A-COORD INPUT: AUGMENTED PEN-BASED INTERACTIONS BY COMBINING AUXILIARY INPUT CHANNELS

MOHAMMAD KHALAD HASAN

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Department of Computer Science
University of Manitoba
Winnipeg, Manitoba, Canada

ABSTRACT

Pen-based interactions are becoming mainstream and are widely popular on a variety of devices, including tabletPCs, mobile devices and tabletop systems. The digital pen has witnessed a number of incarnations as a result of catering to users in creative industries, such as designers, artists and architects. New innovations include the provision of various auxiliary input streams, such as tilt, pressure and roll by means of embedded sensors. Researchers have explored different properties of each channel in isolation of one another. Since the human wrist and fingers can operate two or more of these input channels in conjunction (i.e. pressing and rolling to paint) a natural progression warrants a closer examination of controllability when these channels are operated simultaneously.

In this thesis, I explore a class of interaction techniques I refer to as *a-coord* input which requires users to control two auxiliary channels simultaneously. Through experiments, I explore the design space of *a-coord input* and investigate the effect of changing the order in which the channels are combined. Furthermore, I investigate its effectiveness for discrete-item selection, and multi-parameter selection and manipulation tasks. Finally, this thesis shows the value of *a-coord input* through several applications.

PUBLICATIONS

Some ideas and figures in this thesis have appeared previously in the following publications by the author:

Khalad Hasan, Xing-Dong Yang, Andrea Bunt and Pourang Irani. A-Coord Input: Coordinating Auxiliary Input Streams for Augmenting Contextual Pen-Based Interactions. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '12)*, 2012.

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CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACRONYMS

ANOVA Analysis of Variance

A + B Channel A in conjunction with Channel B

A - > B Channel A followed by Channel B

VC Visual Constraints

No-VC No Visual Constraints

CD Ratio Control to Display Ratio

HCI Human-Computer Interaction

S.E. Standard Error

1

INTRODUCTION

The digital pen has evolved into a sophisticated device for directly interacting with digital information. It has emerged as a promising input device allowing users to measure different inputs with multiple sensors embedded on it. Unlike a desktop mouse, a digital pen not only provides the user with 2D coordinates of the pen tip, but also provides new input features. A digital pen can record different auxiliary inputs such as how much a user tilts the pen (i.e. pen tilt), whether and how much a user is spinning the pen (pen roll), and how much pressure a user is applying (pen pressure) (Figure 1). These new from of auxiliary inputs provide users, such as artists and designers an input device that mimics how they paint or draw on non-digital environments. Over time, digital pens and tablets have evolved to serve users in creative industries [29].

Given its capabilities in comparison to the mouse, it is not surprising that some visionaries tout the pen as becoming a highly relied upon device over the next two decades [26]. Researchers, through various studies, have demonstrated the merits of sensor-based auxiliary input channels. These studies have investigated each auxiliary input in isolation of the others and have demonstrated the utility of tilting, applying pressure, and rolling the pen for numerous digital interactions. These include rapid access to contextual commands [28],

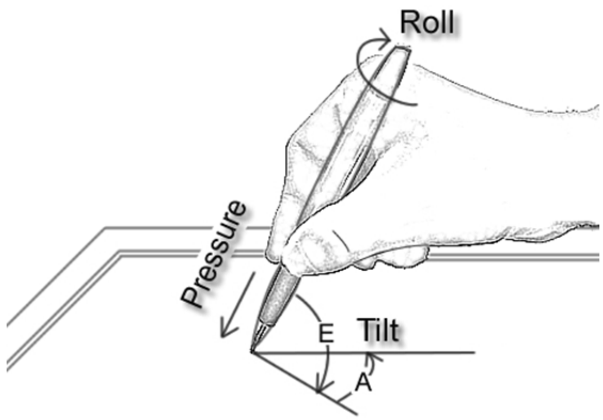


Figure 1: Digital pen input with sensors on the pen includes: pressure, roll, tilt(A) and altitude(E).

fine-grained parameter manipulation [19], and improved stimulus-response compatibility [27].

Prior work has investigated the design space for each of these pen input channels in isolation of one another, or when merged with pen-tip movement [2, 19, 20, 21, 28, 27] or touch [9]. Such research has been instrumental in identifying the fundamental properties and limitations of these auxiliary pen input streams [2, 19, 28]. However, our hands are naturally designed for controlling multiple degrees-of-freedom. For instance, using a screwdriver, we can roll and apply pressure simultaneously to fasten a screw. This task does not require a substantial amount of learning and practice. Therefore, a new collection of data is necessary to explore whether users can control such channels simultaneously, beyond their abilities to do so with highly familiar and well-practiced tasks, such as writing and drawing. If such coordination is possible, this would expand the pen's interactive space.

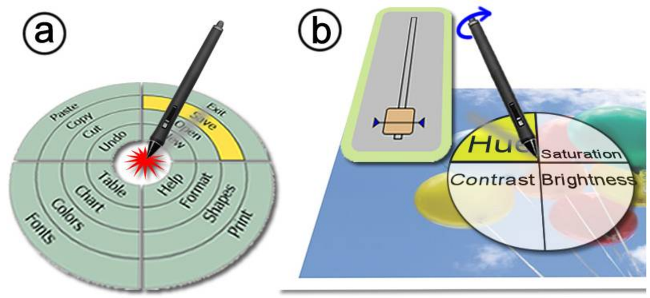


Figure 2: An illustration of (a) contextual 2D menu interaction with a-coord Tilt+Pressure; and (b) multi-parameter selection and manipulation

I build on these earlier results and investigate *a-coord input*, the [coord]ination of at least two different [a]uxiliary channels. It will allow users to use multiple pen input channels simultaneously, such as roll and pressure, or tilt and roll (Figure 2). This form of interaction will provide users with more bandwidth (number of controllable items) as they can operate the channels in parallel. However, the *a-coord input* style raises many human performance questions that warrant intensive research.

In my thesis, I focus on the most important questions regarding such parallel coordination:

- Can users coordinate two auxiliary channels simultaneously?
- Can multi-channel coordination extend the bandwidth that is available from single auxiliary channels?
- For tasks that imply a sequential ordering of channel input (e.g., manipulating roll once a desired level of pressure is reached), does channel order matter?

- Does promoting sequential ordering through input constraints impact user performance compared to a fully dual (i.e., visually unconstrained) mode of operation?
- How does coordination differ between different auxiliary channels? and
- How can *a-coord* be applied to tasks involving continuous manipulation, such as multi-parameter selection and manipulation?

In this thesis, I focus on the investigation of contextual input where pen tip movement is less required to perform a task. Based on the primary features and existing research on a pen's auxiliary channels, I designed four experiments to respond to the above questions. In the first two experiments, I try to answer whether users could coordinate *a-coord input* with extended bandwidth and investigate the impact of channel order with constraining input's feedback and to find the effect of the order through which the channels are invoked. In the third experiment, I investigate how does coordination differ between different *a-coord input* styles for 2D contextual tasks. As continuous manipulation tasks are common in current GUIs [8, 14], in the fourth experiment, I investigate the possibilities of using *a-coord input* for multi-parameter selection and manipulation tasks. Results from these experiments show the potential of *a-coord input* and its comparative performance with other existing techiques [14].

My findings show that *a-coord input* successfully extends the control of auxiliary input from 1D to 2D. I observe a high degree of coordination with 2D contextual tasks, with certain *a-coord input* styles exhibiting more parallelism than others. Also, by showing the visual feedback of the output of one channel at a time, I found that the channel order has only a limited impact. Furthermore, results show that users can apply *a-coord input* to multi-parameter selection and manipulation, a task that involves continuous manipulation. This latter task also has a clearer two-step delineation than the 2D contextual menus, allowing us to test *a-coord input* in a situation where one channel is designated as the leading channel and must be held steady while the user operates the second channel. I follow these experiments with an illustration of how carefully composing the pen's auxiliary inputs can provide a diverse set of interactive techniques.

My contributions include:

- An examination of the coordinated control of the pen's auxiliary channels, which I term *a-coord input*
- An extension of such input for 2D contextual tasks
- Evidence of good coordination with some *a-coord input* styles
- An exploration of the effect of channel order for *a-coord input*
- A demonstration of *a-coord input*'s effectiveness for complex tasks, such as multi-parameter selection and manipulation and
- A demonstration of a varied sample of interactive tasks possible with the pen's auxiliary input channels

The chapters of this thesis are structured as follows. First, chapter 2 discusses the work related to pen-based interaction techniques, including discussions about auxiliary input channels, parallel input control and parameter selection. Then, chapter 3 focuses on the different channel properties and design considerations for *a-coord input*. Chapter 4 presents two experiments to evaluate the performance of *a-coord input* for discrete item selection tasks. Followed by, Chapter 5 describes another study which compares different *a-coord input* and explores the coordination between two simultaneous channels of *a-coord input*. Next, chapter 6 presents one additional experiment to explore the potential of the *a-coord input* for continuous manipulation tasks. In Chapter 7, several prototype applications are presented to demonstrate the use of *a-coord input*. Finally, chapter 8 provides a conclusion and future work.

2

RELATED WORK

The digital pen provides users an interactive way to access digital information directly. Researchers have investigated the role, limitations and capabilities of the digital pen, and have mainly focused on three major inputs provided by a digital pen: pen pressure, pen roll and pen tilt. As my research builds on the benefits and limitations of those input channels, in this section I start with contemporary research that is focused on these auxiliary inputs. Also, I aim to investgate how well a user could simultaneously coordinate two input channels. Therefore, I briefly cover related work in the area of parallel input. Furthermore, researchers have demonstrated that users can use a digital pen for different tasks, such as discrete and continuous target selectiton and the manipulation of objects in two-dimensional spaces. Thus, I conclude this section with a presentation of techniques for multi-parameter selection and manipulation, a task to which I apply my *a-coord input* designs.

2.1 AUXILIARY PEN INPUT CHANNELS

Numerous studies have explored the benefits and limitations of each of the pen's auxiliary input channels. Existing findings with pen pressure, tilt-azimuth (angle around the interaction plane), tilt-altitude (angle between pen and plane) and roll serve as a reference for my design of *a-coord input*.

2.1.1 *Pen Roll*

Pen roll was shown to be useful for mode switching, document navigation, and for fluid parameter manipulation [2, 25]. Bi et al. [2] designed user studies to discriminate intentional pen rolling from incidental pen rolling and to determine usable range for pen rolling, i.e., the range of angle that a user could comfortably roll the pen. In their experiments, authors asked users to perform different tasks like free drawing, writing, and picture tracing using the digital pen which are very common for pen-based activities. Analyzing the results, Bi et al. [2] demonstrated that a rolling angle range of $\pm 10°$ and a rolling speed of -30°/sec to +30°/sec range are incidental and should not be considered as an input action. Furthermore, they demonstrated that a user can easily roll the pen between +90° to -90°.

Miura and Kunifuji [15] used pen rolling to interact with handheld devices. They proposed a novel technique called RodDirect, where they used roll for several applications such as a map viewer, a scheduler, games and different utilities. They found that pen rolling is similar to rotating a knob and it can be also be used in different functionalities such as zooming-in, zooming-out and scrolling.

Suzuki et al. [25] conducted another fundamental experiment demonstrating the users ability to apply pen rolling in different applications. Suzuki et al. developed a paint tool where a user needs to roll the pen to switch between different drawing modes (freehand line, straight line, rectangle and ellipse). They also designed an application that used pen rolling to provide scrolling facilities on a screen. The authors evaluated the usability of their developed tools by conducting several experiments. Results showed that participants effectively controled scrolling with pen rolling, however, some of them found a few tasks (e.g., choosing a drawing color from a color palette) were not easy to do with pen rolling.

2.1.2 *Pen Tilt*

Researchers have developed and evaluated different applications that require users to interact with pen tilt [27, 28, 32, 31, 3]. Tian et al. [27] developed a new form cursor called *tilt cursor*, that dynamically changes shape and orientation based on tilt orientation. They evaluated the performace of tilt cursor for menu item selection and line drawing tasks. Tian et al. [27] found that users could select menu items faster with tilt cursor compared to a fixed-shape arrow cursor. Also, they demonstrated that users could draw lines in less time using tilt cursor compared to other cursor techniques.

Pen tilt could also be used for command selection and direct manipulation tasks. Tian et al. [28] proposed a new menu technique called *tilt menu*, which is similar to a pie menu, consisting of several rounded, fan shaped menu items. The authors allowed users to acess menu items by varying the direction of tilt. Tian et al. [28] found that tilt is much easier to carry out in some directions than in others. Also, they demonstrated that a tilt menu with four or eight items had less errors than twelve menu items and users' response times and error rates were influenced by the size of the tilt menu and the amount of visual feedback. Finally, Tian et al. [28] found that tilt menu had higher overall performance than compared with existing techniques.

Xin et al. [32] conducted studies to compare the performance of pen properties for high precision parameter manipulation. In their experiments, they used a series of target acquisition and selection tasks using pressure, tilt and key press events. Users had a higher task completion time with tilt at the beginning of the experiment, but with increased experience, they needed less time to complete the tasks. Finally, Xin et al. [32] demonstrated that for certain conditions, tilt gave a lower error rate than the pressure and key press techniques for precision parameter manipulation tasks.

Recently, Xian et al. [31] investigated the human ability to perform discrete target selection tasks by changing the pen tilt. They conducted two controlled experiments which revealed a decreasing power relationship between angular width of a target and pointing performance when using the tilt's altitude for selection.

2.1.3 *Pen Pressure*

Pen pressure has received considerable attention in recent years. Ramos and Balakrishnan [18, 19, 21, 20], as well as Ren et al. [22] demonstrated that pen pressure is suited for numerous tasks, including menu selection and single parameter manipulation. Researchers also aimed to find the usable range of pressure that a user can apply on tablet surface and the number of discrete pressure levels that a user can easily discriminate between within a given pressure range.

Ramos et al. [20] investigated users' ability to perform discrete selection tasks by controlling pen pressure. They found that users can effectively perform the selection task using pen pressure if the controllable pressure range is divided into six or fewer discrete pressure levels with adequate feedback. Mizobuchi et al. [16] designed similar studies where they conducted experiments on handheld devices. They also found that a user can use any force range between zero to three Newtons with five to seven discrete pressure levels. Furthermore, Mizobuchi et al. [16] demonstrated that analog feedback (using a bar graph to represent the pressure levels) improved the speed and accuracy of target acquisition more than discrete feedback (using a number to represent the pressure levels). The discrete pressure levels can be further improved with proper pressure space discretization techniques [20] and [22].

Additionally, users can control pen pressure in fine parameter manipulation tasks. Ramos and Balakrishnan [19] proposed a novel technique called Zliding (Zoom Sliding) for high-precision parameter manipulation tasks. Users can use pressure for zoom-in and zoom-out tasks, and drag for sliding tasks. Results from a controlled experiment showed the potential of Zlider for high precision parameter manipulation tasks.

Usually, we apply selection-action techniques in a sequential manner; the action takes place after the selection task. For instance, to delete a file, we first need to select the file and then click on the delete action. Ramos and Balakrishnan [21] overcome this sequential process using two levels of pressure as input. They proposed a novel technique called pressure marks that allows users to perform a selection and an action task simultaneously by changing pen pressure. The authors also demonstrated that pressure marks reduces the time to complete selection-action tasks compared to other techniques.

