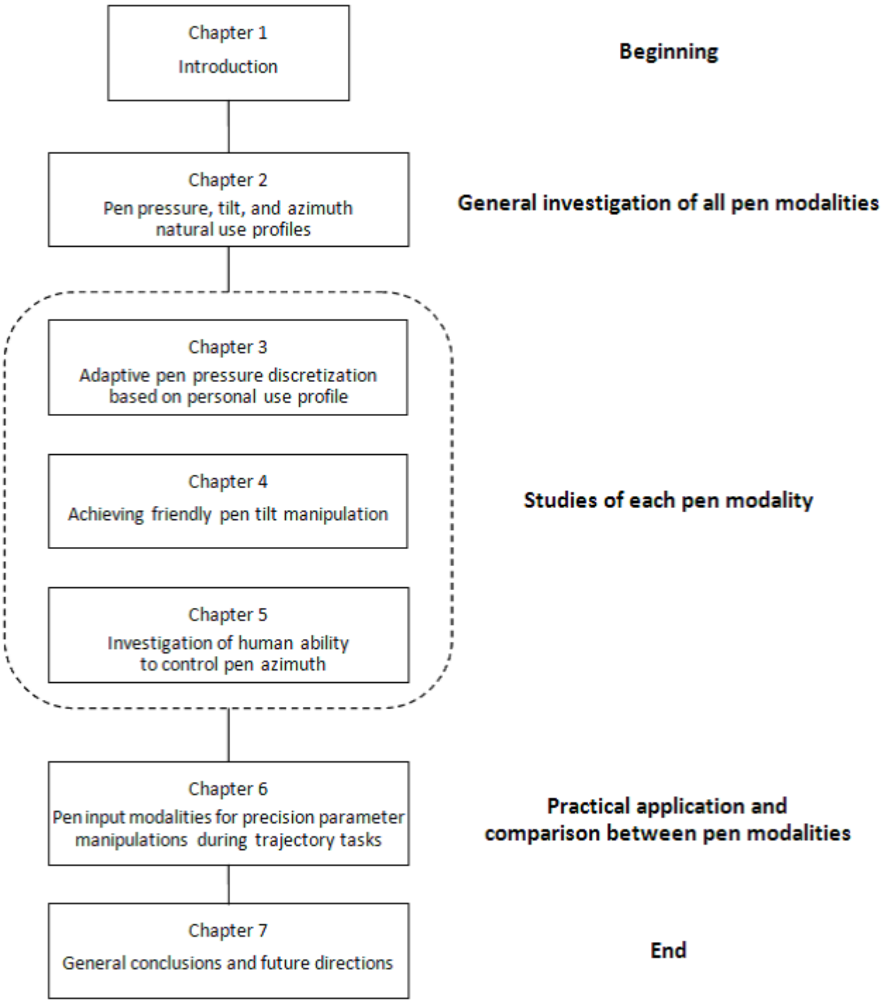

Fig. 1.3 The structure of the dissertation.

Chapter 2

Pen Pressure, Tilt, and Azimuth Natural Use Profiles

2.1 Introduction

The stylus-pen is taken more seriously and is more favored than other input devices such as keyboards and mice in many user environments due to pen's portability, outdoor availability, short learning curve, and ease of manipulation. However, the pen's throughput capacity is considerably inferior to the keyboard's because the pen's potential input channels have not been fully developed, and this makes some pen-based designs such as mode switching very difficult to realize. Fortunately however, besides x-y coordinate pen tip information, most pens provide other inherent input modalities such as pressure, tilt and azimuth (PTA below). These PTA could enhance pen input and support concurrent pen manipulations.

However, how to rationally utilize these PTA is still an open question. Although pens have their PTA spaces, not all PTA values can be easily controlled by users because of the structural limitations of human hand and because of personal pen use habits. There must be some common and rare PTA ranges within which users *naturally* manipulate the pen. And these common/rare PTA ranges can be defined for different uses, for example, to realize rational mode switching. Moreover, the inherent human ability to control each PTA value should be different, which to a certain extent can be reflected by the frequencies of each PTA value during *natural* human pen manipulations. Because continuous PTA values often need to be discretized or mapped to a concrete control, a quantified understanding of pen PTA use profiles could contribute to the process of discretization, mapping, and selecting rational PTA thresholds.

On the other hand, in real applications, two or more pen input modalities are often used in tandem. However, very little literature is available that provides us with a theoretical and practical basis showing whether covariations exist between PTA and whether the PTA use profiles change according to input positions and input contents. Since pen technique is still at the initial stage of development, these basic insights of PTA use profiles could help designers design more efficient interfaces and provide pen-based interface designers a tested foundation. In this light, we quantitatively investigates *natural* PTA use profiles and the covariations between PTA.

Three experiments are presented. PTA use profiles will be quantized by calculating the PTA distributions through sampling the PTA values when subjects perform tasks in these three experiments. In the first experiment, PTA use profiles were investigated in conditions where subjects *naturally* and formally hold the pen before starting to write. This experiment aimed at investigating the initial state of PTA when subjects begin to use the pen. In the second experiment, PTA use profiles were investigated in conditions where subjects *naturally* write three kinds of characters (symbols, letters, and Chinese characters) in 7 character sizes. PTA distributions, commonly/rarely used PTA ranges, PTA averages and standard deviations are reported in Experiments 1 and 2. In the third experiment, the PTA use profiles were investigated in conditions where subjects *naturally* write the same characters as in Experiment 2 but in varied input positions. Moreover, we investigated the possibility that covariations exist between PTA in Experiment 3.

2.2 Related Work

We review the literature in two related areas: the first is pressure; the second includes tilt, azimuth, and rolling.

2.2.1 Pressure

Literature related to pen pressure emerged mainly after the new Millennium, and most focused on novel interactive application designs. Mizuno et al. [68] implemented a virtual sculpting system by converting pen pressure to carving depth and angle. Ramos and Balakrishnan [78] proposed a concept prototype designed for use with pressure-sensitive digitizer tablets to fluidly navigate, segment, link, and annotate digital videos; they also created the Zlider [79] which permits users to use pen pressure to achieve fluid zooming while sliding the pen; and they developed pressure marks [80] that allowed users to perform a selection and an action simultaneously by stroking the pen and changing the pen pressure at the same time.

Some research focused on increasing the input bandwidth by means of pen pressure. Harada et al. [44] used pen pressure as an input modal to augment simultaneous input capacity. Ren et al. [86] proposed the Adaptive Hybrid Cursor to facilitate target selection performance by automatically adjusting cursor size according to pen pressure. Yin and Ren [112] proposed a zoom-based technique to improve pixel-target selection, in which pressure is used as a mode switch.

Besides, some studies have hinted that pen pressure has intrinsic potential that invite special evaluation. To assist in biometric personal identification and digital signature verification, Hook et al. [49] added pressure sensors to a pen for 3D pressure analysis of handwritten characters, words and signatures. Oviatt et al. [72] investigated implicit user adaptive engagement via speech amplitude and pen pressure cues and found that users tended to clarify engagement by increasing the pen pressure.

There were also some studies that focused on exploring the human ability to control pen pressure. Ramos et al. [81] investigated the human ability to perform discrete selection tasks by controlling stylus pressure and found that dividing pressure space into 6 levels resulted in optimal controllability. Mizobuchi et al. [67] further explored the force-based input on handheld devices and found that within the force range 3N, somewhere between 5 and 7 levels of force might be appropriate for accurate discrimination. Li et al. [61] investigated five techniques for switching between ink and gesture modes in pen interfaces, including a pen-pressure based mode switching technique that allowed implicit mode transitions.

2.2.2 Tilt, Azimuth, and Rolling

Compared to the studies on pen pressure, few studies focused on the exploration of pen tilt, azimuth, and rolling. Tilt cursor [98] dynamically reshapes itself to provide the 3D orientation cue of pen so that the stimulus-response compatibility is enhanced. Another technique, Tilt Menu [99], extended the selection capabilities of pen-based user interfaces using 3D pen orientation information. Kuroki and Kawai [55] observed that people hold three physical tools (a syringe, a pen, and a cutter) differently and proposed the use of tilt information for pen interfaces based on this observation. Oshita [71] designed a virtual human figure movement manipulation system that used not only pen pressure but also pen tilt to control a virtual human figure. Bi et al. [16] explored pen rolling around the longitudinal axis of the pen and distinguished between the intentional and incidental pen rolling while users manipulating a pen. Xin et al. implemented a angle widget to manipulate high precision parameters [106]. Xin and Ren investigated the direct and indirect pen tilt input with different visual feedbacks [107]. Xin et al. conducted a comparative study to investigate the pen pressure and tilt in precision parameter manipulation [105]. Xin and Ren investigated the combination of panning and zooming in pen-based interaction [108]. In the widget, zooming is implemented by utilized the pen pressure, tilt, and orientation information whereas panning was implemented by pen sliding.

Besides pen tilt, device tilt was also used as an input mode. Rekimoto [84] presented an interaction technique that used variations in the tilt of a small screen device as input commands. TiltType [74] and TiltText [102] were text entry techniques for mobile devices. The tilt direction and angle of the mobile device were used to aid character selection among a range of given candidates.

2.2.3 Movement Control of Finger, Hand, Wrist, and Forearm

In 1956, two discrete prehensile patterns of hand movement were analyzed form both the anatomical and functional points of view and were termed precision grip and power grip by Napier [69]. In 1966, Hammerton and Tickner [43] measured performance of subjects on a set of 2-dimensional velocity control acquisition tasks when the control was operated by thumb, hand, and forearm. In 1991, Pang et al. [73] investigated the manual discrimination of force using active finger motion. In 1992, Tan et al. [95] investigated the manual resolution of length, force, and compliance. In 1994, Tan et al. [96] investigated the human factors for the design of force-reflecting haptic interfaces. In 1996, Zhai et al. [117] investigated the influence of muscle groups on performance of multiple degree-of-freedom input. In 1997, Balakrishnan and MacKenzie [10] investigated performance differences in the fingers, wrist, and forearm in computer input control. In 2007, Tan et al. [97] investigated the human ability to discriminate and identify finger joint-angle positions using active motion.

Although the aforementioned works explored the utilization of pen input modalities, several aspects remain unexplored: (1) No literature quantitatively investigated *natural* PTA use profiles that resulted in the determination of initial or threshold values further resulting in a lack of efficiency in some designs; (2) Most studies mentioned above investigated only one pen modality, and few comprehensively investigated all three modalities; (3) No literature considered the influence of input position, size, or content on PTA; (4) No evaluations of the covariations between modalities, which are essential if combined use of multiple modalities are to be fully exploited, have ever been investigated. In summary, our review indicates that *natural* PTA use profiles are ripe for systematic investigation. The findings of this study have implications for human-oriented pen use in PTA based user interface designs.

2.3 EXPERIMENT 1 (STATIC PART)

2.3.1 Goals

The goals of the experiment were to investigate the default ranges and spans of PTA when users *naturally* place the pen in contact with the tablet display surface.

2.3.2 Participants

Three female and seventeen male volunteers, ranging in age from 21 to 33, participated in the experiment. To minimize experimental bias due to differences between left and right hand dominant subjects, we ensured that all participants were right-handed according to their own report.

2.3.3 Apparatus

A Wacom Cintiq 21UX interactive LCD graphics display tablet and a wireless stylus with an isometric tip were used in the experiment. The Cintiq 21UX can detect the pressure that a user exerts on the stylus tip from 1 to 1023 levels which corresponds to the force range of 0 to 4 Newtons. If the pen pressure level is over 1023, it is recognized as 1023. The Cintiq 21UX can also detect the tilt angle of the stylus which ranges from 30° to 90° (When the stylus is perpendicular to Tablet surface, the tilt value is 90 degrees). The azimuth of the pen can also be detected by the Cintiq 21UX ranging from 0 to 359 degrees clockwise from the northerly direction.

The experimental program was designed in the Java Environment and ran on a 2.13 GHz Intel Core2 CPU PC with Windows XP Professional SP2. The resolution of the display was set to 1280 by 1024 pixels at 96 dpi (0.27 mm per pixel).

2.3.4 Task and Procedure

Subjects were seated in front of the display tablet which was placed in the horizontal plane. The display edge paralleled the subject's body. In order to avoid the influence of different landing positions on PTA use profiles, a fixed circular input area was shown at the center of the tablet display surface with a diameter of 60 pixels. Subjects were instructed to *naturally* place the pen tip in contact with the tablet display surface with the pen tip fixed within the input area and then to keep the pen tip contact with the surface for 2 seconds so that the pen pressure, tilt and azimuth could be sampled and recorded. A time bar was shown to give subjects a visual cue. Every subject did 20 trials in this experiment. In total, the experiment consisted of 400 trials.

2.3.5 Results

If a pen technique is designed utilizing pen modalities such as pressure, tilt, and azimuth, designers need to know information about pen modalities such as commonly used regions, averages, spans, and rarely used regions. They are crucial to determining the initial values and selecting rational thresholds so that users can manipulate the pen naturally and effectively. Moreover, rarely used regions are useful for switching between ink mode and control mode.

In order to know these commonly used regions, spans, and rarely used regions, we must ensure the pen modalities distributions firstly. According to [24], many measurements, ranging from psychological to physical phenomena can be approximated by Normal (Gaussian) distribution in varying degrees. Thus we explored whether PTA distributions also matched Gaussian distributions.

Results showed that for pen pressure, pen tilt and pen azimuth, p-values of Gaussian distribution hypothesis were 0.59, 0.63, and 0.57 respectively which were greater than the level of significance of 0.05. Thus we could not reject the Gaussian distribution hypothesis. Anderson-Darling normality analysis showed that the Skewness and Kurtosis of Gaussian distribution for pressure, tilt and azimuth were (0.64, 0.02), (0.09, 1.22) and (-0.30, -0.58) respectively. Finally, R-squares were given through a further Gaussian distribution regression analysis. Fig. 2.1 illustrates the results.

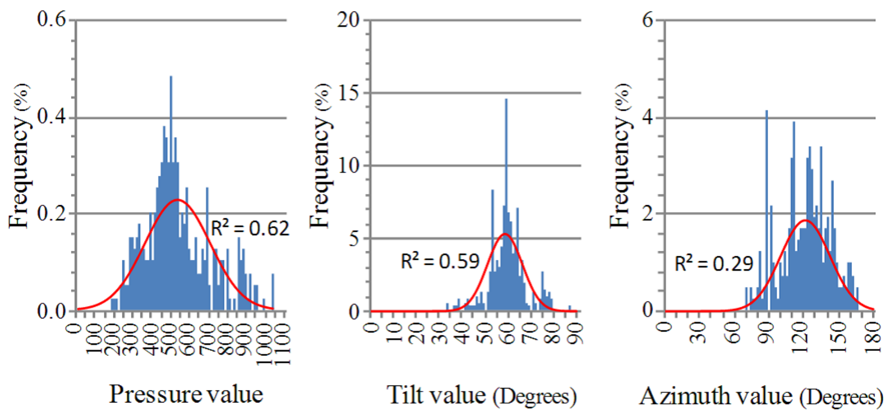

Fig. 2.1 PTA Distributions and Gaussian regressions.

According to the Gaussian distribution, 95% of the sample will fall into the regions of two standard deviation (SD) intervals around the mean value. Thus, the PTA intervals of two standard deviations of the means indicate the default regions when subjects *naturally* placed the pen in contact with the tablet surface (See Fig. 2.2).

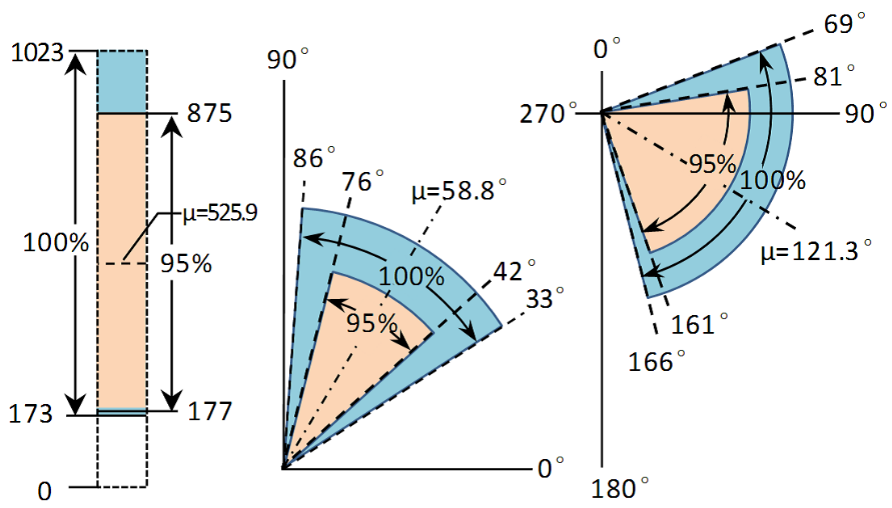

Fig. 2.2 Spans of pen modalities in static situations. From left to right: pen pressure, pen tilt, and pen azimuth. μ represents average pen modality value.

2.3.6 Discussion

As for the experimental device, 1024, 61 and 360 available levels could be detected for pen pressure, pen tilt and pen azimuth respectively. However, only 83%, 88%, and 27% of available pen pressure, pen tilt and pen azimuth space were used during the experiment. The results which reveal PTA ranges may help pen based interface designers improve the performance of their designs. For example, the boundaries of the 2-SD intervals can be used to *naturally* trigger modes. Moreover, if all three PTA 2-SD intervals are taken into account simultaneously, miss-switching rates may be significantly reduced.

For PTA users, it is very difficult to distinguish the change between two adjacent PTA units according to Weber's Law. Thus, dividing PTA space into several intervals or defining the trends of PTA changes may be a more appropriate way to exploit PTA.

Pen pressure was based only on the force users exert on the pen tip, no matter what the pen position, tilt and azimuth were. Thus, pen pressure can be used with any pen gesture. However, pen tilt and azimuth are directly and intrinsically related to pen gestures. Different pen gestures will result in different pen tilt and pen azimuth. Moreover, because of the way the pen is grasped and also because of the physiological hand structure, some special tilt and azimuth gestures were quite difficult to achieve. On the other hand, the pen provides visual feedback about present tilt and azimuth, so users can roughly estimate pen tilt and pen azimuth by both visual and tactile senses. However, it is very difficult for users to estimate pen pressure by tactile sense alone.

2.4 EXPERIMENT 2 (DYNAMIC PART: DIFFERENT SIZES)

2.4.1 Goals

The second experiment investigated PTA use profiles when subjects *naturally* wrote on the tablet display surface in different character sizes.

2.4.2 Design

An informal pilot experiment indicated that when the sizes of characters being written varied, mean pen pressure also varied. In order to investigate the influence of character size on PTA use profiles, seven character sizes which were 50, 100, 200, 400, 600, 800, and 1000 pixels in length were investigated in the experiment.

Because varied writing contents cannot provide a uniform measure of PTA use profiles, arbitrary writing and drawing were not included in the experiment. Nevertheless, we wanted to marginally investigate drawing by input pictographic characters. So, we deliberately chose the characters which were to be written in the experiment. Firstly, we selected Roman characters and symbols which are widely and commonly used. Secondly, we chose Chinese characters as a type of input character because Chinese characters are pictures depicting real world objects and events or graphs that directly represent ideas. Chinese characters contain most basic strokes such as points, lines, turns, crosses, and arcs. Thus, the structure and complexity of Chinese characters were also explored.

2.4.3 Participants and Apparatus

The same 20 individuals who participated in Experiment 1 took part in Experiment 2. And the same apparatus was used as in Experiment 1. All the subjects were familiar with the Chinese characters used in the experiment and were able to write them freely.

2.4.4 Task and Procedure

Subjects were instructed to write three types of characters in seven character sizes on the tablet display which was placed in the horizontal position. Chinese characters were classified by structure and complexity. The characters included:

Symbols: @, ☆, &, ×,

Letters: S, E, M, B,

Chinese characters: (See Table 2.1).

Table 2.1 Chinese characters are classified by structure and complexity.

Structure / Complexity	**Left-to-right**	**Mixed**	**Top-to-bottom**
Simple (1~5 strokes)	人 (2 strokes)	中 (4 strokes)	之 (3 strokes)
Medium (6~10 strokes)	如 (6 strokes)	我 (7 strokes)	宜 (8 strokes)
Complex (beyond 10 strokes)	橘 (16 strokes)	幾 (12 strokes)	蜜 (14 strokes)

Once the experiment started, the character that the user should write was shown in the upper left corner of the display in the font size 36. At the same time, a translucent green square writing area was displayed in different sizes at the center of the display. Subjects were told to write characters as large as the current square size. After each character was finished, subjects needed to press the space bar of the keyboard to switch to another character. Each character in the same condition was repeated 2 times. All characters were mixed and counterbalanced in random order. In summary, the experiment consisted of:

20 participants ×

17 characters ×

7 scales ×

2 repetitions

= 4760 trials.

2.4.5 Results

Experiment 2 took an average of 45 minutes. During the experiment, pressure, tilt and azimuth were sampled every 10 ms when the pen was in contact with the tablet display surface. As a whole, 390,317 records of data were collected.

PTA Distributions

Anderson-Darling analysis showed that the Skewness and Kurtosis of Gaussian distribution are (-0.892, 1.026), (-0.096, 0.018), (-0.323, 5.303) for pressure, tilt and azimuth respectively. R-squares were given through a further Gaussian distribution regression analysis (See Fig. 2.3).

From Fig. 2.3 we found some special values. For pressure, the frequency of value 1023 was extraordinarily high compared to the others. That was because when the

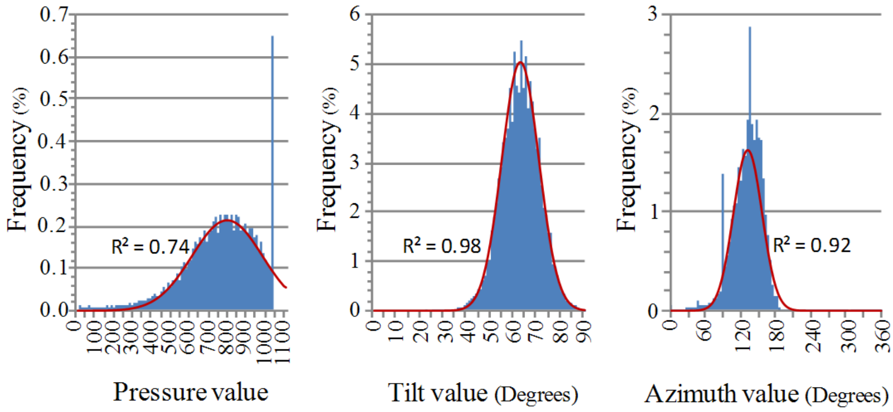

Fig. 2.3 PTA Distributions and Gaussian regressions.

pressure was equal to or more than 1023, the pressure was recognized as 1023. In this situation, the average and standard deviations of pen pressure being calculated from sample space were less than the real average and standard deviations. In order to achieve a more accurate regression and forecast the frequencies of those pressure values which were more than 1023, pressure regression analysis was also performed without the pressure item of 1023. After we removed the pressure item of 1023, R-square of pressure Gaussian distribution regression rose to 0.98.

Pressure had another special aspect worth mentioning. Results show that pen pressure distribution looked like dual Gaussian distributions with the same average but different standard deviations. We suspected this phenomenon was made by the device manufacturer because subjects never wrote deliberately all the time. A series of further informal explorations found that the phenomenon always existed when pen pressure was sampled. Some specific pressure frequencies were always higher than those around them. An extraordinarily higher frequency followed by five normal frequencies, and then two extraordinarily higher frequencies followed by five normal frequencies, which caused the dual Gaussian distribution (See Fig. 2.4).

Although the tilt value range stated by the manufacturer was from 30 to 90, tilts

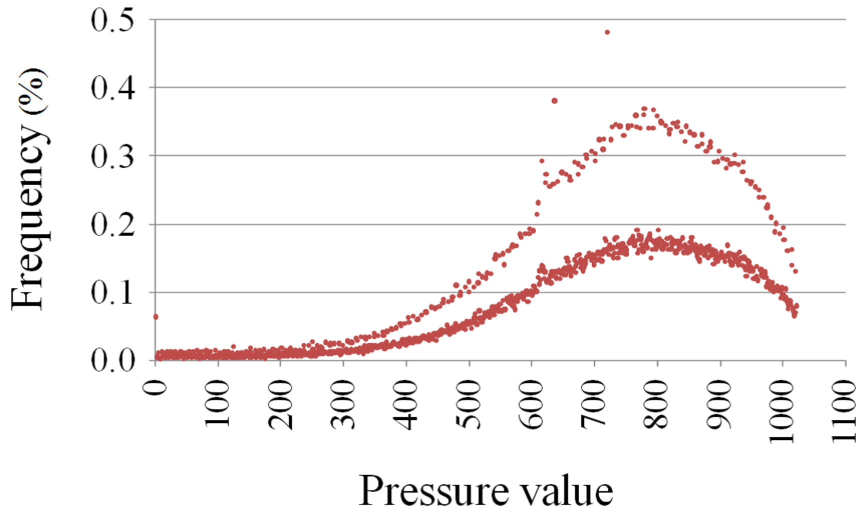

Fig. 2.4 Dual Gaussian distributions of pen pressure. (Pressure item 1023 is removed because of exceedingly high frequency.

from 22 to 29 were also detected. However, tilts from 22 to 29 were difficult to detect because the pen tip often lost contact with the tablet surface. Frequency of tilt from 22 to 29 was only 0.02% in our experiment.

Although all PTA units appeared in the experiment, PTA frequencies in some ranges were very low. For example, frequency of azimuth range [225, 359] was only 0.1% (See Fig. 2.5).

Comparison between Static Holding and Dynamic Writing

Analysis of variance showed a significant main effect for static holding and dynamic writing on pressure ($F_{1,19} = 31.71$, $p < .001$). However, there was no significant main effect on tilt ($F_{1,19} = 2.93$, $p = 0.10$), or azimuth ($F_{1,19} = 3.79$, $p = 0.06$).

Because the force of friction is directly proportional to the magnitude of the normal force, subjects must press the pen tip so that friction force between the pen tip and the tablet display surface is enough to enable writing. In static situations however, subjects

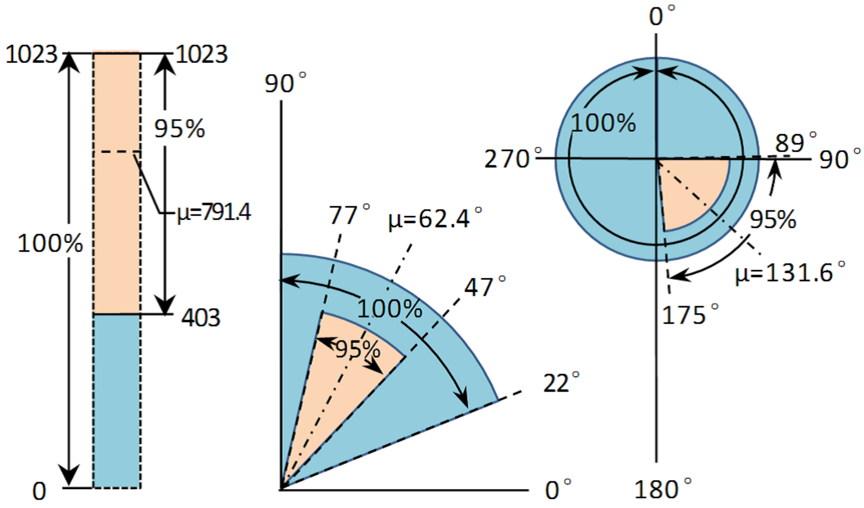

Fig. 2.5 Spans of pen modalities in dynamic writing situations. From left to right: pen pressure, tilt and azimuth.

need not press the pen intentionally with extra force. That is a possible reason why the average pressure in static situations was less than in dynamic situations.

On the other hand, according to the physical structure of the hand and the habitual way the pen is manipulated, both tilt and azimuth should show no major changes in *static* or *dynamic* situations for a specified subject. Nevertheless, the handwriting style of each subject is unique. For example, some preferred rising strokes whereas others preferred to form top-down strokes when they formed the same character radicals.

Size Condition

Repeated measures ANOVA revealed a significant main effect for *character size* on pressure ($F_{6,114} = 155.34$, $p < .001$), tilt ($F_{6,114} = 7.62$, $p < .001$) and on azimuth ($F_{6,114} = 2.59$, $p < .05$). *Post hoc* pair-wise comparisons showed that all *character size* pairs were significantly different on pressure, and that character size 50 was significantly different from other character sizes on tilt, and that character size 100 was significantly different from other character sizes on azimuth. Fig. 2.6 illustrates the results. Span in Fig. 2.6 or other figures in the paper represented two standard deviations interval around the mean value.

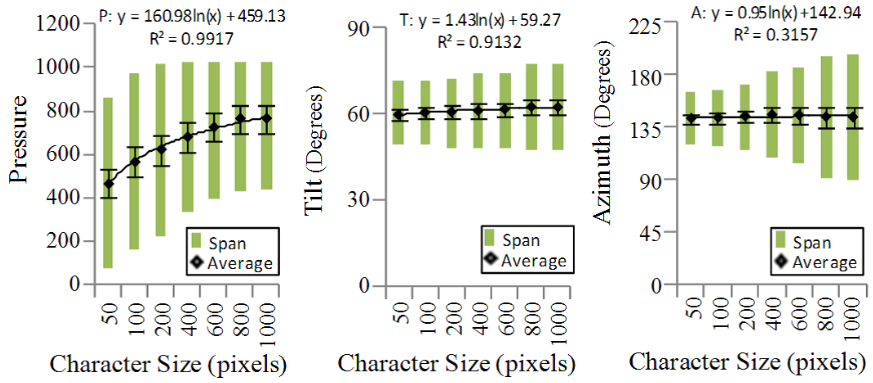

Fig. 2.6 Averages and spans of PTA for each character size condition when subjects wrote naturally.

Results also showed strong fits: regression analysis of PTA by *character size* yielded Logarithmic formulations. Along with the increase in *character size*, average pressure increased rapidly and was stable at around 763 when character size was more than 800 pixels. However, average tilt and average azimuth did not show steady increases or steady decreases. The gap between the lowest and highest average tilt was 2.77 degrees and the gap between the lowest and highest average azimuth was 3.23 degrees.

The possible reasons for pressure variations according to different character sizes were as follows. Firstly, when subjects wrote characters in different sizes, the main muscle groups used to exert force might be different. As the writing size of the characters increased, the muscle/tendon groups applied to the writing task changed from finger and hand muscles/tendons for small characters to include arm muscles for large characters. This coincided with the findings of [10], [43], [69], and [117]. Secondly, the support points of the arms and hands were different when subjects wrote different sizes of characters. When subjects wrote small characters, palms and forearms played the supporting role.

However, when subjects wrote bigger characters, elbows played the supporting role, and sometimes the whole arm was suspended in the air. Thirdly, the psychological expectations of subjects might be different. In order to slide a distance long enough to write bigger characters, subjects would subconsciously exert larger force on the pen tip.

