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Dual-Thumb Pointing and Command Selection Techniques for Tablets

Enhancing Distant Interaction with Large Displays using a Two-Handed Tablet

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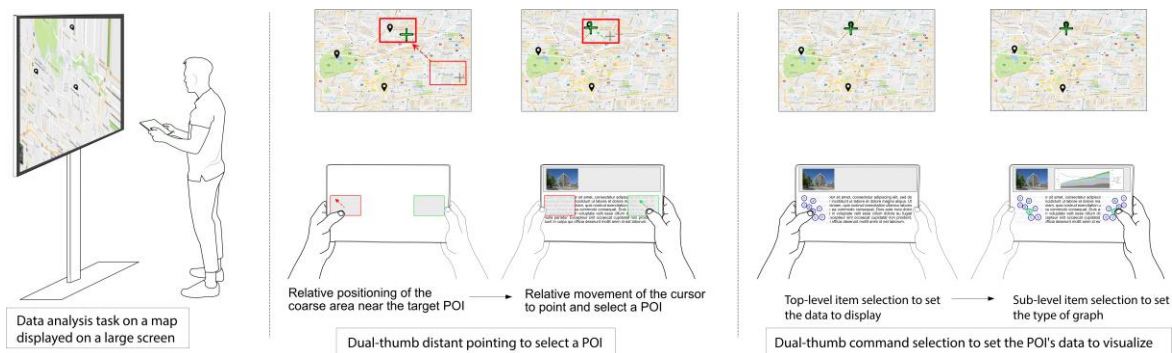


Figure 1. Illustration of dual-thumb pointing and command selection on a two-handed tablet to perform a data analysis task on a map displayed on a large screen.

Tablets are often used as a distant input device to interact with large displays. Users can hold the tablet with two hands when interacting for a long time to avoid fatigue or dropping it. Still, most previous distant interaction techniques consider only one-handed tablets. This paper presents novel interaction techniques to perform distant pointing and command selection tasks using both thumbs while holding the device with two hands. In a first step, we design and evaluate six interaction techniques for distant pointing, based on using one or two thumbs, absolute or relative cursor control and single- or dual-precision pointing. Our results show that a combination of dual-thumb and relative pointing is preferred and more efficient than any other dual-thumb or single-thumb technique we designed. In a second step, we focus on command selection using two thumbs. We designed seven dual-thumb menu techniques based on quarter-pie or half-pie layouts, offering from 64 to 900 items. Our results show that using quarter-pie menu techniques is more efficient, usable and appreciated than using a linear or half-pie menu. Furthermore, we show that augmenting the number of items for quarter-pie and half-pie menu techniques has a low impact on command selection performance. In a third step, we compare our quarter-pie menus to bimanual marking menus. Our results

show that quarter-pie menus are more efficient and less error-prone. We finally provide a set of lessons for designing efficient dual-thumb interaction techniques for two-handed tablets.

CCS CONCEPTS • Human-centered computing~Human computer interaction (HCI)~Interaction techniques~Pointing.

Additional Keywords and Phrases: Dual-thumb input, Tablet-based interaction, Pointing, Command Selection.

1 INTRODUCTION

Thanks to their extended display space, large displays allow users to explore large datasets. In a multi-user context, they act as a shared space [32] and are often mediated through a personal tablet [87]. Previous examples of this combination of devices span across various application domains: in a teaching context, it has been used to display a global view of an anatomical model on the large screen and slices of the model or blood vessels on the students' mobile devices [13]; in a crisis management context [18], it is used to display a map of the crisis area on the large display and specific regions of interest such as shelter locations on the personal tablet of the emergency services staff [44]. As illustrated by these examples, such a device combination offers two advantages: first, the tablet may provide a private pointing surface to access distant elements on the large display or to select commands [18], and second, it can act as a private display space, larger than smartphones, where users can visualise and manipulate the data retrieved from the shared large display [2]. Other solutions to interact with a large display exist, for instance, using gestures or pen input [55, 69], but do not simultaneously increase input capabilities and offer a private display space.

However, using a tablet for a long time raises the problems of how to comfortably and firmly hold the device while preserving its interaction performance [76]: holding a tablet with two hands reduces fatigue [81] and ensures a firmer holding but hinders traditional input with the index finger. Nevertheless, handling the tablet with both hands brings other interaction opportunities: using the fingers on the back of the device or the two thumbs on the front touchscreen. Back-of-device interaction [14] allows using the index fingers without occluding the front screen. However, this solution is not compatible with current tablet technologies that do not offer tactile capabilities on the back of the device. Using the two thumbs on the front screen, hereafter referred to as dual-thumb interaction, has received little attention so far. To our knowledge, dual-thumb input on tablets has only been explored in terms of screen reachability and precision [71, 81] and text input on tablets [9].

In this paper, we explore dual-thumb input on a tablet held with two hands to interact with a large display (Figure 1 – Left). We focus on two fundamental tasks: distant pointing (e.g., selecting a large display target using the tablet touchscreen as input, Figure 1 – Center) and command selection in a hierarchical menu (Figure 1 – Right). Indeed, these two tasks precede any other interaction with the display content, such as reorganising the content, transferring data, scrolling or annotating a shared document, etc. Dual-thumb interaction on a tablet offers several inner advantages and opportunities that we explore in this paper: such interaction is very similar to the regular thumb interaction with smartphones, hence should be easy to learn; it allows to decompose the interaction into two steps (coarse and precise for pointing, top-level and sub-level for menus), each step being associated to one of the two thumbs; finally, interacting with the thumbs limits the tablet display occlusion as opposed to using the index finger, which leads to occluding the tablet with the rest of the hand [74].

First, we designed six interaction techniques for distant pointing on a large display using a two-handed tablet. These techniques result from the combination of four design factors: the precision type (single- or dual-

precision), the number of thumbs used (one as a baseline or two), the cursor control (absolute or relative) and the thumbs usage (similar or different). We experimentally compared these six interaction techniques (2 single-thumb techniques and four dual-thumb techniques) through a user study where participants had to select a distant target displayed on a large display.

Second, we designed seven dual-thumb menu techniques for command selection on a two-handed tablet: in our design, menu items are spread on the left and right sides of the tablet, under each thumb, thus allowing for top-level and sub-level menu items selection. Our techniques combine three design factors: the menu shape (half-pie, quarter-pie or linear as a baseline), the number of arcs and the number of items. We first experimentally evaluated three dual-thumb menu techniques that allow the selection of up to 64 commands (8 top-level items x 8 sub-level items) and compared them with the widely available linear menu controlled with a single hand. Then, we evaluated four dual-thumb menu techniques that allow the selection of one item among 100 to 900 commands. Our goal was to better understand the impact of the number of menu items and layout on performance and usability. In a follow-up study, we assessed the effect of using the Linear menu with the dominant or non-dominant thumb.

Finally, we compared our best dual-thumb menu technique to the dual-hand marking menu introduced by Kin et al. [38].

Our work presents three major contributions: the design and evaluation of novel dual-thumb techniques on a two-handed tablet for distant pointing (1) and command selection (2); and a set of lessons for designing dual-thumb interaction techniques on a two-handed tablet (3).

2 STATE OF THE ART

We synthesise previous works on pointing at distant elements and selecting commands on large displays before focusing on interaction solutions with two-handed tablets.

2.1 Distant pointing on large displays

The size of large displays raises reachability issues [16, 69]. Consequently, multiple works focused on providing solutions to point at distant items [41, 70] mostly through a touch input, mid-air gestures or external devices.

Dedicated touch input for distant pointing [39] is the most common approach. For instance, with HybridPointing for touch [16], the user can perform direct touch pointing with one finger of the dominant hand to select nearby targets, while touching with three fingers simultaneously changes the control-display gain (CD gain), thus allowing for distant pointing. While these approaches offer efficient distant pointing, they require a dedicated portion of the shared screen for interaction, thus inducing occlusions for other users and limiting the actual display space.

Mid-air interaction [73] or gaze-based techniques [88] have also been considered for touchless distant pointing. Shadow reaching [68] uses the distance between the user's mid-air hand and the screen to allow distant pointing based on the user's hand shadow projection. Nevertheless, performing mid-air gestures for a long time is very tiring [29, 34]. Alternatively, Zhai et al. [88] combined gaze and tactile input to control ray-casting. However, using gaze to perform selection may cause discomfort [30].

Finally, external devices [49] such as a stylus or a touchscreen [46] can also support distant pointing. In TractorBeam [55], a stylus casts a ray to a large screen. The use of touchscreens such as smartphones [52] or tablets [12] offers an inner advantage compared to stylus: on top of allowing to perform distant pointing, they

provide an additional private display space to the user. Saidi et al. [64] explored using one or two hands to perform distant selection through an overview+detail paradigm on a tablet laid on a table. Instead of using overview+detail, other approaches, such as ARC-Pad [49], established that dual-precision techniques perform distant selection faster than single-precision techniques. Nancel et al. [52] extended this work with, in particular, ARC-Pad², where pressing with two fingers of the same hand simultaneously controls the absolute position of the cursor on the wall (i.e. a coarse positioning) while pressing with one finger allows for relative pointing (i.e. precise movements of the cursor). While these works provide efficient solutions for distant pointing using dual-precision techniques, they are not directly transferable to situations in which the external device is two-handed. Indeed, holding the mobile device with two hands prevents interaction with the index finger or with two fingers of the same hand.

2.2 Command selection on large displays

The most obvious approach to activate commands on a large display is to use direct touch on the display itself [7, 47]. Several works proposed adaptations of existing tactile menu techniques [3, 45] or new techniques [41] to facilitate command selection on a large display. For instance, Bailly et al. [4] proposed using finger count or radial strokes to access commands using both hands. Reibert et al. [60] proposed a set of bimanual touch gestures on a wall display to interact with a dataset. However, these techniques require the user first to reach and select the content on which the command is applied, which is not always possible due to territoriality [2, 65] and reachability issues [16, 69].

For this reason, other works explored the use of touch with remote content on a large display. In HandyScope 41, a circular widget displayed in front of the user replicates a distant portion of the screen: while one hand allows adjusting the distant part to be displayed, the second hand is used to select objects and apply commands. Displaying the menu items and selecting them, however, occludes part of the shared screen. Using the forearm to display and interact with a large display menu, as in Adachi et al. [1], avoids this issue but requires a complex tracking setup to detect the user's gestures.

To combine the advantages of both direct touch and remote control, previous works focused on using mobile touchscreens such as smartwatches [31] or smartphones [75]. Several interaction techniques have been explored for using a menu on a one-handed smartphone [8, 22]. Pfeuffer et al. [[45]] proposed combining thumb and pen interaction to facilitate command selection, specifically on tablets, while Perelman et al. [56] used another smartphone as an interactor. However, these techniques depend heavily on how the mobile device is grasped.

2.3 Grasping the tablet for distant interaction

Previous work explored how a mobile device [80] or a tablet [76] is held and its impact on interaction [83, 84]. Wobbrock et al. [80] found that two-handed postures to hold a mobile device allow for faster 1D pointing than one-handed postures. Wagner et al. [76] proposed a design space to describe tablet grasp based on three factors: frame, support and interaction. Through an experiment, they identified five spontaneous grasps that users adopt when holding a tablet for approximately 45 minutes. All of their users held the tablet with only one hand, using the palm of their hand or the forearm as support. This allowed using their dominant hand to interact on the tablet screen without limiting its movements by supporting the tablet. However, the participants reported fatigue and thus, switched regularly between multiple tablet grasps, which increased the risk of dropping the tablet. The fatigue increased for tablets held with the non-dominant hand in landscape mode, as the weight of the tablet was

not evenly distributed around the gripping hand. These limitations can be alleviated by holding the tablet with two hands [53, 54, 81, 83, 84].

Odell et al. [53] explored how users grasp a two-handed tablet for thumb interaction. They identified two grips: a first grip where users place the corner of the tablet in their palm, and a second grip, adopted by the majority of their participants, where the tablet is held by its side. Oulasvirta et al. [54] explored the impact of different two-handed grips on the reachable area of a tablet screen. They found that a similaral bimanual grip is more appropriate to enable the ergonomic usage of tablet devices while also enabling back-of-device interaction. Furthermore, they identified six comfortable and stable grips using two hands which they used to adapt the design of their dual-thumb text input on the tablet screen. These two-handed tablet grips are adapted to tablets held in landscape mode. Wolf et al. [81] explored the pointing time for target acquisition on the tablet in landscape mode. They identified that using a two-handed grip allowed relaxing one hand quite a bit, maintaining the grip using the phalanxes, to access the middle of the tablet screen, thus reducing one limitation of two-handed grips in comparison with one-handed grips.

These studies highlight the interest of previous work towards two-handed tablets. These works validated the advantages of the two-handed grasp, and inspired our work to push forward the understanding of this interaction posture. The novelty of our work is to explore how to optimize two fundamental interactions (pointing and command selection) when holding the tablet with two hands, in landscape mode, and in combination with a large display, as most of these works focused on grasping and isolated use.

And yet, when interacting for a long time, holding a tablet with two hands reduces fatigue [81] and ensures a firmer holding. Our goal is thus to design interaction techniques based on a two-handed grip of the tablet.

2.4 Interaction with two-handed tablets

To our knowledge, only a few works have focused on interaction with a two-handed tablet [71, 86]. In this case, touch interaction can be performed either on the back of the device [14, 82], with all fingers except the thumbs or on the device's front screen, only with the thumbs [81].

Regarding back-of-device interaction, Wolf et al. [82] explored the differences between front- and back-of-device tactile gestures on tablets: they established that back-of-device gestures are impacted by users not seeing their fingers on the back, as confirmed by Widgor et al. [77]. Addressing this limitation, LucidTouch [78] used a pseudo-transparent display, allowing the user to see the fingers behind the device as well as the touch points. However, despite its interesting properties, back-of-device input is not compatible with current tablet devices, which have no tactile capabilities on their back.