2.2 PARALLEL INPUT CONTROL

One potential advantage of *a-coord input* is the ability to coordinate the channels in parallel. Though there are no existing studies on simultaneous input control for pen based interaction, researchers have explored users' abilities to operate multiple degrees-of-freedom of input in a number of other contexts (e.g., [1, 10, 13]). Jacob et al. [10] characterized input devices as either integral or separable based on whether they allowed users to manipulate multiple degrees-of-freedom simultaneously. Their study revealed the importance of matching the perceptual nature of a task to that of the input device. Other work has examined the degree of parallelism exhibited in specific settings, such as a 3D docking task [13] and in bimanual interaction [1].

2.3 PARAMETER SELECTION AND MANIPULATION TECHNIQUES

To demonstrate that *a-coord input* can benefit users in a range of tasks, I consider its use in multi-parameter selection and manipulation. Following section briefly contains the related work that mainly focused on this task.

A multi-parameter selection and manipulation usually consists of two distinct steps: i) select a parameter from a set, ii) adjust its value to a target or goal level. Separating an item selection and its parameter manipulation mechanisms in a pen-based interface can be a major drawback for users, and often requires switching between pen and keyboard. However, numerous techniques have been proposed for fluidly merging multi-parameter selection and manipulation.

Pook et al. [17] proposed a new type of contextual pop-up menu called a control menu, which combines the selection and control of an operation. The functionality of control menus is similar to marking menus [11]. To activate the menu, a user needs to press the mouse button for a small period of time, until the menu is displayed centred on the current cursor position. Then he/she moves the cursor in the direction of the desired operation. The menu disappears and the selected operation starts as soon as the cursor has been moved a certain distance (which is called an activation distance) from the centre of the menu. Pook et al. [17] made a comparison with marking menus where they pointed out different advantages of the control menu over marking menus.

Guimbretiere and Winograd [8] proposed FlowMenu, which is a stroke-based interface with a radial layout of regions that define various commands. In this technique, selecting a feature takes place by stroking across a wedge-shaped menu item. Adjusting the value of a parameter occurs by tracing radially around the FlowMenu.

Guimbretiere and Winograd [8] demonstrated that the advantages of the FlowMenu was the pen never has to leave the active surface while using this menu, and direct manipulation tasks can be integrated fluidly.

Later on, McGuffin et al. [14] proposed a new technique, called FaST sliders, which was also focused on parameter selection and manipulation tasks. FaST sliders interface consists of marking menus with a typical linear slider. Users first apply a mark in the marking menu, to select a value that need to be adjusted. The system sets values with an adjusting slider. The user then moves the slider to the desired position. McGuffin et al. [14] conducted an informal user study where they showed that both FaST sliders and FlowMenus effectively support parameter manipulation. However, FaST sliders were easier for participants to learn.

3

CHANNEL PROPERTIES AND DESIGN CONSIDERATIONS

To explore a-coord technique, I first need to draw a comparative analysis of the various auxiliary channels on the pen. In this section I will discuss different characteristics of those auxiliary input channels, i.e., Tilt, Roll, and Pressure. Although a digital pen can sense two different types of tilt, such as Tilt-Azimuth and Tilt-Altitude, in my research I only include Tilt-Azimuth, leaving Tilt-Altitude for future work. Also, I do not explore all of the possible channels, such as hover [7] or capacitance based multi-touch [24] as it would be impractical to do so.

In the following section, I compare the various features of these channels and summarize them in Table 1. I used these to guide my design choices.

3.1 PROPERTIES OF AUXILIARY INPUT CHANNELS

Each of the pen auxiliary inputs has its own properties and characteristics. Those channels can be categorized along five major axes: range of discrete control, bi-directionality, visuo-motor mappings, cyclicality and access method, which are briefly discussed below.

3.1.1 *Range of discrete control*

Initial research on pen-based interactions has mainly focused on finding the number of discrete levels that users can control with different auxiliary input channels. Researchers have identified that this number is 7 ± 1 [20, 16] for pressure, $\pm 80°/10°$ (easily discriminable rotation range) for Roll or 16 levels [2]. For Tilt-Azimuth, performance degrades before attaining 8 discrete levels [31]. These ranges place an upper bound on what is possible in terms of item selection.

3.1.2 *Bi-directionality*

Bi-directionality usually allows users to return to a previous value by changing the movement direction. It allows for better control if the user were to overshoot a desired target. Most input channels for pen-based interaction provide reasonably good control of the input space in the forward and backward directions. Pen roll allows users to rotate a pen in both directions, i.e., clockwise or counter-clockwise. Also, users can tilt a pen to any angle, then reverse the movement. However, pressure is slightly different than the previous two channels. Because of how the sensors operate, pressure affords better control when moving forward and less control returning from higher to lower values [23].

3.1.3 *Visuo-motor mapping*

Visuo-motor mapping defines the mapping between motor space and display space. An intuitive visuo-motor mapping is key to operating auxiliary channels, particularly in the absence of body-based feedback (i.e., Pressure) [20]. Researchers used different types of visuo-motor mappings to display the visual feedback for those input channels. Prior work has employed radial controls for Roll and Tilt as both have bi-directional characteristics in a circular path. However, pressure is usually mapped with linear visual feedback. In addition, Roll and Pressure can also be mapped to a linear or radial control, respectively. On the other hand, mapping tilt-azimuth to a linear control would not be a good match to the corresponding biomechanical operation.

3.1.4 *Cyclicality*

Pen input channels can also be categorized by their cyclical properties, which indicate a channel's ability to reach its initial position without changing the movement direction. Auxiliary pen channel control can be either cyclical or non-cyclical. For example, Roll affords cyclical control, as the user can return to the starting point (for example, an angle of 0°) in a single stroke, without changing movement direction. Tilt-Azimuth has the same cyclical control, as it could reach its initial position with a unidirectional movement.

	Roll	**Pressure**	**Tilt-Azimuth**
Discrete Levels	16	7±1	< 8
Bi-Directionality	Good	Weak	Good
Cyclicality	Cyclical	Non-cyclical	Cyclical
Access Method	Sequential	Sequential	Leaping
Visuo-Motor Mapping(s)	Radial (P) Linear (S)	Linear (P) Radial (S)	Radial

Table 1: A summary of key features of the pen's auxiliary input channels based on the literature (P refers to primary and S refers to secondary).

In contrast, Pressure can only return to its original value if the pen were to be lifted which means it only affords non-cyclical control.

3.1.5 *Access method*

This feature suggests how quickly the user can access an item with a given input channel. This can happen sequentially, by going through each value, or by leaping through a number of intermediary values and going directly to an item of interest, as observed in [28]. Only Tilt-Azimuth works this efficiently, as one can directly tilt the pen (or leap) to the orientation of interest; all the other channels (roll and pressure) require sequentially traversing through the values in their range.

3.2 DESIGN CONSIDERATIONS

In this section, I describe the design choices for proposed *a-coord input*. Guided by the comparative analysis above, I restricted the implementation of *a-coord input* to the following constraints and scope.

3.2.1 *Visual feedback*

Visual feedback can be a parameter for successful interactions, improves the sense of control, reduces error rates, and helps users understand, learn, and quickly adapt to an input device [6]. In the experiments, I design the visual mappings so that they are congruent with motor movement. Tilt is mapped to a radial layout, which is more suitable to the corresponding biomechanical operation. Pressure and Roll are mapped to either a radial or linear layout, to provide flexibility in the visual feedback methods.

3.2.2 *Selection techniques*

Selection is necessary to complete the final step of an action. For Pressure, quickly lifting the pen from the tablet's surface (quick release) or maintaining the same level of pressure within the target for a certain period of time (dwell) have been preferred over selection with the pen's barrel button [20]. For Tilt, Tian et al. [28] proposed using the altitude of tilt for selection. For Roll, Bi et al. [2] proposed using quick release. Prior results also show that a button press with the non-dominant hand provides good control and efficiency [12, 20]. I use this latter method in my studies, since two channels are being controlled at once.

3.2.3 *Discretizing raw sensory input*

Researchers have demonstrated that raw sensor information does not always provide an ideal mapping of sensor values to interactions [23]. Through various studies, they have proposed discretizing the input for better control. Pressure input has been discretized into distinct levels using linear [19], quadratic [5], dynamic fisheye-based [23] or a sigmoid [20] discretization functions. For pressure, a hysteresis function similar to that found in [20] is used. All other channels employed a one-to-one mapping from raw Tilt or Roll motor displacements to visual effecters.

3.3 EXPERIMENTS

Prior studies that have informed the design of pen-based interaction techniques have considered these input channels in isolation of one another. Very little is known about how to use these channels simultaneously for the benefit of novel interactions. Since the human wrist and fingers can operate two or more of these input channels in conjunction (i.e. pressing and rolling to paint) a natural progression warrants a closer examination of controllability when these channels are operated together.

I conducted four experiments to evaludate the design space and effectiveness of *a-coord input*. In the first two experiments, I investigate how well users could control two input channels simultaneously with extended bandwidth. I applied input constraints, i.e., restricting visual feedback to one channel at a time, that implies an order to channel use (e.g., roll before applying pressure or pressure before applying roll). I investigae the effect of such input constraint on *a-coord input* and explore the order effect on input channels, which is discussed in Chapter 4. Results from these two experiments demonstrate the potential of *a-coord input* for pen-based interaction. In the third experiment, I investigate a set of *a-coord input*s for 2D discrete selection task. Also, I investigate the amount of coordination facilited by *a-coord input* (chapter 5). As continuous parameter manipulation tasks are very common, I conduct fourth experiment to measure users' performance with *a-coord input* in a multi-parameter selection and manipulation task, which is discussed in Chapter 6.

4

DESIGN AND EVALUATION OF A-COORD INPUT FOR DISCRETE SELECTION TASKS

In my first set of three experiments, which I collectively refer to as Experiment 1, I investigated whether the human bio-mechanical functions can control 2D discrete selection tasks using two auxiliary channels. I also explored whether *a-coord input* extends the number of controllable items with auxilary input. Furthermore, the performance of *a-coord input* could be affected by the order in which the input channels were combined. Therefore, to find the effect of channel order, I investaged *a-coord input* with input constraints that restricted visual feedback to one channel at a time. This form of visualization implies a sequential ordering of channel input where the cursor was only displayed for one channel at a time. For example, once a user rolls to the right item, pressure feedback becomes available. This is analogous to discrete tasks, such as 2D menus where a second level menu doesn't open until the first level item has been invoked. This form of coordination therefore defines an implicit order in which the two channels are used. For instance, with Roll → Pressure (roll followed by pressure), users apply pressure only after rolling the pen to a desired angle. In the following sections, I will discuss three experiments: Experiment 1(a) that explored Pressure and Roll and is followed by Experiments 1(b) and 1(c) that explored Pressure and Tilt, and Roll and Tilt.

4.1 Experiment 1(a): Pressure and Roll

The goal of this experiment was to investigate the effect of channel order for roll and pressure in a 2D discrete item selection task. I combined the channels into two methods of operation: Pressure and Roll (P$\rightarrow$R) and Roll and Pressure (R$\rightarrow$P), where A$\rightarrow$B denotes that channel A is activated first, followed by B. In addition, I was interested in understanding the limits of control with this form of input.

4.1.1 *Apparatus*

I used a Wacom Intuos4 tablet with an Intuos4 Art Pen. The pen can produce pressure, tilt and roll values with a maximum of 2048 levels of pressure, and 360° of roll and tilt in both orientation and height. The experiment was displayed in full-screen mode on a 22-inch LCD monitor with a resolution of 1680×1050 pixels.

4.1.2 *Participants*

12 participants (seven males and five females) between the ages of 18 and 35 were recruited for this study in exchange of course credit.

Participants had little or no experience with pen-based interfaces. Eleven were right-handed.

4.1.3 *Task and procedure*

I used a 2D discrete target selection task in this experiment. The candidate items were arranged in a 180° fan layout (Figure 3). Participants were asked to select a target using a combination of pressure and roll as quickly and accurately as possible. The item that the cursor was currently residing in was coloured in yellow, and the target was coloured in red. In the case of R→P, participants first selected the correct wedge using roll. Once the wedge was selected, participants had to maintain that level of roll, and apply the correct amount of pressure to select the target item. Thus, selection with R→P occurred by applying pressure while at the same time maintaining a certain rolling angle. Similarly, in the case of P→R, participants first selected the outer circle by applying pressure. Participants then had to maintain that level of pressure and roll the pen to complete the selection. Constrained input feedback was used to emphasize the sequential nature of the channel combination. Participants selected the target by pressing a CTRL key on the keyboard using the left hand. The size of the target was determined by the number of levels in the menu.

Prior to the experiment, participants were shown the experimental setup, and were also given several practice trials in each condition. Breaks were enforced at the end of each block of trials. Participants

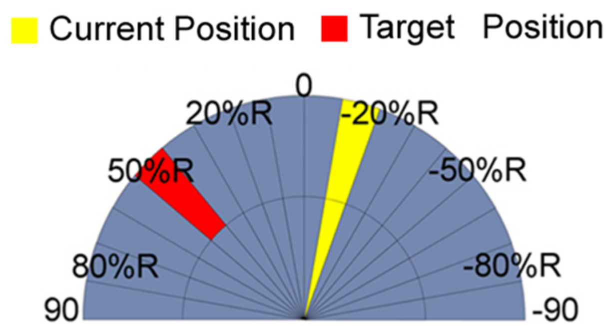


Figure 3: Visually constrained *a-coord input*.

also completed a questionnaire, where they rated the ease-of-use of *a-coord input*. The entire experiment lasted approximately 40 minutes.

4.1.4 *Design*

Pressure readings that were caused by the weight of the pen was excluded as this could confound my results. Therefore, I used a pressure range between 819 and 2048 units (where 2048 was approximately 1.5N of force), or roughly from 40% to 100% of the entire available pressure range. Three numbers of levels (2, 4 and 6) were tested for pressure.

For roll input, I set the initial roll value to 0° as indicated in Figure 3. According to prior work, any rolling angle beyond ±90° is suboptimal [2]. Therefore, I restricted pen rolling to ±90° of its initial value. Like pressure, three numbers of levels (6, 12, and 18) were tested for roll.

Target were placed at 20%, 50%, and 80% of the total input range for each channel. The direction of roll was randomly chosen for each of the 3 target distances (Figure 3). In other words, distance 20% could be randomly interpreted as +20% or -20%.

The experiment employed a 2×3×3 within-subjects factorial design. The independent variables were *Channel Order*: P→R and R→P; Number of Roll Levels (*RL*): 6, 12, and 18; Number of Pressure Levels (*PL*): 2, 4, and 6. *Channel Order* was counterbalanced across participants. Within each *Channel Order*, *RL* and *PL* were presented in increasing order. Each trial of the experiment, representing a *Channel Order* × *RL* × *PL* combination was repeated 36 times by each participant (4 times for each target distance).

4.1.5 *Dependent measures*

Dependant measures included completion time (CT), the number of crossings (NC), and whether or not an error occurred during the trial (ER). Completion time measured the time from a target's appearance to the time participants successfully selected the target. A crossing happened when a participant overshot or undershot a target. For example, if a participant had successfully entered the target, but then accidently moved to the next or previous item before selection, it was counted as a crossing. An error occurred when a participant selected a non-target item prior to completing the trial.

4.1.6 *Results*

Prior to analyzing the data, outliers greater than 3 standard deviations away from the mean completion time (CT) were removed, which represented 1.9% of the total number of trials. The remainder of the data was analyzed using a Repeated-Measures ANOVA with *Channel Order*, *RL* and *PL* as within-subject factors. I applied a Bonferroni correction to all post-hoc comparisons. In the appendix section, summary of the results from experiments is listed to provide the readers with an quick overview of the findings. Also, in this thesis, the threshold value for p is always set to 0.05, i.e., any p values less than 0.05 are reported as statistically significant.