After subjects completed the experiment, they were asked "on which do you think you exerted higher average pressure on the pen tip, bigger or smaller characters?" Interestingly, 16/20 of them answered that writing smaller characters needed higher pressure, which was contrary to the actual experimental results. Moreover, they also believed that they exerted higher pressure on the pen to write complicated characters than to write simple ones, which was also contrary to the experimental results as illustrated below. They thought that "writing small characters made me feel complex because the writing area is limited. I must pay more attention to the details of the characters, which made me exert more force when writing small characters." "I felt very relaxed when writing bigger characters, so I didn't need to exert higher force". This indicates that subjects were concerned more about the mental "tension" in the process of writing than about the physical force they actually exerted.

The disaccord of actual force and subjective feeling was interesting. According to Weber's Law, the change in a stimulus that will be just noticeable is a constant ratio of the original stimulus. In the same writing task, only the character sizes changed, and thus resulted in illusions of extra force exertion. We believed that the illusions might be caused by force sense JND differences from the fingers, arm, and forearm. When writing larger characters, more powerful muscle groups were used.

Character Type Condition

Repeated measures analysis of variance showed a significant main effect for *character type* on pressure ($F_{2,38} = 66.87$, $p < .001$) and on azimuth ($F_{2,38} = 11.24$, $p < .001$). However, there was no significant main effect for *character type* on tilt ($F_{2,38} = 2.75$, $p = 0.08$). Furthermore, the average tilt was about 63 degrees for each *character type*. *Post hoc* pair-wise comparisons show significant differences on pressure for all *character type* pairs, and on azimuth between Chinese characters and the other two character types. Fig. 2.7 illustrates the results.

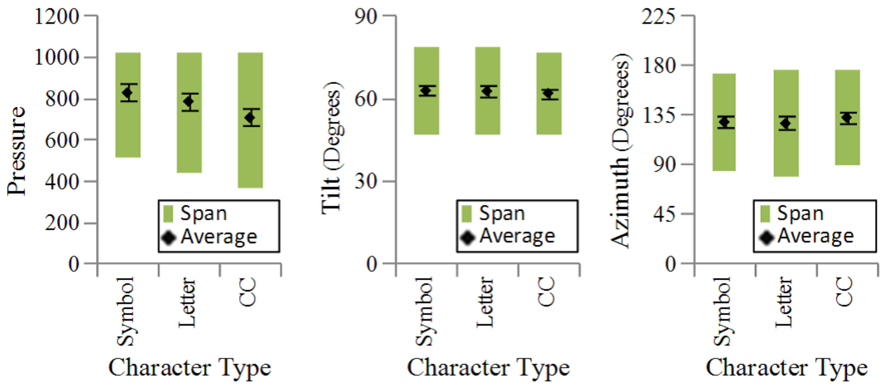

Fig. 2.7 Averages and spans for each character type condition when subjects wrote naturally. CC means Chinese characters.

The possible reason for pressure differences in different *character type* conditions is that the writing of symbols requires fewer pauses than the writing of letters and Chinese characters, thus subjects can write more freely and need not pay so much attention to the details when writing symbols. Conversely, if there were too many pauses, for example when writing Chinese characters, it would be impossible for subjects to exert more pressure for fear that they would write characters inconsistent with their original shapes. Further analysis found that the longer a continuous stroke was, the more pressure the user usually exerted.

Chinese Character Complexity Condition

Repeated measures analysis of variance showed a significant main effect for *Chinese character complexity* on pressure ($F_{2,38} = 39.74$, $p < .001$) and on azimuth ($F_{2,38} = 19.17$, $p < .001$). However, there was no significant main effect for *Chinese character complexity* on tilt ($F_{2,38} = 1.87$, $p = 0.17$). *Post hoc* pair-wise comparisons of *Chinese character complexity* showed significant differences on pressure for all pairs, and on azimuth between complex Chinese characters and the other two complexities of Chinese characters. Fig. 2.8 illustrates the results.

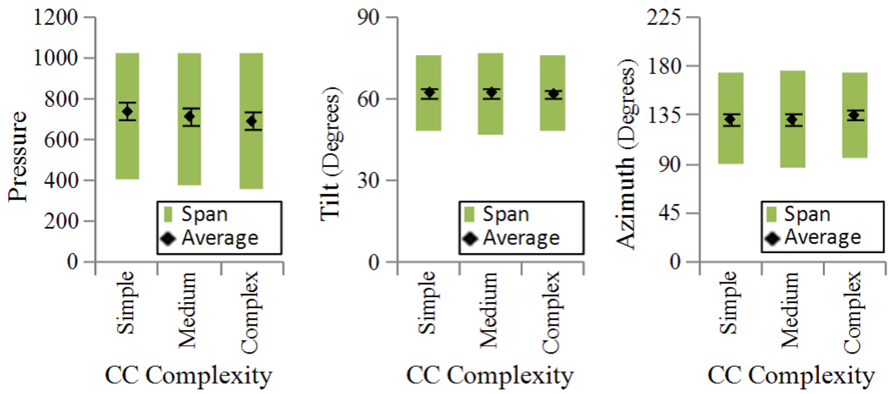

Fig. 2.8 Averages and spans for each Chinese character complexity condition when subjects wrote naturally. CC means Chinese characters.

The results show that subjects exert less pressure when writing complex characters. The possible reason is that the more complicated a character was, the more cautious the subjects became because they wanted to write the characters accurately and consistent with their proper shapes. Furthermore, complicated characters have more strokes than simple ones, and this causes the subjects to pause more often when forming them.

Chinese Character Structure Condition

Repeated measures analysis of variance showed a significant main effect for *Chinese character structure* on tilt ($F_{2,38} = 5.93$, $p < .01$) or on azimuth ($F_{2,38} = 16.46$, $p < .001$). However, there was no significant main effect for *Chinese character structure* on pressure ($F_{2,38} = 0.10$, $p = 0.91$). *Post hoc* pair-wise comparisons showed a significant difference on tilt between left-to-right and top-down Chinese character structures, and on azimuth for all *Chinese character structure* pairs. Fig. 2.9 illustrates the results.

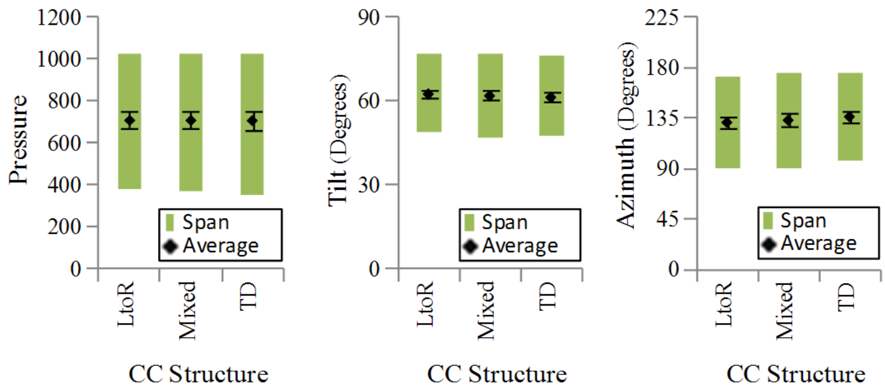

Fig. 2.9 Averages and spans for each Chinese character structure condition when subjects wrote naturally. LtoR and TD represent left-to-right and top-down Chinese character structures respectively.

Chinese character structure was a factor related to the direction of pen tip movement. If the direction was constant, from left to right or from top to down, the pen would swing with less amplitude than in the mixed condition, which made the spans of tilt and azimuth larger in mixed conditions than in left-to-right and top-down conditions.

2.5 EXPERIMENT 3 (DYNAMIC PART: POSITIONS FACTORS)

2.5.1 Goals

The third experiment investigated PTA use profiles and correlations between pen input modalities when subjects *naturally* wrote in different places on the tablet display surface.

2.5.2 Participants and Apparatus

9 individuals who had participated in Experiments 1 and 2 took part in Experiment 3. The same apparatus was used as in Experiments 1 and 2.

2.5.3 Task and Procedure

The entire tablet display surface was divided into 16 equal square input areas. Subjects were instructed to write the same characters as in Experiment 2 in these input areas of the tablet display which was placed in the horizontal position. Target input area was displayed in translucent green and the character that the user was to write was shown in the upper left corner of the display. All characters were mixed and counterbalanced in random order. In summary, the experiment consisted of:

9 participants ×

17 characters ×

16 input areas ×

2 repetitions

= 4896 trials.

2.5.4 Results

Experiment 3 took an average of 53.24 minutes. During the experiment, pressure, tilt and azimuth were sampled every 10 ms when the pen was in contact with the tablet display surface.

Effect of position on PTA

Repeated measures ANOVA revealed a significant main effect for Input area on pressure ($F_{15,120} = 5.98$, $p < .001$), tilt ($F_{15,120} = 28.61$, $p < .001$) and on azimuth ($F_{15,120} = 65.92$, $p < .001$) (See Fig. 2.10, 2.11, and 2.12).

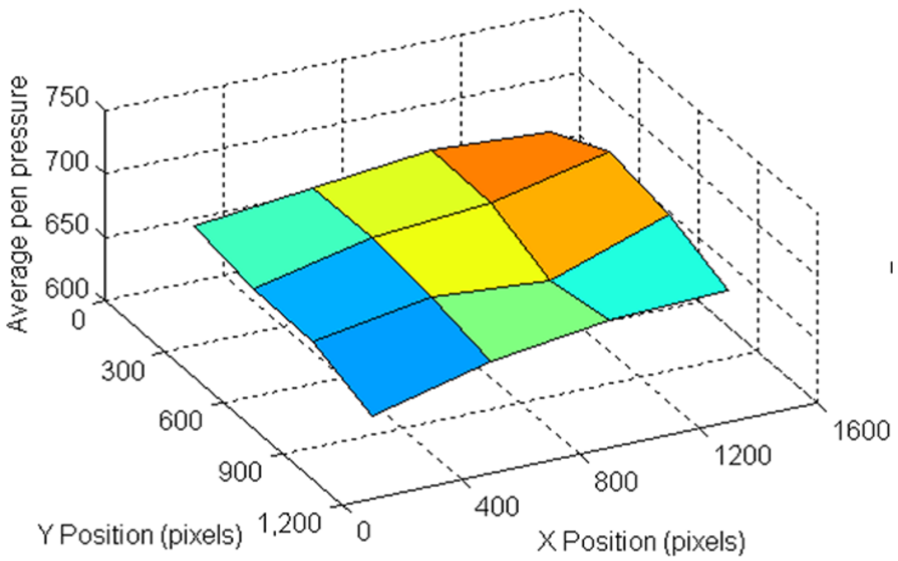

Fig. 2.10 3D perspective illustration of average pen pressure per input area.

Regarding pressure, the highest pen pressure appeared at the upper right corner while the lowest pen pressure appeared at the lower left corner of the display. The more right or upward the position, the larger the pen pressure became. The gap between the highest average pen pressure and the lowest average pen pressure was 50.05. Possible reasons for the pen pressure difference between positions are that 1) the effective muscle

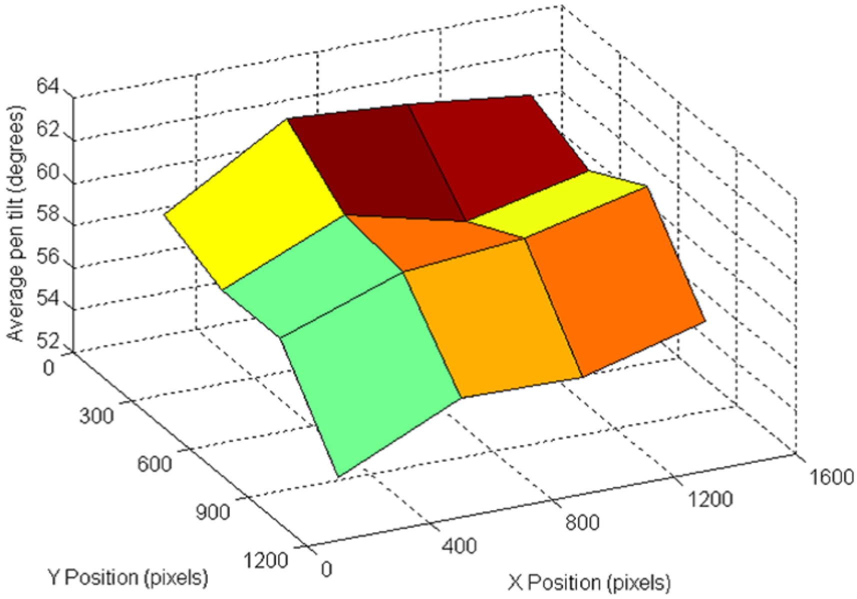

Fig. 2.11 3D perspective illustration of average pen tilt per input area.

groups are different when writing in different positions; 2) As the writing position moved to the right, the effect of the weight of the arm on the pen tip increased.

Regarding tilt, the largest pen tilt appeared at the upper right corner while the smallest pen tilt appeared at the lower left corner of the display. The more right and/or upward the position, the larger the pen tilt became. The results are quite similar with pressure results. The gap between largest average tilt and smallest average tilt is 9.02 degrees.

Regarding azimuth, the largest pen azimuth appeared at the lower right corner while the smallest pen azimuth appeared at the upper right corner of the display. The more left and/or downward the position is, the larger the pen azimuth is. The gap between largest average azimuth and smallest average azimuth is 36.58 degrees.

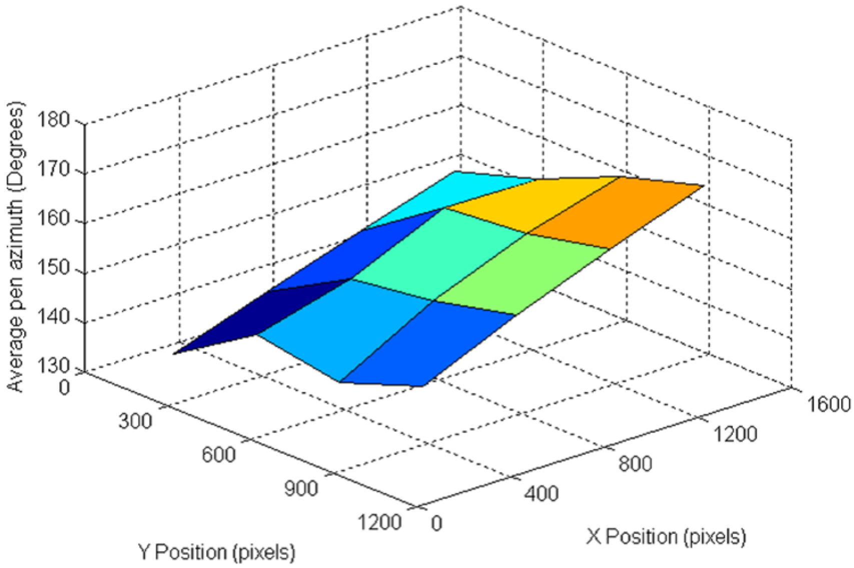

Fig. 2.12 3D perspective illustration of average pen azimuth per input area.

Combination Distribution between PTA

It is very often desirable to use more than two pen modalities at the same time. So the combination distributions of for each pair of modalities were investigated by calculating the frequencies for each pair. Fig. 2.13, 2.14, and 2.15 illustrate the results.

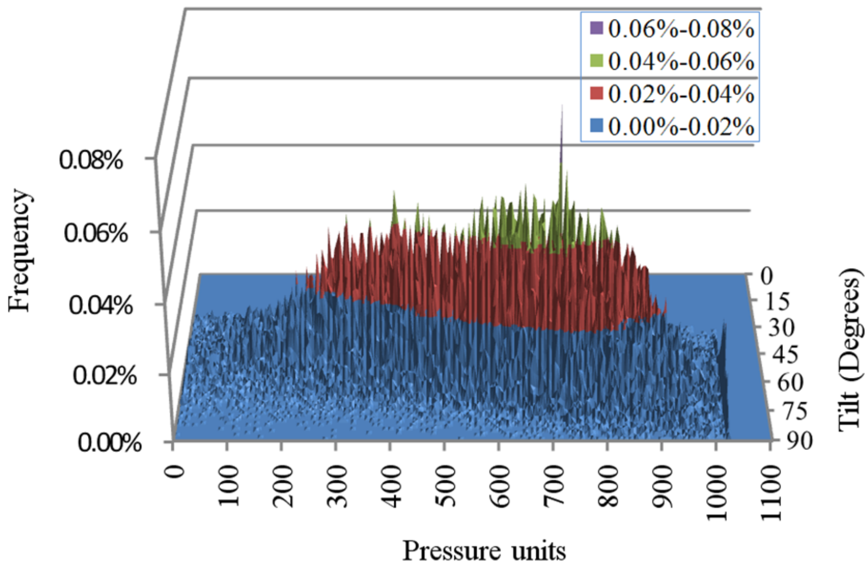

Fig. 2.13 Distributions of pressure and tilt combined.

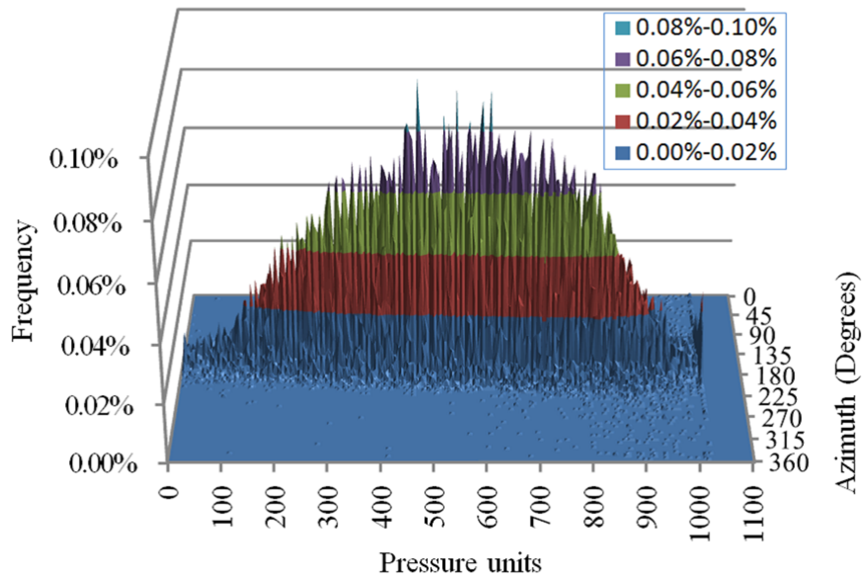

Fig. 2.14 Distributions of pressure and azimuth combined.

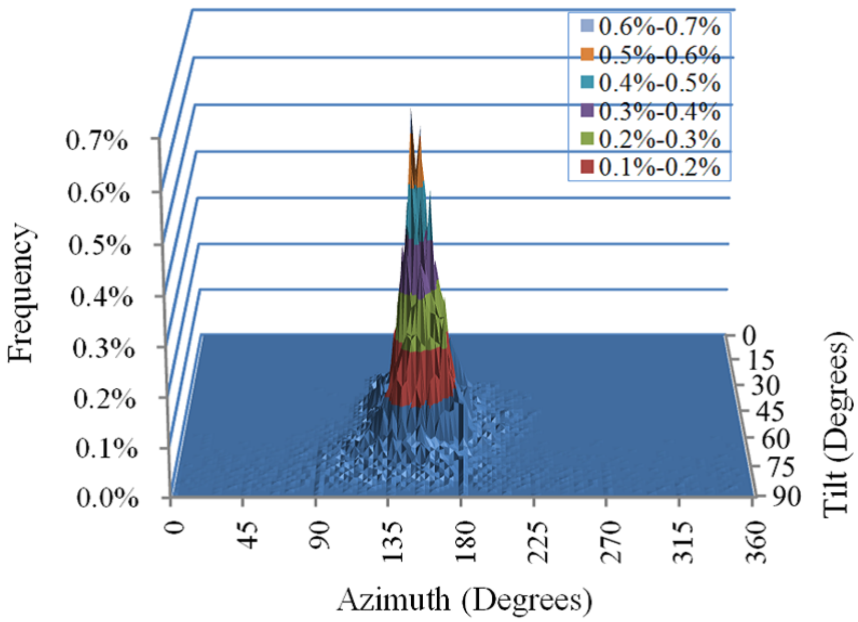

Fig. 2.15 Distributions of azimuth and tilt combined.

Results indicate that many pen modality combinations did not appear during the *natural* writing procedure. Nevertheless, these never appeared combinations are good options for supporting purposes other than *naturally* writing. Regarding the pressure and tilt combination, pressure interval [200, 1023] ∩ tilt interval [28, 90] accounts for 95% use frequency. Regarding the pressure and azimuth combination, pressure interval [78, 228] ∩ azimuth interval [78, 228] accounts for 95% use frequency. Regarding the tilt and azimuth combination, tilt interval [36, 82] ∩ azimuth interval [99,207] accounts for 95% use frequency. As a result, more never appeared tilt and azimuth combinations out of the 95% frequency interval are available than other modality combinations for supporting purposes other than *naturally* writing.

Correlation between PTA

A 2-tailed Pearson Correlation Analysis revealed a strong correlation between pressure and tilt (r = 0.19, $p < .001$), between pressure and azimuth (r = 0.57, $p < .001$), and between tilt and azimuth (r = - 0.11, $p < .001$) (See Fig. 2.16).

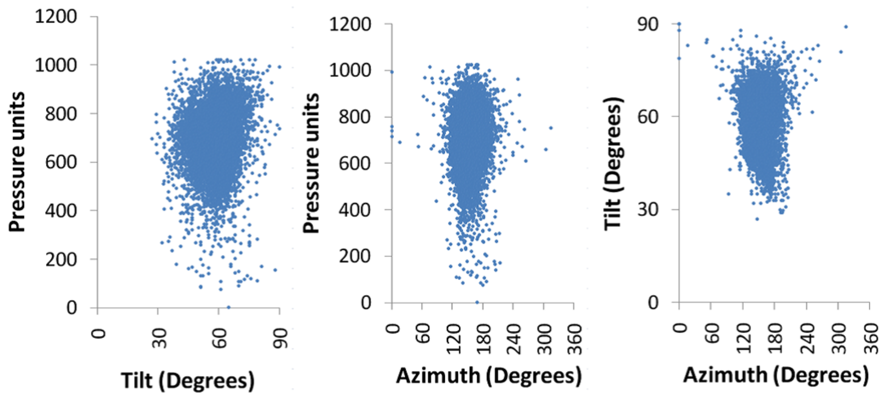

Fig. 2.16 Correlations between PTA.

2.6 DISCUSSION

2.6.1 Design Principles of This Study

Although pen techniques based on PTA have received a lot of attention recently, some of the designs may be deficient and even untenable where consideration has not been given to the *natural* way in which humans use pens. The uniform use of all PTA space does not necessarily result in effective and efficient design because a successful design must be based on a quantified understanding of *natural* pen usage. Thus, this study aimed at providing a general understanding of PTA *natural* use profiles and at giving practical guidance to PTA-based user interface designers.

There are two basic stages of pen manipulation: static holding and dynamic gesturing. We investigated PTA use profiles according to these two stages. Thus, we first investigated static holding in Exp. 1 and subsequently, we investigated dynamic gesturing in Exp. 2 and Exp. 3. Generally, gesturing includes several types of pen manipulations such as writing, drawing, steering, and tracing. In order to investigate *natural* PTA use profiles, any controlled pen manipulations such as steering and tracing tasks were excluded in our exploration. As a result, intentional and incidental PTA uses were not identified in our study. Furthermore, considering that users normally do not roll the pen when *naturally* writing, pen rolling was not investigated in this study. Although free drawing and writing tasks were to be proved different [16], free drawing cannot provide a uniform measure of PTA use profiles because drawing contents and styles are too varied. As a result, we investigated PTA use profiles through character input experiments. Nevertheless, we regard intentional and incidental PTA uses as promising and worthy of exploration in future work.

For writing tasks, the factors that may influence PTA use profiles include contents, sizes, and positions. So we successively investigated dynamic writing in Exp.2 and

Exp.3. However, we also recognize that the investigation of dynamic gesturing should be more comprehensive. And we also regard PTA use profiles in wider pen manipulation types as worthy of exploration in future work.

2.6.2 PTA Space Ranges

Although most pen devices provide PTA space ranges of [0, 1023] for pressure, [30°, 90°] for tilt, and [0°, 359°] for azimuth, there is room to amend the space ranges. For example, results indicate that the maximum pressure level of 1023 was not large enough because too many overflows were found. Also, the tilt space range could be expanded to [30°, 150°], for example, according to pen azimuth intervals [0°,179°] and [180°,359°].

Traditional WIMP user interfaces were not specially designed for pen input, and thus the PTA characteristics might not be fully utilized. Moreover, inherent human hand structures and pen grasping habits influence the use of PTA. The results of *natural* PTA use profiles may benefit PTA based interface designs and inspire designers to develop a more human-orientated interface. For example, results revealed that a pen tilt range of [30°, 40°] is hardly achievable because the pen was obstructed by the hand when the pen tail was oriented towards the arm. As a result, the tilt range of [30°, 40°] should be used cautiously.

2.6.3 Utilizing 2-SD Intervals

PTA ranges of two standard deviation (2-SD) intervals around the mean values represent the common ranges when users *naturally* hold the pen or write. Users feel comfortable and competent when they manipulate the pen in these intervals. Pie menu item placement will benefit from the intervals. For example, when pen azimuth is used to select the pie menu, it is better to set those frequently used menu items within the

2-SD azimuth interval. Conversely, ranges out of 2-SD azimuth intervals can be applied to rarely used pie menu items.

On the other hand, 2-SD intervals are useful in mode switching design. In the dual mode situation, the boundaries of the 2-SD intervals can be used to *naturally* trigger modes. To avoid inadvertent mode triggering, it is better to utilize azimuth rather than other pen modalities to switch modes. If two or more pen input modalities are used in tandem, the miss-trigger rate will be further reduced. According to the results, combination of tilt and azimuth is a better option.

2.6.4 Taking Advantage of Pen Characteristics

Every pen modality has advantages and disadvantages. The pen can provide inherent visual feedback for tilt and azimuth whereas pressure cannot. This natural visual feedback characteristic can promote performance if properly used, as it does, for example, in Tilt Cursor [98]. Nevertheless, there are more available levels of pressure than there are levels of tilt and azimuth, thus pressure is more appropriate for precise manipulation, as, for example, in Zliding [79].

Results showed that each subject had a unique PTA use profile, which can contribute to signature verification because the same characters written in the same shapes by different individuals can still be distinguished by different PTA use profile. If factors such as character type, complexity and structure are considered, recognition accuracy will be further promoted.

2.6.5 Considering Size Factor

Interestingly, the larger and simpler the character was, the more pressure users exerted to write it, which was contrary to the feelings of most subjects. We think the phenomena of inconsistency between feeling and fact is worthy of further exploration through special psychological means. On the other hand, size is a remarkable factor influencing PTA use profiles. If the size factor is fully evaluated, performance of PTA based interface may be improved. For example, pressure marks [80] introduced a method in which users performed a selection and an action simultaneously by stroking the pen and changing the pen pressure at the same time. However, when the targets being selected are many, the stroke size becomes larger and users subconsciously except more force will be exerted on the pen tip, and, as a result, the pen pressure increases. If the threshold between high and low pressure varies according to stroke size, miss-recognition of pressure marks will be decreased.

2.7 FUTURE WORK

2.7.1 Exploration of PTA Use Profiles in More Pen Manipulation Types.

Since the only dynamic pen manipulation type investigated in the study is writing, the results cannot be safely transferred to other tasks such as free drawing and controlled navigating. Future work will explore PTA use profiles in more pen manipulations. Moreover, classification of intentional or incidental PTA manipulations, speed of PTA manipulations, human ability to control PTA, and how to choose proper pen input modality for different tasks will be investigated.

2.7.2 Subjective and Objective Effects on PTA Use Profiles.

Further study will explore the effects of gender, age, direct/indirect pen input devices, pen shape, pen holding postures on PTA use profiles.

2.7.3 PTA Use Profiles in Tracking State.

In the tracking state [39], when pen pressure maintains a zero level, tilt and azimuth can still be detected. We consider that the exploration of PTA use profile in tracking state is well worth our attention.

2.8 CONCLUSION

This chapter provided a statistical understanding of *natural* pen pressure, pen tilt, and pen azimuth use profiles and the commonly/rarely used PTA ranges both in static holding and dynamic character writing situations. Three experiments were reported: Exp. 1 explored PTA use profiles when users *naturally* hold the pen before starting writing; Exp.2 explored the PTA use profile when users *naturally* write three kinds of characters (symbols, letters, and Chinese characters) in seven kinds of character sizes; Exp. 3 explored the PTA use profile and the covariations between PTA when users *naturally* write the same characters as in Exp. 2 in varied input positions. Results show that PTA use profiles fitted Gaussian distribution whereas averages, standard deviations and spans varied. Size condition and position condition significantly affected PTA use profiles. Covariation was found between PTA. The findings of this study have implications for human-oriented PTA use in PTA based user interface designs.

Chapter 3

Adaptive Pen Pressure Discretization Based on Personal Use Profile

3.1 Introduction

Compared with other input devices such as keyboards and mice, pens have advantages of portability, outdoor availability, short-time practice, and convenience for drawing. As a result, pens have gradually become favored and are widely used in Tablet PCs, PDA, and mobile phones. On the other hand, pens are inferior to keyboards and mice in input capacity. A pen tip's x-y information is mapped to the cursor position in traditional WIMP interfaces (in human-computer interaction, WIMP stands for "window, icon, menu, and pointing device", denoting a style of interaction using these elements). Although binary buttons are provided on the pen barrel, unwanted pen tip movement caused by button press often influences the pen manipulation.

In addition to the usual x-y position and binary button press information, most pens provide continuous pressure input and thus the pen input capacity is raised. This pressure input may be used to operate a widget that has several discrete states. The optimal number of levels into which the pen pressure space is divided within human control ability determines the number of states in the multi-state widget. If the number of pen pressure levels is less than the required number of discrete states of the widget, some states in the multi-state widget cannot be achieved.

Ramos et al. [81] explored the design space of pressure-based interactions with styli. They divided the whole pressure space into equal levels (Fig. 3.1) and found that 6 levels resulted in optimal controllability. However, even discretization will not likely afford optimal usability because human ability to control different levels of pen pressure varies over all levels, i.e., some pen pressure levels may be easier to control than others.