The remaining alternative to interact with a two-handed tablet is to use the thumbs on the front screen. While thumb-based interaction for smartphones has been the focus of multiple works [9, 58, 38], thumb-based interaction on tablets, which offer a much larger screen and weigh more than a smartphone, has been scarcely explored. Tu et al. [71] analysed such tactile interaction for pointing and gesturing by comparing the dominant and non-dominant thumb performances. They also established the thumb-reachable area on the screen for each thumb under different conditions and the minimum target size for precise and comfortable thumb-based pointing. In another study [81], interaction techniques were designed for pointing at areas of the tablet screen that thumbs cannot reach: direct pointing, inverse direct pointing (i.e. moving a cursor in the opposite direction of the thumb movement), miniature interaction area and relative pointing. They found that only 74% of the touchscreen is reachable when using direct pointing and that miniature interaction is the best alternative. In the specific case of

text input, the combined use of two thumbs has also been considered: for example, splitting the keyboard into two half-keyboards associated with each thumb is more efficient than the traditional keyboard displayed all across the screen [9]. Finally, Kin et al. [38] studied the bimanual use of a menu on a tablet; however, their tablet was laid on a table, and the interaction was performed with the index fingers instead, which clearly differs from the two-handed grasp and thumb-based interaction that we explore in our paper. They also explored marking menus with two thumbs on a smartphone. However, when using marking menus with two thumbs, the targeted item might be occluded by the user's hand in novice mode. The expert mode might leverage this issue but is particularly appropriate for frequently accessed commands as it requires memorising the position of the items [42]. Instead, our use cases involve contextual menus, whose content is less frequently used and varies according to the selected item, thus requiring more exploration than memorisation.

2.5 Towards dual-thumb pointing and command selection

To summarise, dual-thumb interaction on a two-handed tablet presents interesting interaction opportunities with large displays. Indeed, using an external touchscreen to perform distant pointing on a shared large display avoids the drawbacks of mid-air techniques or direct touch, as shown in section 2.1. Moreover, dual-precision pointing, while requiring two modalities (one for each step), is more efficient than single-precision when using a mobile device for distant pointing [49]. In addition, using a mobile touchscreen to select commands around a shared display facilitates the interaction with data, through tactile input, and offers a personal display space, as underlined in section 2.2. Finally, dual-thumb interaction on a tablet has been scarcely explored beyond its efficient use for text input, as seen in section 2.3. In this work, we thus explore how to use dual-thumb interaction to perform distant pointing and menu selection with two-handed tablets.

3 DESIGN CONSIDERATIONS AND INTERACTION TECHNIQUES FOR DISTANT POINTING

This section presents our design considerations for distant pointing on a large display with a two-handed tablet and describes the resulting interaction techniques we developed.

3.1 Design rationale

We explored the following design considerations to design our distant pointing interaction techniques.

Input area and tablet orientation: While holding the device with two hands, the thumbs have limited reachability of the tablet screen, as experimentally demonstrated by Tu et al. [71], who identified the thumb comfort interaction zone: a half-circle of 38mm radius on each side of the tablet. To comply with these results, we limited the input interaction on the tablet to a restricted input area for each thumb within its comfort zone. These input areas are positioned on each side of the tablet screen at mid-height. Each input area is relatively small, so they both fit on a tablet held in landscape or portrait orientations. Given that previous work only focused on landscape orientation [12, 64, 81] and that the tablet screen in landscape orientation matches the large display orientation, we explored the use of a tablet in landscape orientation only. Finally, to avoid occlusion of the content displayed on the tablet screen, these input areas are displayed semi-transparently, thus allowing to perceive the content below as explored by Jim and Lee [36] for example.

Tablet grip: While we did not constrain the tablet grip, we observed that our users held the tablet with the grip n°3 of the classification of two-hand tablet grips of Oulasvirta et al. [54]. Oulasvirta et al. found this grip to ensure a very good performance for pointing in a dual-thumb context, compared to the other studied grips.

Precision type: We explored two types of precision pointing, single-precision and dual-precision [51]. With single-precision, dragging the thumb on the input area of the tablet moves the cursor on the large display. Notice that this precision type is performed with a single hand only. With dual-precision, pointing is achieved through a two-step process. The first step controls a coarse area, i.e. an area outlining the rough position of the cursor (coarse step). The second step more precisely translates the cursor inside the coarse area from the initially defined rough position (precise step). As established in [49], dual-precision increase pointing efficiency: the coarse step allows for faster and larger movements of the cursor, while the precise step allows for slower and more accurate pointing.

Number of thumbs: We considered both dual-thumb (DT) and single-thumb (ST) interaction. Dual-thumb techniques can only be used with the dual-precision approach. Single-thumb interaction is performed using the dominant thumb only. We decided to include single-thumb interaction as a baseline to better assess the benefits of using a second thumb.

Cursor control: We also investigated two types of cursor control, i.e. absolute or relative. For absolute pointing, dragging the thumb inside the tablet's input area results in the cursor's absolute positioning on the large display, which is quick but not precise. For relative pointing, dragging the thumb inside the input area of the tablet results in relative movements of the cursor displayed on the large display, which offers greater precision but is slower. Consequently, relative pointing allows for clutching, which is impossible with absolute pointing. As in previous works, we decided to always use relative pointing for the precise step with dual-precision, as it offers higher precision than absolute pointing [52]. For the same reason, with single-precision, we only use relative pointing.

Thumbs usage: In the case of dual-thumb interactions, we explored two different usages of the thumbs, either similar or different. With a similar usage, both thumbs perform a similar task (i.e. pointing). Concretely each thumb will control one step of the dual-precision pointing: in our design, we assigned the non-dominant thumb to the coarse step and the dominant thumb to the precise step, following Guiard's guidelines [26]. With an different usage, the two thumbs perform different tasks: the dominant thumb performs the two steps of the pointing task (coarse and precise steps), while the non-dominant thumb is used to switch between the coarse and precise steps.

3.2 Interaction techniques for distant pointing using a two-handed tablet.

Using these design considerations, we designed six interaction techniques for distant pointing on a large display using a two-handed tablet: two single-thumb techniques based on the two possible precision types (single-precision or dual-precision), and four dual-thumb techniques using dual-precision based on two factors, the thumbs usage (similar and different) and the cursor control for the coarse step (absolute or relative).

We use two different naming conventions for single-thumb and dual-thumb techniques. We refer to the precision type for the single-thumb (ST) techniques, leading to the following syntax: ST_[SinglePrecision_Or_DualPrecision]. For the dual-thumb techniques (DT), we refer to the thumb usage and the cursor control in the coarse step, as the precise step is always based on a relative cursor control. This leads to the following syntax: DT_[Sym_or_Asym]_[Absolute_Or_Relative]. We summarise the ST and DT interaction techniques in Table 1 and illustrate them in Figure 2 and Figure 3.

		Dual-Thumb techniques	
		Cursor control (in the coarse step)	
		Absolute control	Relative control
Thumbs role	Similar	<i>DT_Sim_Absolute</i>	<i>DT_Sim_Relative</i>
	Different	<i>DT_Diff_Absolute</i>	<i>DT_Diff_Relative</i>

Single-Thumb techniques	
<i>ST_SinglePrecision</i>	<i>ST_DualPrecision</i>

Table 1. Interaction techniques for distant pointing using a two-handed tablet.

Regarding the input part of our interaction techniques, given that some conditions are based on absolute pointing, the shape of the input area has to match the shape and ratio of the large display: input areas have, therefore, a rectangular shape, and each one measures 38mmx21.4mm to fit in the thumb's comfort zone identified by Tu et al. [71]. For single-thumb techniques, the input area is displayed on the right side of the tablet. For dual-thumb techniques, one input area is displayed on each side of the tablet. In both cases, input areas are displayed semi-transparently on the tablet.

Regarding the output part of our interaction techniques on the large display, the cursor is a green-coloured cross (20x20 pixels with a thickness of 8 pixels). In addition, for dual-thumb techniques, a red rectangle representing the coarse area is also displayed on the large display. While previous work used a circular shape to represent the coarse area on the large display [52], we chose to use a rectangular shape because it allows the user to take maximum advantage of the movements in the rectangular input areas and maintains a visual consistency with the input area shape.

We used the following arguments to define the size of the rectangular coarse area. The tablet screen size is fixed (243x137mm). The maximum width of the input area size is constrained by the comfortable zone identified by Tu et al. [71] and equals 38mm. We thus computed a ratio $k = \text{input area width} / \text{tablet screen width} = 0.156$ and used this same ratio to determine the height of the input area ($137 \times 0.156 = 21.4\text{mm}$). To maintain consistency between the input on the tablet and the output on the large display, we chose to use the same ratio on the output. We thus defined the rectangular coarse area size so that $k = \text{rectangular coarse area size} / \text{large display screen size}$. As the large display screen size is 1430mm x 800mm, the resulting rectangular coarse area size is 223mm x 125mm. During the precise step, the cursor is restrained to remain inside the coarse area on the large display. To avoid confusion, the tablet's input areas are coloured according to the dual-precision step (i.e. red for the coarse step or green for the precise step).

We hereafter detail each of the designed pointing techniques:

ST_SinglePrecision: This technique relies on using a single thumb (ST), in single-precision and with relative pointing (Figure 2 - A). To better match the behaviour of a standard cursor, we implemented a control-display transfer function inspired by [52]. This function implements a pointer acceleration, i.e. the speed of the cursor is based on the rate of the thumb's movements. We used the following transfer function parameters: $V_{\min} = 1$; $V_{\max} = 50$; $\text{ratio}_{\text{inf}} = 0.8$; $\text{CD}_{\max} = 50$; $\text{CD}_{\min} = 1$; $\lambda = 0.02$. This technique behaves very similarly to standard pointing input devices such as touchpads.

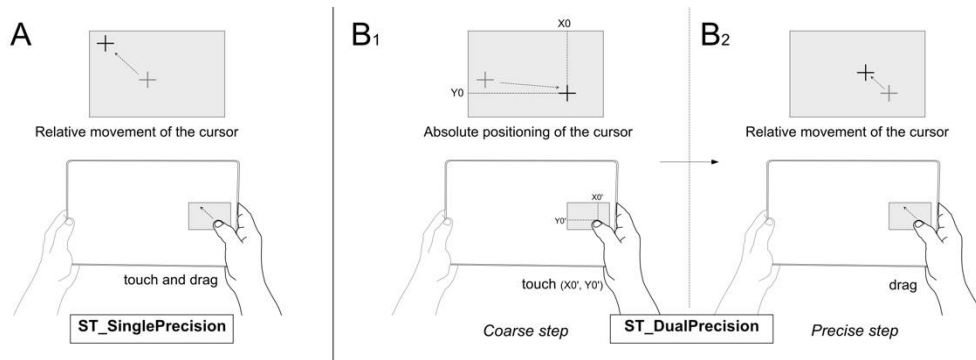


Figure 2. Single-thumb (ST) distant pointing techniques: ST_SinglePrecision (A) and ST_DualPrecision (B).

ST_DualPrecision: This interaction technique relies on using a single thumb (ST), in dual-precision, with a combination of absolute and relative pointing (Figure 2 - B). Primarily inspired by ArcPad [49], it is performed with the thumb instead of the index finger in the original design. Touching the input area with the right thumb controls the coarse step (Figure 2 - B1), while dragging the same thumb inside the input area controls the precise step (Figure 2 - B2). By offering dual-precision with one thumb, this technique may be more efficient than a single-precision one.

DT_Sim_Absolute: This dual-thumb (DT) technique relies on the use of the two thumbs in a similar way, with absolute pointing for the coarse step (Figure 3 - A). This technique is primarily inspired by ArcPad² [52], except it is performed with two thumbs instead of the index and middle fingers in the original design. The left thumb (non-dominant hand) is used to perform the coarse step (instead of two fingers in ArcPad², Figure 3 - A1) and the right thumb to perform the precise step (instead of the index in ArcPad², Figure 3 - A2). With this technique, the user can perform both steps simultaneously.

DT_Diff_Absolute: This dual-thumb (DT) technique relies on using the two thumbs in a different way, with absolute pointing for the coarse step (Figure 3 - C). The coarse and precise steps are performed with the right thumb on the right side of the tablet, Figure 3 - C1 and C2). By default, the right input area is used for the precise step and coloured in green, Figure 3 - C2). When the left thumb presses the left input area, it activates the coarse step, turning the right input area red as feedback, Figure 3 - C1). The user needs to keep the left thumb pressed during the coarse step: as in the original ArcPad² technique, two fingers are pressed during the coarse step. With this technique, users cannot simultaneously perform the coarse and precise steps but use the dominant thumb for both steps, which may result in more accurate movements.