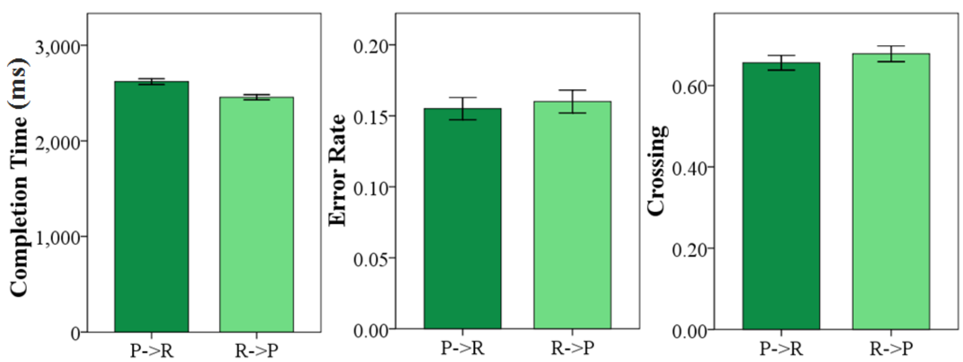
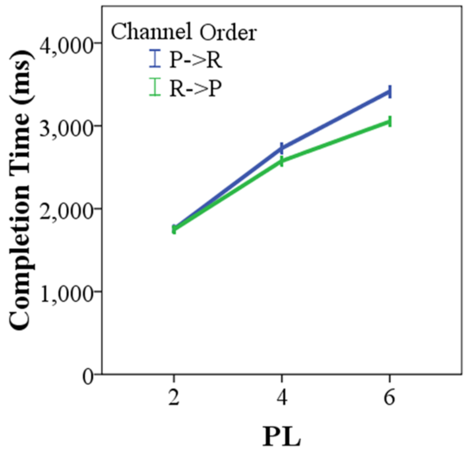


Figure 4: The main effects of *Channel Order* (PR vs. RP) on completion time, error rate and crossings in Experiment 1(A).

Completion Time (CT): Analysis revealed a significant main effect of *Channel Order* on completion time ($F_{1,11} = 7.18$, $p<0.05$), with R→P being more efficient than P→R (Figure 4 left). There were also significant main effects of *PL* ($F_{2,22} = 134.09$, $p < 0.001$) and *RL* ($F_{2,22} = 134.51$, $p < 0.001$) on CT, with all pairwise comparisons being significant ($p<0.005$).



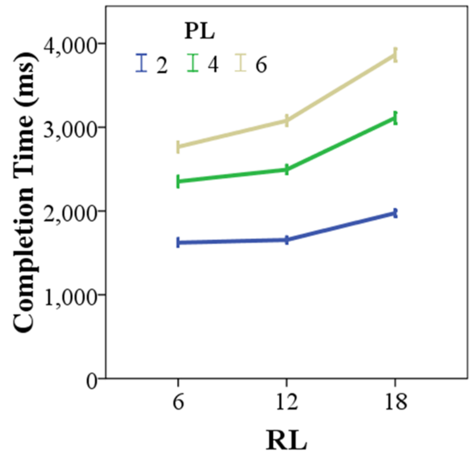


Figure 5: Two interaction effects found in Experiment 1(A) between *Channel Order*×*PL* (left) on and *RL*×*PL* (right) on completion time.

In addition to the main effects, there was a significant *Channel Order*×*PL* interaction on completion time ($F_{2,22} = 9.65$, $p < 0.001$), which is displayed in Figure 5 (left). Post-hoc comparisons only revealed a significant difference between R→P and R→P at 6 Pressure levels (p=0.002). Finally, there was a significant *PL*×*RL* interaction effect on CT ($F_{4,44} = 9.26$, $p < 0.001$), which is displayed in Figure 5 (right). This figure shows a steeper slope between roll levels 12 and 18 with medium and large pressure levels than between roll levels 6 and 12.

Error Rate (ER): The impact of *Channel Order* on error rate (Figure 4 middle) was not significant ($F_{1,11} = 0.19$, p=0.67), however the effects of *PL* and *RL* were ($F_{2,22} = 7.89$, $p<0.005$ and $F_{2,22} = 7.62$, $p < 0.005$) significant. Figure 6 (left) shows the error rates according to channel level. All pairwise comparisons were significant (p<0.05) with the exceptions of Pressure levels 4 and 6 (p=1.00), and Roll levels 6 and 12 (p=0.88). Finally, there was a significant *Channel Order*×*RL*×*PL* interaction effect between ($F_{4,44} = 3.12$, $p < 0.05$) on ER. General

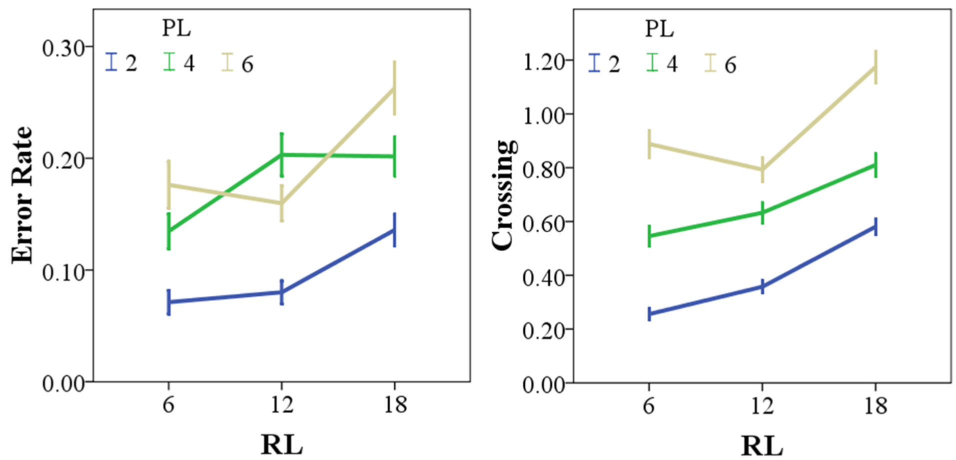


Figure 6: (left) Error rates and (right) number of crossing for each level of Pressure and Roll in Experiment 1(A).

trend for the effect was that 18 items of Roll was uniformly difficult with R→P. On the other hand, with P→R, error rate increased more steadily as the number of Pressure and Roll levels increased.

Number of Crossings (NC): The effect of *Channel Order* on the number of crossings was not significant ($F_{1,11}$ = 0.28, p=0.61), but the effects of *PL* and *RL* again were ($F_{2,22}$ = 33.60, p < 0.001 and $F_{2,22}$ = 35.03, p < 0.001). For *PL* and *RL*, all pairwise comparisons were significant (p<0.01) with the exception of between 6 and 12 levels of Roll (p=1.000). While there was no main effect of *Channel Order* on the number of crossings, there were two significant interactions: *Channel Order*×*PL* ($F_{2,22}$ = 4.29, p < 0.05) and *Channel Order*×*RL* ($F_{2,22}$ = 4.37, p < 0.05). Examining these interactions, however, did not reveal any significant differences between P→R and R→P at any given level of Pressure or Roll. Finally, like for completion time, there was a significant *PL*×*RL* interaction effect ($F_{4,44}$ = 3.08, p <0.05). Figure 6 (right) shows a steeper decline in controllability between 12 and 18 levels of Roll at high Pressure levels than between 6 and 12 levels of Roll.

4.1.7 *Discussion*

Effects of channel order

Interestingly, I found that order matters in visually constrained *a-coord input*. In this case, it was better to use Roll prior to using pressure, most notably when there were 6 Pressure levels available. One explanation for this result might be found by examining the nature of these two channels types separately, based on the results in [2] and [23]. Roll is bidirectional, whereas pressure is not, which effectively means that the former will afford a higher degree of control than the latter. Consequently, users might be better able to handle the additional complexity that a second channel introduces when beginning with Roll. They can easily select and maintain the desired level of roll and then focus on applying the second channel. With Pressure, finding and keeping that initial desired level is more difficult. While plausible explanations exist, I was surprised to see channel order effects and thus examined other pairs of channels to determine whether this was an isolated case or whether this pattern would repeat itself.

Number of controllable items

Results revealed that the task becomes more difficult in terms of completion time, error rate, and number of crossings as the number of items accessible through each channel increases. This is to be expected as users are selecting from a larger set of items. To understand channel limits, I examined interaction graphs of those channels for different levels. I saw fairly good controllability at the lower bound of each channel's usable range (Pressure levels 2-4 and Roll between 6-12 levels). I also found that performance degraded for larger number of items with Roll (12-18), particularly when combined with high levels of pressure.

Ability to control

A high-level comparison with prior work shows that users' abilities to control channels in combination degrades only slightly in comparison to using the input channels separately. For example, with pressure control alone, errors usually range between 7 and 22% [20], whereas in this experiment, mean error rates were 16%. With the simple linear discretization I used here, high error rates are expected. One solution to reduce the error rate would be to fine tune the discretization function [23] such that it is optimal for both channels, or to use two separate discretizations for each channel type. When examining the number of crossings, I see that *a-coord input* is again not far off from results obtained from each channel alone, where pressure would be roughly around 0.5 crossings and roll between 1 and 1.5 crossings.

Subjective feedback

Following the experiment, each participant completed a questionnaire to evaluate his or her personal opinions about the techniques and number of levels that used in experiment. In the questionnaire, participants were asked to rate those upon 5-point Likert scales where it consisted of equally spaced scalar values from 1 – very easy - to 5 – very hard.

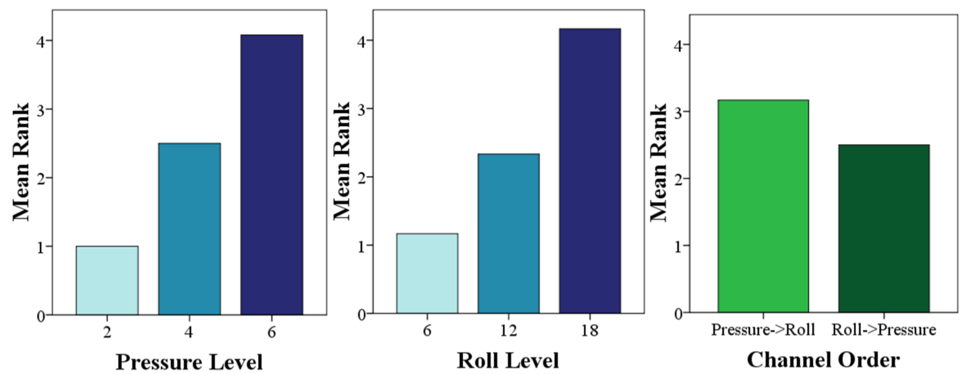


Figure 7: Participants' feedback on techniques and number of levels that used in the experiment.

Participants' subjective impressions from the questionnaire echoed the performance data. They found a-coord input more difficult at the high end of each channel's usable range as displayed in figure 7 left and (middle). Participants also found using Pressure followed by Roll difficult, but they tended to be positive about a-coord input when using the other order figure 7 (right).

4.2 Experiment 1(b) – Pressure and Tilt

In experiment 1(b) I explored a form of *a-coord input* that combines Pressure and Tilt (i.e., Tilt-Azimuth) into two methods of operation: Pressure and Tilt (P→T) and Tilt and Pressure (T→P).

4.2.1 *Study method*

12 different participants (five males and seven females) between the ages of 19 and 32 took part in Experiment 1(b). Participants were recruited from a local university in exchange for course credit. Participants had little or no experience with pen-based interfaces. Eleven were right-handed and none were color blind.

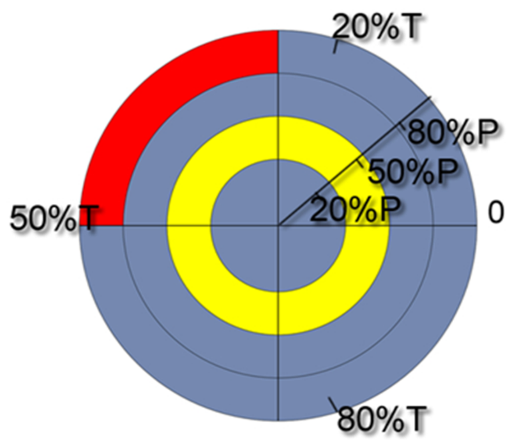


Figure 8: P→T with 4 levels of Pressure and 4 levels of Tilt.

In this study, participants selected targets from a circular layout similar to the 2D pie-menu shown in Figure 8. Figure 8 presents a P→T order with 4 levels of Pressure and 4 levels of Tilt. In this visualization, concentric circles represent pressure values and quadrants represent tilt angles. Here, target distances placed at 20%, 50%, and 80% of the usable range correspond to 72° , 180° , and 288° with Tilt and 1064, 1433, and 1802 pressure units with Pressure. I tested three levels for both tilt and pressure: 2, 4, and 6. The remaining task details, study design, and analysis techniques were similar to those presented in Experiment 1(a).

4.2.2 *Results*

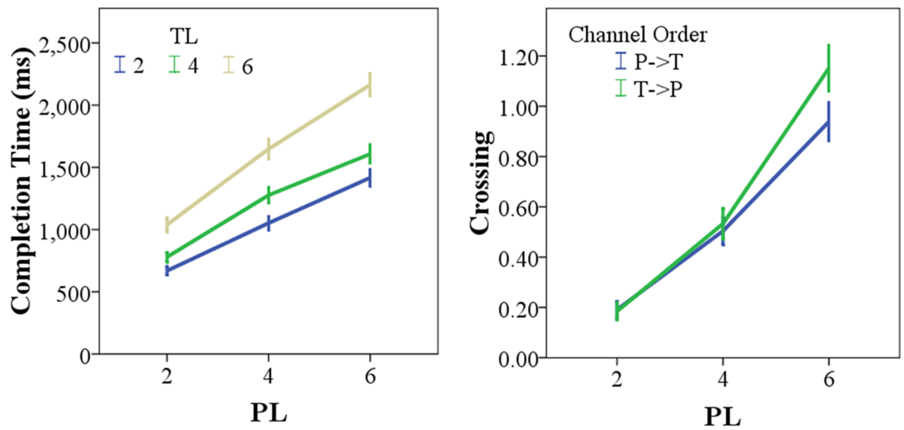


Figure 9: Two interaction effects found in Experiment 1(B): *TL*×*PL* on CT (left) and *Channel Order*×*PL* on NC (right).

Completion Time: Unlike Experiment 1(a), there were no significant main effects of *Channel Order* on completion time ($F_{1,11}$ = 0.006, p = 0.94). There were still main effects of *PL* ($F_{2,22}$ = 198.67, p < 0.001) and *TL* ($F_{2,22}$ = 119.16, p < 0.001) on completion time. Post-hoc pairwise comparisons revealed significant differences (p<0.001) for all pairs of combinations for both *PL* and *TL*. There was a significant *PL*×*TL* interaction ($F_{4,44}$ = 10.90, p < 0.001). Figure 9 (left) displays an increase in completion time for all levels of tilt as the number of pressure items increases. This increase, however, is particularly dramatic with a large number of tilt items.

Error Rate: Results for error rates were similar to those in Experiment 1(a). The effect of *Channel Order* on error rate was not significant ($F_{1,11} = 0.42$, $p=0.53$). The effects of *PL* and *TL* were significant ($p<0.001$), with all pairwise comparisons significant ($p<0.01$), except between TL 2 and 4.