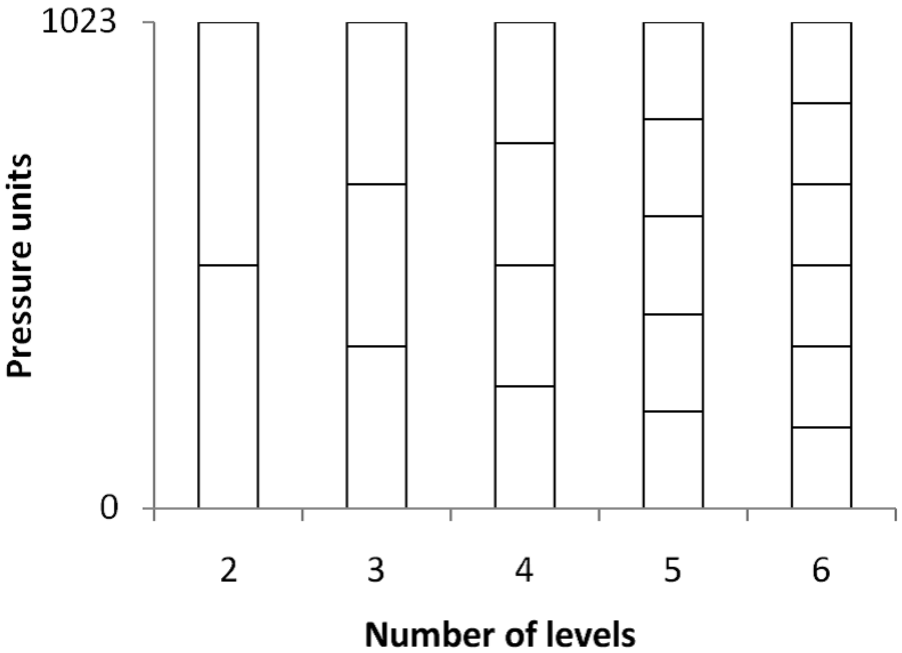

Fig. 3.1 Schematic diagram of even discretization method.

In order to increase the discernible number of pen pressure levels and make the discretization more suitable for user manipulation, we proposed an adaptive pen pressure discretization method based on pen pressure use profiles. We predicted that better performance could be achieved through discretization based on personal pen pressure use profiles than through even discretization. We also wanted to investigate whether 7 or more pen pressure levels could be discriminated by use of our discretization method.

3.2 Related Work

Research on pressure could be traced back to the last century. Herot et al. [46] investigated force input by detecting finger pressures on a pressure-sensitive digitizer and asserted that touch and pressure sensing opened a rich channel for immediate and multi-dimensional interaction. Buxton et al. [18] investigated touch-sensitive tablet input and presented examples such as painting with pressure sensing to suggest ways in which touch tablets could be used.

Literature related to pen pressure emerged mainly after the new Millennium, and most of them focused on novel interactive application designs. Mizuno et al. [68] implemented a virtual sculpting system by converting pen pressure to carving depth and angle. Ramos et al. [78] proposed a concept prototype designed for use with pressure-sensitive digitizer tablets to fluidly navigate, segment, link, and annotate digital videos; created the Zlider [79] that users can use pen pressure to achieve fluid zooming while sliding the pen; and developed pressure marks [80] that allowed users to perform a selection and an action simultaneously by stroking the pen and changing the pen pressure at the same time. Oshita [71] designed a virtual human figure movement manipulation system that used not only pen pressure but also pen tilt to control a virtual human figure.

Some research focused on increasing the input bandwidth by means of pen pressure. Harada et al. [44] used pen pressure as an input modal to augment simultaneous input capacity. Ren et al. [86] proposed the Adaptive Hybrid Cursor to facilitate target selection performance by automatically adjusting cursor size according to pen pressure. Yin and Ren [112] proposed a zoom-based technique to improve pixel-target selection, in which the pressure is used as a mode switch.

Besides, some studies have utilized pen pressure as a clue that supports special analysis. To assist in biometric personal identification and digital signature verification, Hook et al. [49] added pressure sensors to a pen for 3D pressure analysis of handwritten characters, words and signatures. Oviatt et al. [72] investigated implicit user adaptive engagement via speech amplitude and pen pressure cues and found that users tended to clarify engagement by increasing the pen pressure.

There were also some published studies that focused on exploring the human ability to control pen pressure. Ramos et al. [81] investigated the human ability to perform discrete selection tasks by controlling stylus pressure and found that dividing pressure space into 6 levels resulted in optimal controllability. Mizobuchi et al. [67] further explored the force-based input on handheld devices and found subjects distinguished five to seven input levels within the set of ten force ranges actually used. Li et al. [61] investigated five techniques for switching between ink and gesture modes in pen interfaces, including a pen-pressure based mode switching technique that allowed implicit mode transitions. Xin and Ren [109] investigated the value distributions of pen properties. Moreover, Xin and Ren [110] also comparatively investigated pen input modalities for precision parameter manipulations during trajectory tasks.

On the other hand, some studies augmented traditional mice or keyboard with pressure sensors to enhance input. Cechanowicz et al. [20] investigated the technique of augmenting a mouse with pressure sensors to increase input vocabulary and found that 64 modes could be controlled by users using a dual-pressure augmented mouse. Shi et al. [89] improved the control of discrete pressure-based input by using a fisheye method, reducing error rates significantly. Dietz et al. [25] presented a pressure sensitive computer keyboard that independently sensed the force level on every depressed key.

Although the above mentioned studies reported the benefits of pressure as an alternative input channel, they also reported high error rate resulting from pressure-based input. According to previous research, the optimal number of divisions of the pen pressure space was 6. However, in a concrete pen based user interface design, more divisions may provide more flexibility. Also even division of pen pressure space may not result in optimal usability. In this light, we are motivated to find a new discretization method to both increase discernable pen pressure level number and make division of pen pressure space more suitable for user manipulation.

3.3 Design Framework and Method Elaboration

The exploration reported here includes the following work: investigating pen pressure use profiles for subjects in a natural writing and drawing experiment; dividing the pen pressure space into 2 to 12 levels according to personal pen pressure use profiles; and evaluating performance of the new proposed pen pressure discretization method.

Frequency of each pen pressure unit for each subject was calculated according to the results of the natural writing and drawing experiment. Then, the total pen pressure space was divided according to personal pressure use profiles. The first level started from pressure unit 0 and each level accounted for same pressure use frequency. For example, if the pen pressure space is divided into 8 levels, each level will account for 12.5% of pen pressure use frequency according to the results of the natural writing and drawing experiment. If the pen pressure use frequency from pressure unit 0 to 358 accounts for 12.5%, the first level will start at pressure unit 0 and end at pressure unit 358, and the other levels follow analogously. Fig. 3.2 is a schematic diagram of the discretization of pen pressure space with the new proposed method.

The theory underlying the proposed method is based on the hypotheses that 1) higher frequency of pressure unit in natural writing and drawing experiment indicates that subjects use pressure more inherently in that pressure unit and thus they have stronger ability to control that pressure unit; 2) higher frequency of pressure unit gives

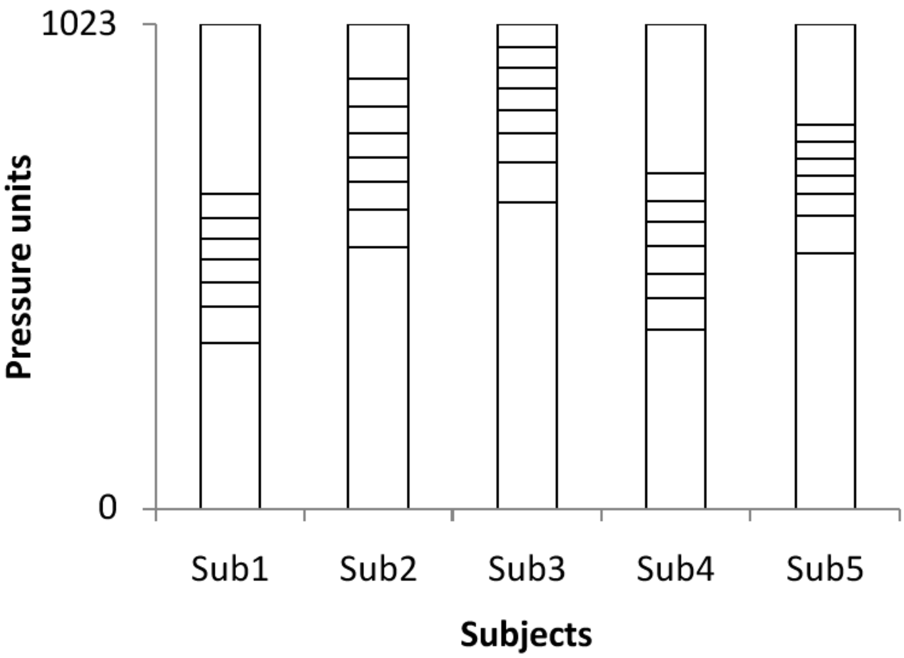

Fig. 3.2 Pen pressure space was divided into 8 levels according to the pen pressure distributions of five subjects. In experiment 2, targets were defined as the adjacent rectangles shown in the figure, which presented the pen pressure levels. The variable level width division for each subject resulted from uniform divisions of pen pressure use frequency.

users more experience, which further enhances the ability to control that pressure unit. As a result, levels containing pen pressure units with higher use frequencies should be allocated fewer pressure units.

In order to achieve the optimal number of pen pressure space divisions, we explored the performance of dividing pen pressure space into 2 to 12 levels. Taking into account that varied level widths may give users varied degrees of tension, we also investigated performance with visual feedback in the form of uniform level widths: although the discretization of pen pressure space was based on personal pressure profile, the presentation of each level was in the same visual width. In this situation, the real widths of each level were varied but the level widths which subjects saw were uniform. On the other hand, sometimes personal pen pressure profile may not be obtained in time, so we also explored the performance of pen pressure discretization based on the aggregation profile of all subjects. Thus, we explored 5 different discretization methods: AN (dividing the pen pressure space according to the aggregation profile of all subjects); AU (dividing the pen pressure space according to the aggregation profile of all subjects with visual feedback of uniform level widths); PN (adaptively dividing the pen pressure space according to personal profile); PU (adaptively dividing the pen pressure space according to personal profile with visual feedback of uniform level widths); and EV (dividing the pen pressure space evenly).

3.4 Experiment 1 - Pen Pressure Use Profile Investigation

3.4.1 Participants

Two female and seven male volunteers from a native university campus, ranging in age from 21 to 32, participated in the experiment. All of them were right-handed according to self-report.

3.4.2 Equipment

A Wacom Cintiq 21UX interactive LCD graphics display tablet and a wireless stylus with an isometric tip were used. The Cintiq 21UX can detect the pressure that a user exerts on the stylus tip from unit 1 to 1023 which corresponds to the force range of 0 to 4 Newton. Pressure unit over 1023 is recognized as 1023.

3.4.3 Task and Procedure

This experiment investigated pen pressure use profiles when the subjects naturally wrote or drew on the tablet display surface. The subjects sat in front of the interactive display tablet which was placed in the horizontal plane. First, the subjects were instructed to write three types of characters on the tablet display. The characters included symbols (@, ☆, &, ×) and letters (S, E, M, B). Then the subjects were asked to draw freehand strokes (e.g. arbitrary curves and straight lines) in a natural manner, for a period of 3 minutes. Pen pressure was sampled every 10 ms while the pen was in contact with the display surface.

3.4.4 Results

Univariate analysis of variance revealed a significant difference in average pressure ($F_{1,8} = 449.94$, $p < .001$) and in standard deviation of pressure ($F_{1,8} = 1405.28$, $p < .001$) among subjects. The average pressure for all subjects was 752.75 with standard deviation 192.04. Fig. 3.3 shows examples of the pen pressure use profiles of two subjects.

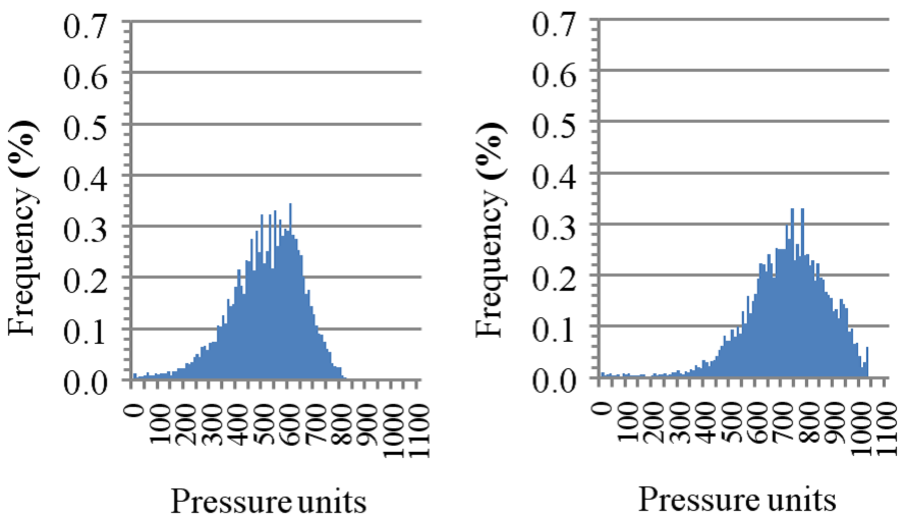

Fig. 3.3 Pen pressure profiles of two subjects.

Results indicate that each subject has a unique pen pressure use profile. This suggests that suitable pressure and the controllability of different pressure units should differ by subjects. As a result, even discretization method of pen pressure space should be ineffective.

3.5 Experiment 2 - Discretization Method Evaluation

3.5.1 Participants and Equipment

The same 9 individuals who participated in Experiment 1 took part in Experiment 2. And the same equipment was used as in Experiment 1.

3.5.2 Task and Procedure

Subjects were seated in front of a display tablet placed in the horizontal plane. 1024 pen pressure units were mapped to a spatial distance of 520 pixels in the screen. A serial target acquisition and selection task was used. The targets were a set of adjacent rectangles which presented pen pressure levels according to the pen pressure use profiles and the number of pen pressure divisions (Fig. 3.2). During each trial, one of the targets was highlighted in red. If the pen pressure was controlled within the range of a certain level, the corresponding rectangle was colored grey. Subjects were instructed to apply the appropriate amount of pressure to match the target pressure level as quickly and accurately as possible. If the pen pressure was controlled within target pressure level, the target color switched to green. Target selection was performed by a space key press on the keyboard. If a misselection was made, a failure icon appeared and an audio tip was given to the subject.

A within-subject full factorial design with repeated measures was used. Five kinds of pen pressure discretization methods (AN, AU, PN, PU, and EV) were investigated. A Latin Square was used to counterbalance the order of appearance of methods. We explored number of levels, or *nLevels*, from 2 to 12 (2 + 3 + 4 + ... + 12 = 77 pen pressure level targets in total). In order to investigate the learning effect, trials were grouped in “blocks”. Each subject was asked to perform 3 blocks of trials for each method. Each block consisted of the 77 different selection tasks described above. Trials were repeated 2 times under the same condition for reliability within each block. Presentation of trials within a block was randomized. In total, the experiment consisted of:

9 subjects ×

5 methods ×

3 blocks ×

77 level targets ×

2 repetitions

=20790 target selection trials

3.5.3 Results

Selection Time

Selection time is defined as the time from when the pen comes into contact with the tablet’s surface until the subject executes target selection by pressing the space key on the keyboard. In selection time analysis, trials in which the subjects committed selection and release errors were excluded. Repeated measures analysis of variance showed a significant main effect on selection time for method ($F_{4,32} = 4.10$, $p < .01$) and nLevels ($F_{10,80} = 97.00$, $p < .001$). However, there was no significant interaction effect on selection time for method × nLevels ($F_{40,320} = 1.18$, $p = 0.22$). Fig. 3.4 and 3.5 illustrate the results. Error bars in the figures indicate the standard errors (the standard deviations of the sampling distribution of the means).

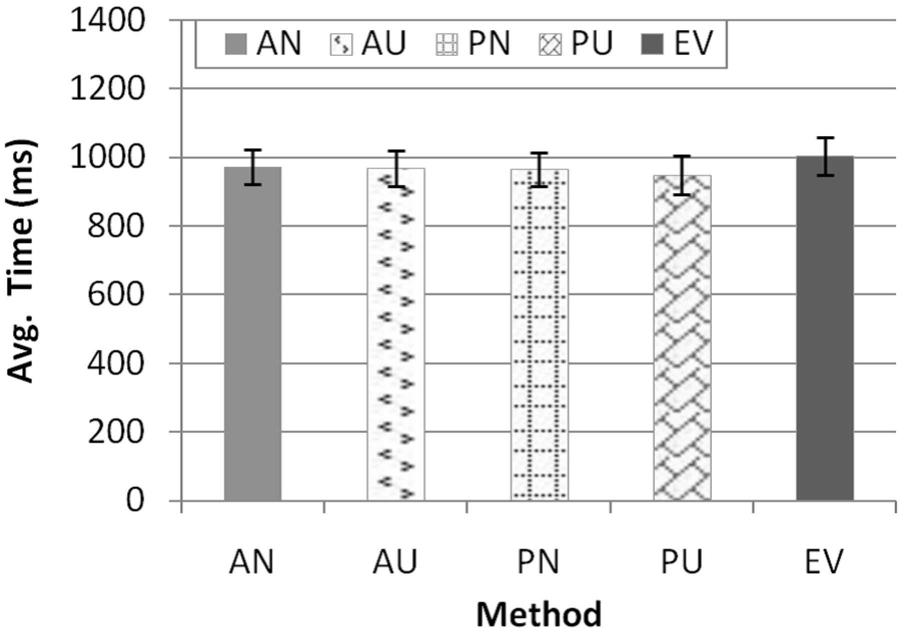

Fig. 3.4 Average selection time per method.

Post hoc pairwise comparisons showed significant differences between method pair (AU, EV) ($p < .05$), (PN, EV) ($p < .05$), and (PU, EV) ($p < .01$). Subjects performed fastest using PU method, and performed slowest using EV method. *Post hoc* pairwise comparisons found significant difference ($p < .05$) between all nLevels pairs except (7, 8) ($p = 0.28$), (8, 9) ($p = 0.14$), and (10, 11) ($p = 0.67$).

A repeated measures analysis of variance showed that block had a significant effect on selection time ($F_{2,16} = 13.42$, $p < .001$). *Post hoc* analysis also found that in block 1, selection time was significantly longer than in other two blocks ($p < .01$) for all discretization methods. Subjects exhibited learning. Fig. 3.6 illustrates the results.

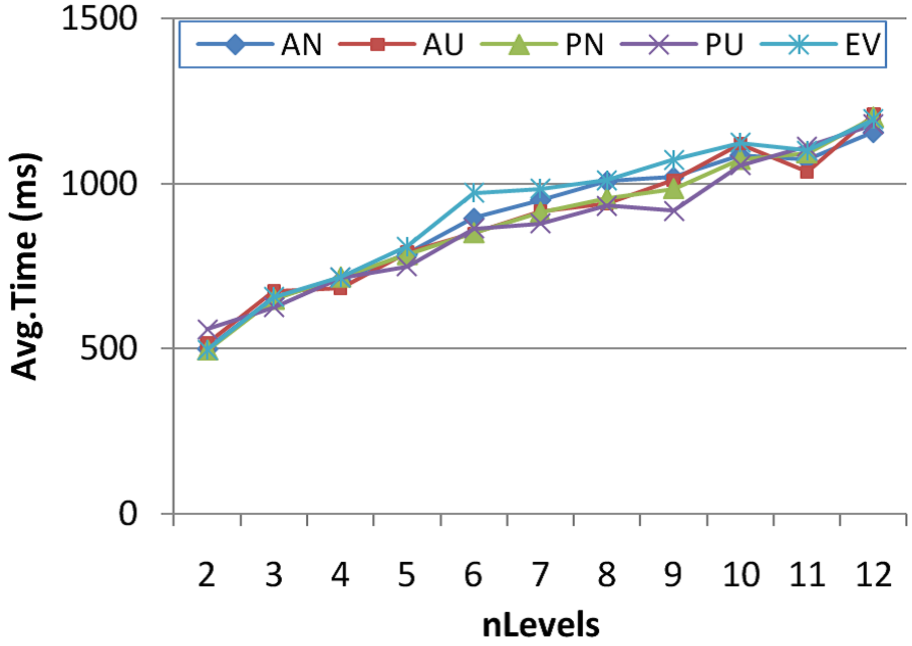

Fig. 3.5 Average selection time per method × nLevels.

Selection Error

Selection error rate was defined as the percentage of trials in which the subjects made erroneous selections. Repeated measures analysis of variance showed a significant main effect on selection error rate for method ($F_{4,32} = 2.99$, $p < .05$) and nLevels ($F_{10,80} = 34.76$, $p < .001$). However, there was no significant interaction effect on selection error rate for method × nLevels ($F_{40,320} = 0.86$, $p = 0.72$). *Post hoc* pairwise comparisons found that subjects committed significantly more selection errors using EV method than using PN method ($p < .05$) and than using PU method ($p < .05$). Subjects committed the fewest selection errors (9.92%) using PU method and the most selection errors (13.51%) using EV method. Fig. 3.7 and 3.8 illustrate the results.

Results showed that selection error rate for EV method was over 10% when the nLevels was more than 5. This is basically consistent with the statement of [81] that dividing pressure space into 6 levels resulted in best performance. However, for the PU method, selection error rate was less than 10% when nLevels <= 8 and was 10.3%

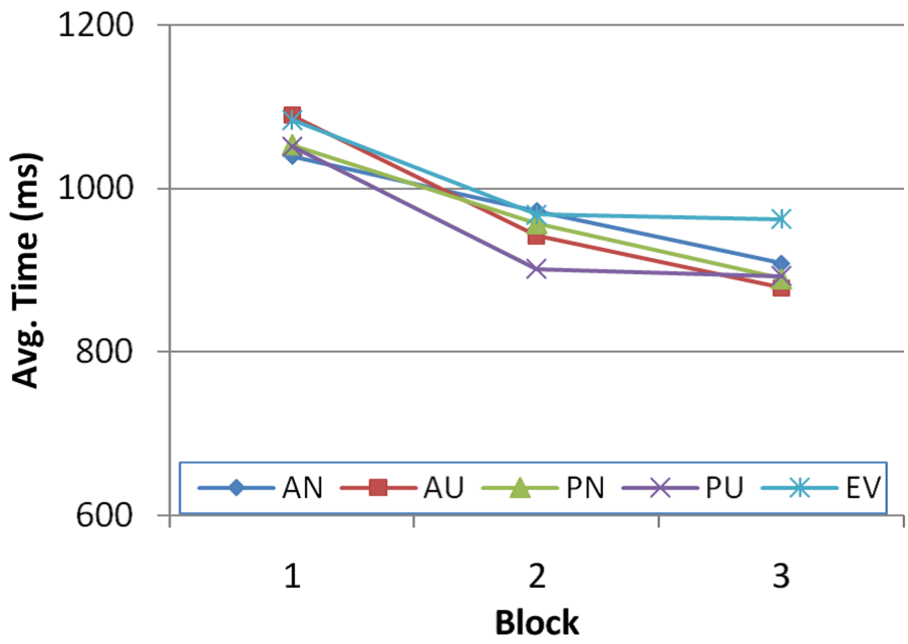

Fig. 3.6 Average selection time per block × method.

when nLevels = 9, which indicates PU method surpassed EV method in the respect of selection error rate.

A further analysis indicates that the subjects committed significantly more errors in first and second level selections using EV method (Fig. 3.9). Moreover, during the experiment, some subjects also complained that lower pen pressure was quite difficult to control.

A repeated measures analysis of variance showed that block had no significant effect on selection error rate ($F_{2,16} = 3.33$, $p = 0.06$). Nevertheless, selection error rate gradually decreased while block number increased. Fig. 3.10 illustrates the results.

Release Error

Subjects sometimes lifted the pen tip and broke contact with the tablet surface when trying to select a low pressure level. Before a selection is performed, if the pen tip does not remain in contact with the surface, a release error is counted and the

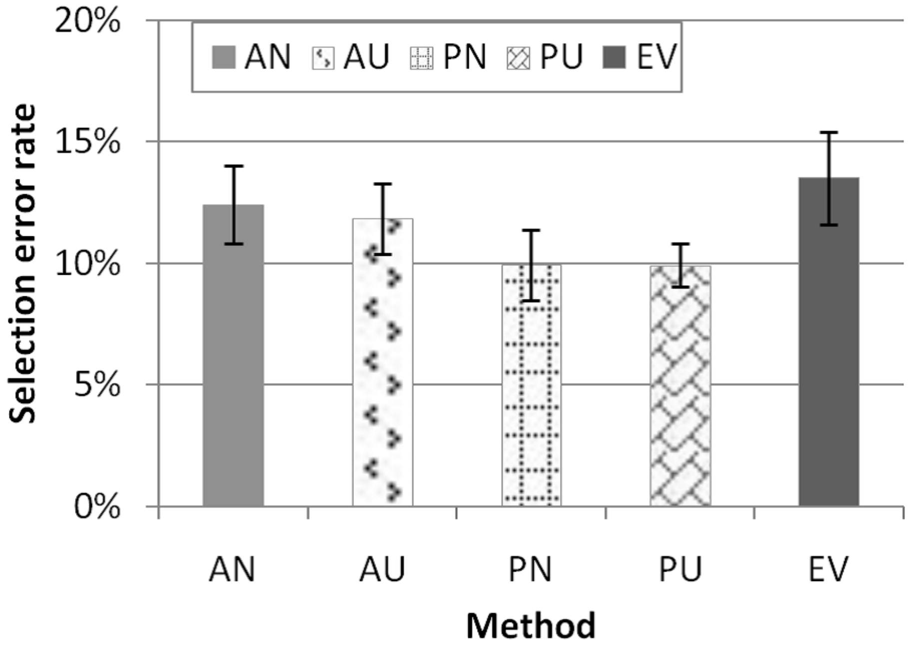

Fig. 3.7 Selection error rate per method.

subject must perform the task again. Repeated measures analysis of variance showed a significant main effect on release error rate for method ($F_{4,32} = 8.06$, $p < .001$). However, there was no significant main effect on release error rate for nLevels ($F_{10,80} = 0.70$, $p = 0.73$) and no significant interaction effect on release error rate for method × nLevels ($F_{40,320} = 1.37$, $p = 0.07$). *Post hoc* pairwise comparisons found that the release error rate for EV was significantly higher than for all other methods ($p < .05$). Fig. 3.11 and 3.12 illustrate the results.

Further analysis found that most of release errors were committed in first and second level selections when using EV method. This again indicates that lower pressure was difficult for user to control. However, using the methods we newly proposed, release error rate was dramatically dropped in first and second level selections. Fig. 3.13 illustrates the results.

A repeated measures analysis of variance showed that block had no significant effect on release error rate ($F_{2,16} = 2.59$, $p = 0.11$). Nevertheless, release error rate decreased

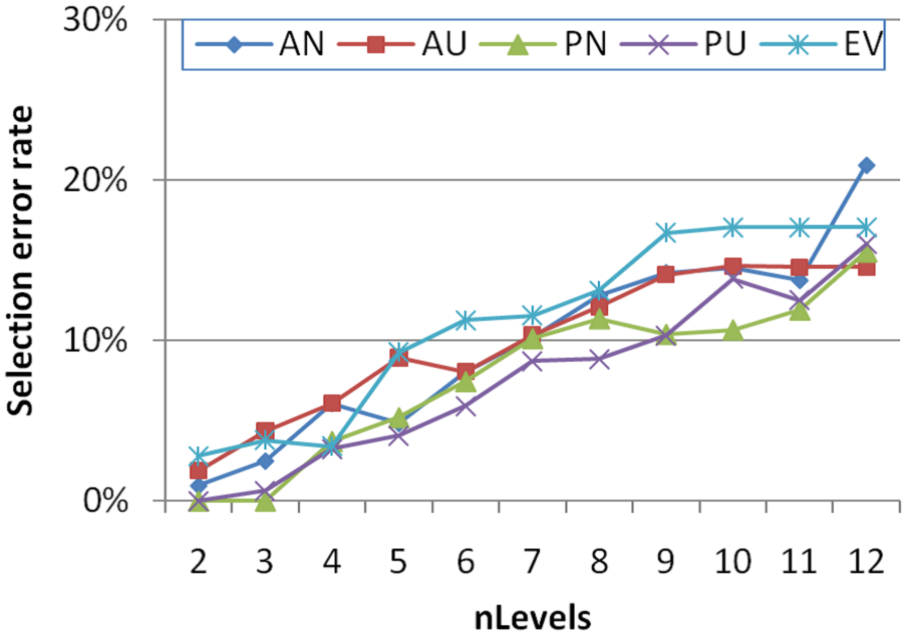

Fig. 3.8 Selection error rate per method × nLevels.

while block number increased when using EV method. Fig. 3.14 illustrates the results.

Number of Crossings

When searching for a target, subjects sometimes crossed the target more than once. Number of crossings, NC, is defined as the number of times subjects controlled pen pressure inside or outside a target in a particular trial, minus 1. Repeated measures analysis of variance showed a significant main effect on NC for method ($F_{4,32}$ =2.78, $p < .05$) and nLevels ($F_{10,80}$ =75.44, $p < .001$). Moreover, there was a significant interaction effect on NC for method × nLevels ($F_{40,320} = 1.70$, $p < .01$), which revealed an interaction effect of method and nLevels on NC. When dividing pen pressure space into 10 levels, a sharp increase of NC was found in the AU method case but was not found in the PU method case. This was probably because personal profile was more appropriate for pen pressure space discretization than aggregation profile of all subjects.

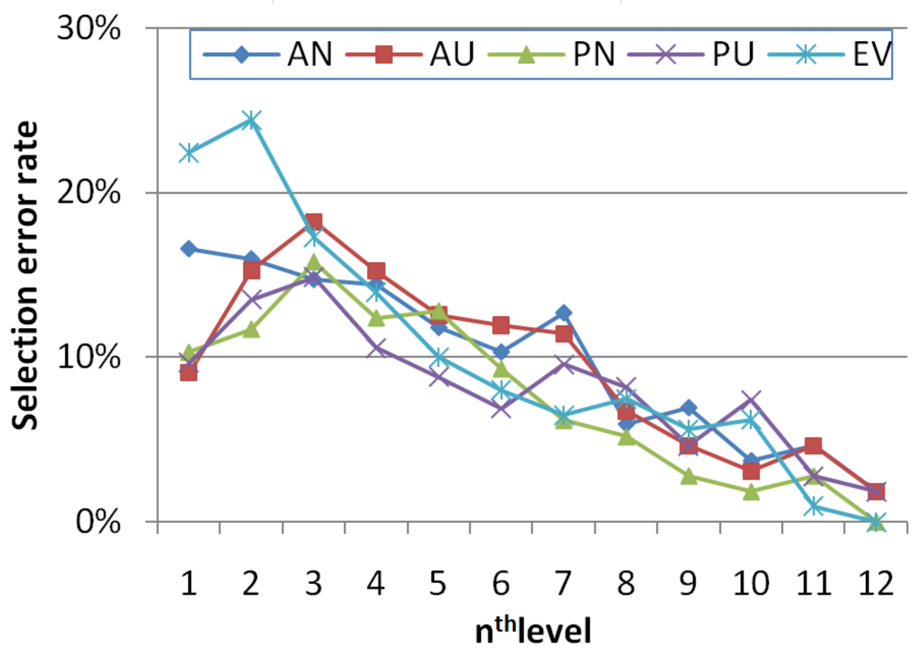

Fig. 3.9 Selection error rate per method × n^{th}level.

Post hoc pairwise comparisons found that the NC for AU method was significantly higher than for PN method ($p < .05$). Fig. 3.15 and 3.16 illustrate the results.