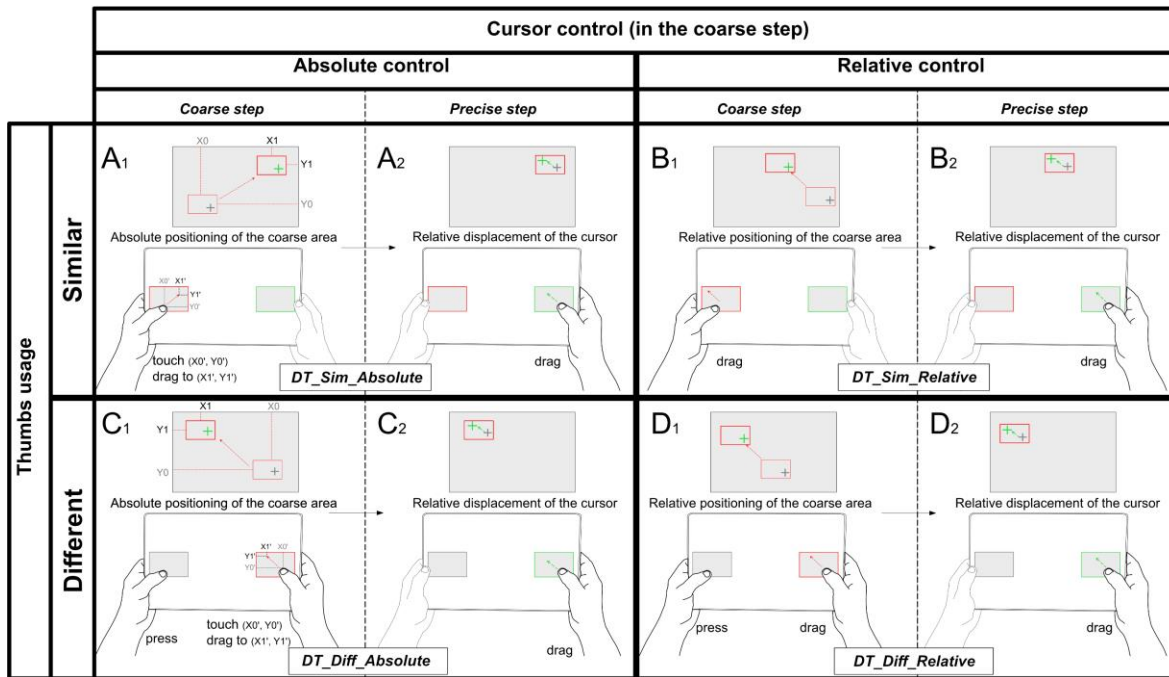


Figure 3. Dual-thumb (DT) distant pointing techniques.

DT_Sim_Relative: This dual-thumb (DT) technique relies on the use of the two thumbs in a similar way, with relative pointing for the coarse step (Figure 3 – B). As a result of using relative pointing for the coarse step (Figure 3 – B1), clutching is allowed when moving the coarse rectangle. Adopting the same relative pointing for the coarse and precise steps (Figure 3 – B2) may appear more coherent for users and may enhance their performance.

DT_Diff_Relative: This dual-thumb (DT) technique relies on the use of the two thumbs in a different way, with relative pointing for the coarse step (Figure 3 – D). The right thumb performs both the coarse (Figure 3 – D1) and precise steps (Figure 3 – D2), while the left thumb press on the left area explicitly activates the coarse step (Figure 3 – D1). The coarse and precise steps are based on relative pointing, hence allowing for clutching.

4 STUDY 1: DISTANT POINTING TECHNIQUES FOR TWO-HANDED TABLETS

This study compares the previously designed interaction techniques for distant pointing on a large display using a two-handed tablet, in terms of performance and usability.

4.1 Task

In this study, participants had to select a distant target displayed on the large display using touch input on the tablet. The design of this study was inspired by the experimental protocol used in previous work to compare distant pointing techniques [52]: we used the same trials definition, sequence and ID range. We adapted to our context the support circle size and cursor acceleration function (as detailed below) because they had been defined for ultra-large screens, offering a larger display space than the large display we used. We also preferred to adopt a dwell time to validate the selection rather than a tapping gesture because this is the only solution we could think of that could be used with all our pointing techniques: a tap would interfere with the technique involving absolute

positioning and a dedicated button on the screen would add occlusion on the screen content and could be cumbersome to reach with the thumb.

Concretely, six targets were placed on a support circle to control the pointing distance; the size of the support circle and the size of the target define the Index of Difficulty (ID) computed as in a traditional Fitts experiment. We considered two support circle sizes (1500px and 3000px) as well as three target sizes (12px, 46px and 190px) to generate four different IDs: 4 (1500px circle and 190px target), 6 (1500px and 46px), 8 (1500px and 12px) and 9 (3000px and 12px). Such IDs are traditional values considered in pointing studies [52]. This ID range complies with previous work such as 16495273 where the index of difficulty ranges from 3.36 to 9.64. According to Beaudouin-Lafon et al. [52], while some work explored higher IDs, e.g. 12 bits [26] and up to 30 bits [27], they have only been studied in the context of multiscale or zoomable interface. Furthermore, while keeping the same ID range than in previous work, we limited the number of IDs to limit the total duration of our study. We kept the two maximum IDs of the range (9 and 8), along with two lower IDs (6 and 4), as our goal was to focus on the more difficult IDs to ensure our results would be valid in the extremes. We used a CD gain of 8.93 for the coarse rectangle area and a CD gain of 1.35 for the precise cursor. We chose these values as, in both cases, they allow the user to go from one edge of the screen (respectively coarse area) to the other edge with a single gesture, removing the need for clutching. Our CD gains were calculated as follows: $\text{Coarse_CD_Gain} = \text{Large_Display_Screen_Size} / \text{Input_Area_Size}$; $\text{Precise_CD_Gain} = \text{Coarse_Area_Size} / \text{Input_Area_Size}$.

For each trial, the user had first to point and select a starting target highlighted in blue (which started the trial) and then point and select its similar target on the support circle highlighted in green (which ended the trial). The target selection was validated after a 500ms dwell time (Figure 4). Using the finger lift-off to validate the trial would not comply with the clutching available in almost all of our techniques (DT_DualPrecision does not allow for clutching). We considered six different angles to position the starting target on the support circle: three on the right half of the large display (0°, 45° and -45°), and three on the left half of the large display (180°, 135°, 225°). The starting target is always on the same side of the large display as the ending target of the previous trial. Between each trial, participants could take a break.

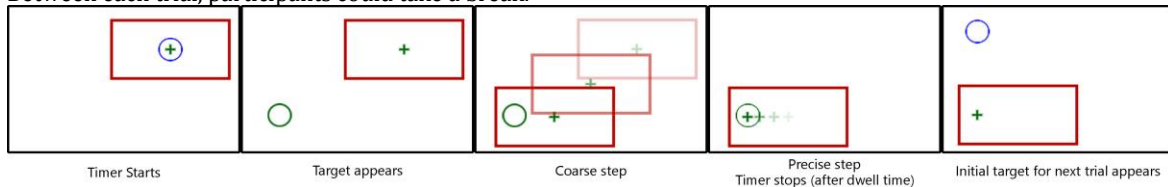


Figure 4. Illustration of our experimental task. From left to right: 1) The trial starts when the cursor is on an initial target (blue). 2) The similar target on the support circle appears (green). 3) The user moves the coarse rectangular area (red), 4) then moves the cursor inside the coarse area to select the target. After a dwell time, the trial ends. 5) Finally, the initial target for the subsequent trial appears.

4.2 Apparatus and implementation

Users were standing in front of a large interactive display showing the targets to select (Figure 5 – Left). We used a Speechi large display (143cm x 80 cm, 3840x2160px) connected to a computer running the large display app. Users held the tablet in landscape orientation with both hands. The tablet displayed the left and right input areas used for the coarse and precise steps. We used a Samsung Galaxy Tab S7 tablet (11.0 inches, 2560x1600px, 498 g). The communication between the tablet and the computer was performed using TCP sockets over a local network provided by a router not connected to the internet. The large display app was developed in C++ using the SFML

library [67] for window handling, drawing and network communication. The tablet app was developed in Java for Android.

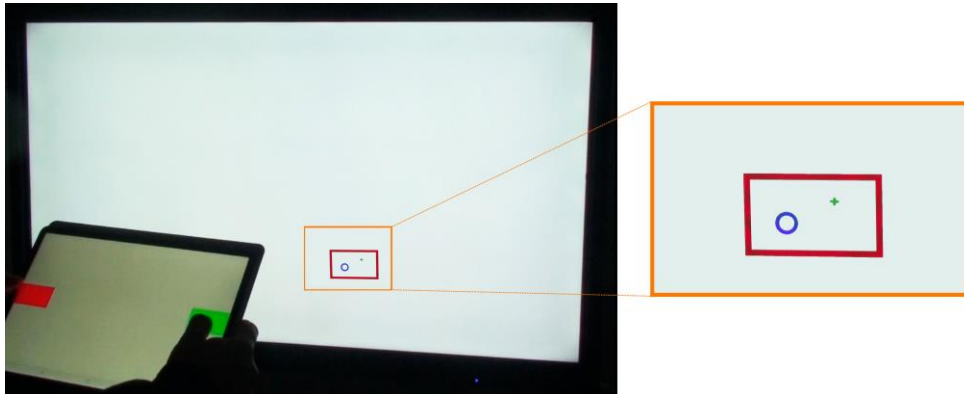


Figure 5. Photo of our experimental interface. Left: A user holding the tablet with two hands in front of the large display. Right: A zoomed view of the precise cursor (cross) and the target (circle) inside the rectangular coarse area.

4.3 Participants

We recruited 12 participants for the experiment at the local university, all with a background in computing science (23.2 years old on average, $SD = 1.42$). Five self-identified as women and seven self-identified as men. They were all right-handed. We disinfected the tablet between each use and applied all the necessary barrier gestures to comply with the ongoing covid sanitary protocols. We complied with the local ethical requirements of our university and asked each participant to fill out an informed consent form.

4.4 Experimental design and collected data

The experiment followed a 6×4 within-subjects design with the Interaction Technique (the six techniques described in section 3.2) and Index of Difficulty ($ID = 4, 6, 8, 9$) as factors. The study was divided into six blocks, each corresponding to one technique. The order of blocks was counterbalanced between participants using a 6×6 Latin Square, with two participants per group. For each interaction technique, participants had to perform 12 training trials (3 for each ID) followed by 24 trials (6 for each ID). The order of the IDs was randomised, but all trials for one ID were performed in a row. We collected 12 participants \times 6 interaction techniques \times 4 IDs \times 6 repetitions = 1728 trials for the experiment and $12 \times 6 \times 4 \times 3 = 864$ for the training. The experiment lasted on average 87 minutes.

4.5 Collected data and data analysis

We measured the trial completion time and the number of overshoots (during the precise step, when the cursor enters the target, then leaves it). After each interaction technique block, users had to fill out a Borg scale [10] to measure the perceived fatigue and a SUS questionnaire [25]. They were also invited to provide informal feedback about the technique. At the end of the experiment, users had to rank the interaction techniques in terms of preference.

In this work, we chose to rely on estimation techniques with 95% confidence intervals and ratio analysis as recommended by the APA [72]. All of our statistical analysis scripts (based on R) can be found here¹. Ratio analysis is an intra-subject measurement that expresses the effect size (pair-wise comparison) and is computed between each arithmetic means. All CIs are 95% BCa bootstrap confidence intervals with 10000 replicates. Our bootstrap method uses a deterministic approach. For the reader more used to interpreting the p-values, a parallel might be drawn with results obtained through the estimation technique and confidence interval reports (see Figure 3 in Krzywinski et al.'s work [40]). Scripts used to compute the geometric mean and confidence intervals were used by Willett et al. [79] and are available online (www.aviz.fr/ci).

4.6 Results

In this section, the most notable result expressed in the text is bolded in the corresponding figure.

4.6.1 Completion time

Overall completion time: We verified that there was no effect on completion time regarding the order of trials per distant pointing technique and we did not observe any learning effect. To perform this analysis, we compared the six repetitions of each interaction technique and index of difficulty. For this analysis, we removed the dwell time from the completion time for each trial. Hence, any validation mechanism could be used to validate a trial. Overall, we found that users required clearly less time to select the target with **DT_Sim_Relative** [4,45s, CI: 4.13, 4.85] than with DT_Diff_Relative [5.03s, CI: 4.67, 5.48], DT_Sim_Absolute [5.29s, CI: 4.93, 5.82], DT_Diff_Absolute [5.46s, CI: 5.10, 5.91], ST_DualPrecision [5.51s, CI: 5.13, 6.04] and ST_SinglePrecision [5.27s, CI: 4.89, 5.72] (Figure 6 - Top). DT_Sim_Relative set-aside, we found no other clear difference between the other interaction techniques.

An intra-subject ratio analysis confirms these results and shows that performing a distant selection with DT_Sim_Relative takes less time than with the other techniques, from 10% less than with DT_Diff_Relative [$DT_Sim_Relative / DT_Diff_Relative = 0.90$, CI: 0.88, 0.90], up to 18% less than with ST_DualPrecision [$DT_Diff_Relative / ST_DualPrecision = 0.82$, CI: 0.80, 0.84] (Figure 6 - Bottom) (Appendix - Table 4, Table 5 and Figure 25 for details and mean difference).

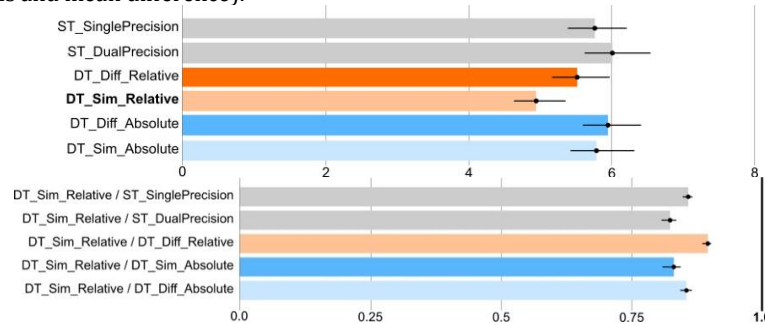


Figure 6. Mean completion time (top) and ratio (bottom) by interaction technique in s (95% CIs).

Completion time per cursor control: The intra-subject ratio analysis establishes that a selection using a dual-precision technique with relative pointing requires 11% less time than when using a dual-precision technique

¹ https://drive.google.com/file/d/1YL4qQHj-G_76mrcBUTlJmo4FCg9XKtsB/view?usp=sharing

with absolute pointing [$DT_{Sym}+Asym_{Relative} / DT_{Sym}+Asym_{Absolute} = 0.89$, CI: 0.87, 0.90] (Figure 7 – Top). This result remains true whether the techniques were based on similar or different usages of the thumbs (Appendix - Table 6 & Table 7).