Number of Crossings: Like completion time and error rate, the effect of *Channel Order* on crossings was not significant ($F_{1,11} = 2.97$, $p=0.11$). Again, there were main effects of *PL* ($F_{2,22} = 113.97$, $p < 0.001$) and *TL* ($F_{2,22} = 44.54$, $p < 0.001$) on error rate. I did, however, find an interaction between *Channel Order* and *Number of Pressure Levels (PL)* ($F_{2,22} = 6.06$, $p < 0.01$), the nature of which is displayed in Figure 9 (right). This interaction effect indicates that at a large number of pressure items, the T→P order becomes more difficult to control than the P→T order.

4.2.3 *Discussion*

Experiment 1(B) reveals that the two orders for combining Pressure and Tilt are comparable in terms of overall speed and accuracy. Results also suggest that one should consider avoiding the high end of Tilt's usable range (more than 4 items) with combined with Pressure, as speed and controllability both begin to degrade. Finally, participants' subjective impressions of combining Pressure and Tilt from the questionnaire tended to be very positive, however, they again found *a-coord input* more difficult at the high end of each channel's usable range.

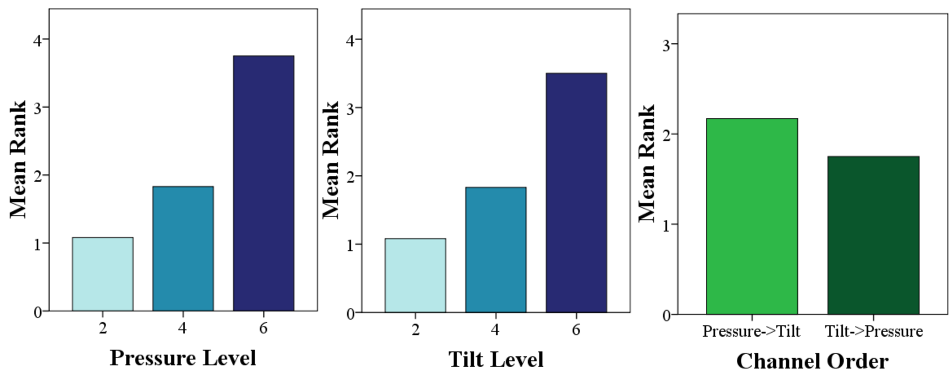


Figure 10: Subjective feedback on pressure levels (left), tilt levels (middle) and channel orders (right)

Subjective feedback

Similar to previous the experiment, participants' feedback was also collected about the techniques and number of levels that used in this experiment. Participants were asked to rate those upon 5-point Likert scales (1 – very easy - to 5 – very hard) in a questionnaires.

A similar trend was found for number of levels where participants found a-coord input was more difficult with higher number of levels as shown in figure 10 (left) and (middle). They also found using Tilt followed by Pressure was easier compared to Pressure followed by Tilt as displayed in figure 10 (right). Their rating was in favor of using tilt first as it provide non-sequential access to the goal item.

4.3 EXPERIMENT 1(C) - TILT AND ROLL

In Experiment 1(c), I examined a 2D discrete selection task using pen tilt in conjunction with its rolling angles.

4.3.1 *Study method*

12 different participants (four males and eight females) between the ages of 18 and 32 were recruited for this study in exchange of course credit. Participants had little or no experience with pen-based interfaces. Eleven were right-handed.

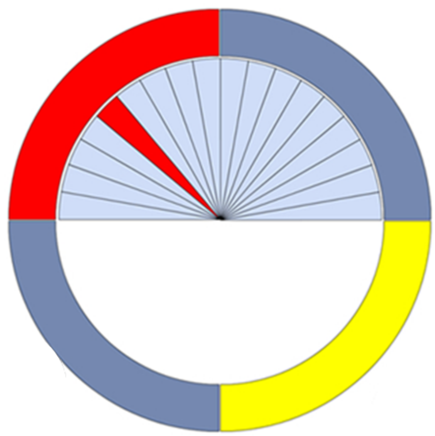


Figure 11: T→R with 18 levels of Roll and 4 levels of Tilt

For the selection task in Experiment 1(c), candidate items for roll and tilt were arranged in a fan and a ring layout respectively (Figure 11). This image shows a T→R order with 18 levels of Roll and 4 levels of Tilt. Here, quadrants represent Tilt, and the widget represents Roll. As in experiment 1(a) I placed targets in three different distances i.e., 20%, 50%, and 80% of the usable range which corresponds to $\pm 18°$, $\pm 45°$, and $\pm 72°$ with Roll. In this experiment, two targets were highlighted in red: the one to be selected with tilt and the one to be selected with roll. I tested tilt levels (*TL*) of 2, 4 and 6; and roll levels (*RL*) of 6, 12, and 18.

4.3.2 *Results*

Completion Time: As in Experiment 1(b), there was no significant differences between T→R and R→T on completion time ($F_{1,11} = 0.31$, $p=0.59$). Main effects were again present for the Number of Roll levels (*RL*) and the Number of Tilt levels (*TL*) ($F_{2,22} = 34.53$, $p < 0.001$ and $F_{2,22} = 40.76$, $p < 0.001$). Post-hoc pair-wise comparisons showed significant differences for all pairs of *RL* and *TL* ($p<0.005$), except RL 6 and 12.

Error Rate: There was no difference between R→T and T→R on error rate ($F_{1,11} = 2.39$, $p=0.15$). There were again main effects for *RL* and *TL* ($F_{2,22} = 15.35$, $p < 0.001$ and $F_{2,22} = 6.62$, $p < 0.01$). Post-hoc pair-wise comparisons revealed significant effects for all pairs of *RL* and *TL* ($p<0.05$), except between *TL* 2 and 4.

Number of Crossings: The results for crossings in Experiment 1(c) were similar to those for the other two measures. There was no main effect of *Channel Order* ($F_{1,11} = 0.21$, $p=0.65$), but there were significant main effects for both *RL* and *TL* ($F_{2,22} = 39.99$, $p < 0.001$ and $F_{2,22} = 26.08$, $p < 0.001$).

4.3.3 *Discussion*

Experiment 1(C) revealed that users are able to combine Tilt and Roll, and that there is no significant difference between Tilt→Roll and Roll→Tilt in terms of speed, accuracy, and controllability. Results also suggest that using Tilt and Roll in combination likely permits the selection of a larger target set than the combinations studied in Experiments 1 and 2, but that it might be best to avoid using 6 or more levels of Tilt. While there were few quantitative differences between the two techniques, feedback on the questionnaire suggests that users may prefer Roll→Tilt.

Subjective feedback

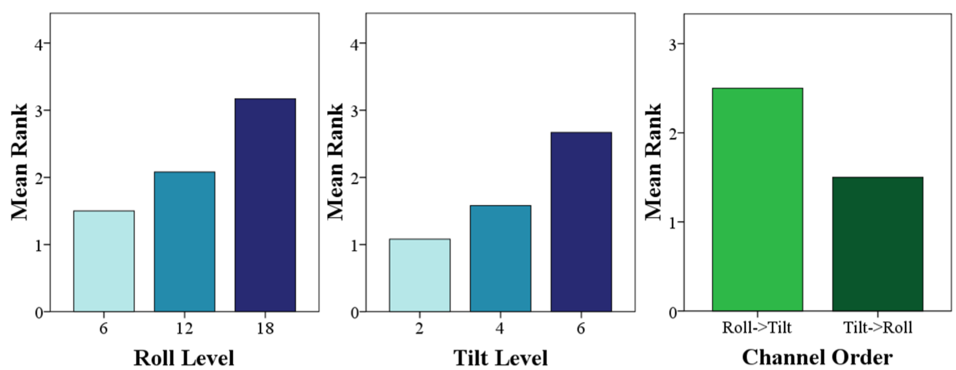


Figure 12: Participants' feedback on number of roll and til levels and channel order that used in the experiment.

Subjective feedback was also collected regarding the techniques and number of levels that used in the experiment. Like the first two experiments, I used a questionnaire where participants were asked to rate those upon 5-point Likert scales (1 – very easy - to 5 – very hard).

Participants found a-coord input was easier with lower number of levels; however it was rated difficult for higher number of levels (both for tilt and roll) as shown in figure 12(left) and (middle). I found similar trends for Tilt, where any channel that combined with tilt first rated as preferred technique.

4.4 GENERAL DISCUSSION: EXPERIMENT 1

Overall, my results support the use of *a-coord input* with input constraints. Except for R→P and P→R, there was no difference in the channel order. Therefore designers could select any order that fits with corresponding biomechanical operation. Also, the results show that *a-coord input* supports a larger set of items than what is possible using any single channel. In addition, I found that users had good control over two concurrent channels in a sequential manner, e.g., selecting with pressure when maintaining a certain amount of roll. Hence, I expect that even higher degrees of freedom are feasible, e.g., combining pen movement or another auxiliary channels such as pen altitude, for tasks that require less fine-grained control.

4.5 EXPERIMENT 2 – INPUT CONSTRAINTS VS NO-INPUT CONSTRAINTS

In Experiment 1, I examined the general feasibility of coordinating two auxiliary channels in conjunction, in the context of constrained input feedback (termed IC). The results can inform the design of interfaces that rely on this form of input, for example selecting different layers of a menu. However, these input constraints could affect *a-coord input*'s performance. Therefore, in this experiment I examine the impact of applying input constraints compared to no-input constraints (termed No-IC) in one of the three channel combinations: Pressure and Roll. By removing these input constraints

(No-IC), I can be better informed as to how *a-coord input* is used in a more parallel manner. In comparing IC vs. No-IC, I looked for differences in efficiency (task completion time, error rate and crossings). I chose to focus on Pressure and Roll because it had a noticeable impact on task completion time, and therefore I expect that if some parallelism occurs for this visually constrained *a-coord input*, it is likely to occur at some level in the other combinations as well.

4.5.1 *Participants and apparatus*

Fourteen participants (13 males and 1 female) between the ages of 21 and 35 participated in this study. Participants had little or no experience with pen-based interfaces. All participants were right-handed. The apparatus was the same as in Experiment 1.

4.5.2 *Task and procedure*

The task and procedure were identical to Experiment 1(a), however, in No-IC mode feedback was supplied for both channels simultaneously, as shown in Figure 13. For IC mode, I used the Roll→Pressure order given that participants were significantly faster with it than with Pressure→Roll.

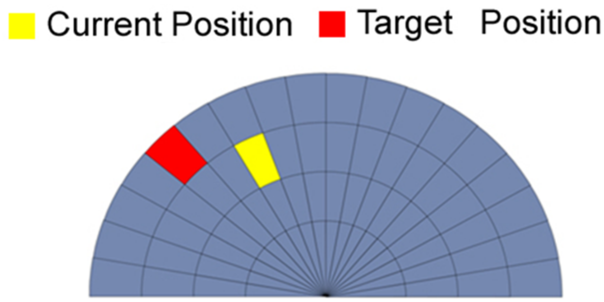


Figure 13: *A-coord input* without input constraints

4.5.3 *Design*

The experiment employed a 2×3×3 within-subjects factorial design. The independent variables were *Mode*: IC and No-IC; *Number of Roll Levels (RL)*: 6, 12, and 18; *Number of Pressure Levels (PL)*: 2, 4, and 6. *Mode* was counterbalanced across participants. Within each mode, *RL* and *PL* were presented in increasing order and the target distances were randomized. Each *Mode*×*PL*×*RL* combination was repeated 18 times by each participant (3 times for each target distance). Dependant measures from Experiment 1 were included here (completion time, error rate and crossings).

4.5.4 *Results*

Outliers greater than 3 standard deviations from the mean completion time were removed again, representing 1.79% of the data.

Completion Time: Analysis revealed that the effect of *Mode* on completion time was not significant ($F_{1,12} = 0.10$, p=0.76). There was a significant *Mode*×*Presentation Order* interaction effect ($F_{1,12} = 7.319$,

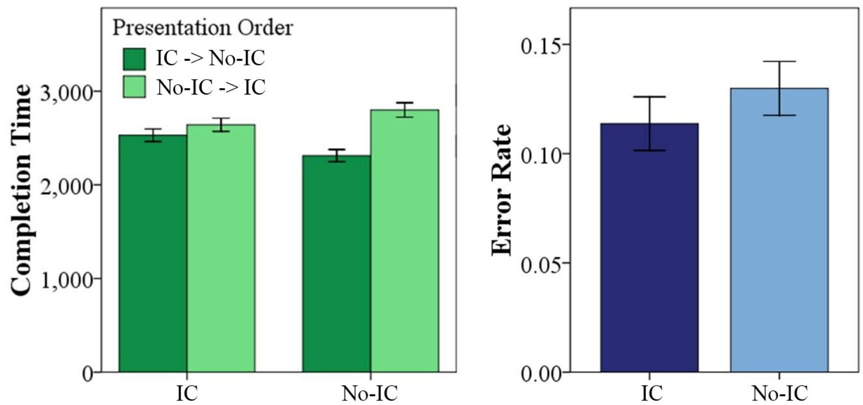


Figure 14: (left) Mean completion times for each mode according to Presentation Order and (right) mean error rates for each mode.

$p<0.05$). Figure 14 (left) displays the nature of this interaction: performance was similar for the IC mode across both orders ($p=0.403$). For the No-IC mode, there was a significant difference between the two presentation orders: those who started with IC were significantly faster than those who started with No-IC ($p<0.005$).

Error Rate and *Number of Crossings*: Analysis revealed marginally non-significant main effect of *Mode* on error rate ($F_{1,12} = 0.93$, $p=0.35$). Figure 14 (right) suggests that participants tended to make fewer errors in the presence of input constraints than they did without. The effect of *Mode* on the number of crossings was not significant ($F_{1,12} = 0.37$, $p=0.55$).

4.5.5 *Discussion*

Experiment 2 revealed that the presence of input constraints does not have a significant impact on *a-coord input*'s performance. However, some interesting results were found from this experiment. First, there is a potential impact of input constraints on controllability, with a trend indicating that the error rate increased when removed. The results also indicate that using input constraints may facilitate learning how to operate two channels in combination. Those who engaged in this mode of operation first were more efficient when the input constraints were removed than those who started without the constraints. Thus, input constraints appear to provide a form of scaffolding for learning *a-coord input*. Finally, I note that users expressed a slight preference for *a-coord input* with no input constraints on the post questionnaire, but both modes were rated highly.

Subjective feedback

Following the experiment, each participant completed a questionnaire to evaluate his or her personal opinions about the techniques. The questionnaire asked the participants to rate those upon 5-point Likert scales where it consisted of equally spaced scalar values from 1 – very easy - to 5 – very hard.

Participants' subjective impressions from the questionnaire echoed the performance data. They found both techniques were easier to control where the average ranking for input constraint mode was 2.33 and no-input constraint was 2.00.

5

COMPARISON OF DIFFERENT A-COORD INPUT AND THEIR COORDINATION

5.1 GOAL AND HYPOTHESIS

The previous two experiments demonstrated the potential of *a-coord input* for discrete item selection tasks. The results showed that channel order has a limited impact on the combinations and input constraints does not have a significant impact on performance of *a-coord* input. In these previous experiments, I compared the performance of *a-coord input* seperately by changing the order, e.g., P→R and R→P. However, there was no comparison between possible *a-coord input*s and how well those combinations would work compared to single-channel techniques where an auxiliary channel is applied twice. As with *a-coord input*, users are allowed to apply two channels simultaneously, an investigation is needed to explore the amount of coordination exhibited among them.