A repeated measures analysis of variance showed that block had a significant effect on NC ($F_{2,16} = 9.82$, $p < .01$). *Post hoc* pairwise comparison showed significant difference between all block pairs ($p < .05$). Fig. 3.17 illustrates the results.

3.6 Discussion

Our results show that the different discretization methods have significantly different effects on the usability of pen pressure for performing discrete selection tasks. In terms of quantitative measures (selection time, selection error rate, release error rate, and NC), PU enabled the fastest performance with the fewest errors, whereas EV the slowest with the most errors. Our results indicate that PU is a feasible discretization method that may be used to advantage in pen-based user interface design.

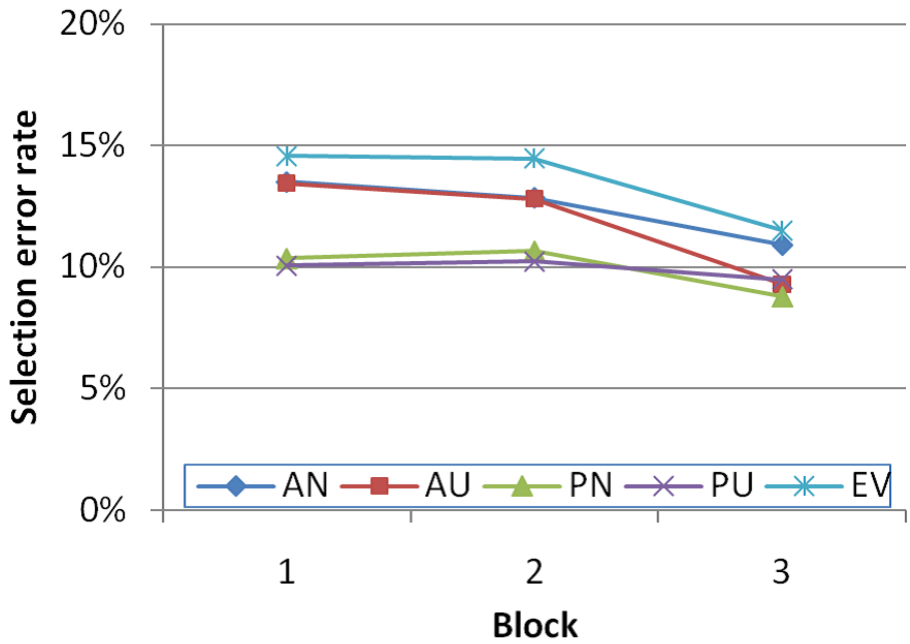

Fig. 3.10 Selection error rate per block × method.

3.6.1 Discernable Number of Pen Pressure Levels

One of the main targets of this research has been to achieve the optimal number of pen pressure levels (ONPL) for different discretization methods. ONPL here was defined as the maximum number of pressure levels that users are able to manipulate with optimum performance. ONPLs were determined from the quantitative measure results. For selection time, ONPL was the maximum number of pressure levels where no significant differences were found between adjacent nLevels pairs. For selection error rate and NC, we set the same acceptability ranges as in [81]: selection error rate less than 8% and NC less than 1. As Ramos et al.'s study [81] did not investigate release error, we determined the release error rate acceptability range by applying the two standard deviations rule [24] to this set of data, yielding the rule of release error rate less than 4.55%. Finally, the General ONPL for each discretization method was obtained from the minimum value among ONPLs. Table 3.1 illustrates the results.

According to the above analysis, the general ONPL for EV method is 4, which is

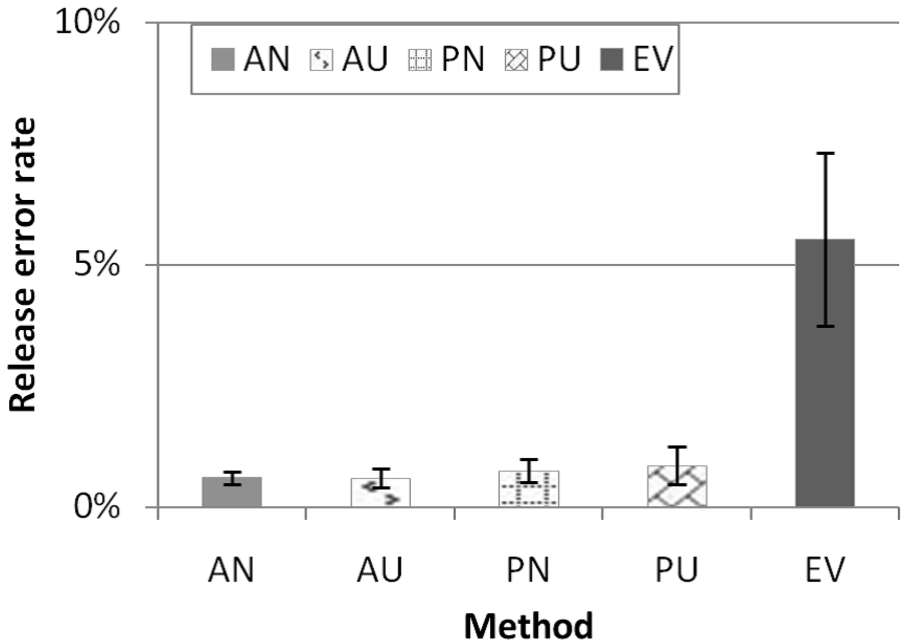

Fig. 3.11 Release error rate per method.

Table 3.1 Optimal number of pen pressure levels (ONPL) for all discretization methods.

Quantitative Measure / Discretization Method	ONPL for Selection time	ONPL for Selection error	ONPL for Release error	ONPL for NC	General ONPL
AN	5	6	12	11	5
AU	8	6	12	9	6
PN	11	6	12	12	6
PU	8	8	12	10	8
EV	5	4	4	12	4

not in agreement with the results of [81]. This is probably because we used a different selection technique, key press, in our experiment. This does not influence the performance comparison between discretization methods since the same selection technique was used throughout the experiment. It is noteworthy that using PU method, the general ONPL was 8, which means that more pen pressure levels were discerned with PU method than with traditional even discretization methods.

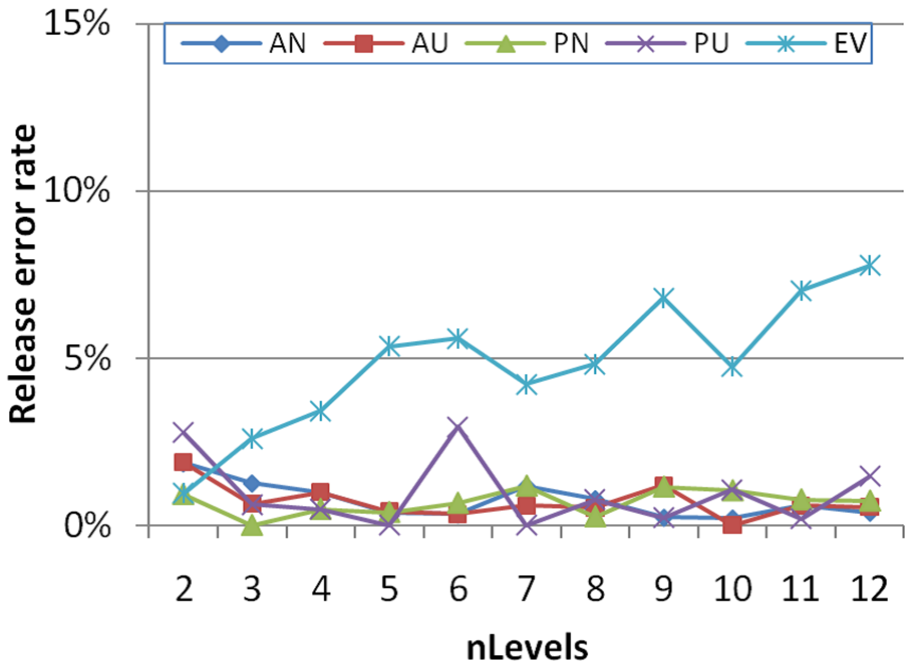

Fig. 3.12 Release error rate per method × nLevels.

3.6.2 Influence of Visual Feedback

As was anticipated at the design stage, visual feedback of uniform level widths enhanced performance of uneven discretization in all quantitative measures except NC. The reason for this performance difference might be nervous tension resulting from varied level widths in a given discretization task. Subjects also reported that varied level widths made the discretization look chaotic and the narrower levels induced psychological pressure before selection. Visual feedback of uniform level widths provided a feasible solution to subjective discomfort. On the other hand however, visual feedback of uniform level widths may have caused an undesirable illusion. Some subjects reported that because some target levels were visually enlarged, they believed that they had a wider tolerance to select the levels, which may be the reason for higher NC with uniform level widths visual feedback than with varied level widths visual feedback.

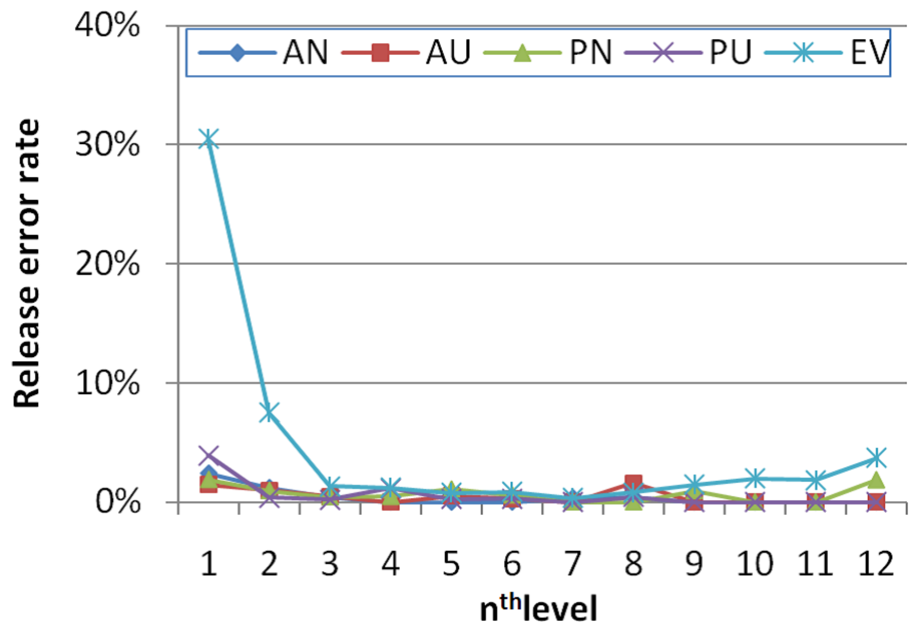

Fig. 3.13 Release error rate per method × n^{th}level.

3.6.3 Pen Pressure User Experience

According to the results of experiment 2, more selection errors and release errors were committed at lower pressure levels in EV method. Some possible reasons are: 1) according to the Web's Law [101], it is almost impossible for users to distinguish pen pressure stimulus change when the change is below the JND (Just Noticeable Difference) threshold, thus lower pen pressure is difficult for users to control; and 2) the pen has its own weight. We measured the pressure produced by the weight of the pen used in the experiments and found that the default pressure was about 185 when the pen tip was perpendicular to the display tablet surface with no extra force exerted on the pen tip. When the pen barely came into contact with the tablet surface, the user did actually lift the pen, and the pen pressure was reported as 0. Moreover, the user had to lift the pen, provided detected pen pressure was less than the pen weight. In this situation, the user had to lift the pen and maintain the pen tip in contact with the surface at the same time, which increased the difficulty of pen pressure control. However, when

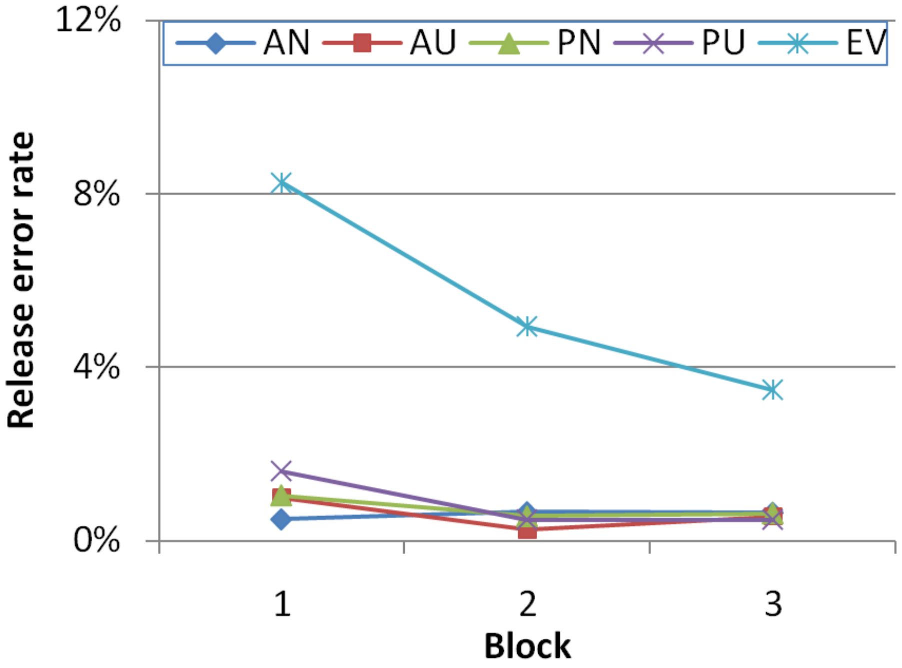

Fig. 3.14 Release error rate per block × method.

the pen pressure was greater than the pen weight, the user did press the pen tip. The switch from lifting to pressing the pen further increased the difficulty of pen pressure control.

Therefore, the improvement of performance at lower pressure levels is critical. Using our discretization method, error rate at lower pressure level selection was significantly reduced. Moreover, subjects also reported that using PU method, the first and second levels were no longer difficult to select. Some subjects also said, "It was convenient to select a given target with PU method." We also believe that PU is a more suitable discretization method for user manipulation because the discretization is based on a personal pen pressure use profile.

Although the aggregation profile was used in AN and AU methods, better performances were achieved than with EV method. In particular, AU method has the same General ONPL as PN method, which verified the feasibility of using aggregation profile as a substitute for personal profiles. Although using aggregation profile did not achieve

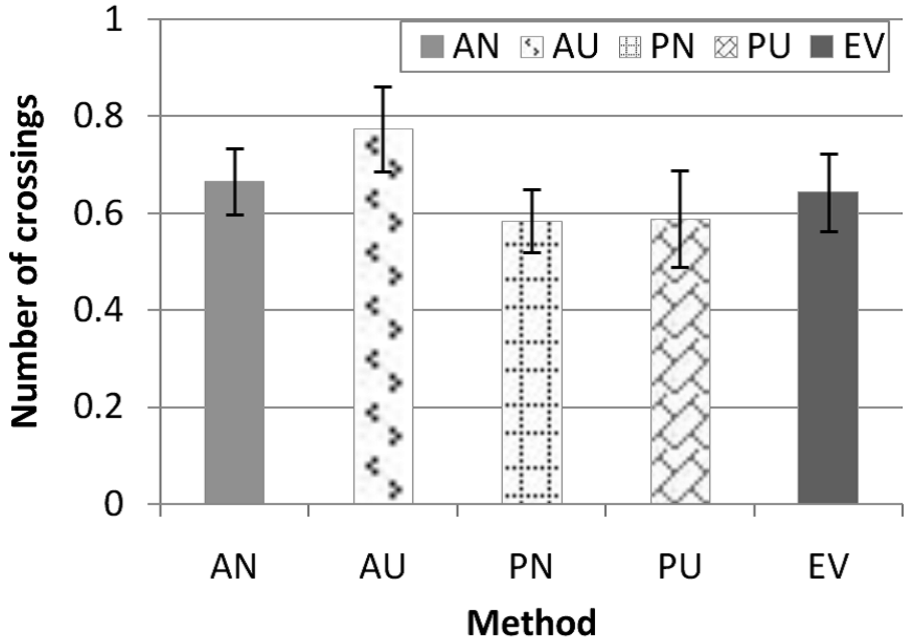

Fig. 3.15 Number of crossings per method.

the best performance, the difficulty in lower pressure control was remedied. Moreover, the methodology of constructing a transfer function from an aggregated user profile to substitute for personal ones may spread to other pen input modalities, e.g. pen tilt input, which we will further explore in future work.

On the other hand, subjects committed the fewest errors at the last level of all discretization methods. The reason for this is that the subjects could press the pen tip with arbitrarily high pressure greater than the penultimate level boundary and as a result they could ensure correct selections. Furthermore, according to Fig. 3.9, the subjects made fewer selection errors at higher levels. This might indicate that users could control higher pressures more precisely than expected. If higher pressures were appropriately exploited, the error rate might be reduced.

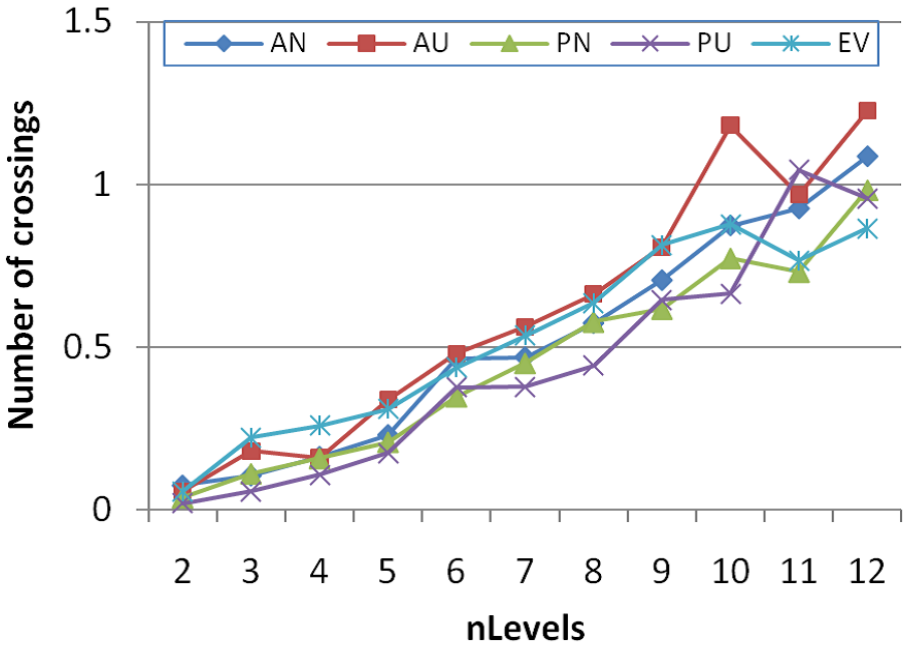

Fig. 3.16 Number of crossings per method × nLevels.

3.6.4 Effective Profiles Achievement

Although the general ONPL was 8 with PU method, there are rooms for improving the performance. The possible ways are:

Achieving personal pen pressure use profile according to concrete tasks and designs

In this study, personal pen pressure use profile was achieved from in a natural writing and drawing experiment. However, we also recognize that the investigation of pen pressure use profile may not be comprehensive because pen manipulation types are many, such as writing, drawing, steering, and tracing. As a result, the profile results obtained through natural writing and drawing experiment may not be safely used in other tasks and designs. It's better to achieve personal pen pressure use profile according to concrete tasks.

Considering subjective factors while achieving personal pen pressure use

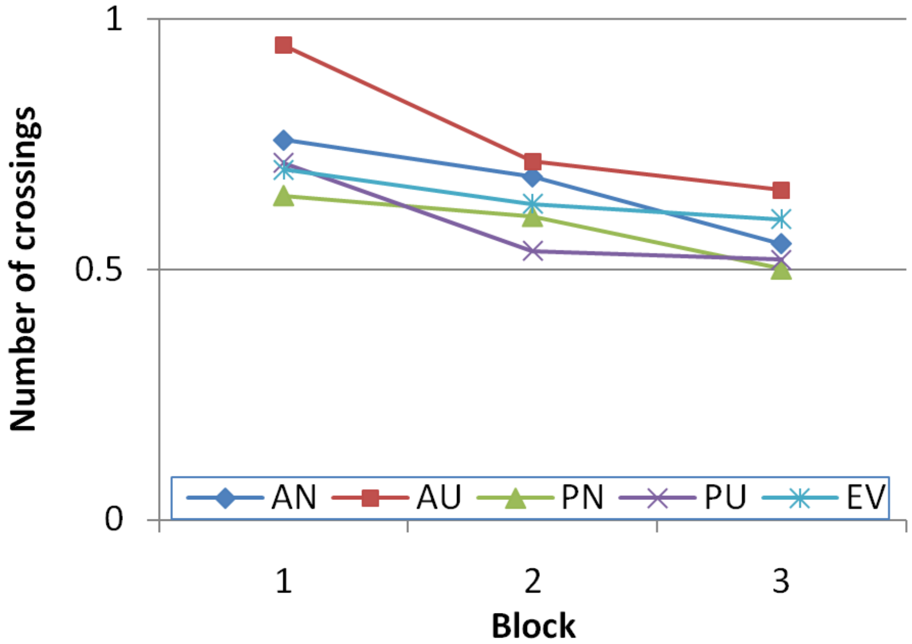

Fig. 3.17 Number of crossings per method × block.

profile

In fact, we found that the personal pen pressure use profile varied according to fatigue, mood, physical condition and pen using habits of the subjects. Therefore, the personal pen pressure use profiles may be varied. It's better to record the pen use profiles of according to different state of the subjects and select the appropriate profile in a concrete pen manipulation. At any rate however, the method in this study was proved to be effective than EV method even according to the aggregation profile of all subjects.

Adjusting the profile during training

We can adjust the pen pressure profile through training and practice to make it closer to the true profile of the subject. As a result, the error rate of each discretized level will be balanced by adjusting the level widths along with the increase of use. If error rate at a certain pressure level are too high, the width of that level will be enlarged, otherwise the width will be reduced.

Using fisheye

We will investigate the feasibility of using the fisheye [42] or visual fisheye function in our discretization to enhance performance at those much narrower levels.

3.6.5 Making the conclusion more general

In statistics, the more subjects, the better results can be achieved, although it may be unrealistic to collect a large number of experimental participants. In our experiment design, regarding the trial numbers in one condition, we had set at least 3 blocks and 2 repetitions for each trial condition when the subject number was 12. So in one experimental condition, the trial number is at least 6 for each subject so that the significant difference was able to be found. However, if the conclusions is used in concrete applications, the results may be questionable. In order to make the conclusion more general, the influence of experimental changes such as different experimental apparatus, different subject ages should be considered. Since the subjective and objective experimental conditions may influence the experimental results, it is probably a promising research project to particularly investigate their effects.

3.7 Conclusion and Future Work

To increase the optimal number of divisions of the pen pressure space and achieve greater pen pressure usability, a new discretization method which divides the pen pressure space according to personal pen pressure use profile is proposed here. We explored here four variations of the method: discretization according to personal/aggregation pen pressure use profile with/without visual feedback of uniform level widths and the traditional even discretization method. We firstly explored the pen pressure use profile of the subjects and then comparatively evaluated performance of the five methods. According to the quantitative measures (selection time, selection error rate, release error rate, and NC), subjects performed fastest and with the fewest errors when the pen pressure space was divided according to personal profile with visual feedback of uniform level widths (PU), and performed slowest with the most errors when the pen pressure space was divided evenly. Moreover, dividing pen pressure space according to the aggregation profile of all subjects also resulted in better performance than dividing pen pressure space evenly. With PU method, the optimal number of divisions of the pen pressure space was 8. Visual feedback of uniform level widths enhanced performance of uneven discretization. Our exploration indicates that PU is a feasible discretization method that may be useful in pen-based user interface design.

Future intended work on this subject will focus on further enhancing the adaptive aspect of the discretization method. The error rate of each level will be balanced by adjusting the level widths along with the increase of use. If error rate at a certain pressure level are too high, the width of that level will be enlarged, otherwise the width will be reduced. Moreover, we will investigate the feasibility of using the fisheye or visual fisheye function in our discretization to enhance performance at those much narrower levels.

Chapter 4

Tilt Utilization: Effective Pen Manipulation Achievement

4.1 Introduction

The pen is favored over other input devices such as keyboards and mice in mobile computing environments due to its portability, outdoor accessibility, short-time learning curve, and ease of manipulation. Consequently, research into pen-based interaction has intensified in recent years, for example, [47], [85], and [54]. Moreover, most pens provide tilt input in addition to x-y coordinate pen tip information, which enhance pen input capacity and efficiency. However, rational use of pen tilt is seldom explored particularly for pen tilt based user interface designs with intuitive and realistic interaction, such as controlling another orientation parameter besides x-y pen tip information. Little literature was found investigating the human ability to control pen tilt.

To provide a general understanding of pen tilt use, this study comprehensively investigates pen tilt input through two experiments: 1) tilt acquisition and 2) tilt pointing. Based on the experimental results, we discuss implications for the design of pen tilt techniques. We also introduce a taxonomy of pen tilt techniques, along with several possible technique designs.

4.2 Related Work

Initially, research on tilt was mainly from the perspective of the tilt of devices, which included many compelling interaction techniques based on the physical manipulation of a small screen device such as PDA. Earlier work by Fitzmaurice et al. [32] investigated the use of positions and tilting actions based on the Chameleon system. They explored the potential of the tilting action as a natural way of issuing commands, e.g., scrolling up or down. Rekimoto [84] presents an interaction technique that uses variations in the tilt of a small screen device as input commands to build several interaction techniques for navigating menus, maps, and 3-D scenes. During operation, only one hand is required to both hold and control the device: which is especially useful for field workers. TiltType [74] and TiltText [102] are text entry techniques for mobile devices. The tilt direction and angle of a mobile device were used to aid character selection from a range of given candidates. Rekimoto and Sciammarella [83] propose a cordless, multiple degree-of-freedom input device that senses physical manipulations of the device itself such as rotating, flipping or tilting.

Harrison et al. [45], Fishkin et al. [29], Hinckley et al. [48], Small and Ishii [91], and Bartlett [12] used tilt sensors to scroll through and select information on a hand-held device. Eissele et al. [28] used tilt operations to achieve successive scroll and link-step actions. Wigdor and Balakrishnan [102] proposed a new technique, TiltText, for entering text into a mobile phone: the phone could be tilted in one of four directions to choose which character on a particular key to enter. Similar work has been done by Partridge et al. [74] and Sazawal et al. [87]. Tilt and orientation have also been used to allow spatially aware display. Fitzmaurice et al. [31] studied how artists took advantage of their ability to reorient their work surface while sketching and writing. Fitzmaurice et al. introduced and explored many issues relating to Rotating User Interfaces (RUIs), as they called it: applications and toolkits for pen-based computing systems that take into account work-plane orientation, angle of rotation relative to the user around the axis perpendicular to the user's work surface. Rahman et al. [77] analyzed the design space of wrist-based interactions and the level of control with the wrist. By investigating the factors that could influence tilt control, they concluded that users could comfortably control at least 16 levels on the pronation/supination axis. Leitner et al. [58] comparatively investigated the performance between a multi-touch and a pen based tilting surface and presented the different usages of tilt change.

Compared to the studies mentioned above, which explored the use of tilt sensed by sensors mounted on the screens (or devices), few studies were found that focused on the exploration of pen tilt. Blaskó et al. [17] present two complementary methods to achieve more fine-grained awareness of user-to-device orientation for a hand-held writing surface: one using computer vision techniques, the other based on stylus-pose. Tilt Cursor [98] provides users with 3D pen orientation as a visual cue. Another technique, Tilt Menu [99], extends the selection capabilities of pen-based user interfaces using 3D pen orientation information. Kuroki and Kawai [55] observed that people hold three physical tools (a syringe, a pen, and a cutter) differently and proposed that the use of tilt information for pen interfaces should be based on this observation. Oshita [71] designed a virtual human figure movement manipulation system that used not only pen pressure but also pen tilt to control a virtual human figure. Bi et al. [16] explored pen rolling around the longitudinal axis of the pen and distinguished between the intentional and incidental pen rolling during pen manipulation.

Although the aforementioned works explored the utilization of tilt input for both device and pen, several aspects remain unexplored: (1) no literature quantitatively investigated the human ability to control pen tilt in acquiring and pointing tasks; (2) no literature investigated the covariation of pen tilting and pen tip movement. However, this covariation has a close relationship with the manipulation accuracy in concrete pen based interface designs; and (3) no literature verified the applicability of the Fitts' law [30] to pen tilt pointing tasks. If the Fitts' law is valid in tilt pointing tasks, the related conclusions and theories of the Fitts' law could be spread to pen tilt pointing tasks. In summary, our review indicates that pen tilt should be systematically investigated. The findings of this study have implications for human-oriented pen use in pen tilt based user interface designs.

4.3 Experiment1 (Tilt Acquiring)

4.3.1 Goal

The goal of the study was to investigate the human ability to acquire a given interval tilt target.

4.3.2 Participants

Twelve native students (2 female, 7 male), ranging in age from 20 to 33, participated in the experiment. To minimize experimental bias due to handedness, we ensure that all participants were right-handed according to self-report.

4.3.3 Apparatus

A Wacom Cintiq 21UX interactive LCD graphics display tablet and a wireless stylus with an isometric tip were used in the experiment. The Cintiq 21UX can detect the tilt angle of the stylus which ranges from 30° to 90°. When the stylus is perpendicular to the tablet surface, the tilt value is reported 90°. The experimental program was designed in the Java Environment and ran on a 2.13 GHz Intel Core2 CPU PC with Windows XP Professional SP2. The resolution of the display was set to 1280 by 1024 pixels at 96 dpi (0.27 mm per pixel).

4.3.4 Task and Procedure

In the experiment, we extended the pen tilt range from [30°, 90°] to [30°, 150°] depending on pen azimuth. [30°, 90°] tilt angle is supported by [0°,179°] azimuth, and [91°, 150°] tilt angle is supported by [180°,359°] azimuth. As a result, pen tilt can be calibrated into 120 units (from 30° to 150°).

120 units were mapped uniformly to a circumferential angle with a radius of 300 pixels on the screen. Pen tilt was utilized to guide the rotation movement of a pink cursor around a fixed point, either clockwise or anticlockwise. A set of equal and consecutive sectors presenting targets with different sector sizes were drawn using dashed lines around the fixed point on the screen. Subjects were seated in front of the display tablet, which was placed in the horizontal plane. The display edge was parallel to the subject's torso. During each trial, one of the targets was highlighted in red. At all times, a pink cursor indicated the pen tilt provided the pen was in contact with the tablet surface. Subjects were instructed to land the pen on the tablet surface with the appropriate amount of pen tilt to guide the pink cursor to the desired target. When the pink cursor entered the target, the target color changed to green. The subject confirmed the selection by pressing the space bar in the keyboard. Subjects were told to strive for both accuracy and speed. If a misselection was made, a failure "ding" sound tip was given to the subject. Fig. 4.1 is the schematic diagram of the experimental tool.