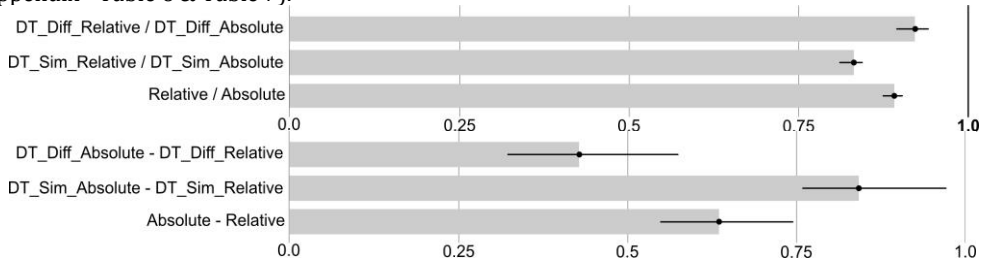


Figure 7. Ratio (Top) and mean difference (Bottom) of completion time per cursor control in s (95% CIs).

Completion time per thumbs usage: Furthermore, our results also show that assigning a similar use to both thumbs requires 7% less time than assigning different usages to the thumbs [$DT_{Sim_{Relative}+Absolute} / DT_{Diff_{Relative}+Absolute} = 0.93$, CI: 0.92, 0.95] (Figure 8 – Top). This result remains true whether the techniques were based on relative or absolute pointing (Appendix - Table 8 & Table 9).

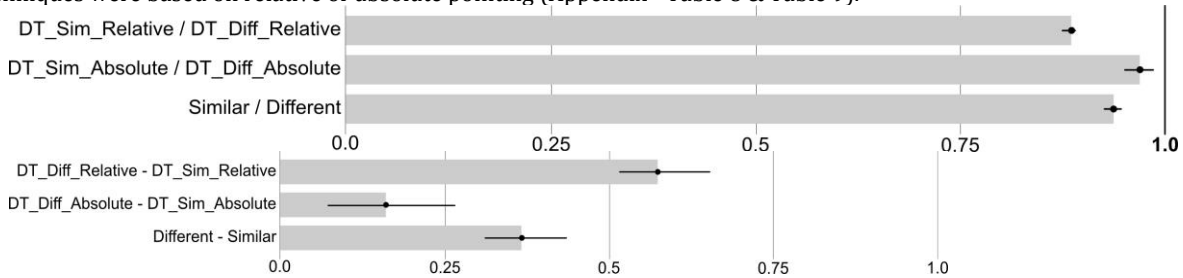


Figure 8. Ratio (top) and mean difference (Bottom) of completion time per thumbs usage in s (95% CIs).

Completion time per ID: We refined the completion time results by ID (Figure 9). For the easiest ID (ID=4), we found no apparent difference between the interaction techniques, probably because the task could be easily achieved with any of them. Regarding ID 6, we observed differences between two groups of interaction techniques: the first group includes the single-precision technique and those based on relative pointing for the coarse step; the second group includes all the techniques based on the absolute pointing for the coarse step, thus including the dual-precision technique involving a single thumb. Users seem to require less time with the first group (**ST_SinglePrecision** [4.23s, CI: 3.90, 4.61], **DT_Diff_Relative** [3.87s, CI: 3.57, 4.19], **DT_Sim_Relative** [4.06s, CI: 3.77, 4.45]) than with the second group (DT_Diff_Absolute [4.75s, CI: 4.40, 5.28], DT_Sim_Absolute [5.09s, CI: 4.73, 5.61] and ST_DualPrecision [5.13s, CI: 4.75, 5.56]) to perform the task. For the hardest IDs (IDs 8 and 9), results clearly establish that users require less time to select a target with **DT_Sim_Relative** ([5.38s, CI: 5.01, 5.84] for ID 8 and [6.29s, CI: 5.88, 6.80] for ID 9) than with any other technique (Figure 9 – Bottom-Left). For all the means and CI, see Appendices Table 10 and Table 11.

Completion time for the coarse and precise steps: For the coarse step (Figure 9 – Top-Right), techniques with relative pointing required less time than techniques with absolute pointing (respectively [1.68s, CI: 1.57, 1.81] for **DT_Sim_Relative**; [1.53s, CI: 1.43, 1.66] for **DT_Diff_Relative**; versus [1.99s, CI: 1.86, 2.17] for DT_Sim_Absolute and [2.03s, CI: 1.91, 2.19] for DT_Diff_Absolute). Regarding the precise step (Figure 9 – Bottom-Right), we found

that only **DT_Sim_Relative** ([1.45s, CI: 1.35, 1.57]) required less time than the three others (respectively [1.67s, CI: 1.56, 1.81] for DT_Diff_Relative; [1.63s, CI: 1.53, 1.78] for DT_Sim_Absolute and [1.64s, CI: 1.54, 1.77] for DT_Diff_Absolute). We believe that having both thumbs performing the same task (pointing) in the same way (relative pointing) confers a homogeneity to the interaction technique that benefits its usability.

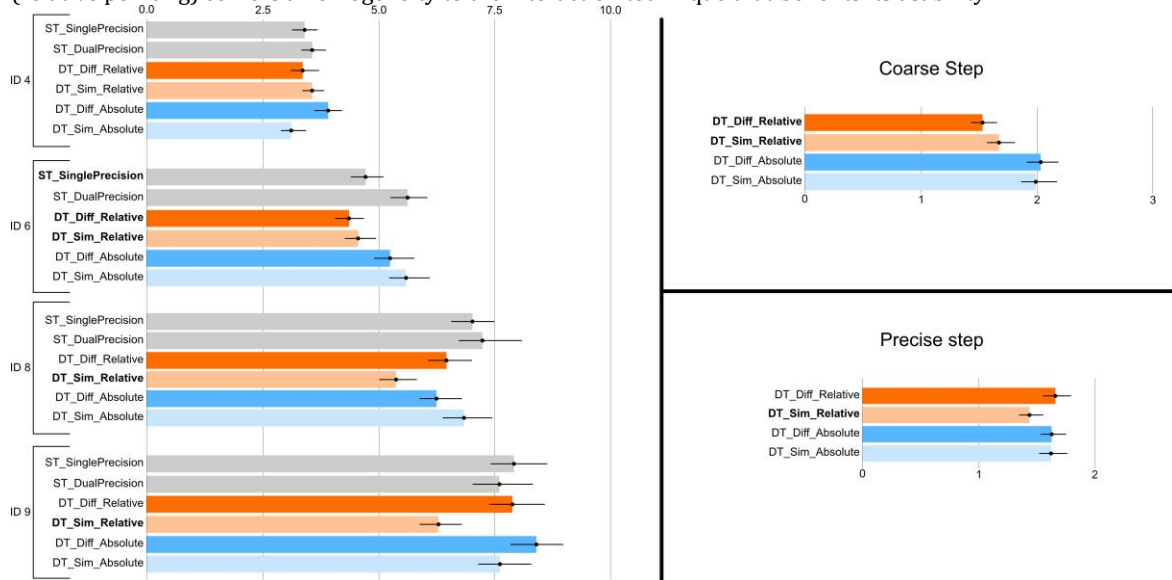


Figure 9. Completion time by interaction technique and ID in s (Left). Time spent on the coarse (Top-Right) and precise (Bottom-Right) steps of the selection for the dual-precision techniques (95% CIs).

4.6.2 Fitts analysis

In this section, we present the linear regression and goodness of fit calculated according to Fitts' law (see Figure 10). To compute the linear regression, we used an R script from Casiez et al. [21]. The results show that the goodness of fit ranges from 0.91 (DT_Diff_Absolute) to 0.98 (ST_SinglePrecision, ST_DualPrecision and DT_Sim_Relative). Detailed results can be found in Table 2. As we did not consider very low IDs, we cannot interpret our intercepts, particularly the negative ones.

To allow for comparison with the rest of the literature, we computed the throughput (TP, in bps) of our techniques. To accommodate the spatial variability observed in responses, we computed the throughput based on effective IDs and effective distances [33, 48]. The resulting throughput values by technique are reported in Table 3. Overall, DT_Sim_Relative has a better throughput than all of the other techniques, confirming our results on completion time.

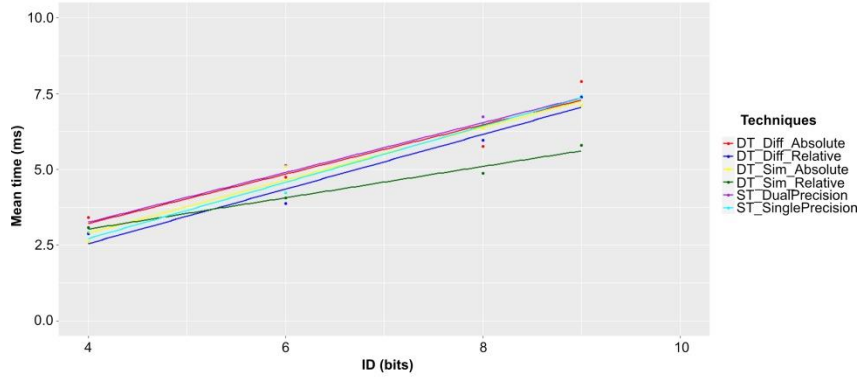


Figure 10. Regression lines for our distant pointing techniques.

Technique	R ²	Intercept	Time	Throughput
ST_SinglePrecision	0.98	1.14	1.06	1.13
ST_DualPrecision	0.97	0.85	1.11	1.20
DT_Sim_Relative	0.98	1.69	1.89	1.41
DT_Diff_Relative	0.96	1.38	1.07	1.21
DT_Sim_Absolute	0.97	0.85	1.11	1.18
DT_Diff_Absolute	0.91	0.64	1.12	1.19

Table 3. Regression line R², coefficients and throughput.

4.6.3 Target Overshoot

Target overshoot (i.e. when the cursor enters the target, then leaves it during the precise step) is clearly minimised when using **ST_DualPrecision** [0.13, CI: 0.076, 0.21] than any other interaction technique (ST_SinglePrecision [0.31, CI: 0.26, 0.35], DT_Sim_Relative [0.32, CI: 0.28, 0.35], DT_Diff_Relative [0.28, CI: 0.23, 0.30], DT_Sim_Absolute [0.26, CI: 0.19, 0.31]; DT_Diff_Absolute [0.28, CI: 0.23, 0.31]) (Figure 11). We believe that users were facing a higher difficulty placing the cursor correctly near the target in the coarse step using ST_DualPrecision, making them more careful in the precise step.

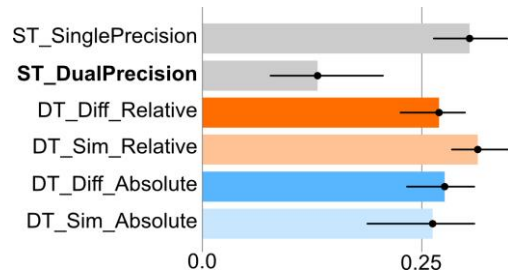


Figure 11. Target overshoot by interaction technique in percent (95% CIs).

4.6.4 Fatigue

We did not find any effect of the order of techniques on fatigue. After each interaction technique block, users had to rate their perceived exertion using a Borg scale [10]. We found a clearly higher perceived fatigue when using ST_DualPrecision [2.42, CI: 1.83, 2.92] than with any other technique (ST_SinglePrecision [1.58, CI: 1.17, 1.75], DT_Diff_Absolute [1.58, CI: 1.17, 1.19], DT_Sim_Absolute [1.42, CI: 1.08, 1.67], DT_Diff_Relative [1.5; CI: 1.17, 1.83] and DT_Sim_Relative [1.33, CI: 1.08, 1.58]) (Figure 12). This result can easily be explained by the effort to perform the initial absolute pointing with ST_DualPrecision, which was considered tedious. Indeed, unlike the other techniques using absolute pointing for the coarse step, ST_DualPrecision did not allow any adjustment of the cursor's absolute position after the initial touch. In addition, as the area to perform the selection is relatively small, and the thumb is larger than the index (leading to an increased fat-finger problem), users often had to perform the coarse step several times before placing the cursor next to the desired location.

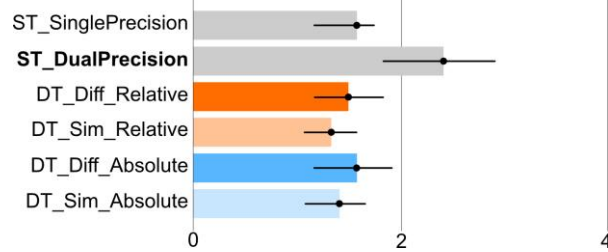


Figure 12. Fatigue by interaction technique in Borg scale (95% CIs)

4.6.5 Usability, users' preference and ranking

Regarding subjective results, participants filled out a SUS questionnaire for each interaction technique (Figure 13). The results established that participants gave an excellent usability score for DT_Diff_Relative [90, CI: 88.13, 91.67] and DT_Sim_Relative [90.42, CI: 87.5, 92.29] and a good usability score for ST_SinglePrecision [82.71, CI: 80.0, 85.42], DT_Diff_Absolute [82.08, CI: 71.04, 86.04] and DT_Sim_Absolute [84.17, CI: 80.42, 88.13]. However, they rated ST_DualPrecision [65.42, CI: 60.42, 69.79] as OK. This lower rating can be explained by the two factors mentioned in the previous section: the area to perform the absolute pointing is small, and the thumb is larger than the index, leading to an increased fat-finger problem.