Therefore, the goal of this experiment was to explore (a) the performance of *a-coord input* compared to single-channel techniques, and (b) explore the amount of coordination of *a-coord input* for discrete selection tasks. In single-channel techniques, the goal could be realized by first applying one channel, a selector, and then the same channel again (i.e., Roll+selector+Roll). The selector would indicate movement into the next dimension. Alternatively one could apply one channel, a selector, and then a different channel. However, this would resemble *a-coord input*, which makes a selector redundant. As in *a-coord input*, visual feedback from two input channels are given at the same time, and a selector is not required to switch between the channels. In this experiment, I used the first design (i.e., input channel + selector + input channel) as a baseline.

Based on the properties of *a-coord input*, I hypothesized the following:
H1: *A-coord input* will take less time to make a discrete item selection as it allows users to control two input channels simultaneously.
H2: The error rate in the baseline technique will be less than in *a-coord input*, as it confirms the selection using one channel at a time.
H3: The number of crossings in *a-coord input* will be higher than in the baseline as it is difficult to control two input channels precisely.

5.2 USER STUDY

5.2.1 *Participants and Apparatus*

Ten right-handed participants (two females) between the ages of 18 and 35 were recruited for this study. Participants had little or no experience with digital pen input. They were paid 10 dollars for their participation.

I used a Wacom Intuos4 tablet with an Intuos4 Art Pen. The pen can produce pressure, tilt and roll values with a maximum of 2048 levels of pressure, and 360° of roll and tilt. I displayed visual feedback in full-screen mode on a 22-inch monitor with a resolution of 1680×1050 pixels.

5.2.2 *Task and Procedure*

I used a 2D discrete-target selection task to test the *a-coord input*. All first level items were arranged in a 360° circular layout (Figure 15). Second level items were placed in concentric rings. I chose this mapping as it would allow us to explore a range of a-coord techniques without introducing any confounds related to unintuitive visuo-motor mappings. The size of each target was determined by the number of items in the menu (i.e., fewer items resulted in larger targets).

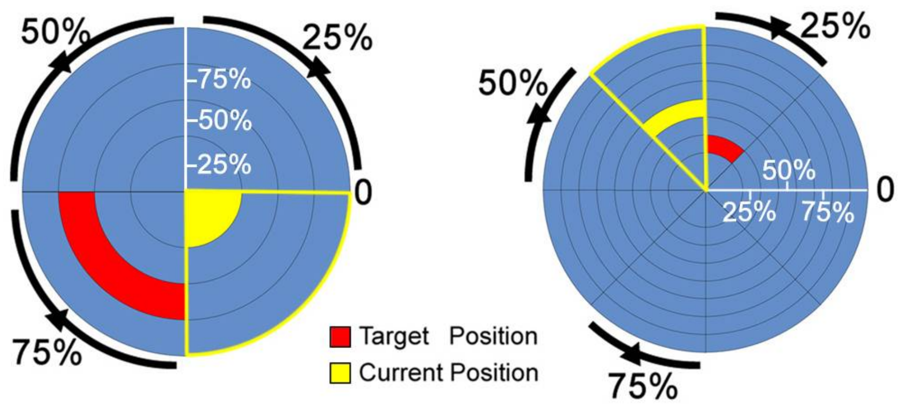


Figure 15: Visual feedback for 4×4 (left) and 8×8 (right) levels. The arrowheads indicate the target wedge.

The target was always highlighted in red. The user's cursor was displayed in yellow. Participants were asked to select the target using either a single channel twice (baseline) or *a-coord input* as quickly and accurately as possible. In the single channel condition, participants first selected the correct wedge using one channel (e.g. pressure or roll). Once the participants landed on the desired wedge, they could then move up to the second dimension in the 2D menu by pressing the CTRL key with the non-dominant hand, and then applying the same channel again. In the *a-coord input* condition, participants selected the wedge using one channel (e.g. roll) and the target item using another channel (e.g. pressure). With *a-coord input*, simultaneous movement across both channels was possible. In both conditions, the final target selection was made by pressing a hardware button (CTRL key) using the non-dominant hand. To undo any action users could simply lift up the pen.

Prior to the experiment, participants were shown the experimental setup, and were given several practice trials in each condition. For the *a-coord input* techniques, participants were shown how channels could be engaged simultaneously (e.g., applying pressure towards the target circle and rolling the pen towards the desired wedge, at the same time). However, participants were not required to engage in parallel action and could complete the task by allocating control to one channel and then the other. Breaks were enforced at the end of each block of trials. The entire experiment lasted approximately 30 minutes.

5.2.3 *Design*

To avoid a combinatorial explosion of different *a-coord input* styles, the study used only three input channels: pressure, roll and tilt. I acknowledge that my results may not generalize to all combinations of *a-coord input*s, but hope to show that at least some combinations provide clear benefits. I used these three channels with the following parameters.

Pressure - I applied a hysteresis function similar to that found in [20]. However, I excluded pressure readings that were caused by the weight of the pen as this could confound results. The range selected was thus between 819 and 2048 pressure units (where 2048 was approximately 1.5N of force). The initial pressure value was mapped to $0°$ as indicated in Figure 15.

Roll - For roll input, I defined the initial roll value of $0°$ as indicated in Figure 15. According to prior work, rolling under $10°$ was usually incidental and anything beyond $\pm 90°$ is suboptimal [2]. Participants could roll the pen in either direction. Since the visual feedback consisted of a full circular layout, I employed a 1:2 mapping between the motor and visual space for roll.

Tilt - For the tilt channel, I only consider tilt in the azimuth angles, where $0°$ was mapped to a tilt to the East as indicated in Figure 15.

Combining these three channels, I get three different a-coord techniques: Roll + Pressure (R+P) (Figure 16a), Tilt + Pressure (T+P) (Figure 16b) and, Tilt + Roll (T+R) (Figure 16c), where the first channel moves along the first dimension (radially) and the second channel controls the cursor in the second dimension (linearly). I selected these visuo-motor mappings based on the properties that described in Chapter 3. I included two baseline single-channel techniques: Pressure + Pressure (P+P) and Roll + Roll (R+R). Tilt + Tilt requires a different visual mapping, since tilt works best with radial feedback, thus I excluded it to avoid introducing potential confounds.

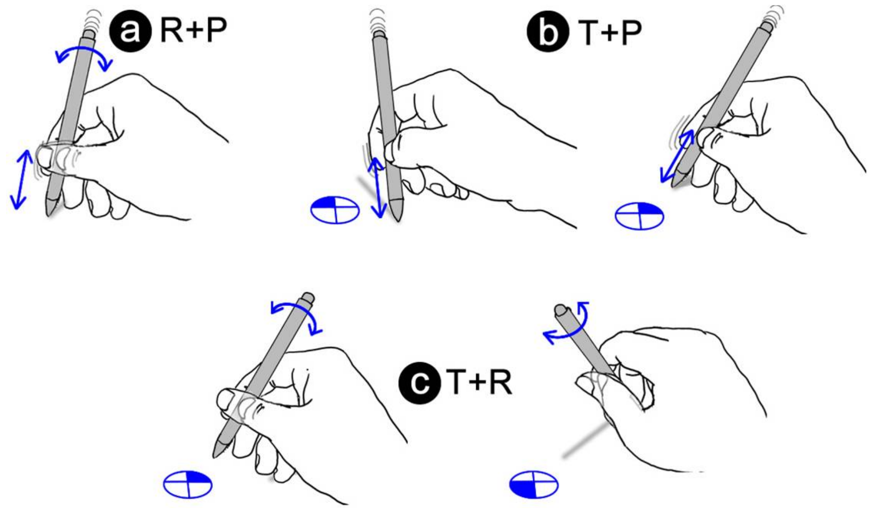


Figure 16: Three a-coord techniques I evaluated. Roll+Pressure (R+P); Tilt+Pressure (T+P); Tilt+Roll (T+R)

As the results from previous experiment showed that the input constraint does not have a significant impact on performance of *a-coord*, I choose to provide feedback of both channels at the same time.

The target was placed randomly at 3 distances: 25%, 50%, and 75%, of the total input range for each channel, for both the first and second dimensions (Figure 15).

Overall, the experiment employed a 5×2×3 within-subjects factorial design. The independent variables were *Technique*: P+P, R+R, R+P, T+P and T+R; *Number of Levels* per dimension: low (4 levels) and high (8 levels) in both dimensions; and *Target Distance* (25%, 50%, and 75%). *Technique* was counterbalanced across participants using a Latin square, while the other factors were presented in random order. Each trial representing a *Technique* × *Number of Level* × *Target Distance* combination was repeated 4 times by each participant.

5.3 RESULTS

The data was analyzed using Repeated-Measures ANOVA and Bonferroni corrections for post-hoc comparisons.

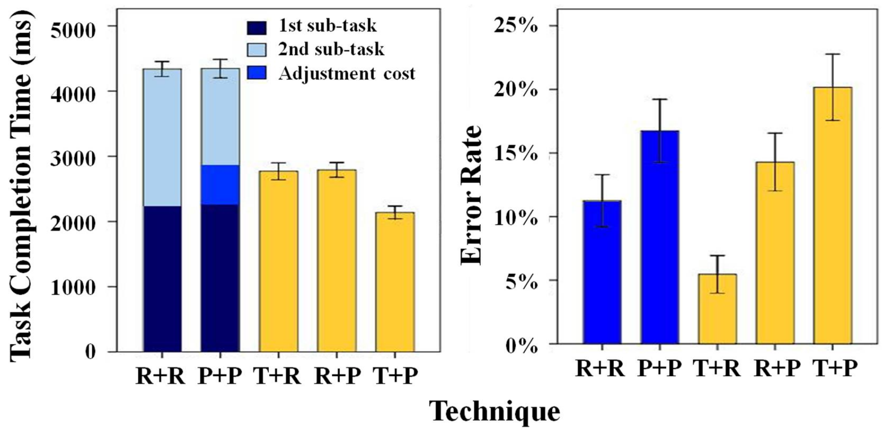


Figure 17: Left: Task Completion Time shown by technique. Right: Error Rate shown by technique. (Error Bars show ±1 s.e.)

5.3.1 *Task Completion Time*

Completion time was the time from the target's appearance to the time participants successfully selected it. The RM-ANOVA yielded a significant main effect of *Technique* ($F_{4,36} = 46.33$, $p < 0.001$) on completion time. The means for each technique are displayed in Figure 17. Post-hoc comparisons showed that the three dual-channel techniques (T+P: 2315 ms, s.e. 182; T+R: 2830 ms, s.e. 185; R+P: 2841 ms, s.e. 179) were all significantly faster than the two single-channel techniques (R+R: 4338 ms, s.e. 127; P+P: 4341 ms, s.e. 231; $p < 0.001$). There was also a trend indicating that T+P was faster than R+P ($p=0.065$), but there was no difference between R+P and T+R ($p = 1$).

The difference between the two single-channel techniques was not significant ($p = 1$).

For the single-channel techniques, completion time can be decomposed into two sequential target acquisition components: the time it takes to make a successful selection on the first level, and the time from the end of the first task to the end of the trial. Since pressure is unidirectional, there was an additional adjustment cost for P+P between the two task components, where participants had to release the pressure after the first task by lifting the pen tip, and to land down the pen again to start the second task (Figure 17 left).

Figure 17 left shows the task decomposition for each of the two single-channel combinations. I observe that participants require less time on the second invocation of the channel. This goes contrary to my expectations that the second invocation should take longer due to the mechanical finger re-adjustment after having invoked that channel once. This is still likely the case, but that users probably built muscle memory from the first phase, given that the targets were all laid out at the same distance in the second level. In retrospect, I created a condition that unintentionally favoured single channel input. Despite this, I found that *a-coord* was more efficient than using a single channel alone.

As expected, there was a significant effect of *Number of Levels* on completion time ($F_{1,9} = 135.2$, $p < 0.001$), with participants slower at 8 levels (4006 ms, s.e. 181) than at 4 levels (2661 ms, s.e. 104). This effect was generally consistent across techniques.

There was no main effect of *Target Distance* on completion time ($F_{2,18} = 1.93$, $p = 0.17$), however, the interaction effect between *Tech-*

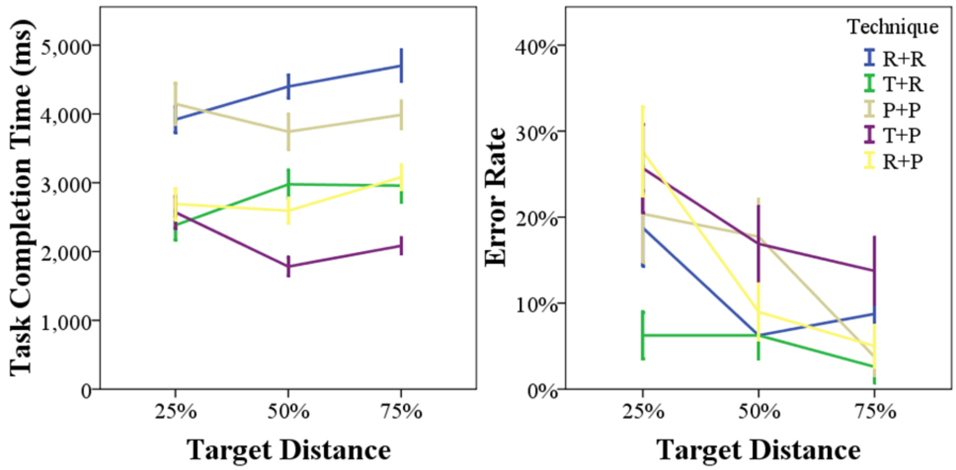


Figure 18: Interaction effect of *Technique* × *Target Distance* on (Left) Completion Time and (Right) Error Rate shown by technique. (Error Bars show ±1 s.e.)

nique and *Target Distance* was significant ($F_{8,72} = 6.15$, $p < 0.001$) as shown in figure 18 (left). The nature of the interaction was difficult to interpret; however, it appears as though the poor performance of techniques involving pressure (P+P, R+P, and T+P) was mainly caused by the poor performance of those techniques when low pressure levels were required (targets at 25%). This is consistent with the findings from the prior work [23], showing that people have difficulty controlling pressure at its lower end.

5.3.2 *Number of Errors*

An error occurred if the participant selected the wrong target. For single channels, errors were recorded only if the item on the second level was not selected properly. The trial did not stop until the proper target was selected.

The RM-ANOVA yielded a significant main effect of *Technique* ($F_{4,36} = 4.47$, $p = 0.01$) on error rate. Post-hoc analysis showed that T+R (5.4%, s.e. 0.9%) had significantly fewer errors than P+P (17.5%, s.e. 3%) (p=0.034). There were also non-significant trends indicating that T+R might be less error prone than R+R (11.2%, s.e. 1.9%, p=0.067) and T+P (20.6%, s.e. 4.6%, p=0.072). There was no significant difference between T+R and R+P (14.3%, s.e. 3.1%, p=0.220), nor were there significant differences between the remaining techniques (p=1).

There were significant main effects of *Numbers of Levels* ($F_{1,9} = 35$, $p < 0.001$) and *Target Distance* ($F_{2,18} = 1.93$, $p < 0.001$) on error rate. Participants made twice as many errors with 8 levels (18.2% s.e. 1.8%) than they did with 4 levels (9.4% s.e. 1.8%). For target distances, there were significantly more errors with targets at 25% distance (23.1%, s.e. 3.3) than with targets at 50% distance (11.3%, s.e. 1.2%) and 75% (7%, s.e. 1.5%) ($p < 0.05$). Post-hoc analysis showed no significant difference between the 50% and 75% distances ($p = 0.1$).