A within-subject full factorial design with repeated measures was used. The independent variables were tilt intervals (5°, 10°, 20°, and 30°) and tilt targets (35°, 57°, 79°, 101°, 123°, and 145°). A Latin Square was used to counterbalance the order of the appearances of Targets. To explore the learning effects, 5 blocks of trials were completed by each subject. Trials under same condition were repeated 2 times. Presentation of

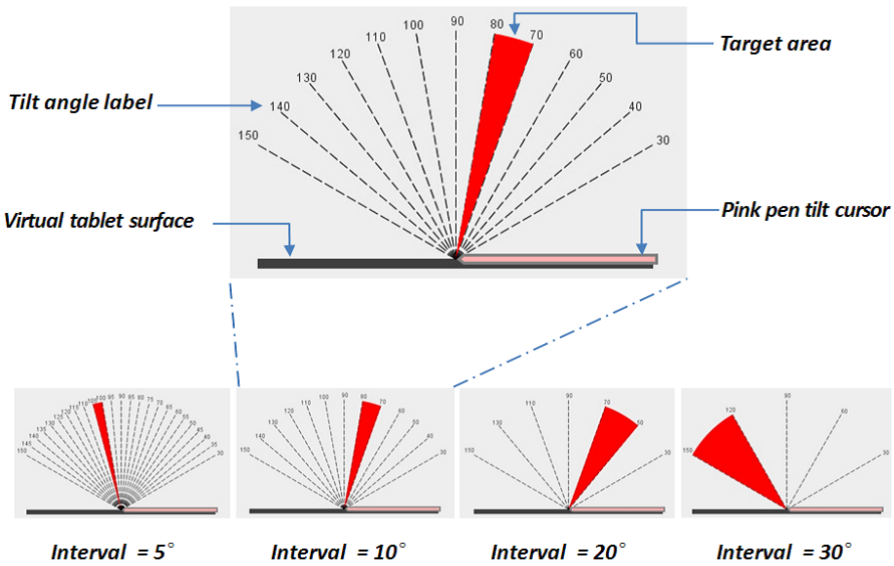

Fig. 4.1 Schematic diagram of the tilt acquiring experimental tool.

trials within a block was randomized. In total, the experiment consisted of:

12 subjects ×

4 tilt intervals ×

6 tilt targets ×

5 blocks ×

2 repetitions

= 2880 target selection trials

4.3.5 Results

Selection Time

Selection time is defined as the period from the time when the pen comes into contact with the tablet's surface until the time when the subject executes target selection by quickly removing the pen from contact with the tablet's surface. Results showed that the narrower the interval, the more time subjects needed to select the target. A further regression analysis of tilt interval × tilt target on selection time showed strong fits of the power relationship of MT = a*I^b with a correlation of $R^2 > 0.98$ where I is tilt interval, and a, b are empirical constants. Fig. 4.2 illustrates the results.

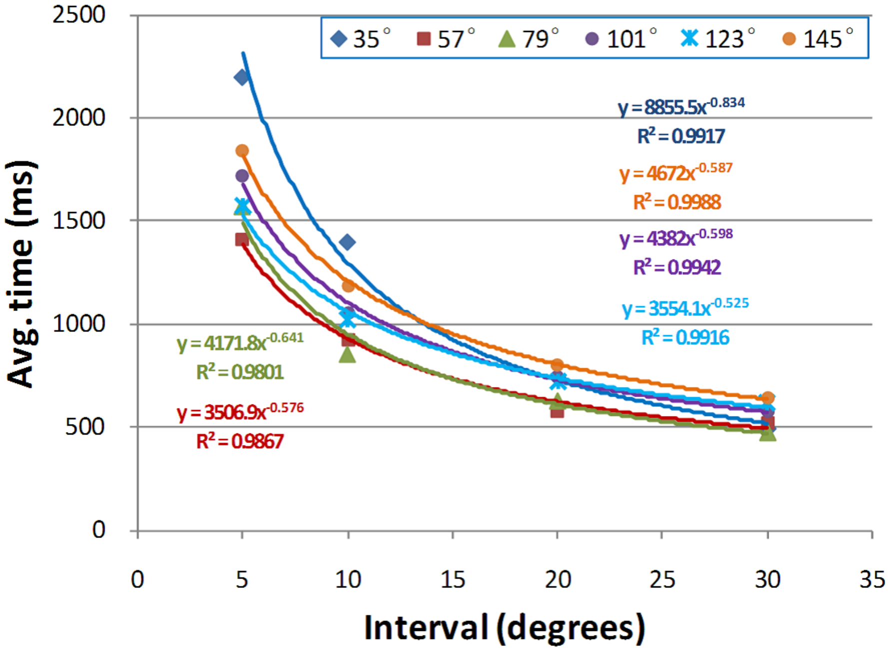

Fig. 4.2 Average selection time per interval × target tilt angle.

Repeated measures analysis of variance showed a significant main effect on selection time for target tilt angle ($F_{5,55} = 6.27$, $p < .001$) and tilt interval ($F_{3,33} = 61.30$, $p < .001$). Moreover, there was a significant interaction effect on selection time for target tilt angle × tilt interval ($F_{15,165} = 4.05$, $p < .001$). When target tilt angle was 57°, subjects achieved the fastest selections, 79° the second fastest, and 145° the slowest. Another pilot study indicated that the comfortable and natural range was 58.8° with SD of 8.6° when subjects naturally placed the pen in contact with the tablet surface. As a result, subjects achieved fastest selection on 57° of tilt target, and subjects had to use more time to adjust the pen to 145° of tilt target. However, 35° target was difficult for subjects to select because the pen was obstructed by the hand when the pen tail was oriented towards the subject's arm. As the interval increased to 10°, the performance for 35° tilt target selection was still the worst, which suggests some influence of hand obstruction.

Post hoc pairwise comparisons showed significant differences between all interval pairs ($p < .005$) and target tilt pairs (35°, 57°), (35°, 79°), (57°, 145°), (79°, 101°), and (79°, 145°) ($p < .01$). The significant interaction effect of target tilt angle × tilt interval on time indicates that the adverse impact of hand occlusion was obviously reduced when the target interval increased.

Selection Error

Selection error rate was defined as the percentage of trials in which subjects made erroneous selections. Subjects committed the fewest errors (3.33%) when tilt interval was 30°, and the most errors (32.38%) when interval was 5°. For tilt targets, subjects committed the fewest errors when the target was 145°, and the most errors when the target was 101°. Repeated measures analysis of variance showed a significant main effect on error rate for target tilt angle ($F_{5,55} = 7.46$, $p < .001$) and tilt interval ($F_{3,33} = 341.42$, $p < .001$). Moreover, there was a significant main effect on error rate for target tilt angle × tilt interval ($F_{15,165} = 2.28$, $p < .01$). Fig. 4.3 illustrates the results.

Post hoc pairwise comparisons showed significant differences between all interval pairs ($p < .001$) and target tilt pairs (35°, 145°), (57°, 145°), (79°, 145°), (101°, 123°), and (101°, 145°) ($p < .005$). The significant interaction effect of tilt target × tilt interval on time indicates that with the increase of interval, subjects tended to commit similar number of errors for different tilt target.

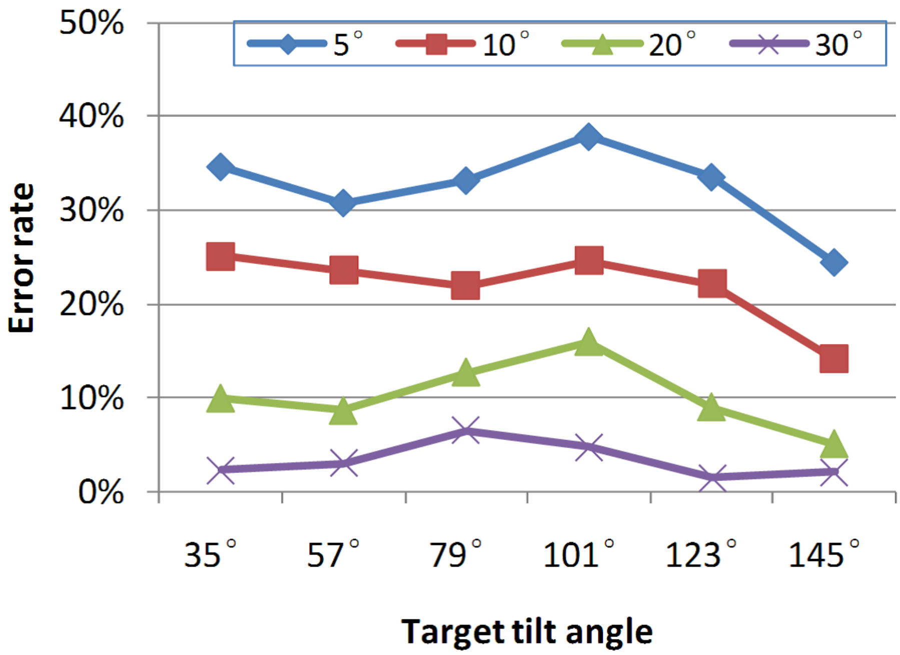

Fig. 4.3 Error rate per interval × target tilt angle.

Number of Crossings

When searching for a target, subjects sometimes crossed the target more than once. Number of crossings, NC, is defined as the number of times subjects controlled pen tilt inside or outside a target in a particular trial, minus 1. Repeated measures analysis of variance showed a significant main effect on NC for tilt target ($F_{5,55} = 10.25$, $p < .001$) and tilt interval ($F_{3,33} = 61.52$, $p < .001$). Moreover, there was a significant interaction effect on NC for target tilt angle × tilt interval ($F_{15,165} = 3.96$, $p < .001$). Fig. 4.4 illustrates the results.

The narrower the tilt interval, the larger NC. Particularly when tilt interval was 30°, subjects could usually achieve the target without additional crossings. On the other hand, subjects crossed the target the fewest times when target tilt was 145°, and the most for tilt target 101° the most. The closer to perpendicular to the tablet surface the pen was, the more crossings occurred. As target interval increased, the influence of

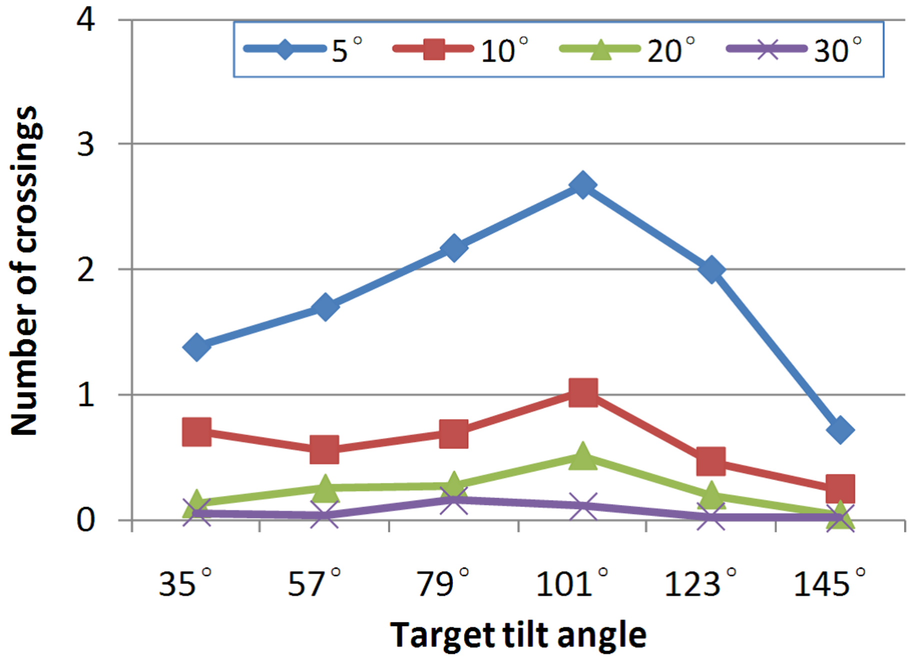

Fig. 4.4 Number of crossings per interval × target tilt angle.

target tilt angle on NC decreased.

Post hoc pairwise comparisons showed significant differences between all interval pairs (p < .001) and target tilt pairs (35°, 79°), (35°, 101°), (57°, 101°), (79°, 145°), (101°, 123°), and (101°, 145°) (p < .005).

Learning effect

We collected 5 blocks of data to investigate the learning effect. Results showed that with the increase of block number, the selection time reduced. Repeated measures analysis of variance showed a significant main effect of block on selection time ($F_{4,44} = 10.55$, $p < .001$) and on NC ($F_{4,44} = 4.31$, $p < .01$). However, no significant main effect was found on Error rate ($F_{4,44} = 0.43$, $p = 0.788$). Fig. 4.5 illustrates the results.

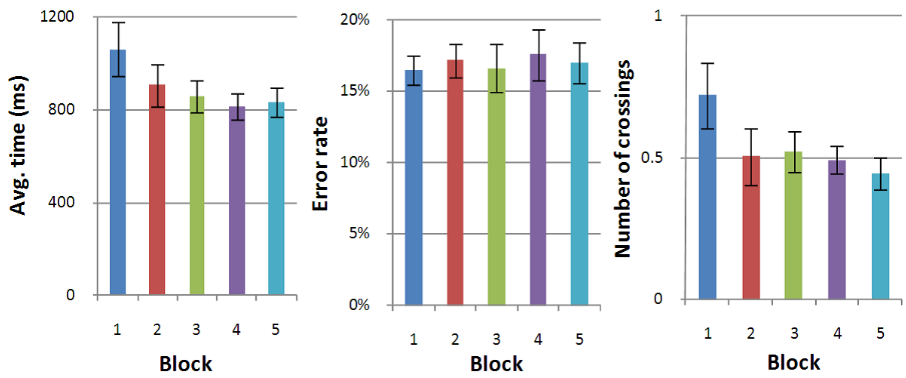

Fig. 4.5 Learning effects of selection time, error rate, and NC × block.

4.3.6 Discussion

Method for conforming selection

At the design stage of the study, we conducted series of pilot experiments to decide the target selection technique. The five candidates considered were 1) Barrel-Button-Click: pressing the stylus' barrel button; 2) Dwell: maintaining the tilt cursor within the target for 1 second; 3) Quick-Release: quickly lifting the pen from the tablet's surface; 4) Stroke: quickly drawing a circle; and 5) Key-Pressing: pressing a key on the keyboard using the non-dominant hand. The pilot study results indicated that the Key-Pressing method was the most appropriate for investigation of pen tilt control, for reasons including: 1) Barrel-Button-Click [60] and Stroke [53] often caused inadvertent pen-tip movement and easily led to pen tilt change. Besides, subjects often rotated the stylus, thus the button may not always be in a position that facilitates pressing; 2) Dwell requires subjects to maintain pen tilt for a given time, which may lead to user fatigue and pen tilt change. Ramos et al.'s study [81] also showed that the time cost for Dwell was high; 3) we investigated the "tilt pointing", which required subjects keep the pen tip in contact with the surface to select the first and the second target in succession. Moreover, a pilot study showed that the requirement for sudden quick-release action often made users feel nervous; 4) previous research indicated that better performance could be achieved with bi-manual than with uni-manual on selection time and error rate ([31], [40], [51], and [87]). In order to make the selection method uniform in the two experiments, Quick-Release was not used.

We also asked the subjects to evaluate the five selection techniques according to fatigue, difficulty, nervousness, and preference on a 7-point Likert scale. Key-Pressing was ranked best, followed by Quick-Release, Barrel-Button-Click, Dwell, and Stroke. Because our purpose was to investigate human ability to control pen tilt, it was necessary to minimize the factors that affected the results. Thus in this study, we regarded the space bar selection method as optimal. Nevertheless, we advocate that it is better to avoid the tilt input task with separate target selection in concrete application designs.

Timing of subjects adjusting the pen tilt

In the experimental procedure, we found that after the target was shown to the subjects, they adjusted the pen to the target tilt in the following ways: 1) roughly tilting the pen in the air initially, and after landing the pen on the tablet surface, finely adjusting the pen tilt; 2) not tilting the pen in the air initially, and after landing the pen on the tablet surface, directly adjusting the pen tilt to the target angle. Most of the pen tilt adjustments were the first case particularly for those target areas falling into the [90°, 180°] tilt interval. We had once wanted to make the procedures of pen tilt adjustment uniform by giving subjects clear instructions. After a detailed discussion, we gave up the idea because we did not want to limit the user's natural manipulation; as a result, subjects could tilt the pen in a personal and comfortable way. Moreover, performance in tilting the pen from one target to another is investigated in the second experiment.

One the other hand, subjects tended to hold the pen in unique gestures. Some grasp-related factors such as the height of pen grasp and manner of coordination of the fingers varied. However, we also found that the pen holding gestures of each subject were uniform in the whole experiment. And as a result, performance evaluation would not likely be influenced by different pen holding gestures.

4.4 Experiment 2 - Tilt Pointing

4.4.1 Goals

The goals were to investigate the human ability to point two tilt targets with different tolerances and to verify the validity of Fitts' law in tilt pointing tasks.

4.4.2 Participants and Apparatus

The same 12 individuals who participated in Experiment 1 took part in Experiment 2. And the same apparatus with the same experimental setup was used as in Experiment 1.

4.4.3 Task and Procedure

Pen tilt was utilized to control the rotation movement of a pink cursor around a fixed point, either clockwise or anticlockwise. A set of equal and consecutive sectors presenting targets with tolerances were drawn using dashed lines around the fixed point on the screen. During each trial, two of the targets were highlighted in red and yellow respectively. Subjects had to land the pen tip in the input area and apply the appropriate amount of pen tilt to rotate the pink cursor into the first desired target, the red one. When the pink cursor entered the first target, the target color changed to green. The subject confirmed the selection by pressing the space bar on the keyboard.

After the first selection, the color of the first target changed to gray and the color of the second target changed to red. The subject had to tilt the pen to select the second target. The subject could not select the second target without correctly selecting the first target. Subjects were told to strive for both accuracy and speed. An error was defined as selecting second target wrongly. If a misselection was made, a failure "ding" sound tip was given to the subject. Fig. 4.6 is the schematic diagram of the tilt pointing experimental tool.

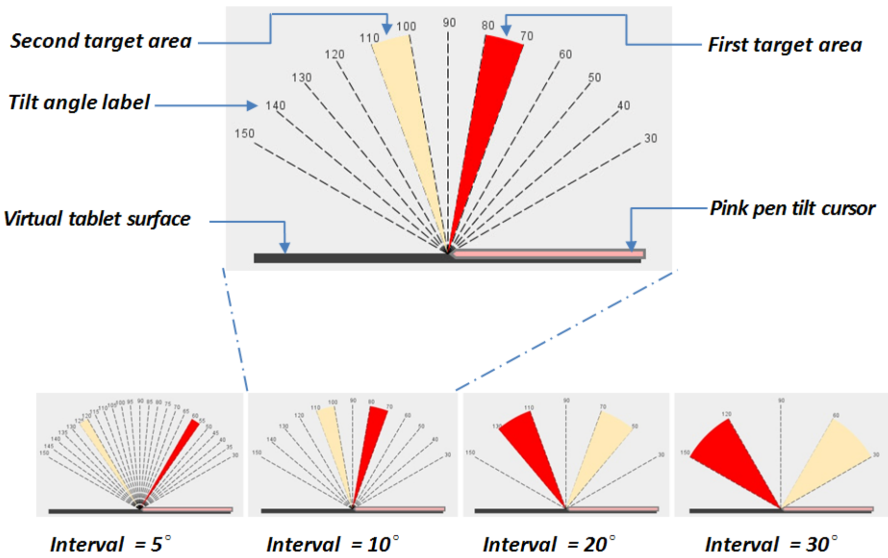

Fig. 4.6 Schematic diagram of the tilt pointing experimental tool.

A within-subject full factorial design with repeated measures was used. The independent variables were tilt intervals, ID (index of difficulty), and tilt directions (left-to-right, and right-to-left). In order that the targets were symmetrical along the vertical line of the tablet and the ID values were relatively decentralized, we designated the following values of intervals and amplitudes (see Table 4.1). The ID values were calculated according to ID = log_2 (A/W+1).

A Latin Square was used to counterbalance the order of the appearances of intervals and the amplitudes. To explore the learning effects, 5 blocks of trials were completed by

Table 4.1 Intervals vs. Amplitudes in Experiment 2.

Interval	5°			10°			20°			30°		
Amplitude	25°	65°	115°	30°	70°	110°	20°	60°	100°	30°	60°	90°
ID	2.58	3.81	4.58	2	3	3.58	1	2	2.58	1	1.58	2

each subject. Trials under same condition were repeated 2 times. Presentation of trials within a block was randomized. Before the formal experiment, subjects were allowed to perform a warm-up practice session until they could understand the task and perform it correctly. In total, the experiment consisted of:

12 subjects ×

4 intervals ×

3 amplitudes ×

2 tilting directions ×

5 blocks ×

2 repetitions

= 2880 target selection trials

4.4.4 Results

Selection Time

Selection time here is defined as the period from the time when the subject confirms the first target selection correctly until the time when the subject executes the second target selection by pressing the space bar on the keyboard. Similar to the results of the first experiment, the narrower the interval, the more time subjects needed to select the target. The subjects generally tilted the pen to the right faster than to the left.

Repeated measures analysis of variance showed a significant main effect on selection time for interval ($F_{3,33} = 176.86$, $p < .001$), tilting direction ($F_{1,11} = 5.45$, $p < .05$) and ID ($F_{7,77} = 47.52$, $p < .001$). However, there was no significant effect on selection time for interval × direction ($F_{3,33} = 2.69$, $p = 0.062$) and ID × direction ($F_{7,77} = 0.682$, $p = 0.687$). *Post hoc* pairwise comparisons showed significant differences between all interval pairs (p < .001). Fig. 4.7 illustrates the results.

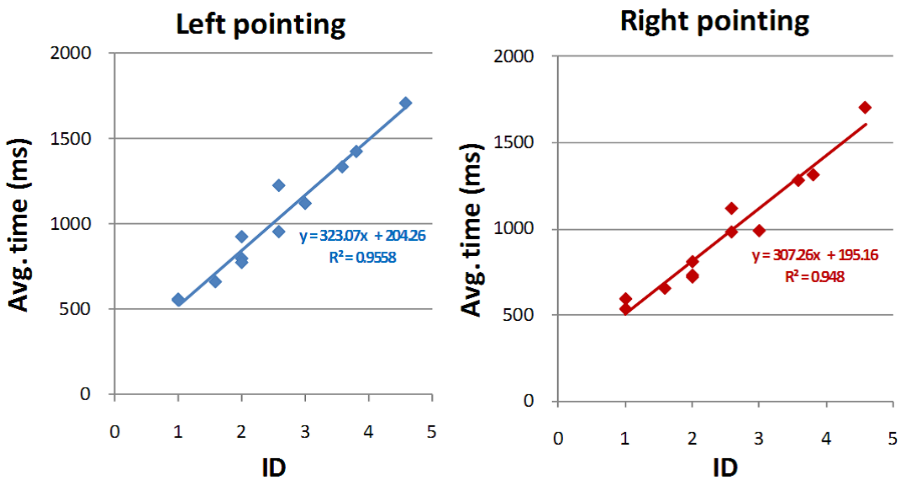

Fig. 4.7 Selection time of left and right pointing for each interval.

Pointing tasks such as pointing by physically touching an object with the hand/finger, or pointing to an object on a computer display using a pointing device, can be modeled by Fitts' law. However, the tasks in this study were different from traditional pointing tasks because the pointing was not performed by the pen tip but by pen tilt. We are also interested to see whether this pen tilt-controlled target pointing task obeys Fitts' law. Fitts' law is used to model the act of pointing. In traditional pointing tasks, the pointing is performed between two objects and the pointing device moved from one target to another. However, when the pen tilt is used, there is a special "pointing" task: users do not change the position of the pen tip but get the pen tilt around. Under such restriction of pen tip stable, whether the Fitts' law is still valid, it is unknown. Linear regression of the experimental data MT by ID for each interval showed high correlations with Fitts' law. All the calculated R-Squares were greater than 0.9. The narrower the target, the better match of Fitts' law. For right-handed subjects, left pointing was a closer fit to Fitts' law than right pointing.

According to Zhai et al.'s study [116], Fitts' law has implications for human-computer interaction. For example, "it has been used as a theoretical framework for computer input device evaluation (e.g. Card et al., 1978 [19]; MacKenzie, 1992 [64]), a tool for optimizing new interfaces (e.g. Lewis et al., 1992 [59]; MacKenzie and Zhang, 1999 [63]; Zhai et al., 2002 [115]), as well as a logical basis for modeling more complex human-computer interaction (HCI) tasks (Accot and Zhai, 1997 [1]). Fitts' law has also inspired alternative interaction techniques (e.g. Accot and Zhai, 2002 [4]; Kabbash and Buxton, 1995 [50]; Zhai et al., 1999 [118]) and gained new understandings, expansions, and applications in human-computer interaction research in recent years (e.g. Accot and Zhai, 2003 [5]; Guiard et al., 2001 [41]; McGuffin and Balakrishnan, 2002 [66]; Zhai et al., 2003 [114])" [116].

The verification of Fitts' law for tilt pointing tasks in our experiment can spread the founding and conclusions of Fitts' law to pen tilt designs.

Selection Error

Because subjects have to accomplish the first target selection correctly to start the second target selection, the error rate was defined here as the percentage of trials in which subjects made erroneous selections of the second targets. Results indicated that the narrower the interval, the more errors subjects committed. Repeated measures analysis of variance showed a significant main effect on error rate for interval ($F_{3,33} = 5.86$, $p < .005$) and ID ($F_{7,77} = 3.11$, $p < .01$). However, there was no significant effect on error for tilting direction ($F_{1,11} = 0.053$, $p = 0.822$), interval $\times$ direction ($F_{3,33} =$

0.631, p = 0.6) and ID × direction ($F_{7,77}$ = 1.211, p = 0.307). Fig. 4.8 illustrates the results.

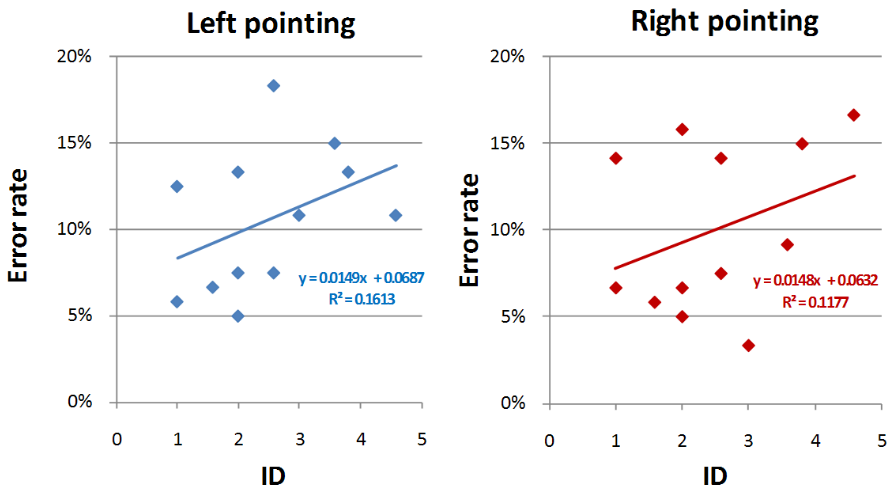

Fig. 4.8 Error rate of left and right pointing for each interval.

Number of Crossings

The NC was calculated only for the second target selections. Repeated measures analysis of variance showed a significant main effect on NC for interval ($F_{3,33}$ = 82.62, p < .001) and ID ($F_{7,77}$ = 16.81, p < .001). However, there was no significant effect NC for tilting direction ($F_{1,11}$ = 0.2, p = 0.663), interval × direction ($F_{3,33}$ = 0.631, p = 0.6) and ID × direction ($F_{7,77}$ = 0.76, p = 0.622). Fig. 4.9 illustrates the results.

Learning effect

For selection time, subjects exhibited learning. Results showed that with the increase of block number, selection time decreased. Repeated measures analysis of variance showed a significant main effect on selection time for block ($F_{4,44}$ = 7.08, p < .001). Moreover, there was a significant interaction effect on selection time for tilt direction

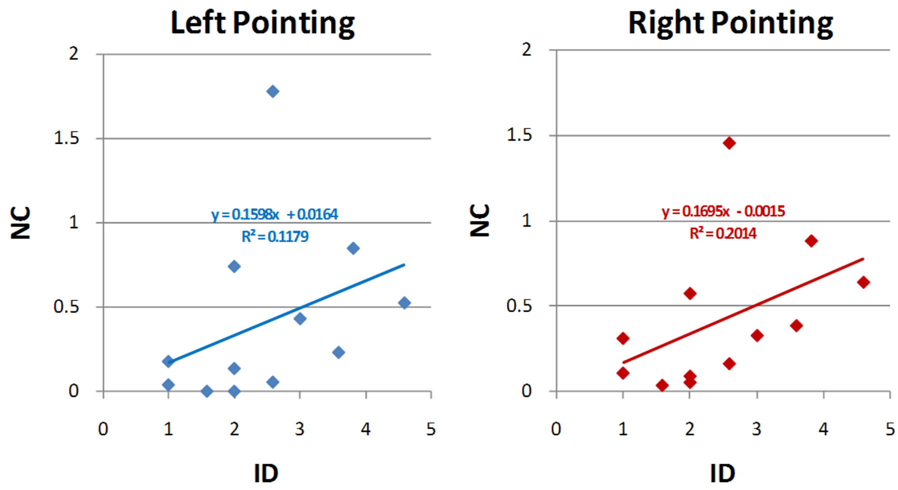

Fig. 4.9 NC of left and right pointing for each ID.

× block ($F_{4,44}$ = 3.17, p < .05). Subjects achieved better learning effect in tilting to the left than in tilting to the right. In block 5, subjects used almost the same time to accomplish the target selections.

No learning effect was found with increased block number for error rate. Repeated measures analysis of variance showed no significant effect on error rate for block ($F_{4,44}$ = 0.939, p = 0.451). Moreover, there was no significant interaction effect on error rate for tilt direction × block ($F_{4,44}$ = 1.529, p = 0.21).

No learning effect was found with increased block number for NC. Repeated measures analysis of variance showed no significant effect on NC for block ($F_{4,44}$ = 0.087, p = 0.986). Moreover, there was no significant interaction effect on NC for tilt direction × block ($F_{4,44}$ = 1.716, p = 0.163). Fig. 4.10 illustrates the results.