These results are confirmed by the ranking provided by users at the end of the experiment. Users placed in 1st or 2nd position DT_Sim_Relative ten times, DT_Diff_Relative six times and ST_SinglePrecision four times while DT_Sim_Absolute was placed in the 3rd or 4th position eight times and DT_Diff_Absolute in the 5th position seven times. Finally, ST_DualPrecision was ranked at the last position by every user (12 times).

Informal feedbacks confirm these results as users commented about DT_Relative that “It is the easiest technique I used. I don’t like absolute pointing” (P2). Participants also stated, “I don’t like using a mode, I still have to use my two thumbs, but all the effort is on the right hand” (P5). Finally, regarding ST_DualPrecision, ten participants reported similar comments to what P9 expressed: “this technique is really difficult to use. I can’t find precisely where I should put my thumb to be close to the target, so each time I’m really far and I have to move a lot to hit the target, it’s really annoying.” (P9)

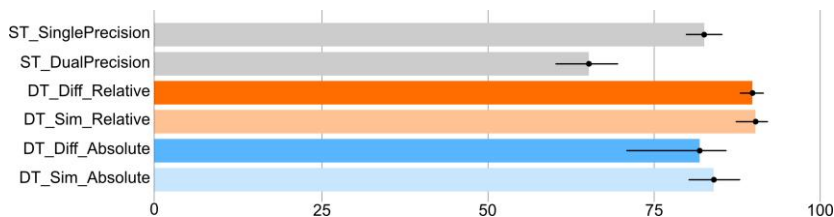


Figure 13. SUS score by interaction technique (95% CIs).

4.6.6 Summary

To sum up, we established that a similar usage of both thumbs is more efficient than an different one and that relative pointing is more efficient than absolute pointing. These two results remain true under any thumb usage and cursor control conditions. Coherently, the results reveal that DT_Sim_Relative, a dual-thumb technique involving similar usage of the two thumbs and based on relative pointing, is the most efficient and preferred technique among our six designs. We further discuss the resulting lessons in the Discussion section.

In an ecological context, after pointing a distant element on the large display, users might have to manipulate the selected data to activate controls or trigger commands displayed in contextual menus. Displaying such menus on the large display screen would occlude other content. Thus, displaying the menus on the two-handed tablet is particularly relevant. Therefore, the next step of our work focuses on command selection on a two-handed tablet using dual-thumb interaction.

5 DESIGN CONSIDERATIONS AND INTERACTION TECHNIQUES FOR COMMAND SELECTION

In this section, we focus on the design of menu techniques for command selection on a two-handed tablet. After introducing the design considerations for this task, we describe the resulting eight menu techniques we designed and implemented.

5.1 Design rationale

To design our menu techniques, we explored the following set of design considerations:

Menu levels and input distribution: We considered two-level hierarchical menus, as most previous works on command selection. As underlined for the design of the distant pointing techniques, when holding the tablet with two hands, each thumb can only reach a limited area on each side of the tablet. Hence, we decided to position each menu level on one side of the tablet. To follow the Western reading direction (left to right), we chose to affect the control of the top-level menu to the left side of the tablet with the non-dominant hand and the control of the sub-level menu to the right side with the dominant hand. The sub-level menu is only displayed after a top-level menu item is selected. As for the dual-thumb pointing techniques, each level of menus is displayed semi-transparently, thus preventing the occlusion of the content displayed on the tablet before invoking the menus.

Menu shape: Our menu shapes are based on a pie-menu principle which has been proven to be efficient for command selection on multiple tactile devices, including tablets [22, 61, 85]. However, the circular shape of a pie menu would not fit within the input area of the thumb without using small items. Therefore, we considered two alternatives that would fit inside the thumb comfort zone: half of a circle (*Half shape*) or a quarter of a circle (*Quarter shape*). For the Quarter shape, we kept the top part of the circle, as the lower one could be more difficult to access due to the physical constraints of the thumb. We compared our two pie-based menu shapes to the most widely available menu on mobile devices: a *Linear* shape.

Number of items: We focused on menus offering 64 items (8 top-level items x 8 sub-level items) which is the norm in the literature on menu selection [20]. We also designed menu techniques extending this number of items, ranging from 100 to a maximum of 900 items. While having so many menu items might seem extreme, previous work, such as MarkPad [23], has proposed similarly large menus to allow users to make clusters of commands (i.e., the goal is not necessary to employ all the possible items).

Number of arcs: We used concentric circular arcs of increasing radius to place the menu items on the Half or Quarter menu shapes. The center of the first arc was set 17 mm away from the screen edge and at the mid-height of the tablet. In their work, Tu et al. [71] considered thumb length to identify the comfortable interaction area on the tablet screen. We based our menu item position and distance to the bezel on their findings. Thus ensuring that our results are valid for the average human's thumb length. We limited the maximum number of circular arcs to three to comply with previous recommendations regarding thumb reachability when holding a tablet with both hands [71]. However, our second and third arcs are placed beyond the 38mm area identified by Tu et al. [71]. While this may induce a difference in terms of performance between the dominant and non-dominant thumb, all of our targets remain under 75mm, which, according to Tu et al. [71], does not impact the precision of the selection. For menus offering 64 items, the number of arcs ranged from 1 to 2; for menus with more than 64 menu items, it ranges from 2 to 3.

5.2 Menu techniques.

Using the previous factors, we designed eight menu techniques: one baseline (Linear menu technique) and seven techniques for dual-thumb command selection (hereafter referred to as dual-thumb menu techniques).

5.2.1 Linear Menu technique

The Linear menu was used as a baseline and is inspired by the most common menus on tablet applications [17, 24]. Each level of the Linear menu contains eight menu items (9.6mm diameter, as recommended by Tu et al. [71]). The most frequent position for linear menus on tablet applications is on the left side of the screen (e.g. Google Calendar, Gmail, etc.). The menu items were therefore placed on the left side of the tablet, 38mm away from the bezel, to conform to the recommendations of Tu et al. [71]. Items are displayed in a semi-transparent way.

5.2.2 Dual-thumb menu techniques

Regarding dual-thumb techniques, the top-level and sub-level menus share the same properties (menu shape, number of arcs and number of items). The menu item size was 9.6mm. Menu items were placed on concentric circle arcs, whose center was 17mm from the bezel. The radius was 21mm for the first circle, 32.6mm (21+9.6+2mm spacing) for the second and 44.2mm (21+9.6*2+2*2mm) for the third circle arcs. Again, these

measures agree with the results of Tu et al. [71], ensuring enough accuracy and comfort for the user to reach them. As mentioned, menu items are displayed semi-transparently on both sides of the tablet.

We named our dual-thumb menu techniques using the shape first, followed by the number of items on each existing arc, which leads to the following syntax for a technique with three arcs: [Shape]_[Number_Items_Arc1]_[Number_Items_Arc2]_[Number_Items_Arc3]. We summarise the design of our seven dual-thumb menu techniques in Figure 14 and describe their design in the following paragraphs.

We first designed three dual-thumb menu techniques supporting 64 (8 x 8) menu items:

- Quarter_4_4: This layout is based on a Quarter shape. As it is impossible to have eight menu items on one quarter circle arc (due to its length and the target size), we used two arcs, with four items on each arc.
- Half_8: This layout is based on a Half shape with eight items evenly distributed on a single arc.
- Half_4_4: This layout is based on a Half shape with two arcs and four items on each arc. This design increases the space between each item on the arc, potentially reducing the risk of selection errors.

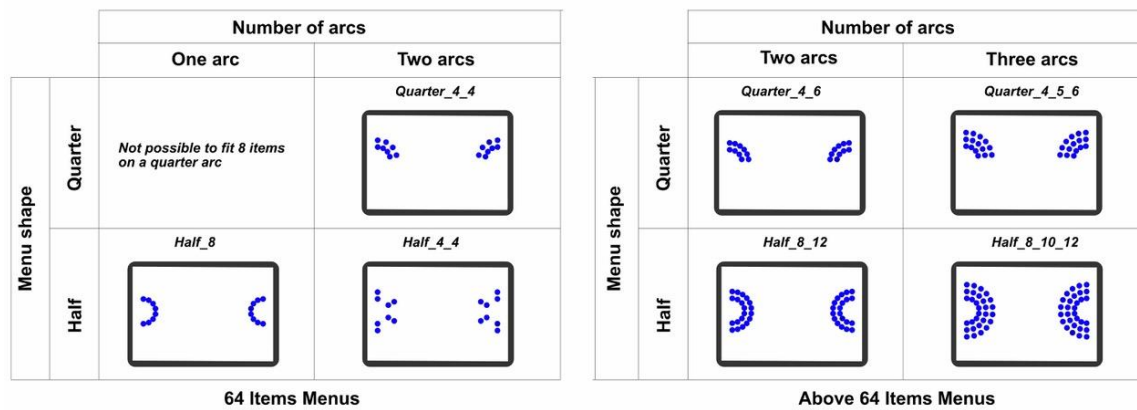


Figure 14. Dual-thumb menus are designed with 64 items (Left) or more than 64 items (Right).

We finally designed 4 four dual-thumb menu techniques supporting more than 64 menu items. These four techniques extend one of the previous designs by adding more items on each arc when possible or by increasing the number of arcs, as follows:

- Quarter_4_6: This design extends the Quarter_4_4 technique by increasing the number of items on the second arc to six. This technique thus supports selection among 100 items (10 x 10).
- Quarter_4_5_6: This design extends the Quarter_4_6 technique by adding a third arc with five menu items in-between the two existing arcs. This technique thus supports selection among 225 items (15 x 15).
- Half_8_12: This design extends the Half_8 technique by adding a second arc with twelve items. This technique thus supports selection among 400 items.
- Half_8_10_12: This design extends the Half_8_12 technique by adding a third arc with ten items between the two existing arcs. This technique thus supports selection among 900 items (30 x 30).

6 STUDY 2: COMMAND SELECTION WITH A TWO-HANDED TABLET

This study compares the previously presented menu techniques for command selection on a two-handed tablet. The experiment is divided into two sessions: the first session aims to compare the menu techniques with 64 menu

items (including the linear baseline); the second session seeks to study the impact of scalability (inserting more menu items) on our techniques. We also conducted a follow-up study comparing our best technique for 64 menu items to two positions for the Linear menu: on the left side, thus complying with the most usual position of such menus, and on the right side of the tablet screen, thus allowing its use with the dominant hand.

6.1 Task

In this study, participants had to select menu items using a two-handed tablet in landscape mode. Before each trial, the tablet displayed two circular buttons, one on each side of the tablet's screen, and the current trial number and the total number of trials to perform with the current menu technique. Touching and releasing the two circular buttons simultaneously started the trial, i.e. the trial only started after both thumbs were lifted. Once the trial started, the top-level menu was displayed on the left side of the tablet, with the menu item to select highlighted in yellow. Users had to touch and release the correct menu item with their thumb to select it. After a valid top-level item selection, the selected item turned green. When using dual-thumb menu techniques, the sub-level menu was displayed on the right side of the tablet, with the item to select highlighted in yellow. With the linear menu technique, the top-level menu disappeared and was replaced by the sub-level menu, using a different colour, still on the left side of the tablet. If the user selected the wrong item (either on the top or sub-level), the trial ended and was counted as an error. The trial starting screen was displayed again, and users had to perform the same trial until they correctly selected the top and sub-level menu items. Users could take a break between trials. After completing all the trials for a given layout, users had to fill out a SUS questionnaire and were invited to provide informal feedback on the technique.

6.2 Apparatus and implementation

The apparatus was identical to the one of our first study (see section 4.2). The large display was placed in front of the user, at the same position and orientation as in our first study and displayed only a map to contextualize the menu selection. There was no direct link between the task on the tablet and the map displayed on the large display. A new Android app was developed (in Java) for this study (see Figure 15).



Figure 15. Screenshots of our tablet app, from left to right: Participants had to press both cyan buttons to start a trial; then they had to select the highlighted top-level menu item; and, finally, the highlighted bottom-level menu item.

6.3 Participants

We recruited 12 participants for the experiment at the local university, all with a background in computing science (22.6 years old on average, SD = 2.27). Six self-identified as women and six self-identified as men. They were all right-handed. No participant took part in the previous study. We complied with the local ethical requirements of our university and asked each participant to fill out an informed consent form.

6.4 Experimental design and collected data

The experiment followed a within-subjects design with the techniques as the only factor. The study was divided into two sessions; the first one involved the four techniques with 64 menu items (Linear, Quarter_4_4, Half_8, Half_4_4) and the second one the four other techniques with more than 64 menu items (Quarter_4_6, Quarter_4_5_6, Half_8_12, Half_8_10_12). All participants performed the first session before the second one. The order of the techniques within the first and second sessions was counterbalanced across participants (4x4 Latin Square for both sessions, with three users per group).

For the first session, participants had to perform 16 training trials (4 predefined top-level menu items x 4 predefined sub-level menu items), followed by 64 trials (one for each of the 8x8 combinations of top and sub-level menu items). Participants performed 16 training trials for the second session, followed by 72 trials (2 repetitions of 6x6 combinations involving six predefined top and sub-level menu items). In both sessions, the trials were randomised.

We collected 12 participants x (4 techniques x 64 item selections + 4 techniques x 72 item selections) = 6528 trials for the experiment and $12 \times 8 \times 16 = 1536$ for the training. The experiment lasted on average 58 minutes.

6.5 Collected data and data analysis

We measured the trial completion time and the number of errors (wrong item selections). After each technique, users filled out a SUS questionnaire [25] and provided informal feedback. After each session, users had to rank the four tested techniques in terms of preference. We did not measure fatigue in this study as all of our techniques rely on the same tablet grasp (two-handed) and simple touch inputs in a reachable area [71]. We used the same method as in the previous study for data analysis (see section 4.5).

6.6 Results

In this section, the most notable result expressed in the text is bolded in the corresponding figure.