Finally, there was a significant *Technique* $\times$ *Target Distance* interaction effect ($F_{8,72} = 0.07$, $p < 0.05$) as displayed in figure 18 (right). Similar to the results for completion time, the interaction was at least partly due to the techniques involving pressure, where the error rate decreased rapidly as the target distance increased.

5.3.3 *Number of Crossings*

A crossing happened when a participant overshot or undershot a target, i.e. if a participant successfully entered the target, but accidently moved over to the next or previous item before selection, it was counted as a crossing.

The RM-ANOVA yielded a significant main effect of *Technique* ($F_{4,36} = 8.23$, $p < 0.001$) on the number of crossings. Post-hoc analysis showed that T+R (0.69, s.e. 0.1) had significantly fewer crossings than R+R (1.00, s.e. 0.9, p=0.036) and P+P (1.69, s.e. 0.14, p=0.011). The differences between other two a-coord techniques (T+P: 1.09, s.e. 0.13; R+P: 1.20, s.e. 0.13) were not significant (p>0.30). There were no significant differences between the remaining techniques ($p > 0.25$).

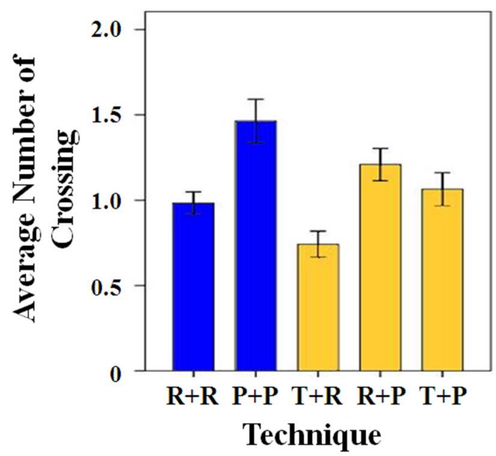


Figure 19: Number of Crossings shown by technique. (Error Bars show ±1 s.e.)

There were significant main effects of *Number of Levels* ($F_{1,9} = 249.00$, $p < 0.001$) and *Target Distance* ($F_{2,18} = 118.54$, $p < 0.001$) on the number of crossings. Similar to the number of errors, the participants made twice as many crossings with 8 levels (1.56, s.e. 0.04) than with 4 levels (0.71, s.e. 0.06), and these effects were consistent across techniques. In terms of *Target Distance*, participants made more crossings with targets at 25% distance (1.88, s.e. 0.08) than at 50% distance (0.98, s.e. 0.07) and at 75% distance (0.55, s.e. 0.05). All pairwise comparisons between distances were significant ($p < 0.01$). There was also a significant interaction effect of *Technique* × *Target Distance* ($F_{8,72} = 11.28$, $p < 0.001$) that was similar in nature to that of completion time and error rate.

5.4 DISCUSSION

A-coord Input Performance

Results from the experiment reveal several trends. Users were faster with all *a-coord input* styles tested, than with using an auxiliary channel twice. Based on the results across all measures, Tilt+Roll afforded the best overall results, with completion times below those of the single channels, and error rates in an acceptable range. The primary cause of Tilt's performance is that Tilt does not require users to traverse a range of items before reaching the target (Table 1). Additionally, Roll can control a larger number of items than Pressure. While Tilt+Pressure showed a trend towards being the fastest technique, it also exhibited a high error rate, making it perhaps the least desirable technique of all three a-coord styles.

Error Rates

Error rates that observed in this experiment are similar to the ranges found in earlier studies on single channel input (see [2], [20], [28]). These range between 5% and 20%, and can be minimized with better discretization functions [23] and by using fewer items [28]. Additionally, improvements can be achieved by providing training to users to improve with learning [23].

Extending the Number of Controllable Items

Results show that any *A-coord* technique with 4×4 items has a comparable performance to other single channel techniques. These results show that users can extend the range of discrete items that was previously possible to select with single auxiliary channels. *A-coord input* increases the range by a factor of 2 to 3 times. Even with a conservative extension of up to 4×4 items, error rates across *a-coord input* are within the bounds of what was previously reported with single channels alone.

Coordination

I examine the amount of coordination facilitated by *a-coord input* by breaking down the total completion time by the amount of control exhibited by each individual channel (Figure 20). There were a few trends as described bellow.

First, while users still operate both channels in conjunction, they tend to stabilize one channel before completing the task with the other. This result goes contrary to my initial expectation that both channels would always be operated together, instead of one leading the other. Furthermore, stabilizing one channel before the other

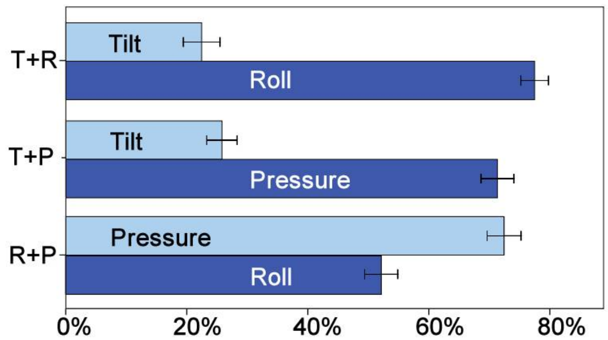


Figure 20: Average percentage of time consumed by each channel over the length of a trial.

might explain the improved efficiency and error rates obtained with certain a-coord styles. For example, users stabilize Tilt very quickly, which may explain why combinations with this channel, such as Tilt+Roll, worked better than other techniques.

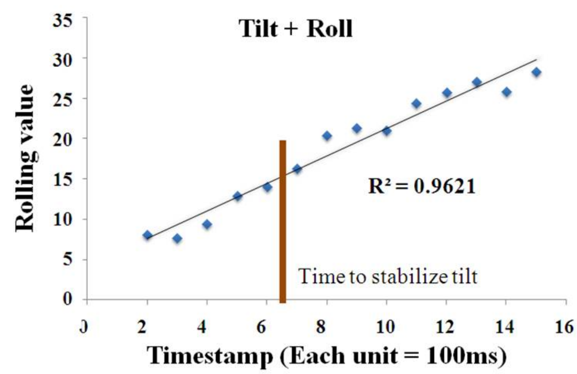


Figure 21: Degree of control with the non-leading channel until the leading channel stabilizes. With Tilt+Roll, Roll is controlled in a linear fashion across the trials.

The fact that Tilt takes considerably less time to stabilize than either roll or pressure is to be expected due to the non-sequential nature of acquiring items through tilt-azimuth. Users take roughly 22% of the total task time to operate and stabilize tilt. This corresponds to a value between 700 and 850 msecs, which matches very closely performance when tilt is operated alone, as shown in earlier work [28]. Input with the second channel, i.e. Roll or Pressure with Tilt, takes approximately 75% of the total task time (i.e. users seem to take the remaining 25% of total task time to select the target with the button using the non-dominant hand). With Roll+Pressure, I see that users on average operate Roll at 50%, and Pressure at 72% of total task time. These results indicate that users stabilized the first channel before proceeding to the final goal. They may also suggest that channels with large controllable input ranges (Table 1), i.e. in this case Roll or Tilt, get stabilized before those with less control.

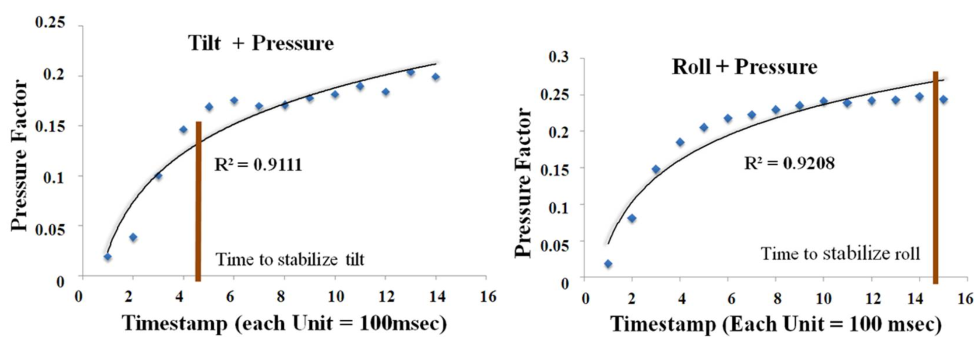


Figure 22: Left and Right: the non-leading channel Pressure is controlled in a logarithmic manner profile for all users.

I further examine the performance of the non-leading channel (i.e. the channel which stabilized last) for the period in which both channels operate simultaneously. Figure 21 and Figure 22 illustrate this scenerio for all a-coord combinations, where the red vertical bar represents the timestamp when the leading channel stabilizes. For example, during the period it takes Tilt to stabilize (22% of the overall task time in Tilt+Roll or roughly 700 msecs, represented in Figure 21). I observe several trends in those graphs with R^2 (correlation of coefficient [30]) above 0.9 where any R^2 value above 0.6 is considered to having a strong correlation. With Tilt+Roll I find that while users are operating Tilt, the values of Roll grow linearly and this continues even after Tilt is stabilized. In the case of Tilt+Pressure and Roll+Pressure, the non-leading channel Pressure is controlled in a logarithmic manner. This suggests that during the period when both channels are operating, pressure quickly ramps up and then slows down after the leading channel stabilizes.

Overall, these observations on channel coordination suggest that users tend to operate both channels conjunctively, within the time frame used for operating the leading channel. The conjunctive operation of *a-coord input* has the potential to yield performance gains in tasks other than 2D discrete item selection. I demonstrate how to extend this conjunctive operation to a different task in next study.

6

A-COORD INPUT FOR CONTINUOUS MANIPULATION TASKS

Results from previous studies reveal that users can conjunctively coordinate two auxiliary channels. This suggests that a-coord input has the potential to support more items than it is possible with single channel input. To explore a-coord input with additional common tasks, I conducted another experiment where I tested a-coord input through multi-parameter selection and manipulation, a task that involves continuous manipulation and inherently has a two-step structure.

The common task of multi-parameter selection and manipulation requires users to select a desired parameter before they can actually change its value. I adapt a-coord input such that users concurrently chose a parameter and manipulate it. This form of interaction would be suitable for users who know a priori the value of the target parameter they wish to set. In these situations, a-coord input could be used to select and manipulate the value of a parameter through a single and continuous action. The pen's auxiliary channels were designed for continuous tasks, such as for drawing. I therefore harness this natural design feature in a multistep fashion.

With *a-coord input*, one channel is used to select a parameter and the other channel is used to perform a continuous manipulation task.

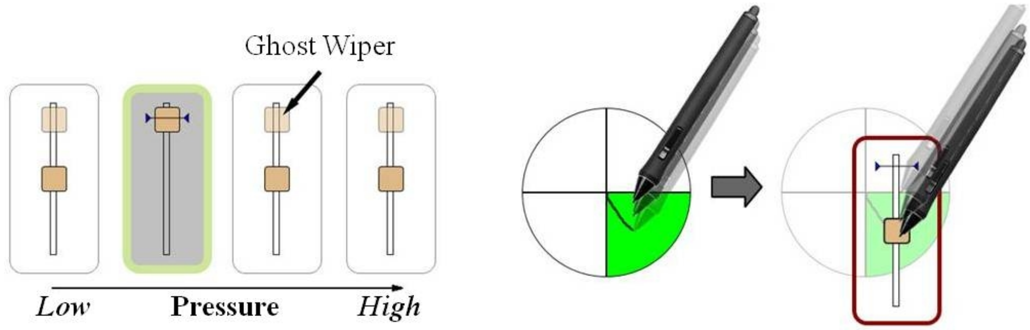


Figure 23: (Left) Use Pressure to select a desired slider, and use Roll to adjust the position of the wiper. (right) FaST Slider [14] that consists of marking menus with a linear slider.

Figure 23 (left) shows how to adjust the value of multiple parameters, e.g. an image's brightness or contrast, with P+R. A user can move between sliders using pressure. Only the active slider is highlighted, and its value can be altered by rolling the pen. Users can press a CTRL key on the keyboard to confirm the selection. With *a-coord input*, rolling the pen while pressing will unintentionally change the value of all sliders, active or inactive. To address this issue, I introduce a ghost wiper on every slider. Ghost wipers are semi-transparent and work the same way as real wipers but, without changing the value of the parameters. They only show the potential change of the value. When users press the selection key, the change takes place on the active slider, while all other sliders remain unchanged (Figure 23 left).

6.1 GOAL AND HYPOTHESES

This study measures user performance with *a-coord input* in a multi-parameter selection and manipulation task. Unlike 2D discrete item selection, the two sub-tasks in a multi-parameter selection and manipulation task are asymmetric, i.e. each channel plays a different role – one is for discrete item selection and the other is for continuous variable manipulation. The two-step process requires users to hold the leading channel steady while manipulating the non-leading channel, thus testing the users' ability to maintain control with *a-coord input*. An additional distinction between this task and 2D selection is that manipulating a continuous variable requires finer control. I only used Roll for manipulating the continuous variable, as my pilot studies showed that Pressure did not afford sufficient bi-directional control for fine-grained input, and Tilt did not map naturally to such a task. I thus mapped parameter selection to Pressure and Tilt resulting in testing P+R and T+R. Finally, I was also interested in knowing if *a-coord input* affords a comparable performance to an existing multi-parameter selection and manipulation technique. I included the FaST Slider [14] as a baseline technique in the study (Figure 23 right). Other techniques exist (as described in the related work section) but FaST sliders have shown to be easily to learn, unlike FlowMenus [10], for example.

Based on the properties of *a-coord input*, I hypothesized the following:

H1: *A-coord input* will be faster in multi-parameter selection and manipulation tasks as it doesn't have any additional switching costs and allows users to control multiple input channels simultaneously.

H2: Error rates in FaST Slider will be lower than *a-coord input* as FaST Slider consists of two sequantial tasks and confirms the selection using one channel at a time.

6.2 USER STUDY

6.2.1 *Participants and Apparatus*

Twelve right-handed participants (2 females) between the ages of 20 and 35 were recruited for this study. Participants had little or no experience with pen-based interfaces. I used the same apparatus as in Experiment 2.

6.2.2 *Task and Procedure*

For the a-coord techniques, participants were asked to select a slider using Pressure or Tilt, and then use Roll to adjust the position of the wiper to a target value shown by a vertical bar (Figure 23 left). The wiper was initially placed in the middle of the slider at 180 pixels (50.4 mm in real world units). Rolling the pen 1° in the counter-clockwise direction moved the wiper up by 1 pixel, and vice versa. When the wiper reached the target value, participants pressed the CTRL key using the non-dominant hand to confirm a selection.

With FaST Slider, participants first selected a slider using a marking menu [11]. The slider appeared at the position where the participants lifted the pen (Figure 23 right). They then used the pen tip to drag the wiper to the target value, pressing the CTRL button to confirm selection. The height of the entire slider widget remained the same for all techniques.

A trial ended when participants successfully changed the desired parameter to the target value. Prior to the study, participants were given practice trials to familiarize themselves with all techniques.

6.2.3 *Design*

The experiment employed a 3×2×2×3 within-subjects factorial design. The independent variables were *Technique*: P+R, T+R, and FaST Slider; *Number of Parameters*: Low (4) and High (6); *Granularity*: Coarse-grained, Fine-grained; and *Target Distance*: Near, Mid, and Far.

Number of Parameters - As the third study showed that task completion time and error rate increased with 8 items, in this experiment, 6 items were used in the *High* and 4 items in the *Low* condition.