Covariation with pen tip displacement

When the pen was tilted to select a given target, the pen tip also moved accordingly. This pen tip movement could not be avoided in the pen tilting procedure. Results showed that the narrower the target interval, the more pen tip movement was produced

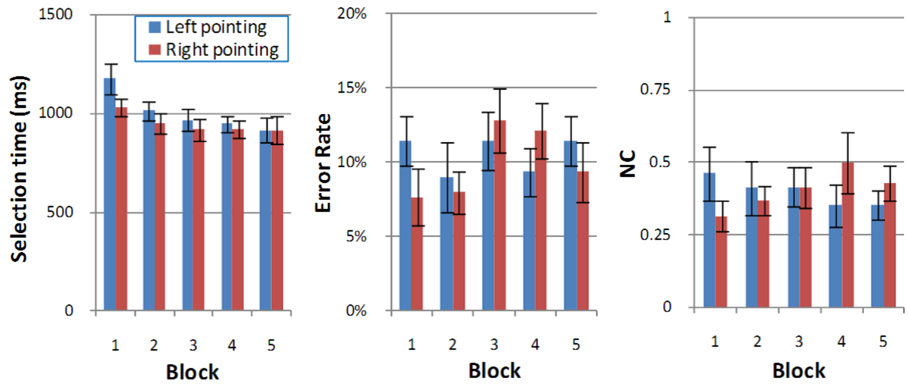

Fig. 4.10 Learning effects of selection time, error rate, and NC for block × tilting direction.

in the course of pen tilting. The wider the amplitude between the two targets, the more pen tip movement. Repeated measures analysis of variance showed a significant main effect on pen tip displacement for interval ($F_{3,33} = 11.23$, $p < .001$) and ID ($F_{7,77} = 20.36$, $p < .001$). However, there was no significant effect on pen tip displacement for tilting direction ($F_{1,11} = 0.3$, $p = 0.876$), interval × direction ($F_{3,33} = 0.911$, $p = 0.446$) and ID × direction ($F_{7,77} = 17.758$, $p = 0.172$). Fig. 4.11 illustrates the results.

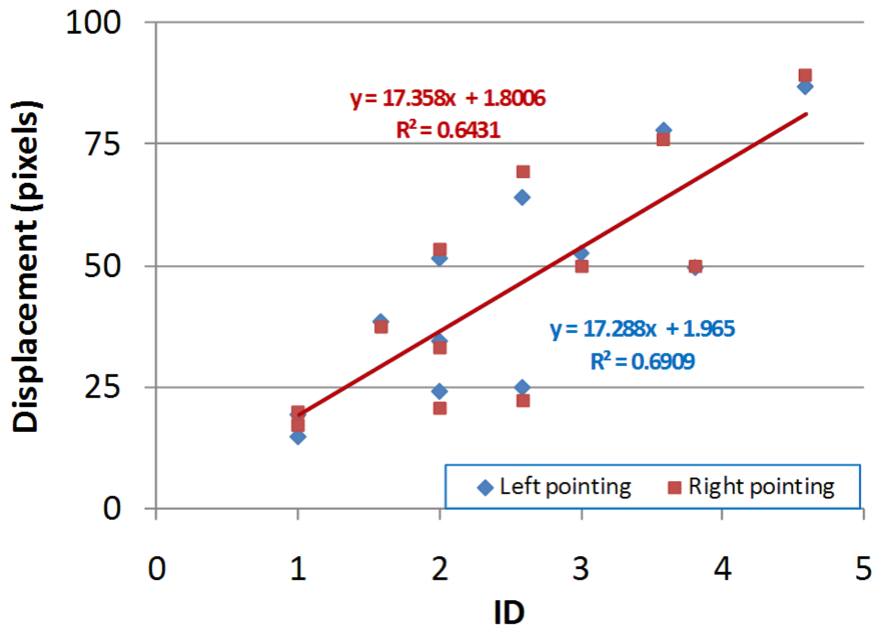

Fig. 4.11 Pen tip displacement of left and right pointing for each ID.

No learning effect was found with increased block number for pen tip displacement. Repeated measures analysis of variance showed no significant effect on pen tip displacement for block ($F_{4,44} = 0.478$, $p = 0.752$). Moreover, there was no significant interaction effect on pen tip displacement for tilt direction × block ($F_{4,44} = 43.97$, $p = 0.238$). Fig. 4.12 illustrates the results.

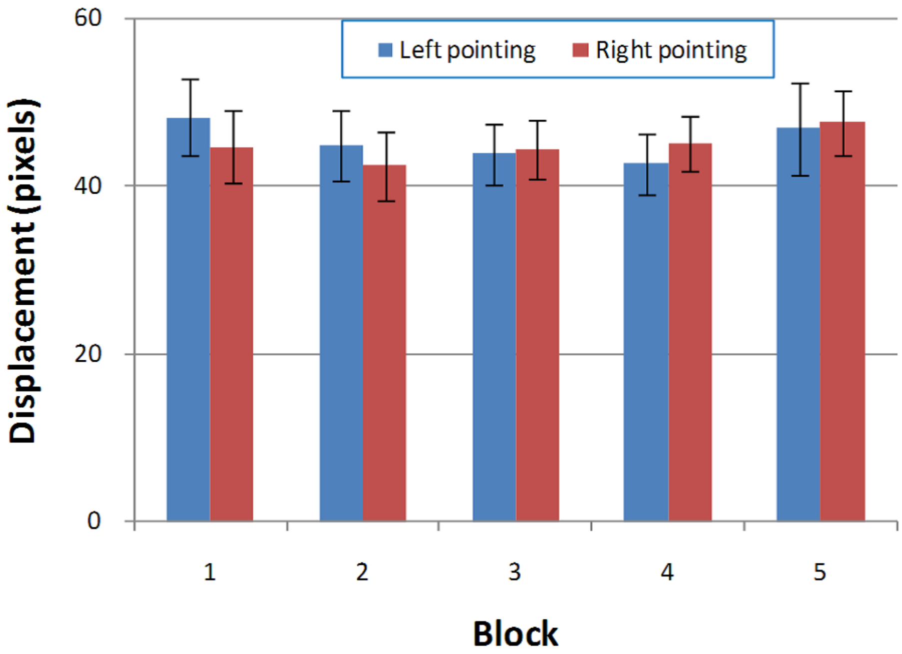

Fig. 4.12 Pen tip displacement for block × tilting direction.

4.5 Discussion

4.5.1 The ability to control pen tilt

Pen tilt acquiring

One of the main targets of this study was to investigate the human ability to control pen tilt effectively. In the tilt acquirement experiment, for selection time, subjects selected the target within 1 second for tilt intervals 20° and 30°, and within approximately 1 second (1.06 second) for tilt interval 10°. In blocks 3, 4, and 5, selection time reached a plateau (selection times in block 5 for tilt intervals 5°, 10°, 20°, and 30° were 1.53s, 0.99s, 0.66s, and 0.51s, respectively). On the other hand, for different tilt targets, subjects exhibited different ability to acquire them. For tilt target 35°, and 145°, subjects cost longer time to acquire them. Nevertheless, when interval is 20° and 30°, subjects could acquire each tilt target within 1 second. For interval 10°, subjects could acquire the targets within 1 second for tilt target 57°, 79°, 101°, and 123°. For error rate, subjects committed less than 10% errors for interval 30° for each tilt target. When interval 20°, the error rates were less than 10% for all tilt targets except target 79° and 101°. When tilt interval were 5° and 10°, error rates were more than 10%. The average NCs were less than 1 except interval 5°. In block 5, the NCs for all target tilt were less than 1.

In addition, subjective evaluation also suggested that the user-accepted tilt intervals were 20°, 30°, and 10° for target area [50°, 130°]. As a result, users could acquire all tilt target areas with interval 30°, and tilt intervals [35°, 79°] and [101°, 145°] with interval 20°. It was also found that human ability to select a tilt target fitted the power relationship of MT vs. Interval.

Pen tilt pointing

In the tilt pointing experiment, regarding selection time, subjects selected the target within 1 second for tilt intervals 20° and 30°, and within approximately 1 second (1.08 second) for tilt interval 10°. The selection times in block 5 for tilt intervals 5°, 10°, 20°, and 30° were 1.34s, 0.99s, 0.77s, and 0.59s, respectively. One the other hand, for different ID, selection time obeyed Fitts' law. For error rate, subjects committed fewer than 10% errors for intervals 10°, 20°, and 30° in block 5. The average NCs were fewer than 1 except for interval 5°. In block 5, the NCs for all target tilts were less than 1. Left pointing achieved better performance than right pointing in terms of selection time, error rate, and NC.

According to the above analysis, tilt intervals less than 10° were too difficult to control and performance degraded drastically. Considering the tradeoff of selection speed, accuracy, and number of discernable pen tilt intervals, 20-degree-tilt intervals could gave rise to best performance.

4.5.2 The feasibility of expanding the range of pen tilt

The results of our experiment indicated that pen tilt range could be expanded from [30°, 90°] to [30°, 150°] to enhance the pen input capacity. In addition, the human ability to control of the right side and left side are not significantly different for a right-handed user. On the other hand, subjects also reported that pen tilt provided them with inherent visual feedback from which they could be roughly aware of the present pen tilt angle. Moreover, learning effect results indicated that better performance could be achieved after more practice.

4.5.3 The covariation between pen tilt and pen tip movement

As inadvertent movements decrease accuracy in pen tilt selection tasks, the experimental results were helpful to increase the accuracy of pen tilt manipulation. We believe that more effective pen tilt based interface could be designed if the influence of covariation is considered.

4.5.4 The choice of mapping methods

The experimental results indicate that the human ability to control different levels of pen tilt varies according to human hand structure and pen use habits, e.g. some pen tilt intervals such as [30, 50] degrees were difficult to acquire. An optimum design should reduce or eliminate the negative factors between hand and pen. A proper mapping method from pen tilt to control is required to maximize the number of pen tilt levels that a person can distinguish among, and minimize the error rate for tasks where a person is asked to target a particular subdivision of the pen tilt space.

4.6 Pen Tilt Techniques

In terms of manner of operation, pen tilt can be used in both discrete selections, e.g., choosing an item from a list or pie menu, and consecutive variant manipulations, e.g. varying brush size in a painting system. Moreover, in a concrete pen based interface, pen tilt change can be mapped either to displace of a cursor in the interface, or to the angle/orientation change of a target, or to scale of a manipulation. Taking into account the factors mentioned above, we developed a taxonomy of pen tilt utilization which describes the nature of our proposed pen tilt techniques (see Table 4.2).

Table 4.2 A taxonomy for the design of pen tilt techniques.

	Manner of Pen tilt manipulation	
	Discrete	Consecutive
Target	Fan menu 3D manipulation Subobjects creation	Granularity widget 3D manipulation
Cursor	Magic Pen Mode switching	Projection cursor

Based on our experimental results, a series of interactive techniques are proposed to demonstrate the potential of pen tilt to enhance pen-based interactions.

4.6.1 Fan menu

The pen tilt is mapped onto different discrete intervals for the selection of the items on the menu. The menu could have several variations in form such as Fan menu and Tilt list menu (Fig. 4.13 a) though the basic interactive mechanism is the same: after the pen tip contacts the tablet surface, the user can adjust pen tilt to switch among different menu items. Moreover, the pen tilt could also be used in a marking menu [56] to extend the number of available items.

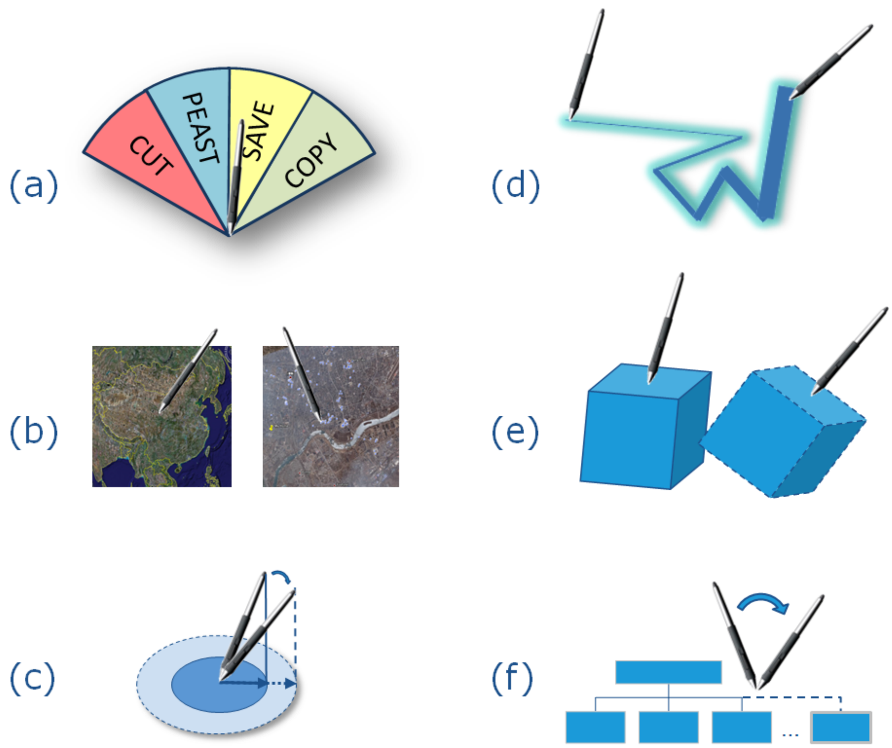

Fig. 4.13 The conceptual designs of pen tilt techniques: (a) Fan menu; (b) Granularity widget; c) Projection cursor; (d) Magic Pen with implicit mode switching; (e) 3D manipulation; (f) Subobjects creation.

4.6.2 Granularity widget

Pen tilt can be used to manipulate a parameter with variable precision. A slider is an object in a GUI with which the user may set a value by moving an indicator. The slider can be augmented with pen tilt (Fig. 4.13 b) so that the sliding action is produced by varying the pen tip x-y coordinate position, and the granularity of the sliding is adjusted by variation of pen tilt. This mechanism can be used to adjust the granularity of a control such as number of steps of scrolling, or speed of frame forward in a video. For example, in map navigation, the reader can easily navigate the map to either coarse or fine scale by adjustment of pen tilt.

4.6.3 Projection cursor

As pen tilt changes, its projection varies accordingly. In this light, a projected cursor was designed here based on the projection of the pen (Fig. 4.13 c). The lower the pen tilt value, the bigger the cursor size will be. A cursor with zoomable size can be utilized for selection of one or multiple targets, or for specification of an area. The pen tilt cursor can also give users visual feedback on pen tilt or be used to determine operating range.

4.6.4 Magic Pen with implicit mode switching

In GUIs, some tasks require more than one step to switch among different operations. If a seamless switch mode is available, two or more techniques can be coupled. Pen tilt has the potential to be used in mode switching. Magic Pen (Fig. 4.13 d) couples two types of painting ("hard" pen and "soft" pen). In drawing tasks, higher pen tilt results in a "hard" pen whose stroke width is consistent while lower pen tilt invokes "soft" pen whose stroke width can be changed by pen pressure.

4.6.5 3D manipulation

Through the manipulation of a 3D object with pen tilt, more intuitive interaction may be achieved (Fig. 4.13 e). For example, a 3D object could be rotated according to the variation of pen tilt. If tilt is coupled with azimuth, the whole profile of a 3D object could put in perspective for the user.

4.6.6 Sub-objects creation

Pen tilt can aid the concurrent pen manipulation. In the drawing of an organization chart or a flowchart, the number of sub-objects can be determined by pen tilt (Fig. 4.13 f).

4.7 Conclusion

This study presented two controlled experiments, pen tilt acquirement and pointing, that empirically investigated human ability to use pen tilt to perform discrete target selection tasks. Results revealed a decreasing power relationship between pen tilt interval and selection time and an incremental linear covariation relationship between Index of Difficulty and pen tip displacement. This study also verified the applicability of Fitts' law in the pen tilt pointing experiment. Results also indicate that 20 degrees pen tilt interval presented the optimal performance regarding selection time, error, number of crossings, and number of tilt divisions. Human ability to control pen tilt and the implications of pen tilt utilization are discussed. In addition, a taxonomy of pen tilt based techniques along with a series of possible pen tilt scenarios is given. This study presents a general understanding of pen tilt utilization, which may be useful in pen-based user interface design.

4.7 Conclusion

Chapter 5

An Empirical Study of Human Ability to Control Pen Azimuth

5.1 Introduction

Pen-based interaction is an attractive human interface paradigm. With advances in hardware technology, pen computing in the form of handhold devices and tablets has made pen-based interfaces increasingly relevant to mainstream applications. Consequently, research into pen-based interaction methods has intensified in recent years, for example [47], [61], and [85].

Stylus pens, like mice, are able to use two-dimensional coordinate information, but they also offer other potential input modalities which are not available with mice but which are natural aspects of pen usage, and can be used to affect a wide variety of interaction techniques with minimal user effort.

Pen azimuth input could serve to further increase human-computer communication bandwidth. To date, pen azimuth input has seldom been used, in only a few applications ([71], [98], and [99]). In particular, the literature lacks a body of empirical knowledge on the human ability to control pen azimuth, which could be used as a guide for designing appropriate pen azimuth techniques. In this light, we will experimentally investigate pen azimuth. Considering that this is the first study which investigates the human ability to control pen azimuth: it will have implications for pen based interface designs.

In the following section we first briefly review previous efforts on this topic. Next, we explore the human ability to control pen azimuth by conducting an experiment where participants perform discrete target selection tasks by varying the azimuth of a pen. Based on the experimental results, we discuss implications for the design of pen azimuth techniques. We also present several possible conceptual pen azimuth techniques.

5.2 Related Work

To date, no investigations specially focused on pen azimuth were found, and few involved pen azimuth in relative literature. Few studies explored pen tilt, azimuth, and rolling. In one study, Tilt cursor [98] dynamically reshaped itself to provide the 3D orientation cue of the pen so that the stimulus-response compatibility was enhanced. Another technique, Tilt Menu [99], extended the selection capabilities of pen-based user interfaces using 3D pen orientation information. Kuroki and Kawai [55] observed that people hold three physical tools (a syringe, a pen, and a cutter) differently and proposed that the use of tilt information for pen interfaces should be based on this observation. Oshita [71] designed a virtual human figure movement manipulation system that used not only pen pressure but also pen tilt to control a virtual human figure. Xin and Ren [110] implemented a widget to manipulate high precision parameters. They comparatively investigated the performance of inherent pen input modalities (pen pressure, tilt, azimuth, and rolling) used for precision parameter manipulation during pen sliding actions and found that pen azimuth exhibited the worst performance. Bi et al. [16] explored pen rolling around the longitudinal axis of the pen and distinguished between intentional and incidental pen rolling which occurs in pen manipulations.

Besides pen tilt, device tilt was also used as an input mode. Rekimoto [84] presents an interaction technique that uses variations in the tilt of a small screen device as input commands. TiltType [74] and TiltText [102] are text entry techniques for mobile devices. The tilt direction and angle of a mobile device were used to aid character selection from a range of given candidates.

Although the aforementioned works explored the utilization of pen input azimuth, no literature quantitatively investigated the human ability to control pen azimuth. Our review indicates that the human ability to control pen azimuth should be systematically investigated. The findings of this study have implications for pen azimuth based user interface designs.

5.3 Experiment

5.3.1 Goal

The goal of this study is to explore the human ability to implement discrete selection tasks by controlling the pen azimuth.

5.3.2 Participants

Two female and ten male volunteers, ranging in age from 20 to 24, participated in the experiment. To minimize experimental bias due to differences between left and right hand dominant subjects, we ensured that all participants were right-handed according to their own report.

5.3.3 Apparatus

A Wacom Cintiq 21UX interactive LCD graphics display tablet and a wireless stylus with an isometric tip were used in the experiment. The azimuth of the pen can be detected by the Cintiq 21UX ranging from 0 to 359 degrees clockwise from the northerly direction. The experimental program was designed in the Java Environment and ran on a 2.13 GHz Intel Core2 CPU PC with Windows XP Professional SP2. The resolution of the display was set to 1280 by 1024 pixels at 96 dpi (0.27 mm per pixel).

5.3.4 Task

In the experiment a series of target selection task was used (see Fig. 5.1). The pen azimuth was utilized to guide the rotation movement of a pink arrow cursor around a fixed point, either clockwise or anticlockwise. The pin arrow cursor displayed after the pen came into contact the tablet surface. Pen azimuth (from 0 to 359 degrees) was mapped uniformly to a circumferential angle (from 0 to 359 degrees). A set of equal and consecutive sectors presenting targets was drawn using dashed lines around the fixed point. The appearance of the target was experimentally determined. During each experimental trial, one of the sectors was highlighted in red to show that it was the desired target. Subjects were asked to apply the appropriate amount of pen azimuth to rotate the pink cursor to the desired target. When the pink cursor entered the target, the target color changed to green. Subjects confirmed the selection by pressing the space bar on the keyboard. Participants were told to strive for both accuracy and speed. If a misselection was made, a failure icon appeared and a sound tip was given to the subject.

5.3.5 Procedure and Design

A within-participants factorial design with repeated measures was used. We explored orientation divisions of 30 degrees, 60 degrees, and 90 degrees of intervals and as a result generated 12, 6, and 4 orientation targets for each kind of division. Fig. 5.2 is the schematic diagram of the divisions. In order to facilitate analysis, the divisions

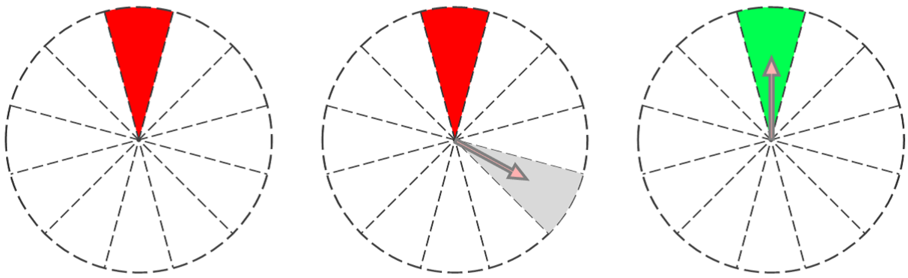

Fig. 5.1 Left: a target was displayed in red. Middle: the subject applied appropriate amount of pen azimuth to rotate the pink arrow cursor. Right: when the cursor entered the target, the target color switched to green.

were numbered as shown in the figure. Each subject was asked to perform 5 blocks of trials. Each block consisted of the 22 (12 + 6 + 4) selection tasks described above. Trials were repeated 2 times under the same conditions for reliability within each block. Presentation of trials within a block was randomized. In total, the experiment consisted of:

12 subjects ×

22 orientation targets ×

5 blocks ×

2 repetitions

= 2640 trials

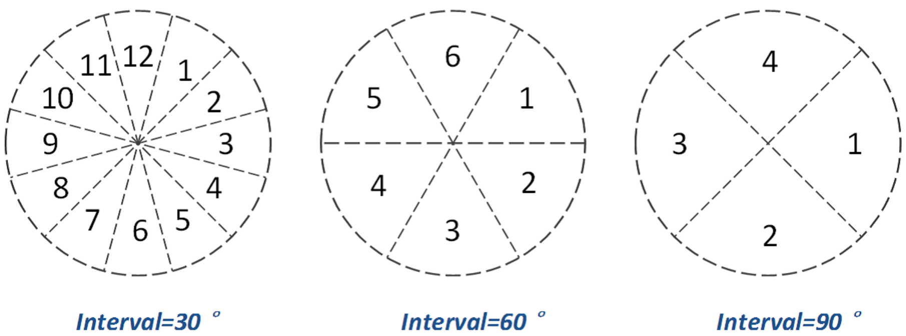

Fig. 5.2 Schematic diagram of the azimuth targets in each interval condition.

5.3.6 Results

Selection Time

Selection time here is defined as the period from the time when the pen comes into contact with the tablet surface until the time when the subject confirms the target selection by pressing the space bar on the keyboard using the nondominant hand. Results showed that the narrower the interval, the more time subjects needed to select the target.

Repeated measures analysis of variance showed a significant main effect on selection time for interval ($F_{2,22} = 84.33$, $p < .001$), for partition ($F_{11,121} = 11.09$, $p < .001$) when the interval was 30 degrees, or for partition ($F_{5,55} = 7.41$, $p < .001$) when the interval was 60 degrees. However, there was no significant main effect on selection time for partition ($F_{3,33} = 1.75$, $p = 0.18$) when interval is 90 degrees. *Post hoc* pairwise comparisons showed significant differences between all interval pairs ($p < .005$). *Post hoc* pairwise comparisons indicate that the partitions were able to be grouped as [-15, 105], [105, 165], [165, 195], [195, 255], [255, 285], and [285, 345] according to the significant differences in terms of selection time for 30 degrees of interval, and grouped as [30, 90], [90, 150], [150, 330], and [-30, 30] for 60 degrees of interval. However, for 90 degrees of interval, *post hoc* pairwise comparisons did not find significant difference between all the partition pairs. Fig. 5.3 illustrates the results.

Selection Error

Selection error rate was defined here as the percentage of trials in which subjects made erroneous selections of the target. Results indicated that the narrower the interval, the more error subjects committed. Repeated measures analysis of variance showed a significant main effect on selection error for interval ($F_{2,22} = 23.38$, $p < .001$). However,

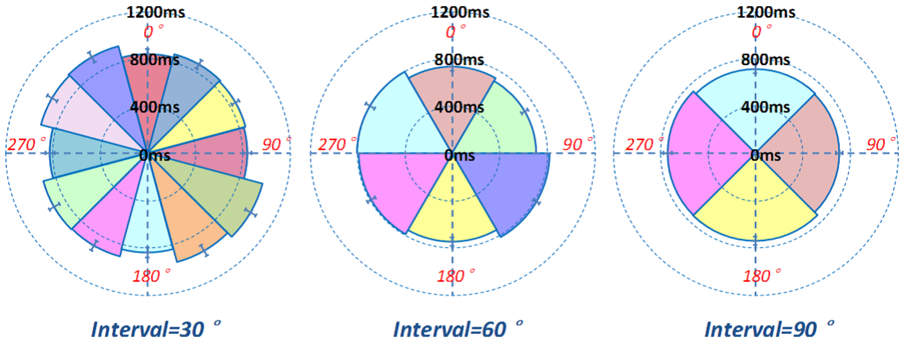

Fig. 5.3 Average selection time per interval × partition.

there was no significant main effect on selection error for partition ($F_{11,121} = 1.54$, $p = 0.13$) when interval was 30 degrees, for partition ($F_{5,55} = 0.54$, $p = 0.75$) when interval was 60 degrees, or for partition ($F_{3,33} = 2.38$, $p = 0.09$) when interval was 90 degrees. *Post hoc* pairwise comparisons showed significant differences between [30, 60] and [30, 90] interval pairs ($p < .001$) but no significant difference between [60, 90] interval pair ($p = 0.79$).

Post hoc pairwise comparisons showed significant differences between [1st, 6th], [1st, 9th], [3rd, 7th], [4th, 7th], [5th, 9th], [6th, 7th], [7th, 8th], [7th, 9th], and [7th, 12th] partition pairs ($p < .05$) when interval was 30 degrees, and between [2nd, 3rd], and [2nd, 4th] partition pairs ($p < .05$) when interval was 90 degrees. However, no significant difference was found between all partition pairs for 60 degrees interval. Fig. 5.4 illustrates the results.

Release Error

Before a selection is performed, if the pen tip does not remain in contact with the surface, a release error is counted and the subject must perform the task again.

Repeated measures analysis of variance showed a significant main effect on release error for partition ($F_{11,121} = 8.56$, $p < .001$) when interval was 30 degrees, for partition

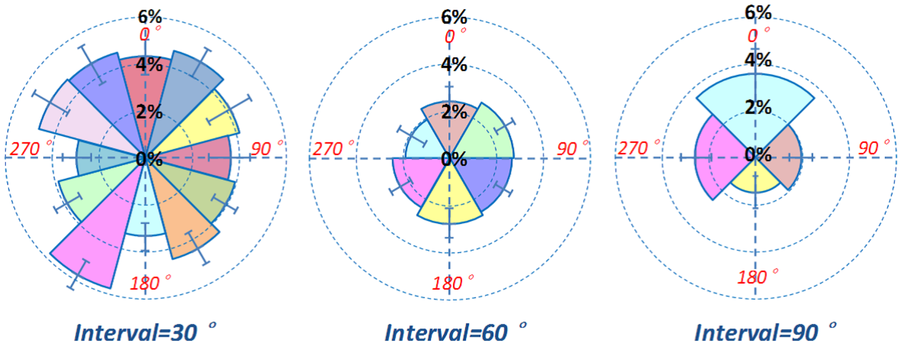

Fig. 5.4 Selection error rate per interval × partition.

($F_{5,55} = 6.07$, $p < .001$) when interval was 60 degrees, or for partition ($F_{3,33} = 9.37$, $p < .001$) when interval was 90 degrees. However, there was no significant main effect on release error for interval ($F_{2,22} = 1.13$, $p = 0.34$).

Post hoc pairwise comparisons showed significant differences between [1st, 6th], [1st, 7th], [1st, 8th], [1st, 9th], [1st, 11th], [2nd, 3rd], [2nd, 6th], [2nd, 7th], [2nd, 8th], [3rd, 9th], [3rd, 10th], [3rd, 11th], [3rd, 12th], [4th, 6th], [4th, 7th], [4th, 8th], [4th, 11th], [5th, 6th], [5th, 9th], [5th, 11th], [6th, 9th], [6th, 10th], [6th, 11th], [6th, 12th], [7th, 9th], [7th, 10th], [7th, 11th], [7th, 12th], [8th, 9th], [8th, 10th], [8th, 11th], and [8th, 12th] partition pairs ($p < .05$) when interval was 30 degrees and between [1st ,3rd], [1st, 5th], [2nd, 3rd],[2nd, 5th], [3rd, 5th], [3rd, 6th], [4th, 5th], and [4th, 6th] partition pairs ($p < .05$) when interval was 60 degrees and between [2nd, 3rd], and [2nd, 4th] partition pairs ($p < .005$) when interval was 90 degrees. Fig. 5.5 illustrates the results.

Number of Crossings

When searching for a target, subjects sometimes crossed the target more than once. Number of crossings, NC, is defined as the number of times subjects controlled pen azimuth inside or outside a target in a particular trial, minus 1.

Repeated measures analysis of variance showed a significant main effect on NC

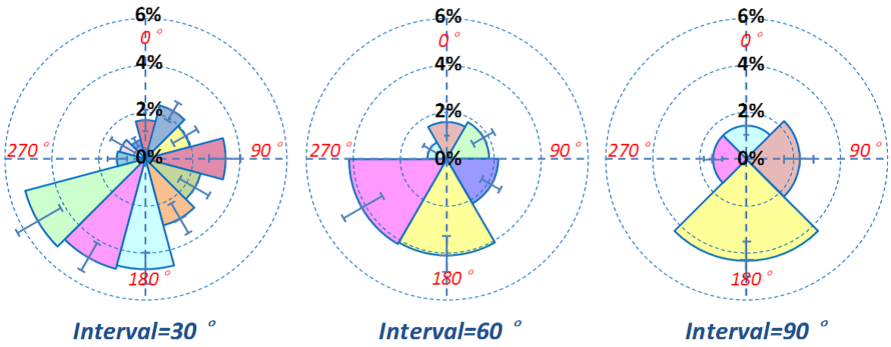

Fig. 5.5 Release error rate per interval × partition.

for interval ($F_{2,22}$ = 30.51, p < .001) and for partition ($F_{11,121}$ = 3.34, p < .001) when interval was 30 degrees. However, there was no significant main effect on NC for partition ($F_{5,55}$ = 2.05, p = 0.09) when interval was 60 degrees, or for partition ($F_{3,33}$ = 0.21, p = 0.89) when interval was 90 degrees. *Post hoc* pairwise comparisons showed significant differences between all interval pairs (p < .005).