6.6.1 Completion time

We verified that there was no effect on completion time regarding the order of trials per command selection technique and we did not observe any learning effect. In the first session, as there were no repetitions, we compared two groups of 32 trials (the first 32 trials versus the last 32 trials). In the second session, we compared the two repetitions. In this section, we present the completion time results for each technique. We separate the results of each session. We grouped their results because we did not find any difference between the top and sub-level menu item selection time.

For the first session (64 menu items), the results reveal that selecting the correct menu item with **Quarter_4_4** [1.06s, CI: 1.01, 1.13] takes less time than with Half_8 [1.15s, CI: 1.11, 1.22], Half_4_4 [1.18s, CI: 1.14, 1.25] and Linear [1.22s, CI: 1.15, 1.29] (Figure 16 - Left). We found no clear difference between Half_4_4, Half_8 and Linear regarding average completion time.

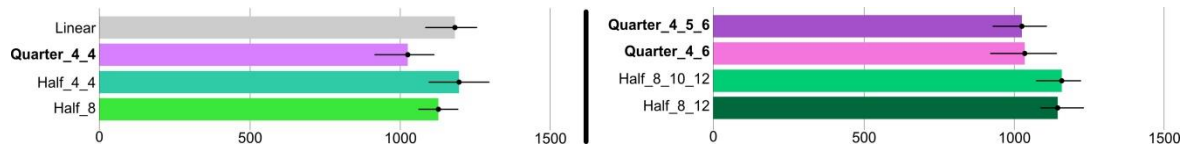


Figure 16. Completion time by technique for the first session (Left) and the second session (Right) in ms (95% CIs).

An intra-subject ratio analysis (Figure 17 - Top) confirms that participants required 13% less time with Quarter_4_4 than with Linear [Quarter_4_4 / Linear = 0.87, CI: 0.82, 0.89]. This ratio analysis also revealed an additional difference between Half_8 and Linear: participants required 9% less time with Half_8 than with Linear [Half_8 / Linear = 0.91, CI: 0.86, 0.94]. This intra-subject ratio analysis revealed no apparent difference between Half_4_4 and Linear. The first session thus establishes that two of our three pie-based dual-thumb menu techniques are more efficient than a single-thumb traditional linear menu. Mean differences can be found in Figure 17 - Bottom and Appendix - Table 12.

For the second session (menu techniques with more than 64 menu items), we found that users clearly required less time to select the correct menu item with Quarter_4_6 [1.05s, CI: 1.00, 1.12] and Quarter_4_5_6 [1.06s, CI: 1.01, 1.12] than with Half_8_12 [1.16s, CI: 1.13, 1.21] and Half_8_10_12 [1.17s, CI: 1.13, 1.24] (Figure 16 - Right).

While we did not directly compare the techniques from the two sessions, it is interesting to note that the menu selection time is similar for the Quarter techniques in both sessions (around 1000ms) and for the Half techniques in both sessions (around 1160ms). We acknowledge that our experimental setup was not designed for such comparison; however, these results tend to indicate that Quarter and Half menu shapes are robust to a rise in the number of menu items.

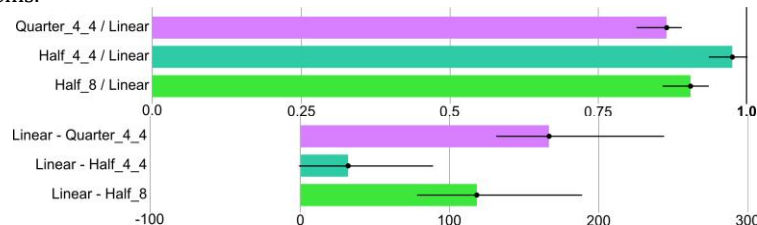


Figure 17. Ratio (Top) and mean difference (Bottom) of completion time for the first session techniques in ms (95% CIs).

To study if the gesture direction has an impact on the completion time, we compared the top four targets (in top and sub-levels) of Half_8 with the four bottom targets. We found that selecting the four top targets required 1140ms while selecting the four bottom targets required 1154ms. These results do not reveal any clear difference in terms of completion time according to the gesture direction. As Quarter_4_4 outperforms Half_8, this difference is not due to the position of the items on the upper quarter. A plausible explanation would be that as the trial starts on thumb release, users may anticipate the direction of the target in Quarter_4_4 (always on the top-right of the thumb's start position). They can thus start moving the thumb as soon as the trial starts and before locating the target. This would shorten the ballistic movement phase of the pointing. Another possible explanation would be that in Quarter_4_4 items are closer to each other, limiting visual search compared to Half_8.

6.6.2 Selection errors

Regarding selection errors, we found no apparent difference between the techniques in both sessions (CIs and means can be found in Appendix Table 12 and Table 14). On average selection error is 4%.

6.6.3 Usability, users' preference and ranking

Participants filled out a SUS questionnaire for each technique (Figure 18). According to the regular interpretation of the SUS score 25, the results established that participants considered the usability of Quarter_4_4 [92, CI: 89.58, 93.96] and Quarter_4_6 [92, CI: 88.75, 93.75] as being the best imaginable, while the usability of Quarter_4_5_6 [89.79, CI: 86.25, 92.92], Half_8 [87.71, CI: 82.92, 90.21] and Half_8_12 [86.67, CI: 82.29, 91.04] was considered excellent, and the usability of Linear [82.92, CI: 76.46, 87.92], Half_8_10_12 [79.79, CI: 73.33, 84.58] and Half_4_4 [78.75, CI: 74.17, 82.50] was just rated as good. Two factors can explain these ratings: first, users found that leaving too much space between the menu items (Half_4_4) was visually disturbing; second, users did not like the techniques with a high number of items.

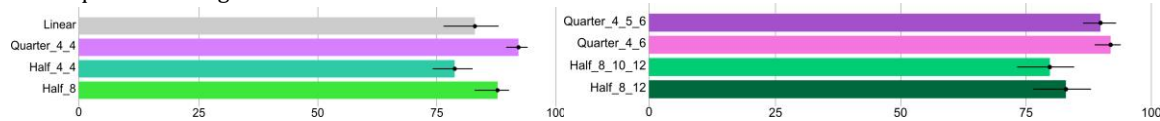


Figure 18. SUS scores for the first session (Left) and Right session (Right) techniques.

These results were confirmed by the ranking provided by users at the end of the experiment. Indeed, for the first session, users placed Quarter_4_4 in 1st or 2nd position eleven times, Half_8 eight times, Linear three times and Half_4_4 two times. Furthermore, Linear was placed in 4th position eight times. For the second session, Quarter_4_6 was placed in 1st or 2nd position twelve times, Half_8_12 seven times and Quarter_4_5_6 five times. Half_8_10_12 was always rated 4th because the number of targets was deemed too large.

The informal feedbacks align with these results as two users described Quarter_4_4 as very intuitive, ensuring all targets' easy reachability and pleasant use with both hands (P1, P6). One participant also stated, "I prefer the Quarter layouts because it is harder to select a target on the bottom half of the circle" (P3).

6.6.4 Follow-up study

To further generalise our results, we performed a follow-up study, confronting our best dual-thumb technique with a variant of the Linear menu. In our study, the Linear technique used as a baseline was placed on the left side of the tablet screen. As said earlier, this menu position is the most common in tablet apps [17, 24]. However, we wanted to assess the impact on our results of using the Linear menu on the right side, hence requiring its manipulation with the dominant thumb. We thus compared the Linear menu placed on the left side (Linear) with a Linear menu placed on the right (LinearRight) and our best technique from the first session (Quarter_4_4).

We used the same experimental protocol described earlier (i.e. task, apparatus, implementation, collected data, etc.). The order of the three techniques was counterbalanced across participants. We recruited twelve participants for this follow-up study (23.3 years on average, SD = 2.49). Four self-identified as women and eight self-identified as men. They were all right-handed and none had been involved in the previous studies. We complied with the local ethical requirements of our university and asked each participant to fill out an informed consent form.

The results revealed a similar completion time for Linear (on the left) ([1176ms, CI: 1146, 1215]) and Quarter_4_4 ([1068ms, CI: 1022, 1090]) than in our Study 2, which confirms our previous findings. We could not find a clear difference between the use of a linear menu on the right side of the tablet ([1194ms, CI: 1165, 1234]) and the linear menu on the left (Figure 19 - Left). An intra-subject ratio analysis (Figure 19 - Right) confirms that Quarter_4_4 requires 10% less time than Linear for menu item selection [Quarter_4_4 / Linear = 0.90, CI: 0.87,

0.94] (13% in study 2) and 10% less time than LinearRight [Quarter_4_4 / LinearRight = 0.90, CI: 0.87, 0.93]. This ratio analysis did not reveal a time difference between LinearRight and Linear ([LinearRight / Linear = 1.01, CI: 0.97, 1.07]). Mean difference can be found in Appendix – Table 15 & Figure 26.

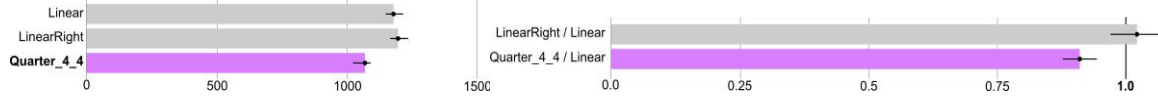


Figure 19. Selection time (Left) and ratio (Right) for Linear, LinearRight and Quarter_4_4 in ms (95% CIs).

6.6.5 Summary

To sum up, for menus with 64 items, participants clearly took less time using the dual-thumb menu technique with a Quarter shape than with the traditional single-thumb Linear technique, independently of its position on the screen (left or right). For menus with more than 64 items, the Quarter techniques allows to select up to 225 items with a limited increase in time compared to the 64 items version. We further discuss the resulting lessons in the Discussion section.

7 STUDY 3: COMPARING THE BEST DUAL-THUMB MENU TECHNIQUE WITH MARKING MENUS

Our previous study used the most widely available menu on tablets (Linear Menu) as a baseline to ensure the ecological validity of our results. To further extend the value of our results, we decided to compare our best technique to a solution from the research literature designed for a two-handed mobile device. This solution, proposed by Kin et al. [38], is the only menu technique on a two-handed mobile device we are aware of and which involves dual-thumb marking menus (MM).

Hence, we designed a third study to compare dual-thumb Marking-menu techniques [38], in novice and expert modes, to the best dual-thumb menu technique from the previous study (Quarter_4_4).

7.1 Task, apparatus and implementation

The task, apparatus and implementation were identical to our second study (see sections 6.1 and 6.2). To start a trial, both thumbs had to be lifted from the tablet screen.

7.2 Marking menu technique

For this experiment, we implemented two modes of the dual-thumb marking menu technique presented by Kin et al. [38]: MM_Expert and MM_Novice. As explained in the related work section, the expert mode of marking menus is particularly relevant in the context of frequently accessed commands which can be memorised. However, our context of use slightly differs: in our work, we envision contextual menus associated with previously selected elements using distant pointing. These menus are harder to memorise as they change according to the selected item; hence displaying the menu items would be more relevant. We thus decided to explore both novice and expert modes, while Kin et al. [38] only evaluated the expert mode of their dual-thumb marking menu. In their work, Kin et al. compared Two-Handed Simultaneous Marking Menu (2HS) with Two-Handed Ordered Marking Menu (2HO) and found no significant difference between the two in terms of total time, although 2HS had a shorter thumb movement time than 2HO (from start to end of the gesture). As we focus on contextual menus (i.e. not always known in advance and involving hierarchical menu and sub-menu exploration) and as none of our menu techniques offered simultaneous usage of both hands, we based our marking menu design on the 2HO version of their work. Besides, in our study, we focus on the same total time as Kin et al. (reaction time plus

movement time), so both techniques were equally valid as baselines. Another difference with Kin et al. is that their menu was tested on a smartphone with two thumbs or on a tablet laid on a surface and using the two indexes. We hence adapted their solution to a two-handed tablet version based on dual-thumb interaction.

For both modes, we considered the 8-2 (eight items on a two-depth menu) marking menus introduced by Kin et al. [38]. This decision complies with our menu design which includes 8x8 menu items. Similar to our dual-thumb menu techniques, the first level of the marking menu was placed on the left side of the tablet and the second level on the right side. The eight menu items were placed on a circular (Figure 20 - Right) shape (N, NE, E, SE, S, SW, W, NW) centered at 25mm from the starting thumb position, which fits in the comfortable input area [71] and allows strokes of 25mm length as recommended by Kurtenbach [43]. During the stroke, the currently selected target was highlighted. During the stroke, the direction was computed between the current thumb position and the initial thumb position. After releasing the thumb, the highlighted menu item was selected. After completing the correct two strokes and lifting the two thumbs, the trial ended.

For both modes, before each trial, the tablet displayed two circular buttons (one on each side of the tablet's screen), the current trial number and the total number of trials to perform with the current menu technique. Touching and releasing the two circular buttons simultaneously started the trial, i.e., the trial only started after both thumbs were lifted. Then, the instructions for each mode were displayed (detailed below). As in Kin et al.'s work [38], the instruction disappeared when the user placed any of his fingers on the tablet screen to start the marking menu gestures: this time corresponds to the reaction time defined by Kin et al. After the correct strokes are performed (movement time of Kin et al.), the trial ends. The total trial time collected in this study can thus be compared to the total time of Kin et al., corresponding to the addition of reaction time and movement time.

For MM_Expert, the instructions consisted of two arrows, representing the strokes to be performed to select the current trial menu items. They were displayed on the top of the tablet screen (Figure 20 - Left).

For MM_Novice, the marking menu is directly displayed (Figure 20 - Right) on each side of the tablet. As in our previous study, the target item is displayed in a different colour. After selecting the correct menu item on the top-level, the bottom-level was displayed. Between each trial, participants could take a break.