Granularity - I used wipers of 2 different sizes to adjust the level of granularity. For the fine-grained setting, I used a wiper of 15 × 30 pixels (4.5 × 8.4 mm), and for the coarse-grained setting, I used a wiper of 30 × 30 pixels (8.4 × 8.4 mm).

Target Distance - I randomly placed the target within 3 intervals: Near (10%-30%), Mid (40%-60%), and Far (70%-90%), of the total input range. For rolling, the direction of roll was randomly chosen for each of the 3 target distances (i.e., clockwise or counter-clockwise rolling). For instance, the Near distance could be randomly set to be between $\pm(9^\circ$ - $27^\circ)$.

Technique - Technique was counterbalanced across participants using a Latin square, while the other factors were presented in a random order. The study consisted of four blocks with 2 trials each. There were 3 *Techniques* × 2 *Numbers of Discrete Items* × 2 *Granularities* × 3 *Target Distances* × 4 *Blocks* × 2 *Repetitions* × 12 *Participants* = 3,456 trials in total.

6.3 RESULTS

The data was analyzed using a Repeated-Measures ANOVA and Bonferroni corrections for post-hoc pair-wise comparisons.

6.3.1 *Task Completion Time*

RM-ANOVA yielded a significant effect of *Technique* ($F_{2,22} = 23.86$, $p < 0.001$) on task completion time. The means for each technique are displayed in Figure 24 left. Post-hoc comparisons showed that T+R (1703 ms, s.e. 91) was significantly faster than FaST Slider (2219 ms, s.e. 88) and P+R (2339 ms, s.e. 106) ($p < 0.001$). The difference between FaST Slider and P+R was not significant ($p = 1$).

Also, there was a significant effect of *Number of Parameters* ($F_{1,11} = 23.84$, $p < 0.001$). Participants were significantly faster at controlling 4 items (1994ms, s.e. 69) than 6 items (2180ms, s.e. 89) ($p<0.001$). This

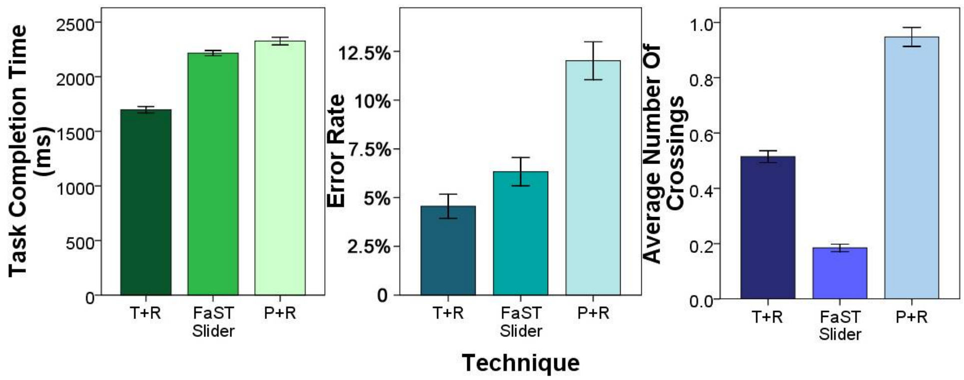


Figure 24: Left: Task completion times. Middle: Error rates. Right: Number of crossings.

trend was also found in the previous experiments, where participants were faster in controlling lower levels of items. I also found main effect of *Granularity* ($F_{1,11} = 75.98$, $p < 0.001$). Post-hoc pair-wise comparisons revealed significant differences between coarse-grained (1933ms, s.e. 81) and fine-grained (M=2241ms, s.e. 78; p< 0.001) tasks. Furthermore, there was a main effect of *Target Distance* ($F_{2,22} = 34.84$, $p < 0.001$). Post-hoc pair-wise comparisons showed that participants were significantly faster when the targets were located at the Near distance (1932ms, s.e. 74) than any other distances (p<0.001). However, no significant difference was found between targets located at the mid (2124ms, s.e. 85) and far (2205ms, s.e. 80) distances.

In addition to the above main effect, there were significant interactions between *Technique* × *Number of Parameters* ($F_{2,22} = 22.79$, $p < 0.001$), *Technique* × *Granularity* ($F_{2,22} = 4.89$, $p = 0.01$), and *Technique* × *Target Distance* ($F_{4,44} = 5.25$, $p = 0.001$) (Figure 25). These effects demonstrate that T+R was always faster than P+R and FaST Sliders, but that differences between the latter two were more nuanced. In

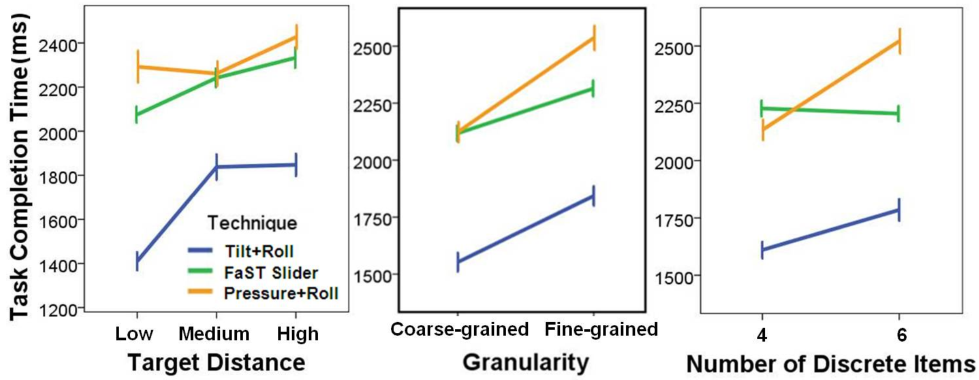


Figure 25: Interaction effects for completion time.

some conditions (e.g. coarse-grained and 4 levels of discrete items), P+R had a performance comparable to FaST Slider.

6.3.2 *Number of Errors*

The RM-ANOVA yielded a significant main effect of *Technique* ($F_{2,22} = 12.48$, $p < 0.001$) on the number of errors (Figure 24 middle). Post-hoc analysis showed that P+R (12.1%, s.e. 1.7%) had significantly more errors than T+R (4.5%, s.e. 1%) and FaST Slider (6.3%, s.e. 1.5%) ($p < 0.05$). There was no significant difference on between T+R and FaST Sliders ($p = 0.82$). There was, however, a significant main effect of *Number of Parameters* ($F_{1,11} = 9.01$, $p < 0.05$) on the number of errors. Post-hoc pair-wise comparisons revealed that participants were more error prone when controlling 6 items (8.7%, s.e. 1%) than 4 items (6.6%, s.e. 1%). Also, I found a significant main effect of *Granularity* ($F_{1,11} = 7.76$, $p < 0.05$) on the number of errors. Participants had selection errors with fine-grained (9.2%, s.e. 1.3%) than coarse-grained (6.1%, s.e. 1.1%) tasks. Furthermore, the results showed a main effect of *Target Distance* ($F_{2,22}$ = 26.22, p < 0.001) on the number of errors as well. Post-hoc comparisons showed that targets located at the Near (11.4%, s.e. 1.4%) distance were significantly more error prone than the Mid (7.4%, s.e. 1.5%) and Far (4.1%, s.e. 0.7%) target distances (p < 0.001). However, the difference between Mid and Far was not significant (p = 0.07). Also, there was a significant *Technique* × *Target Distance* interaction ($F_{4,44}$ = 22.03, p < 0.001), indicating that the difference between P+R and the other two techniques occurred mainly at Low target distances where P+R was more error prone.

6.3.3 *Number of Crossings*

RM-ANOVA yielded a significant main effect of *Technique* ($F_{2,22}$ = 73.863, p < 0.001) on the number of crossings (Figure 24 right). FaST Slider (0.18, s.e. 0.03) had fewer crossings than T+R (0.51, s.e. 0.4, p<001), which had fewer crossings than P+R (0.95, s.e. 0.06, p<0.001). All pair-wise comparisons were significant (p < 0.001). There were significant interactions between *Technique* × *Number of Parameters* ($F_{2,22}$ = 10.33, p = 0.001), *Technique* × *Granularity* ($F_{2,22}$ = 5.37, p < 0.05) and *Technique* × *Target Distance* ($F_{4,44}$ = 19.75, p < 0.001), however, the relative ordering of the 3 techniques remained constant.

In addition, there was a main effect of *Number of Parameters* ($F_{1,11}$ = 20.79, p < 0.001) on the number of crossings. Participants had significantly more crossings with 6 items (0.61, s.e. 0.04) than with 4 items (0.51, s.e. 0.03) (p < 0.001). Also, results showed a main effect of *Granularity* ($F_{1,11}$ = 26.90, p < 0.001) on the number of crossings. Post-hoc pair-wise comparisons revealed significant differences between coarse-grained (0.48, s.e. 0.03) and fine-grained (0.63, s.e.0.04; $p < 0.001$) tasks. Finally, I found a main effect of *Target Distance* ($F_{2,22} = 39.19$, $p < 0.001$) on the number of crossings. Post-hoc pair-wise comparisons showed significant differences between all values of *Target Distance* ($p < 0.005$), where participants did less crossing when targets were located at the Far (0.36, s.e. 0.03) distance, followed by the Mid (0.53, s.e. 0.04) and Near (0.79, s.e. 0.05) distances.

6.4 DISCUSSION

6.4.1 *Task Completion Time*

Results from this experiment show that *a-coord input* can be applied to a task involving continuous manipulation and a more distinct two-step process than the discrete item selection task studied in previous experiments. Of the techniques evaluated, combining T+R led to the lowest completion times and had comparable performance to an existing technique, FaST Sliders. In addition, FaST Sliders had a similar task completion time to T+P thus partially affirming H1. As with *a-coord input*, users can control input channels simultaneously and there is no additional cost to switch from one channel to other, it provided a better or similar performance compared to existing techniques.

6.4.2 *Error Rate*

I found similar trends in the error rate for all techniques. Results showed that T+R had the lowest error rate. In addition, FaST Sliders was more error prone compared to T+R, however, it had a similar error rate to P+R (Partially supports H2). Results revealed that any controllability difficulties with *a-coord input* did not lead to increased selection times or errors. This indicates that any a-coord combination should have a comparable performance with other existing techniques in terms of error rate.

6.4.3 *Number of Crossing*

As to be expected, FaST Sliders exhibited the lowest number of crossings. This is due to the fact that FaST Sliders involves two separate operations, as opposed to needing to hold the pen steady in a tilt orientation or applying a certain amount of pressure while rolling. Furthermore, it is clear from the result that maintaining a Tilt value while rolling was more controllable than maintaining a certain Pressure value. Also, results showed that the number of crossings increase when any auxiliary input channel combines with pressure. I found similar results in the third experiment, thus confirming the limited controllability of pressure by the participants. Although the results showed that combining Tilt and Roll was superior to combining Pressure and Roll for a task of this nature, the latter combination can still have a comparable performance with a careful design, e.g. few discrete items for pressure and coarse-grained control for rolling.

7

APPLICATION SCENARIOS

Building on the findings from previous experiments, I explore the design space of *a-coord input*'s interaction techniques. I implemented prototype applications to demonstrate the potential of this form of input for several categories of techniques: extending the number of commands for contextual input, improved stimulus response compatibility, 3D manipulation and volumetric data navigation, dynamically adjusting the CD ratio, enhancing existing interaction techniques and 2D navigation.

7.1 EXTENDING THE COMMAND SPACE FOR IN-CONTEXT INPUT

Numerous pen-based applications benefit from triggering commands contextually. For example, changing the characteristics of a pen brush while drawing can reduce the amount of unwanted pen displacement. Current contextual menus require the user to lift the pen off the area of input to aim at and select a target command. With *a-coord input*, users can select from a large number of hierarchically organized contextual menus with both Tilt-&-Pressure and Tilt-&-Roll.

7.1.1 *Tilt-&-Pressure menus*

Figure 26: Tilt-&-Pressure menu for 2D selection tasks.

Tilt menus are useful in supporting contextual menu selection [28]. However, its limitation lies in the fact that it supports a very limited number of menu items and cannot be used to select 2D or sub-menu items. *A-coord input* is a potential solution to accomodate more menu items in a tilt menu. For a small number of 2D menu items, my results support the use of Tilt-&-Pressure. The first level menu items could be activated by orientating the pen in a given direction. Pressure can then be employed to trigger items in the second level sub-menu (Figure 26).

7.1.2 *Tilt-&-Roll menus*

Tilt-&-Pressure menus are limited by the number of second level menu items that can be selected. Results from Experiment 4 suggest that Tilt-&-Roll (Figure 27) can be utilized in conjunction for a larger number of submenu items.

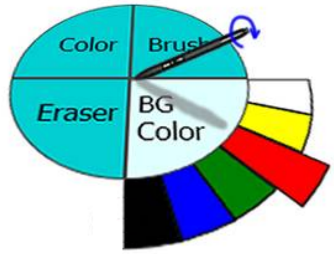


Figure 27: 2D context menu for Tilt-&-Roll.

7.2 EXTENDED STIMULUS-RESPONSE COMPATIBILITY

Certain tasks fit more naturally with the currently existing input channels on the pen. For example, rolling was shown to fit more naturally with rotation tasks [2]. However, since roll is limited in its allowable range, *a-coord input* can extend that range to support a larger number of tasks.

7.2.1 *Roll-360*

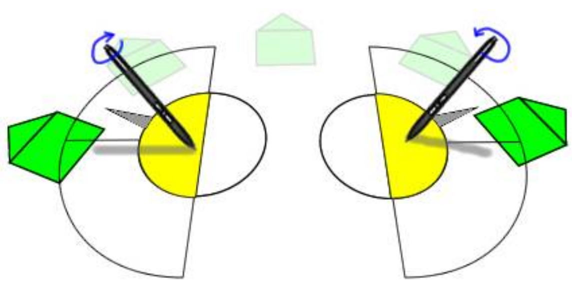


Figure 28: Illustration of Roll-360.

Recall that the usable range of roll is from +90° to -90° (i.e., 180° total degrees). Combining roll with two tilt orientations extends the range to a full 360°. Figure 28 illustrates this technique when rotating a house from 180° to 0°. Once the user exhausts the roll's range in the left hemisphere, the user tilts the pen to the right hemisphere. The user can easily access the remaining angles by continuing to roll in the extra space provided by tilt.

7.3 3D MANIPULATION

3D manipulations such as scaling or rotation are very common tasks in current 3D GUIs. These tasks require users to access handles that are positioned on the object's axes (red arrow in Figure 29). With a pen, these handles become difficult to select.

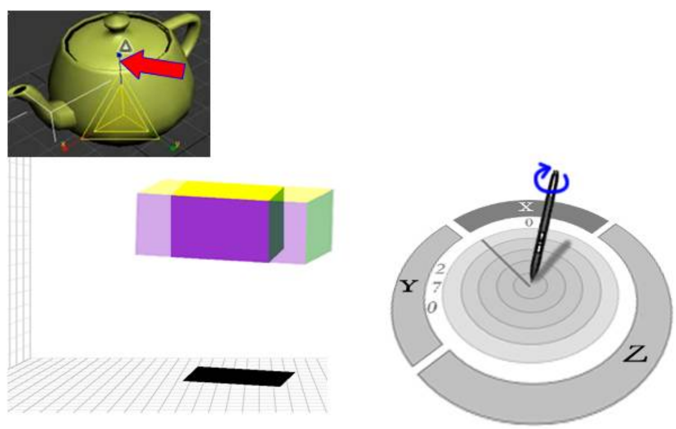


Figure 29: Illustration of using Tilt-&-Roll for 3D transformation tasks.