Post hoc pairwise comparisons showed significant differences between [1st, 3rd], [1st, 5th], [1st, 6th], [1st, 9th], [1st, 10th], [1st, 12th], [2nd, 3rd], [2nd, 9th], [2nd, 11th], [3rd, 4th], [3rd, 8th], [3rd, 11th], [4th, 9th], [4th, 11th], [5th, 11th], [7th, 9th], [8th, 9th], [9th, 10th], [9th, 11th], [9th, 12th],and [11th, 12th] partition pairs (p < .05) when interval was 30 degrees and between [2nd, 4th], and [4th, 5th] partition pairs (p < .05) when interval was 60 degrees. However, no significant difference was found between all partition pairs for 90 degrees interval. Fig. 5.6 illustrates the results.

5.4 Discussion

5.4.1 The ability to control pen azimuth

According to the quantitative measures of selection time, selection error rate, release error rate, and number of crossings, results show that the narrower the target

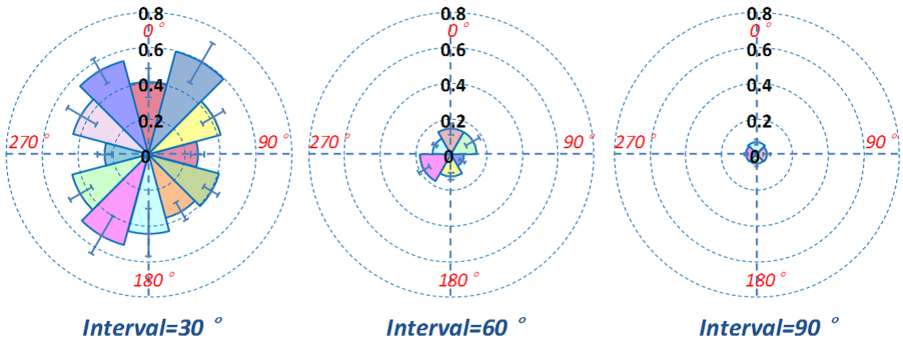

Fig. 5.6 Average number of crossings per interval × partition.

azimuth tolerance, the better was target acquisition performance. In addition, different azimuth targets also presented different performance. We also found that the performance on azimuth targets in due direction was much better than in oblique direction. For example, north is much better than north-west. Moreover, south-east was worst because of occlusion by the hand for right-handed subjects. When the azimuth interval was greater than 60°, there was no significant differences between azimuth intervals.

5.4.2 Application scenarios

As an input modality of the pen, azimuth can be used in pen based interfaces and technique designs. We here present several pen azimuth based conceptual designs which may be implemented in our future work.

Azimuth Menu

The pen azimuth is mapped onto different discrete intervals to select the items on the menu. The menu can have several variations in form such as pie menu and list menu (Fig. 5.7 a) though the basic interactive mechanism is the same: after the pen tip contacts the tablet surface, the user can adjust pen azimuth to switch among different menu items.

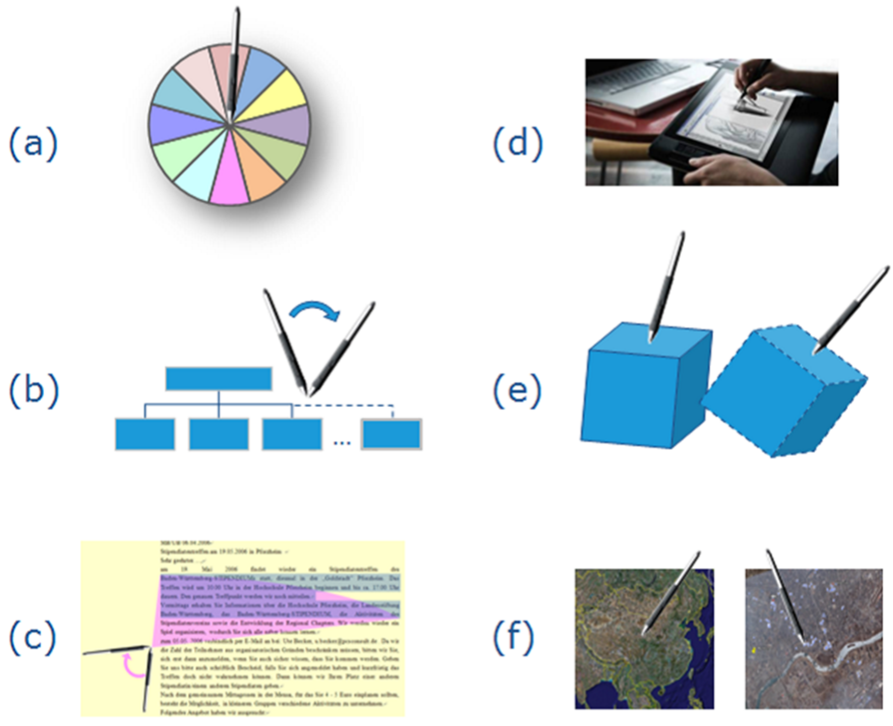

Fig. 5.7 The conceptual designs of pen azimuth techniques: (a) Azimuth menu; (b) Subobjects creation; c) Area selection; (d) Mode switching; (e) 3D manipulation; (f) Map navigation.

Sub-objects Creation

Pen azimuth can aid concurrent pen manipulation. In the drawing of an organization chart or a flowchart, the number of sub-objects can be determined by pen azimuth (Fig. 5.7 b).

Area Selection

As pen azimuth changes, its projection varies accordingly. In this light, pen azimuth can aid area selection (Fig. 5.7 c). Pen azimuth can also give users inherent visual feedback on pen position or or be used to determine operating range.

Mode switching

A typical and common problem for pen based interface design is the method for switching between ink and control mode [61]. If a seamless switch mode is available, two or more pen manipulations can be coupled. Pen azimuth provides a possible way to serve for mode switching (Fig. 5.7 d).

3D manipulation

Through the manipulation of a 3D object with pen azimuth, more intuitive interaction may be achieved (Fig. 5.7 e). For example, a 3D object could be rotated according to the variation of pen azimuth. If azimuth is coupled with pen tilt, the whole profile of a 3D object could put in perspective for the user.

Map navigation

Pen azimuth can be used to manipulate a parameter with variable precision. For example, in map navigation, the reader can easily navigate the map to either coarse or fine scale by adjustment of pen azimuth (Fig. 5.7 f).

5.5 Conclusion

Pen azimuth input has been utilized in some pen-based interface designs. Although attractive, no empirical study of the human ability to control pen azimuth in pen-based interfaces has been conducted previously. The current work is one systematic attempt at filling this void. We present an experiment that investigated the human ability to use pen azimuth to perform discrete target selection tasks. Experimental results show that the narrower the target azimuth tolerance, the better performance was achieved to select the target. The performance of azimuth targets in due direction was much better than in oblique direction. When the azimuth interval is more than 60°, there are no significant differences between azimuth intervals. Based on the results of our experiment, some possible designs of pen azimuth techniques are presented.

Chapter 6

Pen Input Modalities for Precision Parameter Manipulations during Trajectory Tasks

6.1 Introduction

In pen-based user interfaces, adjustment of a parameter as well as its granularity, or manipulation of a value besides x-y cursor movement, is usually required, such as changing a rectangle's scale with different levels of granularity and adjusting the color of a line while drawing. However, compared with that of other input devices such as keyboards and mice, the input throughput capacity of pens is less because the pen input channel is restricted to x-y coordinate data. Thus it is generally difficult to use the pen to adjust both a parameter and the granularity without other input modalities.

In this background, research has been conducted on the use of inherent pen input modalities such as pen pressure, tilt, azimuth and rolling to enhance the pen input capacity. Some of these studies, for example [81], focused on human ability to control these modalities, while others, for example [78], designed novel interaction techniques based on the pen modalities. However, most of these studies investigated only one or two pen input modalities. In particular, regarding precision parameter manipulation, only performance using pen pressure has been investigated [79]. Utilization of other inherent pen input modalities to achieve precision parameter manipulation during trajectory task remains unexplored. This gap in the literature motivates us to systematically evaluate performance using pen input modalities to realize precision parameter manipulations during trajectory tasks.

In this study, four kinds of inherent pen input modalities, *Pressure*, *Tilt*, *Azimuth*, and *Rolling*, used for high-precision parameter manipulation were comparatively investigated by both qualitative and quantitative analysis. Here *Pressure* means the pressure exerted on the stylus pen tip by the user. *Tilt* means the angle between the tablet surface and the pen body. *Azimuth* is the angle from the north direction on the tablet surface to the vertical projection of the pen on the tablet surface. *Rolling* means the angle the user rolls the pen around its longitudinal axis.

We conducted experimentation to evaluate the performance of these pen modalities and compared them with *Key Pressing* using the non-preferred hand. We elaborate the experimental design, present the results, and discuss the advantages and disadvantages of each pen modality. This study provides pen-based interface designers with a general understanding of pen input modality choice for precision parameter manipulation during trajectory tasks.

6.2 Related Work

Literature related to pen pressure emerged mainly after the new Millennium, and most of them focused on novel interaction technique designs. Mizuno et al. [68] implemented a virtual sculpting system by converting pen pressure to carving depth and angle. Ramos et al. [78] proposed a concept prototype designed for use with pressure-sensitive digitizer tablets to fluidly navigate, segment, link, and annotate digital videos; created the Zlider [79] that users can use pen pressure to achieve fluid zooming while sliding the pen; and developed pressure marks [80] that allowed users to perform a selection and an action simultaneously by stroking the pen and changing the pen pressure at the same time. Similarly, Harada et al. [44] used pen pressure as an input modal to augment simultaneous input capacity. Ren et al. [86] proposed the Adaptive Hybrid Cursor to facilitate the target selection tasks by automatically adapting the size of the cursor based on pen pressure input. Yin and Ren [112] proposed a zoom-based technique to improve pixel-target selection, in which the pressure is used as a mode switch.

There were also some published studies that focused on pen pressure characteristics and/or explored the human ability to control pen pressure. Ramos et al. [81] investigated the human ability to perform discrete selection tasks by controlling stylus pressure and found that dividing pressure space into 6 levels resulted in optimal controllability. Li et al. [61] investigated five techniques for switching between ink and gesture modes in pen interfaces, including a pen pressure based mode switching technique that allowed implicit mode transitions. Zhou et al. [120] comparatively investigated the performance of pen pressure and tilt in a cursor control experiment. Xin and Ren [111] proposed a new pen pressure discretization method according to personal use profiles, with which the optimal number of divisions of the pen pressure space is 8.

Compared to the studies on pen pressure, few studies that focused on the exploration of pen tilt, azimuth, and rolling were found. Tilt Cursor [98] provided users with 3D pen orientation as visual cues. Another technique, Tilt Menu [99], extended the selection capabilities of pen-based user interfaces using 3D pen orientation information. Oshita [71] designed a virtual human figure movement manipulation system that used not only pen pressure but also pen tilt to control a virtual human figure. Bi et al. [16] explored pen rolling around the longitudinal axis of the pen and determined the intentional and incidental pen rolling while users manipulating a pen. Alonso et al. [9] investigated the interpretation of users emotions via physiological and behavioural inputs. They developed an embedded tangible interface to afford and measure a rolling behaviour. And the proposed the Wigo prototype regarding rolling as a relaxed movement. Fukutoku et al. [33] investigated the pen properties in trajectory-based tasks; and the optimal azimuth angle for trajectory-based tasks in pen-based interface [34].

There has been a consistent effort to develop controls and interactions tailored for precise parameter selection and manipulation tasks. This issue was firstly addressed by [76] and [88]. In 1994, Ahlberg et al. [6] developed the Alphaslider which was a compact selector that allowed users to quickly pick a single item from a list of thousands, essentially by providing 3 sub-sliders with different levels of granularity. Hinckley et al. [48] evaluated the scrolling technique using a reciprocal framing task and found that mouse wheel scrolling could be improved by acceleration algorithms. Albinsson and Zhai [7] proposed Precision-Handle and Cross-Keys to complement existing techniques for touch screen interaction. Aliakseyeu et al. [8] investigated the multi-flick, which consisted of repeated flick actions, by designing several flick-based scrolling techniques and found that multi-flick was a promising technique that outperformed the common scrollbar under numerous conditions.

Although the aforementioned works explored the utilization of pen input modalities to widen the stylus input vocabulary available to the user, only two are close to our current inquiry. One, the Zlider [79], is a high precision parameter mechanism for fluid integrated manipulation of zooming via pen pressure input during pen sliding. But a major different point from this study is that their study only employed pen pressure modality, while this study fully investigated four different pen input modalities. The other study [120], evaluated cursor control from pen input modalities with the pen tip stationary, while this study focuses on precision parameter manipulation with the pen tip moving, which should have broader relevance to practical utilization of digital pens.

6.3 Design Framework

In order to investigate the performance of pen input modalities for precision parameter manipulation during trajectory tasks, we designed a widget that incorporates the pen sliding mechanism and a precision parameter that users can manipulate it at different levels of granularity (Fig. 6.1). Sliding action was produced by varying the pen tip x-y coordinate position. The granularity of the sliding is adjusted by variation of the values of the different pen input modalities or by number of key presses during pen sliding. At all times a needle indicates the value of the parameter being manipulated, and a vernier shows the granularity level.

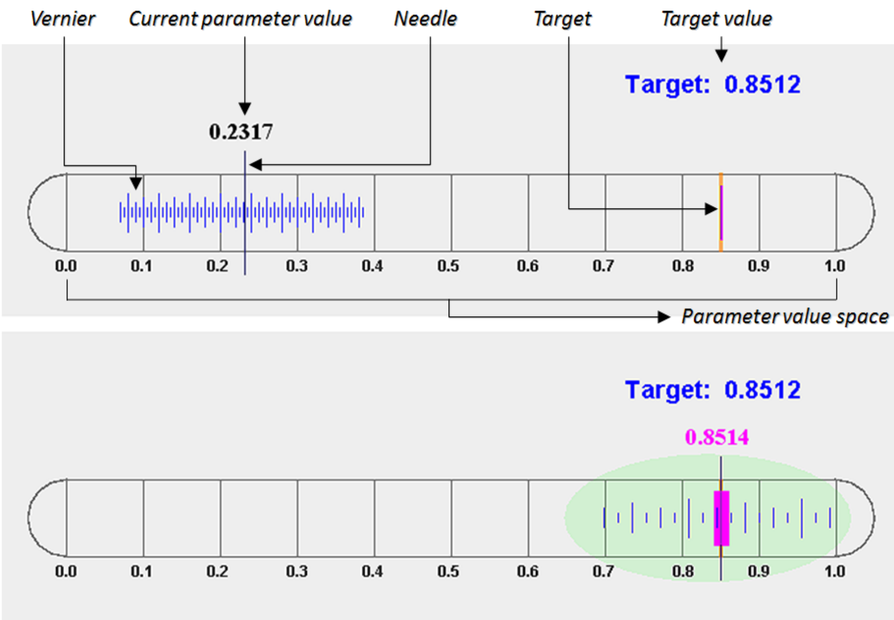

Fig. 6.1 The widget (upper: a target is displayed in the center of a light gray rectangle. The user can move the needle along the vernier by sliding the pen horizontally. Lower: the user can change the granularity level of pen sliding as well as the target width for ease of target selection.)

The widget consists of a rectangular working area. Users can slide the needle within the parameter space of [0.0, 1.0]. At the beginning of each trial, the needle was displayed at the start point of the workspace on the left and a target was displayed in a light gray rectangle which had three possible widths: *0.0004*, *0.0026* and *0.0060*, referred to as narrow, medium and wide target areas respectively. The target could be located at three different distances from the start point of the workspace on the left: *0.1680*, *0.4478* and *0.8512*, presenting near, mid and far distances respectively.

The subjects were instructed to slide the pen to control the needle to locate and select the given targets as quickly and accurately as possible. The subject could slide the pen to control the needle at a coarse granularity level so that the needle approached the target quickly. As the needle neared the target, if the target width was too small for easy selection, the subject could change the granularity level of sliding in five different ways: increasing the pressure exerted on the pen tip, increasing the pen tilt[*1], rotating the pen counterclockwise, rolling the pen clockwise, and pressing constantly on the right arrow key to manipulate at finer granularity levels, or by doing the reverse of any of those actions. We use an exponential function similar to that in the Zlider [79], of the form $base^{f(p)}$, $base^{f(t)}$, $base^{f(a)}$, $base^{f(r)}$, or $base^{f(num(k))}$ to calculate the granularity level, where *f(p)*, *f(t)*, *f(a)*, *f(r)*, and *f(num(k))* were functions of detected pen pressure, tilt, azimuth, rolling angle and the number of presses of the left or right key with the user's non-preferred hand.

To enable impartial comparisons, the same start and end value for each function were set. In order to determine the natural and preferable pen tilt, azimuth, and rolling manipulation modes, we performed a set of informal pilot experiments along with

[*1] The farther left of pen terminal, the larger the tilt angle. In the experiment, we extended the tilt range from [30, 90] to [30, 150] degrees depending on pen azimuth. [30, 90] degrees tilt angle is supported by [0,179] degrees azimuth, and [91, 150] degrees tilt angle is supported by [180,359] degrees azimuth.

questionnaire surveys. Results showed that for the condition of pen tip to remain stable, the Northeast-Southwest direction tilting was optimum whereas for the condition of pen sliding, the horizontal direction was preferred. Thus we chose horizontal orientation to realize tilt manipulation. Results also showed that for azimuth, a counter-clockwise rotation was preferred and for rolling, a clockwise rolling around the longitudinal axis of the pen was preferred. Thus we chose counterclockwise pen azimuth rotation or clockwise pen rolling to realize the precision parameter manipulation.

To make the widget more easily understood and manipulated, several types of visual feedback were provided in the widget. A numeric label indicated the current value of the parameter being manipulated. When the pen pressure, tilt, azimuth, rolling angle or the number of key presses exceeded the thresholds, a gray opaque ellipse would appear. Meanwhile, the granularity of the vernier changed according to pen pressure, tilt, azimuth, rolling angle or the number of key presses, and the charcoal gray clone target area also expanded or contracted accordingly. If a misselection was made, a failure icon appeared and a sound tip was given to the subject.

6.4 Experiment

6.4.1 Participants

Two female and seven male volunteers from a native university campus, ranging in age from 21 to 32, participated in the experiment. All of them were right-handed according to self-report. Five had the experience of using pen tablet, and others had no prior experience with such devices.

6.4.2 Apparatus

A Wacom Cintiq 21UX interactive LCD graphics display tablet with a wireless stylus with an isometric tip was used in the experiment. The experimental software was designed in Java Environment and ran on a 2.13 GHz Intel Core2 CPU PC with Windows XP Professional SP2. The resolution of the display was set to 1280 by 1024 pixels at 120 dpi.

The Cintiq 21UX can detect the pressure that a user exerts on the stylus pen tip from 1 to 1023 levels which corresponds to the force range of 0 to 4 Newtons. If the pressure level is over 1023, it is recognized as 1023. The Cintiq 21UX can also detect the tilt angle of the stylus which ranges from 30 degrees to 90 degrees (When the stylus is perpendicular to the tablet surface, the tilt value is 90 degrees). The azimuth of the pen can also be detected by the Cintiq 21UX ranging from 0 to 359 degrees clockwise from the northerly direction. The rolling angle of the pen can be detected ranging from 0 to 359 degrees according to counterclockwise pen rolling. Moreover, the pen rolling angle being detected is related to current pen azimuth. When the pen tail orientates the southerly direction, the rolling angle is reported 0.

6.4.3 Task Design

A within-subject full factorial design with repeated measures was used. The independent variables were *Technique* (*Pressure*, *Tilt*, *Azimuth*, *Rolling*, and *Key Pressing*), *Width* (*0.0004*, *0.0026* and *0.0060* scale values), and *Distance* (*0.1680*, *0.4478* and *0.8512* scale values from the start point). A Latin Square was used to counterbalance the order of the appearances of techniques. To explore the learning effects, 6 blocks of trials were completed by every participant. Trials under same condition were repeated 2 times. Presentation of trials within a block was randomized. In total, the experiment consisted of:

9 participants ×

5 techniques ×

6 blocks ×

3 width conditions ×

3 distance conditions ×

2 repetitions

=4860 target selection trials

6.5 Results

This experiment took an average of 1.16 hours per participant. After each block, subjects were allowed an optional 10-minute break.

6.5.1 Selection Time

For *Selection Time*, it fitted in accordance with the Fitts' law [30]: the farther and the narrower the target was, the more time was needed to select the target. Repeated measures analysis of variance showed a significant main effect on *Selection Time* for *Width* ($F_{2,16} = 69.01$, $p < .001$) and *Distance* ($F_{2,16} = 74.40$, $p < .001$). Furthermore, there was also a significant main effect on *Selection Time* for *Technique* ($F_{4,32} = 4.68$, $p < .01$)and *Technique* × *Width* ($F_{8,64} = 2.58$, $p < .05$). However, there was no significant main effect on *Selection Time* for *Technique* × *Distance* ($F_{8,64} = 1.54$, $p = 0.22$). *Post hoc* pairwise comparisons showed significant differences between all pairs of *Techniques* across all levels of the *Width* condition or all levels of the *Distance* condition. It is worth noting that in the narrowest *Width* condition *0.0004*, *Pressure* performed significantly better than other pen input modalities and even better than *Key Pressing*. Fig. 6.2

and 6.3 illustrate the results.

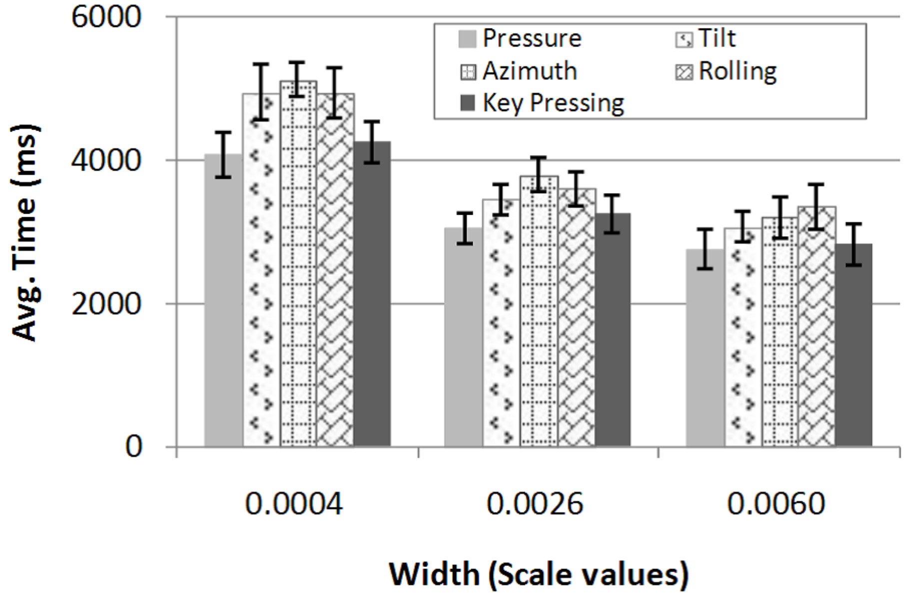

Fig. 6.2 Average selection time per technique × width.

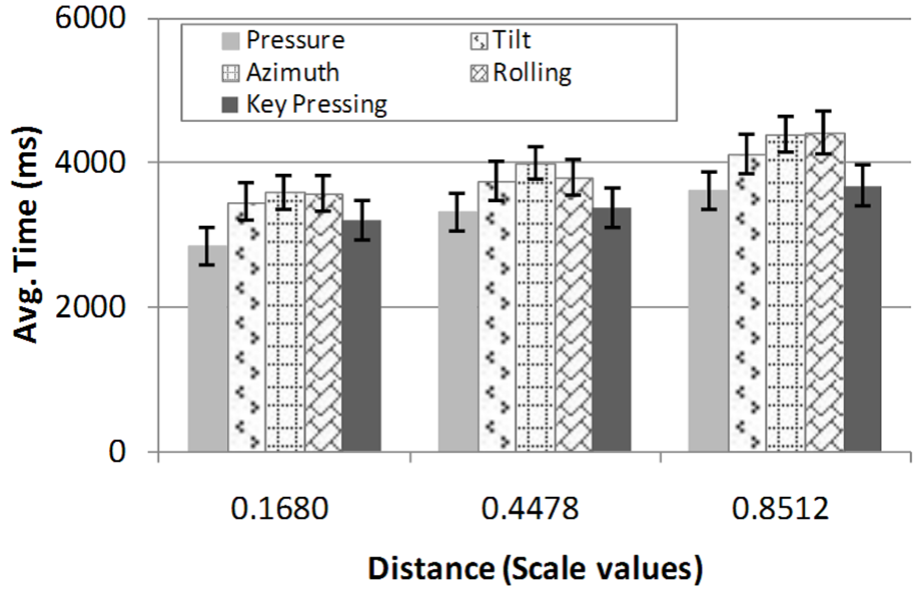

Fig. 6.3 Average selection time per technique × distance.

Since we recorded data for all 6 blocks, we expected to see a learning effect. A repeated measures analysis of variance showed that block had a significant effect on

Selection Time ($F_{5,40} = 3.31$, $p < .05$). *Post hoc* analysis also found that in block 6, for all pen input modalities, *Selection Time* was significantly shorter than in other blocks ($p < .05$), whereas for *Key Pressing*, *Selection Time* was longer than in other blocks.

The overall decreases of *Selection Time* from block 1 to block 6 for *Pressure*, *Tilt*, *Azimuth*, *Rolling*, and *Key Pressing* were 176.66 ms, 477.37 ms, 504.08 ms, 759.87 ms and -222.24 ms respectively, which indicated that participant performance improved the most with *Rolling* (Fig. 6.4). On the other hand, with *Key Pressing*, performance worsened. A possible explanation for this is that using two hands diverted users' attention from target selection and also caused user fatigue.

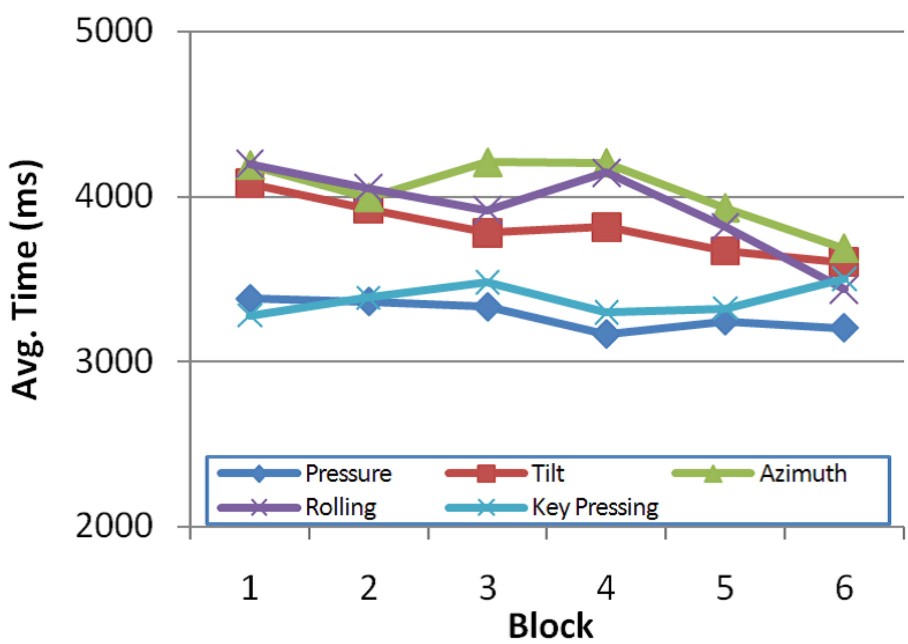

Fig. 6.4 Average selection time per block × technique.

As can be seen in Fig. 6.5, selection time for some of the pen modalities still decreased after 6 blocks of trials. In order to explore the learning effect in more detail, the subjects were asked to perform another 6 blocks of trials to further investigate the learning effect. As shown in Fig. 6.5, *Pressure* enabled the fastest selection, while *Azimuth* exhibited the slowest selection. Performance with *Tilt* was slightly faster than with *Rolling*.

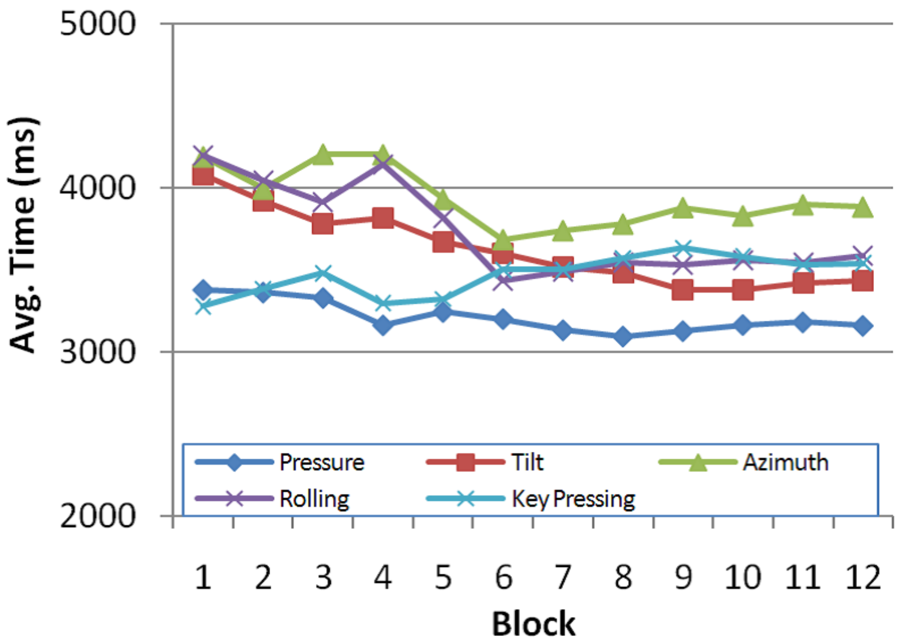

Fig. 6.5 Average selection time per block × technique.

6.5.2 Error Rate

Repeated measures analysis of variance showed a significant main effect on *Error Rate* for *Width* ($F_{2,16} = 19.29$, $p < .001$). However, there was no significant main effect on *Error Rate* for *Technique* ($F_{4,32} = 1.09$, $p = 0.38$) and *Distance* ($F_{2,16} = 0.76$, $p = 0.48$). Furthermore, there was also no significant main effect on *Error Rate* for *Technique* × *Width* ($F_{8,64} = 0.54$, $p = 0.82$) and for *Technique* × *Distance* ($F_{8,64} = 1.35$, $p = 0.23$). Subjects committed the fewest errors (4.41%) while using *Pressure* and *Tilt*, and the most errors (6.87%) while using *Azimuth*. Fig. 6.6 and 6.7 illustrate the results.