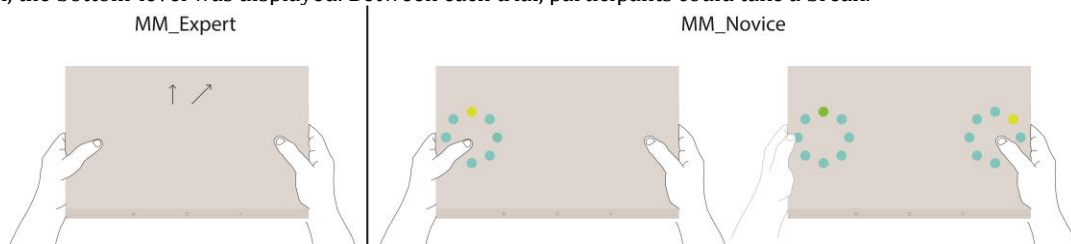


Figure 20. Screenshots of our tablet app, the same target was used for both marking menu modes. MM_expert instructions displayed at the beginning of the trial (Left). MM_Novice top-level menu displayed at the start of the trial with the current target in dark green (Center). Sub-level menu appears after the top-level menu item selection (Right).

7.3 Participants

We recruited 12 participants at the local university, all with a background in computing science (25.1 years on average, $SD = 3.08$). Two self-identified as women and ten self-identified as men. They were all right-handed. No participant took part in the previous studies. We complied with the local ethical requirements of our university and asked each participant to fill out an informed consent form.

7.4 Experimental design and collected data

The experiment followed a within-subjects design with the Technique (MM_Expert, MM_Novice, Quarter_4_4) as the only factor. The order of the techniques was counterbalanced across participants (3x3 Latin Square, with 4 users per group).

Participants had to perform 16 training trials (4 predefined top-level menu items x 4 predefined sub-level menu items), followed by 64 trials (one for each of the 8x8 combinations of top and sub-level menu items). The trials were randomised.

We collected 12 participants x 3 techniques x 64 item selections = 2304 trials for the experiment and 12x3x16 = 576 for the training. The experiment lasted on average 22 minutes.

7.5 Collected data and data analysis

We measured the trial completion time and the number of errors (wrong item selections). After each technique, users filled out a SUS questionnaire [25] and provided informal feedback. After each session, users had to rank the three tested techniques in terms of preference. We used the same method as in the previous study for data analysis (see section 4.5).

7.6 Results

In this section, the most notable result expressed in the text is bolded in the corresponding figure.

7.6.1 Completion time

We verified that there was no effect on completion time regarding the order of trials per command selection technique and we did not observe any learning effect. To perform this analysis, as there was no repetition, we compared two groups of 32 trials (the first 32 trials versus the last 32 trials). The results revealed a similar completion time for **Quarter_4_4** than in our previous studies ([1018ms, CI: 982, 1068]), confirming our previous findings. We also found that selecting a menu item with both MM_Novice ([1576ms, CI: 1512, 1649]) and MM_Expert ([1317ms, CI: 1285, 1354]) requires more time than with Quarter_4_4 (Figure 21 - Left).

An intra-subject ratio analysis (Figure 21 - Right) confirms that Quarter_4_4 requires 35% less time than MM_Novice for menu item selection [Quarter_4_4 / MM_Novice = 0.65, CI: 0.63, 0.67] and 23% less time than MM_Expert [Quarter_4_4 / MM_Expert = 0.77, CI: 0.74, 0.81]. We identify two plausible causes justifying the extra time required with marking menus. First, the thumb movement from the center of the marking menu towards the user's hand might be harder to perform than the movements of our Quarter_4_4 technique; Second, with marking menu in novice mode, targeted items may be hidden by the hand, thus inducing a longer completion time. Mean difference can be found in Appendix - Table 16 & Figure 27.

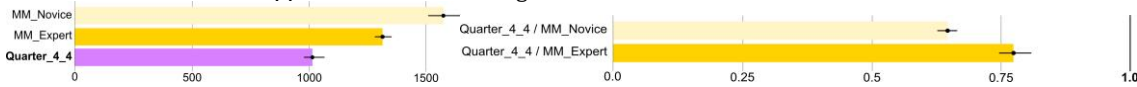


Figure 21. Selection time (Left) and Ratio (Right) for MM_Novice, MM_Expert and Quarter_4_4 in ms (95% CIs).

7.6.2 Selection errors

We found that users made more errors (selecting the wrong menu item) when using MM_Expert ([15.5%, CI: 12.5, 19.3]) than **MM_Novice** ([7.4%, CI: 4.9, 9.2]) or **Quarter_4_4** ([4.8%, CI: 3.3, 5.9]) (Figure 22). This result can be

explained by the marking menus having eight directions: the precision required to perform a stroke in one of the eight directions without feedback (for MM_Expert) might explain these errors.

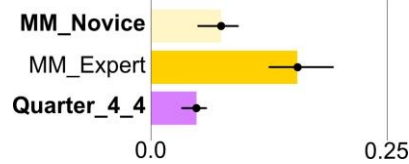


Figure 22. Selection error by interaction technique in percent (95% Cis).

7.6.3 Usability, users' preference and ranking

Participants filled out a SUS questionnaire for each technique (Figure 23). According to the regular interpretation of the SUS score [25], the results established that participants considered the usability of Quarter_4_4 [87.7, CI: 82.08, 90.21] as excellent and the usability of MM_Novice [83.75, CI: 77.17, 87.29] and MM_Expert [78.13, CI: 72.92, 81.88] as good. These ratings can be explained by the fact that, for MM_Novice, one menu item was occluded by the thumb at the beginning of the trial (SW on the left side of the tablet screen and SE on the right side), leading to difficulties in the selection process. Regarding MM_Expert, we believe that the higher error rate explains the difference in terms of usability.

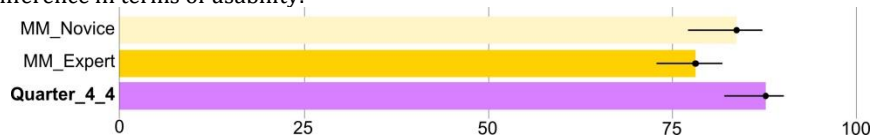


Figure 23. SUS score by interaction technique (95% Cis).

These results were confirmed by the ranking provided by users at the end of the experiment. Indeed, users placed Quarter_4_4 in 1st position twelve times, MM_Novice in the 2nd position twelve times and MM_Expert in the last position twelve times.

7.6.4 Summary

In summary, participants clearly took less time using Quarter_4_4 than dual-thumb marking menus, whether in novice or expert mode. We also found that using a dual-thumb marking menu in expert mode induces more errors than using it in novice mode or using Quarter_4_4.

8 DISCUSSION

We discuss the lessons learned from our studies, some limitations of our work and then we envision future work.

8.1 Lessons learned about distant pointing with a two-handed tablet

From our first study, we extract three lessons for the design of distant pointing techniques with a two-handed tablet:

Lesson 1: An optimal Dual-Thumb technique outperforms Single-Thumb pointing techniques

When handling a tablet with two hands, our best dual-thumb pointing technique allows for a time gain of 14% compared to the best single-thumb technique (ST_SinglePrecision, Appendix – Table 4) and is clearly preferred. This is particularly interesting as most existing pointing techniques (mouse, touchpad, tactile screen) are one-handed only.

Lesson 2: Similar usage of both thumbs improves the pointing efficiency

With dual-thumb techniques, especially for difficult tasks (high pointing ID), adopting a similar usage of each thumb, i.e., each thumb controlling the cursor of one step of the dual-precision technique, is more efficient than adopting an different thumb usage, i.e. one thumb being used to switch between the coarse and precise steps while the other controls the cursor. This is in line with previous works which established the benefit of similar thumb usage in bimanual interaction (where each hand is assigned an identical role) over different thumb usage [550]. However, to our knowledge, our work is the first that demonstrates similar benefits for dual-thumb interaction.

Lesson 3: Relative pointing for the coarse step improves the efficiency

Our results establish that when using dual-precision techniques, a relative cursor control for the coarse step is more efficient than an absolute cursor control. This interesting finding extends the outcomes of ArcPad and ArcPad² studies [49, 52]. Indeed, ArcPad showed that dual-precision techniques with absolute pointing during the coarse step are more efficient than single-precision ones based on relative pointing. ArcPad² showed that using absolute pointing to adjust the coarse position further after the initial touch enhanced the dual-precision performance. Our work confirms that these two results remain valid in the context of a two-handed tablet and dual-thumb interaction. We further established that using relative pointing in each step of the dual-precision approach is even more efficient than using absolute pointing for the coarse step. Manipulating the coarse and precise cursors using the same cursor control aligns with the ergonomic criteria “consistency” [6], which encourages maintaining the same design choices in similar contexts. We hypothesise that this consistency minimises the user’s cognitive efforts and enhances technique efficiency.

8.2 Lessons learned about menu selection with a two-handed tablet

From our second experiment, we can extract three lessons:

Lesson 1: Two thumbs are better than one (again)

When handling a tablet with two hands, using two thumbs for menu selection allows for a time gain of up to 13% compared to using only one thumb on a linear menu and is clearly preferred. Our results show that distributing the menu items under each thumb is promising. This lesson is consistent with the pointing task and confirms the general value of adopting a dual-thumb interaction approach.

Lesson 2: Quarter menu shape is more efficient than Half

Among our dual-thumb menu techniques, using the Quarter shape requires less time and is preferred to the Half shape. We hypothesise that since menu items displayed in a Quarter shape are closer to each other, this could have favoured the visual search process and contributed to enhancing the comfort of use. Overall, this is an interesting result extending previous work focusing on the performance comparison between single-thumb half-pie and linear smartphone menus [85]. Besides, our work is the first to compare half and quarter pie-menus to our knowledge.

Lesson 3: Quarter and Half menu techniques favour scalability

While we did not directly compare the techniques from the first and the second sessions, we found similar selection times for the Quarter techniques in both sessions and for the Half techniques in both sessions. These first results, which should be further explored, tend to show that using the Quarter or Half menu shape with a large number of menu items (up to 900) does not hinder their performance. This could lead to command grouping as envisioned by Fruchard et al. [23].

Lesson 4: Quarter menu is more efficient than Marking-Menus

When comparing our best technique, Quarter_4_4, to dual-thumb marking menus, we found that it is less error-prone and requires less time. Although marking menu seems very close to Quarter menu in terms of design, the existing differences (circular shape vs quarter shape, stroke vs tap) and properties of the MM (expert mode with no feedback) affect the performance of command selection in a dual-thumb context.

8.3 Limitations and future work

A first limitation of our work is that we did not implement pointer acceleration in the dual-thumb interaction techniques for the precise step, although we implemented it for the single-thumb with single-precision technique (ST_SinglePrecision). Since users found it particularly useful in the ST_SinglePrecision technique, integrating pointer acceleration in our dual-thumb techniques could have led to even better performances.

While the used CD gain allows the users to avoid clutching, it is based on the ratio between the tablet size and the input area size (constrained by Tu et al. [71] findings): applied to the large display size this ratio determines the coarse rectangle size. In our context, using a greater CD gain would reduce the precision while using a lower CD gain would support higher accuracy but force clutching, which would reduce the performances of our techniques. Our CD gain calculation, based on the input size of the tablet screen and the large display screen size, prevents these issues. In fact, there is a breaking point where our CD gain calculation does not allow being precise enough to select any target on the distant screen. In our context, the lowest target size being 12px, a CD gain superior to 12 for the precise step would make some selections impossible to perform. In this case, a smaller CD gain would be required, thus inducing clutching. To calculate in which conditions the CD gain would be superior to 12, we use the ratio presented in section 3.2.

$$\begin{aligned} \text{PreciseCDGain} &= \text{CoarseAreaSize} / \text{InputAreaSize} \\ k &= \text{CoarseAreaSize} / \text{LargeDisplaySize} \end{aligned}$$

By combining these two equations, we obtain:

$$\text{LargeDisplaySize} = (\text{PreciseCDGain} * \text{InputAreaSize}) / k = (12 * 38) / 0.156 = 2923\text{mm}$$

Hence, we find that the large display screen size should be of 2923mm wide, which is close to double the size of our current setup (1430mm wide). And yet, in our experiment, users actually performed clutching in multiple occasions: clutching can be more efficient in the user's perspective compared to placing their thumb in one corner of the input area and dragging it to the opposite corner.

We also only considered the situation where the large display matched the landscape orientation of the tablet. However, the large display could be positioned in portrait orientation, leading to a mismatch between both devices. In this context, users could grasp the tablet in portrait orientation, or, to avoid manipulating the tablet, the input areas on the tablet could be rotated. More studies are needed to validate the performance of our techniques with these setups.

In our studies, our 12 participants are members of a computer science department of the University. In addition, as in Tu et al. [71], we deliberately chose right-handed participants in our experiments to avoid any bias caused by handedness. While this panel is limited, it allowed us to explore the interest and performances of distant pointing and menu selection techniques in the context of distant interaction with a large display. In our first experiment, we only collected expertise with tactile interaction and did not collect the user's expertise with laptop touchpads, which could have an impact on our results. In the future, it would be interesting to extend our participant panel to include a broader diversity.

In our statistical analysis, we used arithmetic means to compare our interaction techniques. While this approach is valid [19], using geometric means for time and error data allows correcting for positive skewness in time measurements and dampens the effect of potential extreme trial completion times. However, after analysis of our data with geometric means, we found no differences with our result conclusions.