I demonstrate that 3D manipulation tasks, such as scaling or rotation, can be carried out with the Tilt-&-Roll input channel. Tilt can be used to select the axis of manipulation and roll effectuates the task. I could use a mode switch, i.e., pressing a keyboard button to move between rotation and scaling.

7.4 volumetric data navigation

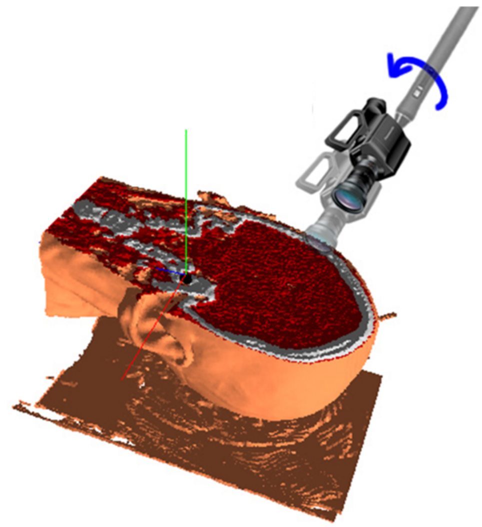


Figure 30: Illustration of using Tilt-&-Roll for Volumetric Data Navigation.

Volumetric data has been extensively used in different medical applications in recent years. Navigating volumetric data often requires users to change the viewing angle of a virtual camera while manipulating the camera's depth. Figure 30 illustrates *a-coord input* in volumetric data navigation, where tilt is incorporated to change the orientation of the clipping plane and roll is used to manipulate the depth of the plane.

7.5 dynamically adjusting cd ratio

Selecting a discrete item with rolling is error-prone when the width of the target is less than 10°. However, in many applcations, users are required to perform high precision manipulation tasks where pen roll would not be a suitable solution. *A-coord input* could be

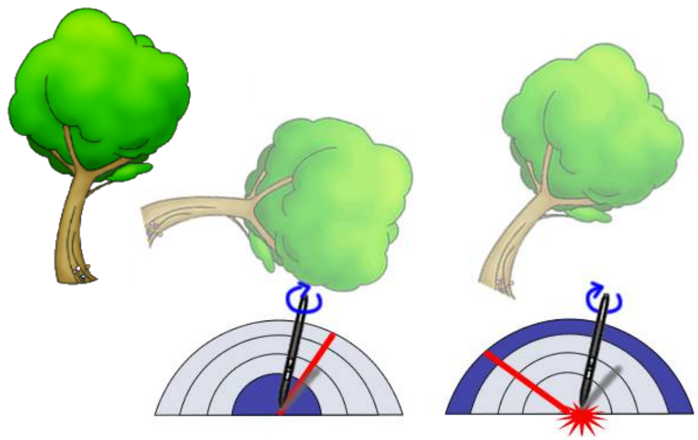


Figure 31: Illustration of using CD ratio with acoord input.

applied to this kind of scenario, where one channel will be applied to change the CD ratio to support precise manipulation. Figure 31 illustrates the use of pressure to adjust the CD ratio of roll. As the user approaches the target using a 1:1 ratio, further movement can be refined by applying a constant amount of pressure. As the CD ratio is increased, users have more fine-grained control over their rolling actions. In the application, I increase the ratio at a rate of 2:1 with each increasing level of pressure.

7.6 EXTENDING EXISTING TECHNIQUES

Researchers have proposed a fair number of techniques with single auxiliary input channels. I use an example to demonstrate how existing techniques can be extended using *a-coord input*.

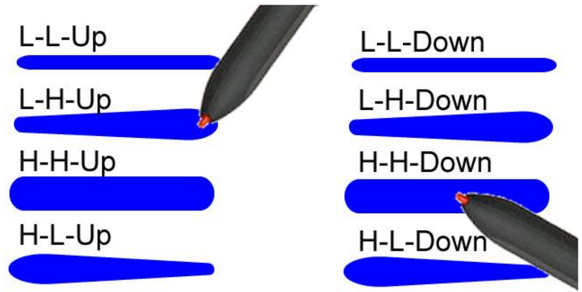


Figure 32: Pressure-&-Tilt marks. H: high pressure. L: low pressure. Up: tilt up. Down: tilt down

7.6.1 *Pressure-&-Tilt marks*

Ramos and Balakrishnan [21] proposed a novel technique called *pressure marks* that allows users to perform a selection and an action task simultaneously by changing pen pressure. Due to the difficulty of controlling pressure during hand movement, pressure marks [21] support only 2 levels of pressure during movement. Pressure-&-Tilt Marks integrate two levels of tilt (up and down) into pressure, resulting in a total of 8 different marks. All the applications proposed with Pressure Marks, such as pressure marking menus, could benefit from this extended range as shown in the figure 32.

7.7 2D NAVIGATION

Navigating large workspaces such as digital maps requires frequent pen tip movement for panning or for switching between panning and zooming. With *a-coord input*, panning and zooming can be carried out concurrently by using tilt and roll (Figure 33). In my application, I assign zoom to roll and pan to tilt. Tilt can be used to pan in 4

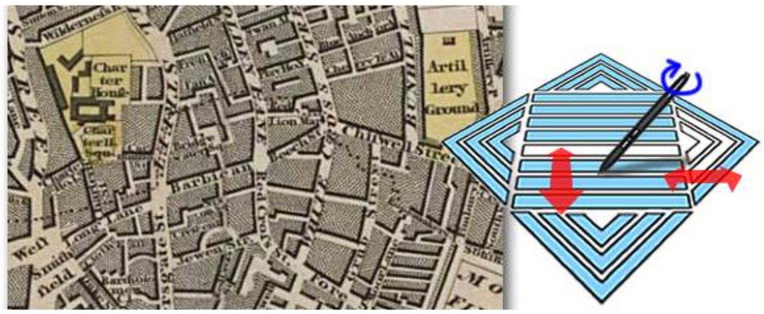


Figure 33: Illustration of using tilt and roll to navigate a digital map.

different directions: right, up, left, and down. The speed of panning can be adjusted by the altitude of the pen.

8

CONCLUSION AND FUTURE WORK

The digital pen supports numerous interactive tasks through various auxiliary input streams such as tilt, pressure and roll. However, when users perform pen-based tasks they usually rely on one input channel, and it is often used isolation from the other channels. The use of a single input channel can limit the users' speed in accomplishing the tasks. In this thesis, I investigate a new form of pen-based input interaction called *a-coord input*, which allows users to use multiple input channels simultaneously. *A-coord input* is intended to enable users to perform simultaneous tasks using a pen. I demonstrate that *a-coord input* is a promising enhancement to pen-based interactions. Furthermore, I investigate the benefits *a-coord input*'s design space through four experiments, which systematically studied several fundamental questions of this input style.

Results from my studies confirm that *a-coord input* can effectively improve the bandwidth of the pen's auxiliary channels with high efficiency and accuracy (i.e., task completion time and error). This form of input supports selecting a larger set of discrete items than single channels alone. To explore the design space of *a-coord input* in details, I compared its performance with and without input constraints. This constraints imply some level of sequential input, while the other techniques are engaged by executing these channels in parallel. Results from a set of experiments revealed that the style of coordination does not impact the overall performance. However, my results show a trend that if users control several channels sequentially before allowing them to use parallel control of multiple channels, users' performance usually improves. Results are encouraging as they suggest that pen-based interaction does not have to be restricted to one input channel, and that users can effectively work with multiple channels simultaneously with equal precision in a wide range of tasks.

In addition, my results revealed that users can reliably use *a-coord* to operate parallel input channels, and that those channels are operated in parallel for at least some duration of the task. In addition, *a-coord input* has comparable performance to existing techniques in a continuous parameter manipulation task. Empirical results support the use of *a-coord input* when single channels do not provide sufficient bandwidth or degrees-of-freedom.

The work in thesis represents only some initial steps in multi-channel pen-based interaction. Additional empirical work is required to: (i) identify more precise usable ranges for different channel combinations; (ii) test how generalizable my results are across all other channel combinations; (iii) identify the effect of different visual mappings to each *a-coord input*; and (iii) empirical verification of the value of *a-coord input* in the application scenarios that proposed in my thesis. The answers to these questions can help make *a-coord input* a reliable, effective and common interaction method for pen-based interfaces.

The main contributions of this work are the following:

- To my knowledge this is the first systematic and thorough examination of the controllability and limitations on coordinating two auxiliary pen input channel simultaneously.
- The exploration of a novel interaction technique, *a-coord input*, that allows users to control a larger input range than is available with single channels.
- A demonstration of the effectiveness of *a-coord input* for discrete item selection and continuous parameter manipulation tasks.
- A demonstration of some sample interactive tasks possible with the pen's auxiliary input channels.

A RESULTS FROM EXPERIMENTS

A.1 EXPERIMENT 1A RESULTS: PRESSURE AND ROLL

Task Completion Time

Main and Interaction effect		
Channel Order	$F_{1,11} = 7.18$	$p < 0.05$
PL	$F_{2,22} = 134.09$	$p < 0.001$
RL	$F_{2,22} = 134.51$	$p < 0.001$
Channel Order×PL	$F_{2,22} = 9.65$	$p < 0.001$
PL×RL	$F_{4,44} = 9.26$	$p < 0.001$

Error rate

Main and Interaction effect		
Channel Order	$F_{1,11} = 0.19$	$p = 0.67$
PL	$F_{2,22} = 7.89$	$p < 0.005$
RL	$F_{2,22} = 7.62$	$p < 0.005$
Channel Order×RL×PL	$F_{4,44} = 3.12$	$p < 0.05$

Number of Crossings

Main and Interaction effect		
Channel Order	$F_{1,11} = 0.28$	$p = 0.61$
PL	$F_{2,22} = 33.60$	$p < 0.001$
RL	$F_{2,22} = 35.03$	$p < 0.001$
Channel Order×PL	$F_{2,22} = 4.29$	$p < 0.05$
Channel Order×RL	$F_{2,22} = 4.37$	$p < 0.05$
PL×RL	$F_{4,44} = 3.08$	$p < 0.05$

A.2 EXPERIMENT 1B RESULTS: PRESSURE AND TILT

Task Completion Time

Main and Interaction effect		
Channel Order	$F_{1,11} = 0.006$	$p = 0.94$
PL	$F_{2,22} = 198.67$	$p < 0.001$
TL	$F_{2,22} = 119.16$	$p < 0.001$
PL×TL	$F_{4,44} = 10.90$	$p < 0.001$

Error rate

Main and Interaction effect		
Channel Order	$F_{1,11} = 0.42$	$p=0.53$
PL	$F_{2,22} = 30.02$	$p < 0.001$
TL	$F_{2,22} = 16.29$	$p < 0.001$

Number of Crossings

Main and Interaction effect		
Channel Order	$F_{1,11} = 2.97$	$p = 0.11$
PL	$F_{2,22} = 113.97$	$p < 0.001$
TL	$F_{2,22} = 44.54$	$p < 0.001$
Channel Order×PL	$F_{2,22} = 6.06$	$p < 0.01$

A.3 EXPERIMENT 1C RESULTS: TILT AND AND ROLL

Task Completion Time

Main and Interaction effect		
Channel Order	$F_{1,11} = 0.31$	$p=0.59$
RL	$F_{2,22} = 34.53$	$p <0.001$
TL	$F_{2,22} = 40.76$	$p < 0.001$

Error rate

Main and Interaction effect		
Channel Order	$F_{1,11} = 2.39$	$p = 0.15$
RL	$F_{2,22} = 15.35$	$p < 0.001$
TL	$F_{2,22} = 6.62$	$p < 0.01$

Number of Crossings

Main and Interaction effect		
Channel Order	$F_{1,11} = 0.21$	$p = 0.65$
RL	$F_{2,22} = 39.99$	$p < 0.001$
TL	$F_{2,22} = 26.08$	$p < 0.001$

A.4 EXPERIMENT 2 RESULTS: INPUT CONSTRAINTS VS NO INPUT CONSTRAINTS

Task Completion Time

Main and Interaction effect		
Mode	$F_{1,12} = 0.10$	$p = 0.76$
Mode×Presentation Order	$F_{1,12} = 7.319$	$p < 0.05$

Error rate

Main and Interaction effect		
Mode	$F_{1,12} = 0.93$	$p = 0.35$

Number of Crossings

Main and Interaction effect		
Mode	$F_{1,12} = 0.37$	$p = 0.55$

A.5 EXPERIMENT 3 RESULTS: COMPARISON OF DIFFERENT A-CO-ORD INPUT

Task Completion Time

Main and Interaction effect		
Technique	$F_{4,36} = 46.33$	$p < 0.001$
Number of Levels	$F_{1,9} = 135.2$	$p < 0.001$
Target Distance	$F_{2,18} = 1.93$	$p = 0.17$
Technique×Target Distance	$F_{8,72} = 6.15$	$p < 0.001$

Error rate

Main and Interaction effect		
Technique	$F_{4,36} = 4.47$	$p = 0.01$
Number of Levels	$F_{1,9} = 35$	$p < 0.001$
Target Distance	$F_{2,18} = 1.93$	$p < 0.001$
Technique×Target Distance	$F_{8,72} = 0.07$	$p < 0.05$

Number of Crossings

Main and Interaction effect		
Technique	$F_{4,36} = 8.23$	$p < 0.001$
Number of Levels	$F_{1,9} = 249.00$	$p < 0.001$
Target Distance	$F_{2,18} = 118.54$	$p < 0.001$
Technique×Target Distance	$F_{8,72} = 11.28$	$p < 0.001$

A.6 experiment 4 results: a-coord input for continuous manipulation tasks

Task Completion Time

Main and Interaction effect		
Technique	$F_{2,22} = 23.86$	$p < 0.001$
Number of Parameters	$F_{1,11} = 23.84$	$p < 0.001$
Granularity	$F_{1,11} = 75.98$	$p < 0.001$
Target Distance	$F_{2,22} = 34.84$	$p < 0.001$
Technique × Number of Parameters	$F_{2,22} = 22.79$	$p < 0.001$
Technique × Granularity	$F_{2,22} = 4.89$	$p = 0.01$
Technique × Target Distance	$F_{4,44} = 5.25$	$p = 0.001$

Number of errors

Main and Interaction effect		
Technique	$F_{2,22} = 12.48$	$p < 0.001$
Number of Parameters	$F_{1,11} = 9.01$	$p < 0.05$
Granularity	$F_{1,11} = 7.76$	$p < 0.05$
Target Distance	$F_{2,22} = 26.22$	$p < 0.001$
Technique × Target Distance	$F_{4,44} = 22.03$	$p < 0.001$

Number of Crossings

Main and Interaction effect		
Technique	$F_{2,22} = 73.863$	$p < 0.001$
Number of Parameters	$F_{1,11} = 20.79$	$p < 0.001$
Granularity	$F_{1,11} = 26.90$	$p < 0.001$
Target Distance	$F_{2,22} = 39.19$	$p < 0.001$
Technique × Number of Parameters	$F_{2,22} = 10.33$	$p = 0.001$
Technique × Granularity	$F_{2,22} = 5.37$	$p < 0.05$
Technique × Target Distance	$F_{4,44} = 19.75$	$p < 0.001$

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COLOPHON

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The typographic style of the thesis was based on André Miede's wonderful `classicthesis` $\LaTeX$ style available from CTAN. My modifications were limited to those required to satisfy the constraints imposed by my university, mainly 12pt font on letter-size paper with extra leading. Miede's original style was inspired by Robert Bringhurst's classic *The Elements of Typographic Style* [4].

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