Post hoc pairwise comparisons found that in the *0.0004 Width* condition, the *Error Rate* was significantly higher than in the other two *Width* conditions. Ordinarily, if a target tolerance width is narrower than the granularity of pen tip moving, it is impossible for users to achieve fine target selection using only pen tip x-y coordinate information:

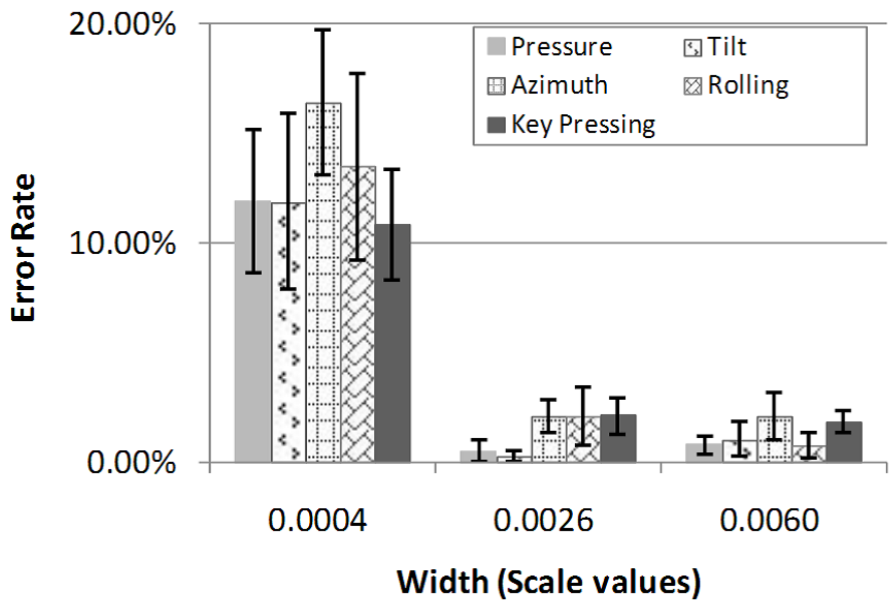

Fig. 6.6 Average error rate per width × technique.

the fine target selection must be supplemented by means of some other input modalities, methods or techniques. The results indicate that *Pressure* and *Tilt* are good candidates.

Repeated measures analysis of variance showed that block had no significant effect on *Error Rate* ($F_{5,40} = 0.60$, $p = 0.70$). The overall decreases of *Error Rate* from block 1 to block 6 for *Pressure*, *Tilt*, *Azimuth*, *Rolling*, and *Key Pressing* were -0.62%, 1.85%, 3.09%, -3.09%, 4.32% respectively.

6.5.3 Number of Crossings

When searching for targets, subjects sometimes crossed the targets more than once. This reflects some subjective factors such as subjects trying to bring the target area within the range of visual attention, and subjects inadvertently sliding too fast. On the other hand, multiple crossings also give information about the suitability, feasibility and stability of a certain pen input modality in our experimental tasks.

Repeated measures analysis of variance showed a significant main effect on *Number*

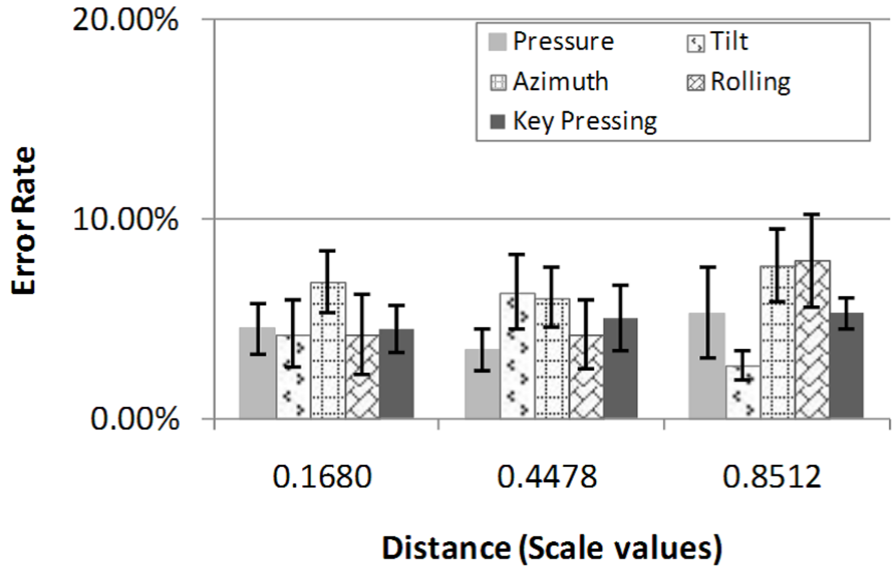

Fig. 6.7 Average error rate per distance × technique.

of Crossings for *Width* ($F_{2,16} = 32.40$, $p < .001$). However, there was no significant main effect on *Number of Crossings* for *Technique* ($F_{4,32} = 1.94$, $p = 0.13$) and for *Distance* ($F_{2,16} = 1.91$, $p = 0.18$). Moreover, there was also no significant main effect on *Number of Crossings* for *Technique* × *Width* ($F_{8,64} = 0.90$, $p = 0.52$) and for *Technique* × *Distance* ($F_{8,64} = 1.38$, $p = 0.22$). Subjects crossed targets the fewest times on *Pressure* (2.26 on average) and the most times on *Azimuth* (2.85 on average). Fig. 6.8 illustrates the results.

An analysis of *Number of Crossings* across experimental blocks showed a strong learning effect ($F_{5,40} = 5.98$, $p < .001$). *Post hoc* analysis also found that in blocks 5 and 6, the *Number of Crossings* was significant fewer than in the other blocks. The overall decreases of *Number of Crossings* from block 1 to block 6 for *Pressure*, *Tilt*, *Azimuth*, *Rolling*, and *Key Pressing* were 0.41, 0.90, 0.30, 0.32, and 0.02 respectively. Fig. 6.9 illustrates the results.

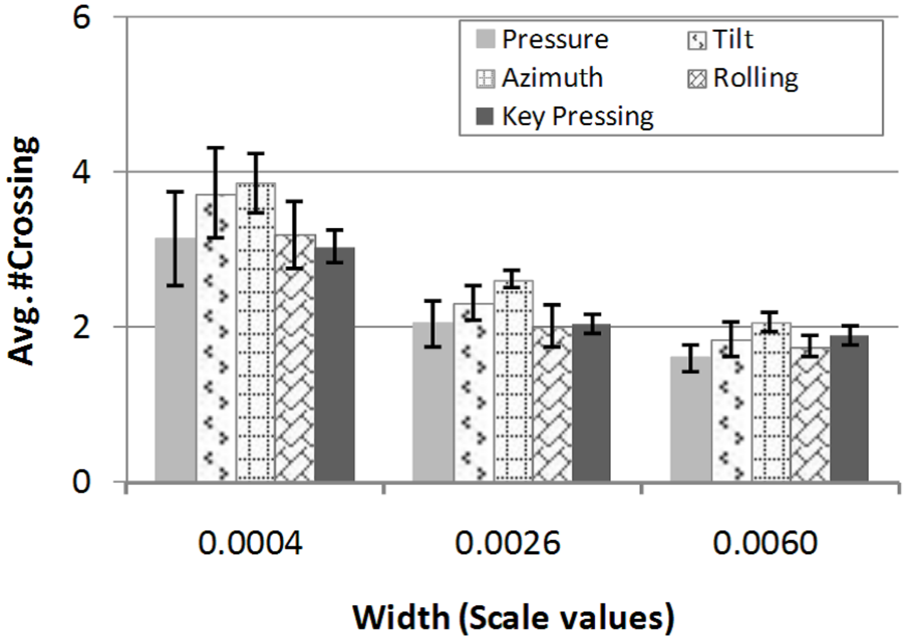

Fig. 6.8 Average crossings per width × technique.

6.5.4 Effective Width

Although tolerance widths of targets were given, users still performed the selections nearer the targets than the given tolerance widths because they preferred more accurate selections. In our experiment, we calculated *Effective Width* of each *Technique* so that the accuracies of successful targets selections could be identified.

Repeated measures analysis of variance showed a significant main effect on *Effective Width* for *Width* ($F_{2,16} = 96.27$, $p < .001$) and *Technique* ($F_{4,32} = 1.94$, $p < .01$). Moreover, there was also a significant main effect on *Effective Width* for *Technique* × *Width* ($F_{8,64} = 2.13$, $p < .05$). *Post hoc* pairwise comparisons found that *Pressure* had the narrowest *Effective Width* while *Azimuth* had the widest. Thus, using *Pressure* resulted in the most accurate target selections. Fig. 6.10 illustrates the results.

A further regression analysis of *Effective Width* vs. *Target Width* yielded a strong fit to the Power relationship with correlation of R-Squares greater than 0.99 for all the pen input modalities.

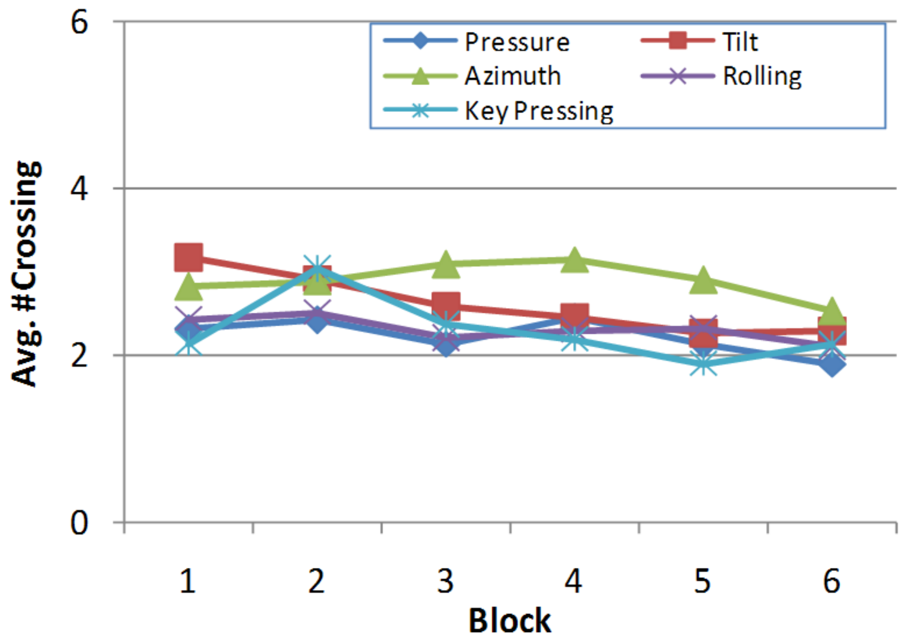

Fig. 6.9 Average crossings per block × technique.

6.5.5 Subjective Evaluation

After subjects had completed the experiment, a questionnaire was given to them to evaluate the techniques. Techniques were ranked for *Fatigue*, *Difficulty*, and *Nervousness* on 7-point Likert Scales (Fig. 6.11). Moreover, the subjects were asked to rank the techniques in terms of *Preference*.

In general, subjects regarded *Pressure* as the best technique while *Azimuth* the worst according to *Fatigue*, *Difficulty*, and *Nervousness* evaluation results. That was consistent with the *Preference* results. However, participant opinion was not uniform. Five participants ranked *Pressure* as their most preferred technique, two *Tilt*, one *Rolling* and one *Key Pressing*.

5/9 subjects preferred *Pressure*. They reported that using *Pressure* was "subconscious" and "natural" because when looking for an unknown target or trying to see an object more clearly, they naturally wanted to press harder on the pen tip. "Pen pressure is easier to control in the experiment," and "it was simple to use pressure."

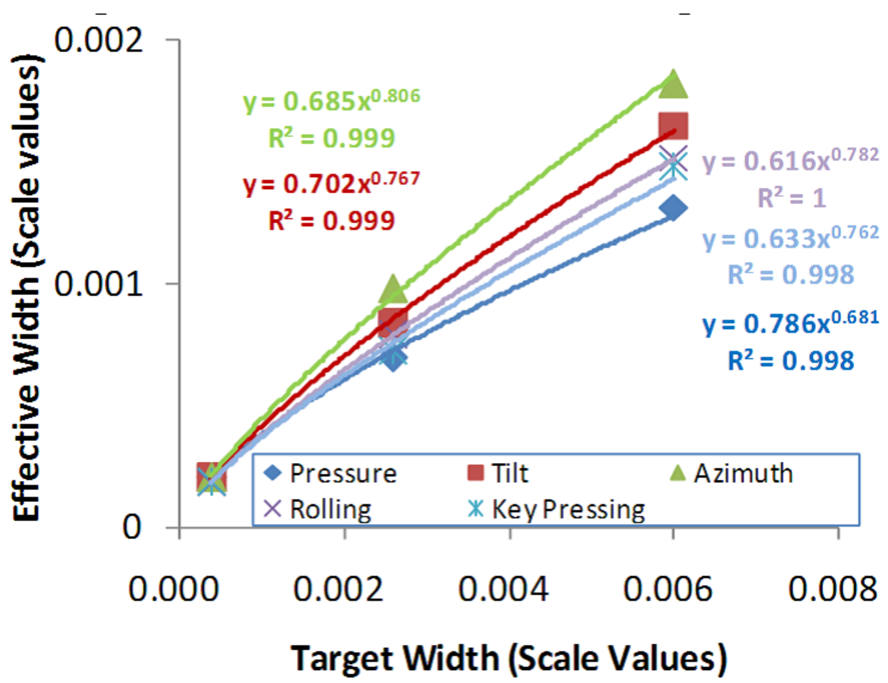

Fig. 6.10 Effective width vs. target width for each technique. Power regression lines are shown.

Furthermore, they believed that using pen pressure brought almost no accidental pen tip movement while tilt, azimuth, and rolling often caused accidental pen tip movement. However, long time pen tip pressing also made subjects tired. Moreover, subjects often unconsciously changed pen pressure while sliding the pen, thus causing an unwanted scale granularity variation. In order to avoid unwanted pressure change, subjects must continuously monitor pen pressure by tactile sense as well as by the visual feedback presented in the interface of our experimental widget. Some subjects complained that "changing pressure only according to tactile sense is not easily perceived;" "Pressure made me nervous because it is too sensitive;" And "maintaining stable pressure made my arm sore and tired."

Tilt and *Azimuth* were regarded as easily causing fatigue. Possible reasons for this include: 1) users have to frequently tilt or rotate the pen to adjust the granularity while sliding the pen; 2) if the expected granularity was achieved, users often kept a fixed pen

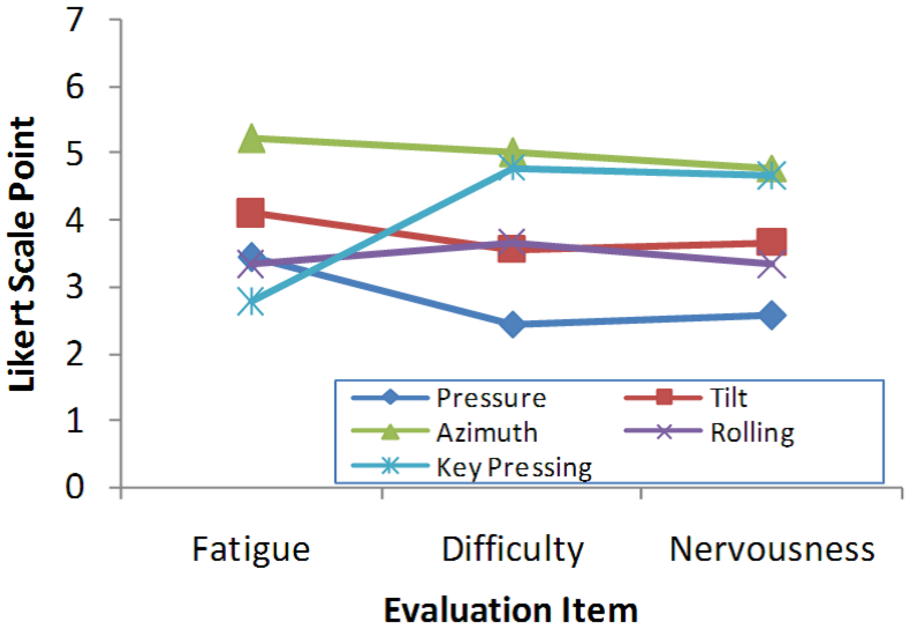

Fig. 6.11 Subjective Evaluations with 7-point Likert Scale.

gesture until they finished the selection. Several subjects complained that "my hand and forearm often hang up when I used tilt and azimuth, and thus my arm felt sore and tired." Moreover, "tilting the pen while sliding, particularly to an uncommon angle, violated the naturalness of pen use habit;" "For some special pen tilt or azimuth, it was almost impossible for me to keep it steady;" "For long time manipulations, I will not choose tilt and azimuth." However, subjects also reported that tilt and azimuth provided them with inherent visual feedback from which they could be roughly aware of the present scale granularity.

Most subjects believed that *Rolling* was a promising technique. After practice, users could usually control pen rolling fluently as they wanted. "*Rolling* gave me the feeling of a radio tuner," thus "it was easy to grasp the technique".

Those who had little experience of using a stylus pen preferred using their non-preferred hands. They reported that "the task was separated in two parts: adjusting the scale granularity and sliding the pen. Thus both of my hands could work together;"

And "parallel bimanual manipulation made the task easy." On the contrary, those who had more pen use experience, especially more than 2 years, advocated that using only the pen with the dominant hand rather than both hands was more rational and simple because the non-preferred hand was free. They complained that "using both hands was troublesome."

6.6 Discussion

According to the quantitative measures (*Selection Time*, *Error Rate*, *Number of Crossings*, and *Effective Width*) and subjective evaluations, *Pressure* enabled the fastest performance and, remarkably, even surpassed bimanual manipulation. Adjusting a parameter while sliding the pen is a common manipulation in pen-based interaction, so even tiny improvements may result in significant benefits to users. On the other hand, although performance of inherent pen input modalities other than *Pressure* did not surpass bimanual manipulation, they did have specific advantages. As well, the non-preferred-hand-free concurrent manipulation was positively rated by users, preferred to bimanual manipulation.

6.6.1 Advantages and Disadvantages of Pen Modalities

Our experimental results indicate that *Pressure* consistently performed satisfactorily. The possible reasons for this include: 1) adjusting pen pressure while sliding the pen is more natural and intuitive to users than adjusting other pen modalities; 2) users can take up any pen posture as they want and need not attend to pen posture when using pen pressure, since pen pressure is not influenced by different pen postures. However the other pen modalities are influenced by different pen postures; 3) unlike *Tilt* and *Azimuth*, *Pressure* typically did not produce unintentional pen tip movement, and thus speed and accuracy were better in the pressure experimental task. On the other hand, subjects reported difficulty remaining aware of the pressure level through only tactile sense because the pen did not provide them with inherent visual feedback on pressure value. Moreover, pen pressure value has the characteristics of 0-started and 0-ended. It is impossible for users to achieve a non 0 pressure value immediately after putting down the pen. It is also impossible for users to maintain a non 0 pressure value while lifting the pen.

Adjusting pen tilt and azimuth required extra time. In addition, the subjects sometimes had to maintain an unnatural pen gesture to use pen tilt or pen azimuth while sliding the pen; this also caused user fatigue. However, as for *Error Rate*, *Tilt* was excellent. In the *0.0004* and the *0.0026 Width* conditions, users committed the fewest errors with *Tilt*, as expected for high precision parameter manipulation tasks. With decreased *Width* scale, *Tilt* was very stable. This was likely because subjects could maintain a designated tilt angle more consistently than a designated pressure value, due to the visibility of pen tilt. We regard the visibility of pen tilt or azimuth as advantageous because it seemed that this feature could be used in many different application scenarios, e.g., users could directly invoke different menu items in a pie menu by simply positioning the pen at a certain tilt or azimuth angle. Besides, significant learning effects occurred with *Tilt* and *Azimuth.* With increased use experience, users gradually became comfortable with using the *Tilt* and *Azimuth.* In block 6, the *Selection Time* gaps between *Pressure* and *Tilt/Azimuth* were markedly reduced.

Unlike *Pressure*, *Tilt* and *Azimuth* can achieve a non-0 value through different user pen gestures. Moreover, when the pen is lifted, *Tilt* and *Azimuth* need not return to any default values. Thus using pen tilt or azimuth can invoke either a monotonous increase or a monotonous decrease after the pen is put down as a result of simply tilting the pen forward or back, or adjusting the pen azimuth clockwise or counterclockwise, which can be mapped onto zooming in and zooming out respectively.

To most subjects, *Rolling* was acceptable; they reported that it caused almost no fatigue. Some users reported enjoying *Rolling* because they found rolling the pen was quite similar to rotating a tuner knob. Moreover, users thought that accidental pen tip movement caused by rolling didn't significantly affect accuracy. At any rate, the accidental pen tip movement caused by *Tilt*, *Azimuth* and *Rolling* can be compensated for in real applications via specific technical treatment.

For users who had little pen use experience, using the non-preferred hand was welcomed. Although bimanual performance gave good results, it is not the ideal technique either since it requires using two hands at the same time.

Although we have discussed the advantages and disadvantages of pen modalities in precision parameter manipulations during trajectory tasks, it should be noted that the advantages and disadvantages may vary according to different tasks. Choice of effective pen input modality should be based on task type. If the user has to control an orientation parameter, *Azimuth* may be more intuitive and convenient for user manipulation. Besides, in real applications, two or more pen input modalities are often used in tandem. If a task requires the control of more than one parameter simultaneously, combined use of multiple pen modalities may be more appropriate. We regard the combination use of pen input modalities as promising and worthy of exploration in future work.

6.6.2 Users' Habits and Expectations

According to user preference, uni-manual manipulation was favored over bi-manual manipulation. Users wanted to achieve improved manipulation using only a pen so that they could accomplish the experimental tasks with only their dominant hands.

On the other hand, users also hoped that uni-manual manipulation could be simpler and more effective. Thus *Pressure* was the most highly rated technique because of its "natural" and "simple" characteristics. We also found that subjects often paid attention to additional overhead factors which influenced the results of their performing. For example, when using *Tilt*, *Azimuth*, or *Rolling* during pen sliding actions, unwanted pen tip movement often occurred, which was complained about by most of the subjects thus again *Pressure* was highly rated.

Subjects exhibited learning. When a new technique was first presented, subjects were often not used to the new technique. However, after a period of practice, most of them could find a unique and appropriate operation method in order to perform the given task. Once they acquired the knack, they could easily perform the task and enjoy the knack. Moreover, if they found something was really helpful to them, e.g. after they found that the inherent visual feedback of *Tilt* and *Azimuth* made selection easier, they would generally make full use of that feature.

6.7 Conclusion

Four kinds of inherent pen input modalities (*Pressure*, *Tilt*, *Azimuth*, and *Rolling*) used for high precision parameter manipulation during pen sliding were comparatively investigated. We conducted an experiment to evaluate their performance and compared them with *Key Pressing* using the non-preferred hand. Our results indicate that subjects performed fastest and with the fewest errors when using *Pressure*. However, performance with *Azimuth* was the worst, and subjects evaluated *Azimuth* as unsuitable for the experimental tasks because of it conflicted with their pen use habits. *Tilt* showed slightly faster performance and achieved lower error rate than *Rolling*. Moreover, *Tilt* achieved the lowest error rate in some *Width* and *Distance* conditions. Nevertheless, participant performance improved the most with *Rolling*, and *Rolling* was favored over *Tilt* in subjective evaluations. Our experimental results verify the feasibility of concurrent pen manipulations based on pen input modalities and provide pen-based interface designers with a general understanding of pen input modality choice for precision parameter manipulation during trajectory tasks.

Chapter 7

General Conclusions and Future Directions

7.1 General Conclusions and Contributions

Pen-based interaction is taken more seriously increasingly. Although pen has many advantages, the input throughput capacity of the pen is less than other traditional input devices. Inherent pen input modalities (pressure, tilt, and azimuth) provide possible ways to enhance the input throughput. However, rational use of these inherent pen modalities is still a challenge because most of the natural pen modalities characteristics remain unexplored. Moreover, for these modalities used in tandem, the covariations between these modalities and the optimal modality for a concrete application are unknown. At any rate, theoretical and practical foundations are lack in pen modality based interface designs. Thus, this dissertation focuses on the comprehensive understanding of pen pressure, tilt, and azimuth in natural pen manipulation according to human ability to control them and personal pen use habit. The founding of the dissertation also attempts to aid designing advanced interaction techniques that suit for pen devices with higher performance and more satisfactory user experience.

Chapter 2 explored human natural use profiles of pen pressure, tilt, and azimuth (PTA). Three experiments were reported both in static and in dynamic conditions. The natural pen modalities distributions and the influence of input contents, input size, and input position on pen modalities use profiles were explored. Exp. 1 explored the PTA use profile when users naturally held the pen before starting to write; Exp. 2 explored the PTA use profile when users naturally wrote characters in different sizes; Exp. 3 explored the PTA use profiles and the covariations between PTA when users naturally wrote characters in different positions. Results show that PTA use profiles fitted Gaussian distribution whereas averages, standard deviations and spans varied. Size and position conditions significantly affected PTA use profiles. Covariations were found between PTA.

Chapter 3 specially investigated pen pressure. Continuous pen pressure can be used to operate multi-state widgets. Traditionally, the whole pen pressure space is divided into equal levels and the optimal number of pen pressure division is 6. In order to increase the optimal number of divisions of the pen pressure space and achieve greater pen pressure usability, a new pen pressure discretization method was proposed in chapter 3. Four variations of the method: discretization according to personal/aggregation pen pressure use profile with/without visual feedback of uniform level widths and the traditional even discretization method were presented and comparatively evaluated with an experiment. Results indicated that with the new proposed method, the optimal number of divisions of the pen pressure space is 8. More pen pressure levels are discerned with the new method.

Pen tilt and azimuth are seldom investigated modalities. Chapter 4 investigated human ability to control pen tilt according to static and dynamic pen tip conditions. Two experiments along with quantitative and qualitative analysis were conducted to investigate tilt acquirement and tilt pointing. Results indicated that the narrower the target tolerance is, the more time subjects need to acquire the target; the tilt pointing tasks fits the Fitts' Law; human can easily and effectively control pen tilt during tilt acquiring and tilt pointing tasks when tilt interval equals 30 degrees.

Chapter 5 specially investigated the human ability to control pen azimuth. An experiment along with quantitative and qualitative analysis was conducted to investigate pen azimuth acquirement. This chapter was by far the first study to systematically investigate the pen azimuth in respect of human control ability. Results showed that the narrower the target azimuth tolerance, the more time subjects need to acquire the target; and that the performance of azimuth targets in due directions are much better than in oblique direction; and that south-east is worse because of the occlusion by hand; and that when pen azimuth interval is beyond 60 degrees, it is easy for human to manipulate.

Up to now, no literature comparatively investigated the performance of all three input modalities (pressure, tilt, and azimuth). Chapter 6 comprehensively and comparatively investigated each pen input modality for precision parameter manipulations during trajectory tasks. This chapter firstly solves a common problem in pen-based interaction: concurrent parameter adjustment is not easily accomplished in devices using only a pen tip. Then the performance of inherent pen input modalities and Key Pressing with the non-preferred hand used for precision parameter manipulation during pen sliding actions are investigated. Results showed that pen pressure enabled the fastest performance along with the lowest error rate, while azimuth exhibited the worst performance. Tilt showed slightly faster performance and achieved a lower error rate. The experimental results afford a general understanding of the performance of inherent pen input modalities in the course of a trajectory task.

In summary, this paper quantitatively investigated natural pen input modalities use profiles, the covariations between pen input modalities, human ability to control pen pressure, tilt, and azimuth, utilization of pen pressure, tilt, and azimuth, and the performance comparisons between these modalities. The findings of this study have implications for human-oriented pen use in pen based user interface designs. This paper provides pen-based interface designers with a general understanding of pen input modality in HCI (human computer interaction) field.

7.2 Future Directions

So far, pen technique is still at the initial stage of development, basic insights on pen pressure, tilt, and azimuth could help designers design more efficient interfaces. There are a lot of rooms to research into the pen input modalities. In the process of the study, we also found several respects promising and worthy of further exploration in future work.

Firstly, exploration of pen input modality use profiles in more pen manipulation types with subjective and objective effects has research value. Classification of intentional or incidental PTA manipulations, speed of PTA manipulations, the effects of gender, age, direct/indirect pen input devices, pen shapes, pen holding postures on PTA use profiles will be investigated in the future.

Secondly, combined use of pen input modalities is promising. In a real pen based application, it is common to use the pen input modalities in tandem so that users feel natural and comfortable. However, there is a lack of systematic exploration of the combination use of pen modalities, particularly in respect of human ability to control them. Moreover, the validities of psychology models such as Fitts' law, steering law, Webber's law in condition of two or three modalities are worthy of verification.

Based on the founding of the dissertation, we should have designed some efficient pen technique and/or user interface. However, due to the tight schedule and tasks, many innovative ideas cannot be implemented. In the future, we will design a series of pen modality based interface/application, such as azimuth widget, fan menu, and pressure palette. Moreover, we will apply and verify our results and conclusions of the thesis in concrete applications and varied scenarios.

At last, we will investigate the feasibility of utilization of pen input modalities in conjunction with other input channels such as audio, visual, and tactile input, and will further explore the multi-modal interaction in hand-held mobile computing and for children, and people with physical disabilities.

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Appendix A

Publications

A.1 Articles in refereed journals

[1] Y. Xin and X. Ren. A study of inherent pen input modalities for precision parameter manipulations during trajectory tasks. *IEICE Transactions: the Institute of Electronics, Information and Communication Engineers*, E92-D(12):2454-2461, 2009.

[2] Y. Xin and X. Ren. An investigation of adaptive pen pressure discretization method based on personal pen pressure use profile. To appear in *IEICE: the Institute of Electronics, Information and Communication Engineers*, E93-D(5), 2010.

A.2 Articles in full paper refereed international conference proceedings

[3] Y. Xin, X. Ren, and D. Li. A comparison of pen pressure and tilt in precision parameter manipulation. In *CSSE 2008: International Conference on Computer Science and Software Engineering*, volume 2, pages 1070-1073, 2008.

[4] Y. Xin and X. Ren. A study of value distributions of pen properties. In *NEINE' 08: International Conference of Next Era Information Networking*, pages 196-200, 2008.

[5] F. Fukutoku, Y. Xin, and X. Ren. The optimal azimuth angle for trajectory-based tasks in pen-based interface. In *NEINE' 08: International Conference of Next Era Information Networking*, pages 393-396, 2008.

A.3 Articles in abstract refereed international conference proceedings

[6] Y. Xin and X. Ren. Direct and indirect pen tilt input with visual feedbacks. In *APCHI 2008: The 8th Asia-Pacific Conference on Computer-Human Interaction*, pages 119-120, 2008.

A.4 Articles in local conference proceedings

[7] Y. Xin, X. Ren, and J. Yin. The implementation of angle precision parameter manipulation. In *SJCIEE 2007: Shikoku-section Joint Convention of the Institutes of Electrical and related Engineers* , page 338, 2007.

[8] Y. Xin and X. Ren. An exploration of panning and zooming combination in pen-based interactions. In *SJCIEE 2008: Shikoku-section Joint Convention of the Institutes of Electrical and related Engineers*, page 393, 2008.

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