From a usage point of view, our menus are displayed vertically centred on each side of the tablet. While controlling the menu position was required in our study to alleviate potential biases, such position on the tablet screen could be inconvenient for the users depending on the user's hand position when holding the tablet. To better fit with the user's hold of the tablet, a potential solution would be to detect the position of the thumb along the bezel and display the menu and input area accordingly: concretely using a trigger gesture, such as a bezel tap [66], could be a solution. Although very unlikely, if users hold the tablet on the top, they must adopt a variant of our menu technique, such as a quarter menu with only the bottom half part. Finally, the user could hold the tablet at different positions with each hand: the menus and input areas would thus be displayed at different heights on the screen, impacting their performance. Those particular situations will be explored in future work.

Beyond pointing and command selection on 2D surfaces, an interesting extension of our work will be to explore dual-thumb interaction in multi-dimensional contexts, such as 3D manipulation [59]. This would require thinking about the mapping of the multiple dimensions across the two thumbs.

Another significant extension of our work would be exploring a multi-user scenario [[17], [27]] to verify if our dual-thumb interactions would benefit collaboration compared to direct manipulation on the large display. Indeed, our solution reduces the risk of display occlusion by hand but would insert multiple moving cursors on the shared content, which could be disturbing or confusing.

8.4 Application contexts for combining distant pointing and menu selection

In this paper, we explored the distant pointing task and the command selection task separately. However, in an ecological context, these two tasks would be intertwined, and thus, a switching mechanism would be required. In order to provide a first insight into how these two tasks could be combined, we designed an ecological prototype. This prototype allows analysing and manipulating the data related to urban planning. We combined a wall screen, displaying a 2D map of a neighbourhood, with tablets, held by the users standing in front of the display. The tablets can be used for distant pointing on the screen (see Figure 24 – Top-Left), displaying contextual menus (see Figure 24 – Top-Right), showing charts representing the data available on the 2D map (e.g. building occupation, available parking spots, etc.) and selecting commands to edit the 2D map data (e.g. adding a new building to the neighbourhood).

In our prototype, the distant pointing validation is performed using our DT_Sim_Relative technique. To validate the selection, a button is displayed on the tablet under the right input area. After the validation, the distant pointing input areas are hidden and the quarter menu is displayed. A “back” menu item allows returning to distant pointing while other menu items allow displaying a chart or executing a command.

Other solutions could be used to switch between distant pointing and command selection. A short dual-thumb press might be sufficient to activate the pointing mode, while a long dual-thumb press might activate the menu mode. Alternatively, we might consider using bezel taps or swipes [66] to activate distant pointing.

Beyond the wall display scenario, our interaction techniques could be used in other contexts. For example, to interact with a tabletop screen as demonstrated in Figure 24 (Bottom-Left and Bottom-Right). Our techniques could also be particularly useful for interaction with AR Head-Mounted Displays (HMDs). As demonstrated in

Holobar [63], where a smartphone is used to perform command selection in AR, our menu design could be used to accelerate command selection and to point on surrounding 2D windows [57]. Finally, our menu techniques can be helpful in any ubiquitous scenario where a tablet is held with two hands, such as during supervision or inventory tasks.

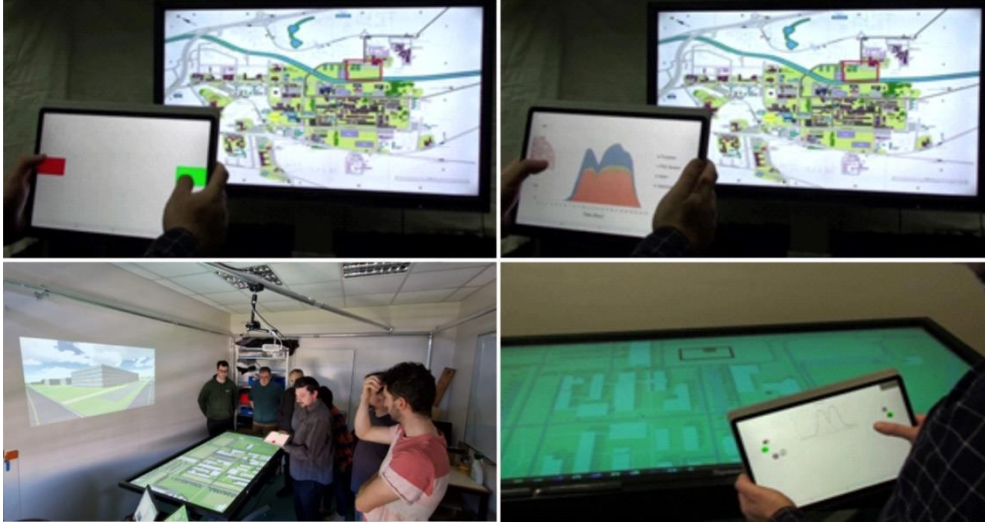


Figure 24. Pointing (Top-Left) and Command selection (Top-Right) in our usage scenario. Our techniques can also apply to other scenarios, such as interacting with a tabletop (Bottom-Left) or with multi-display environments (Bottom-Right).

9 CONCLUSION

This paper explored dual-thumb interaction techniques on a two-handed tablet to perform distant pointing and command selection on a large display. We first designed six interaction techniques for distant pointing using one or two thumbs. We also explored three factors: the precision type, the cursor control and the thumbs usage. We performed an experiment to compare these techniques for pointing on a large display. Our results show that only one of our dual-thumb distant pointing techniques is faster than the two single-thumb techniques. Indeed, our studies reveal that using absolute pointing for the coarse step does not lead to better performances than single-thumb interaction and that assigning different roles to both thumbs does not increase performance. Furthermore, a common advantage of dual-thumb interaction over single-thumb is the possibility to perform simultaneous manipulation, which can lead to increased performances. However, while our first study participants could perform both the coarse and precise steps simultaneously in some cases (similar thumb usage), we did not observe such behavior. From this study, we conclude that dual-thumb interaction doesn't just increase performance by allowing simultaneous use of both thumbs, but also by the use of the two thumbs for two different parts of the task. Our work thus contributes to better understand how the design of dual-thumb interaction impacts its performance compared to single-thumb interaction. Then, we designed several menu techniques dedicated to dual-thumb command selection. These layouts are based on a half or a quarter pie shape and provide from 64 up to 900 menu items. Our menu techniques design factors include the number of menu items, the number of arcs on which they are placed and the shape of the menu. We compared our dual-thumb menus to a traditional single-thumb linear menu. Our results show that dual-thumb menu techniques based on a quarter pie allow for more efficient command selection and are preferred over half-pie, single-thumb linear

menus or dual-thumb marking menus. Finally, we compared our best technique, Quarter_4_4, to marking menus in expert and novice modes. Our results show that Quarter_4_4 requires less time, is preferred and is less error-prone than dual-thumb marking menus. Overall, these studies established that dual-thumb interaction is a powerful approach to improve interaction with a two-handed tablet.

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A APPENDICES

A.1 Additional results for distant pointing with a two-handed tablet

Technique	MeanTime	Lower_CI	Upper_CI
DT_Sim_Relative / ST_SinglePrecision	0.86	0.85	0.87
DT_Sim_Relative / ST_DualPrecision	0.82	0.81	0.84
DT_Sim_Relative / DT_Diff_Relative	0.90	0.88	0.90
DT_Sim_Relative / DT_Sim_Absolute	0.86	0.84	0.87
DT_Sim_Relative / DT_Diff_Absolute	0.83	0.81	0.84

Table 4. Ratio analysis of the completion time of DT_Sim_Relative over the other techniques in s (95% CIs).

Technique	MeanTime	Lower_CI	Upper_CI
ST_SinglePrecision - DT_Sim_Relative	0.82	0.74	0.91
ST_DualPrecision - DT_Sim_Relative	1.06	0.96	1.23
DT_Diff_Relative - DT_Sim_Relative	0.57	0.52	0.65
DT_Sim_Absolute - DT_Sim_Relative	0.84	0.76	0.97
DT_Diff_Absolute - DT_Sim_Relative	1.00	0.91	1.15

Table 5. Mean difference analysis of the completion time of DT_Sim_Relative over the other techniques in s (95% CIs).

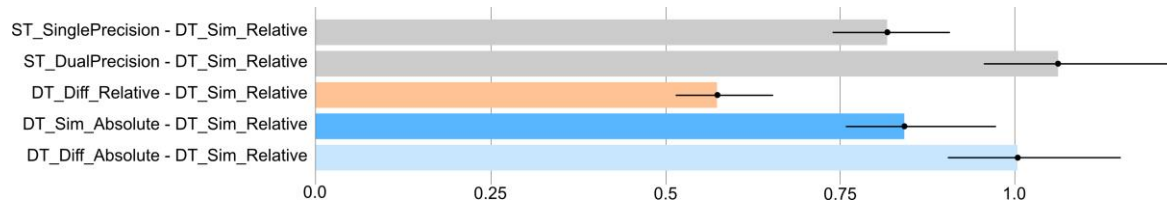


Figure 25. Mean difference of completion time of DT_Sim_Relative over the other techniques in s (95% CIs).

Technique	MeanTime	Lower_CI	Upper_CI
DT_Sim+Diff_Relative / DT_Sim+Diff_Absolute	0.89	0.87	0.90
DT_Sim_Relative / DT_Sim_Absolute	0.85	0.84	0.86
DT_Diff_Relative / DT_Diff_Absolute	0.93	0.90	0.94

Table 6. Ratio analysis of the completion time of dual-thumb relative techniques over absolute techniques in s (95% CIs).

Technique	MeanTime	Lower_CI	Upper_CI
DT_Sim+Diff_Absolute - DT_Sim+Diff_Relative	0.64	0.55	0.75
DT_Sim_Absolute - DT_Sim_Relative	0.84	0.76	0.97
DT_Diff_Absolute - DT_Diff_Relative	0.43	0.32	0.58

Table 7. Mean difference analysis of the completion time of dual-thumb relative techniques over absolute techniques in s (95% CIs).

Technique	MeanTime	Lower_CI	Upper_CI
DT_Sim_Relative+Absolute / DT_Asym_Relative+Absolute	0.93	0.92	0.94
DT_Sim_Relative / DT_Diff_Relative	0.90	0.88	0.90
DT_Sim_Absolute / DT_Diff_Absolute	0.97	0.95	0.98

Table 8. Ratio analysis of the completion time of dual-thumb similar techniques over different techniques in s (95% CIs).

Technique	MeanTime	Lower_CI	Upper_CI
DT_Diff_Relative+Absolute - DT_Sim_Relative+Absolute	0.37	0.31	0.44
DT_Diff_Relative - DT_Sim_Relative	0.57	0.52	0.65
DT_Diff_Absolute - DT_Sim_Absolute	0.16	0.07	0.27

Table 9. Ratio analysis of the completion time of dual-thumb similar techniques over different techniques in s (95% CIs).

Technique	MeanTime	Lower_CI	Upper_CI
ST_SinglePrecision	7.02	6.57	7.50
ST_DualPrecision	7.24	6.72	8.09
DT_Sim_Relative	5.38	5.02	5.84
DT_Diff_Relative	6.47	6.07	7.02
DT_Sim_Absolute	6.85	6.38	7.46
DT_Diff_Absolute	6.26	5.89	6.80

Table 10. Completion time of distant pointing techniques for the index of difficulty 8 in s (95% CIs).

Technique	MeanTime	Lower_CI	Upper_CI
ST_SinglePrecision	7.92	7.42	8.64
ST_DualPrecision	7.61	7.03	8.33
DT_Sim_Relative	6.29	5.88	6.80
DT_Diff_Relative	7.89	7.39	8.59
DT_Sim_Absolute	7.61	7.14	8.29

DT_Diff_Absolute	8.40	7.84	8.98
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Table 11. Completion time of distant pointing techniques for the index of difficulty 9 in s (95% CIs).

A.2 Additional results for command selection with a two-handed tablet

Technique	MeanTime	Lower_CI	Upper_CI
Linear - Quarter_4_4	166.51	131.30	244.14
Linear - Half_4_4	31.92	-0.70	88.80
Linear - Half_8	118.24	77.78	188.52

Table 12. Mean difference relative to Linear for the first session (95% CIs).

Technique	MeanTime	Lower_CI	Upper_CI
Linear	0.04	0.02	0.07
Quarter_4_4	0.05	0.02	0.07
Half_4_4	0.06	0.04	0.08
Half_8	0.03	0.01	0.05

Table 13. Selection errors by interaction technique for the first session in percent (95% CIs).

Technique	MeanTime	Lower_CI	Upper_CI
Quarter_4_5_6	0.05	0.03	0.08
Quarter_4_6	0.05	0.03	0.07
Half_8_10_12	0.05	0.04	0.07
Half_8_12	0.04	0.03	0.07

Table 14. Selection errors by interaction technique for the second session in percent (95% CIs).

Technique	MeanTime	Lower_CI	Upper_CI
Linear - Quarter_4_4	108.47	68.30	148.48
LinearRight - Quarter_4_4	126.13	88.93	164.85

Table 15. Mean difference relative to Quarter_4_4 for the follow-up study in ms (95% CIs).

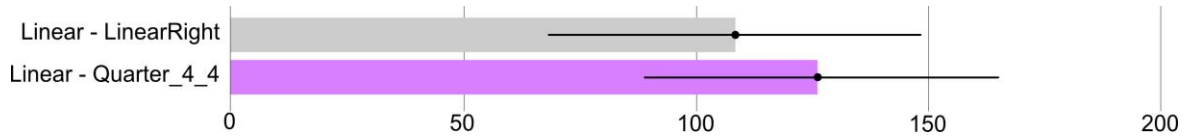


Figure 26. Mean difference relative to Quarter_4_4 for the follow-up study in ms (95% CIs).

Technique	MeanTime	Lower_CI	Upper_CI
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Quarter_4_5_6	0.05	0.03	0.08
Quarter_4_6	0.05	0.03	0.07

Table 16. Mean difference relative to Quarter_4_4 in ms (95% CIs).



Figure 27. Mean difference relative to Quarter_4_4 in ms (95% CIs).