Rapid Command Selection on Multi-Touch Tablets with Single-Handed HandMark Menus

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ABSTRACT
Fast command selection is important for touch devices, but there are few techniques that allow accelerated selection while still providing a large command set. HandMark menus [25] propose the use of the hands as landmarks for fast memory-based selection. However, the original HandMark menus rely on bimanual operation, and earlier studies provided only limited evidence for the value of hand-based landmarks as a reference frame for spatial memory. In this paper we address these limitations. We introduce adapted HandMark menus that can be operated with one hand (while the other hand holds the tablet); the new version changes bimanual selection operations into sequential actions with one hand. We carried out three studies of these HandMark menus. The first study showed that the adapted menus still allowed fast performance and the development of spatial memory, even with one-handed use. The second study focused on the value of hands as landmarks, by comparing HandMark menus against a hidden popup menu. This study showed that using the hand as a reference frame significantly improved performance, and was strongly preferred by participants. Our work extends HandMark menus and shows that they are an effective selection method for tablets, and provides new evidence about the value of the hands as a spatial landmark for interaction.

Author Keywords
Command selection; landmarks; tablets; spatial memory.

ACM Classification Keywords
H.5.2. Information interfaces (e.g., HCI): User Interfaces.

INTRODUCTION
Fast command selection is as important for touch devices as it is for traditional WIMP systems, but techniques that allow quick operation for experts are uncommon on touch interfaces. One promising approach to providing a higher performance ceiling for experts involves the use of spatial location memory (e.g., [10, 22, 25]) – once users learn command locations in a spatially-stable interface, they can make selections based on memory rather than visual search.

In these techniques, an important element in the transition from search-based novice operation to memory-based expert operation is the support provided for the development of spatial memory. Landmarks play a critical role in this development, because they provide an external reference frame for remembering locations. Landmarks provide anchors for people's spatial memory as they move towards full "survey knowledge" [18] of command locations – for example, people can remember items at the corners of a grid better than they remember items in the middle.

A few touch-based selection techniques have considered landmarks and spatial memory as mechanisms for improving performance. For example, the FastTap technique [10] lets people make selections using a multi-touch tap on a grid of items; the structure of the grid provides an external reference frame for remembering command locations (e.g., "top left"). The limited structure and size of the grid, however, means that FastTap provides only a few landmarks, and cannot accommodate a large number of commands (20 items in a 4x5 grid [10]).

A more recent technique uses a rich source of landmarks on a touch interface – the user's hands – to assist the development of spatial learning and to increase the number of available commands. HandMark menus are a bi-manual technique that takes advantage of the user's knowledge of their own hand, and uses the hand as a reference frame for locating commands [25]. Two versions of HandMark menus have been introduced: one that lays out commands around the user's spread-out fingers, and one that arranges commands in a grid positioned between the thumb and forefinger. In both menus, one hand is used as the anchor for the menu, and the other hand is used to select an item.

Initial studies of these techniques showed that they were as fast or faster than equal-capacity standard toolbar techniques, and that they were strongly preferred by participants [25]. In addition, these studies provided early evidence that the benefits of the HandMark menus were associated with the value of the hand as a landmark.

However, there were several limitations to previous work on the HandMark approach. First, the techniques require bi-manual operation, which is feasible for tabletop systems but inappropriate for tablet use in mobile settings (where one hand is needed to hold the device). Second, the previous studies did not strongly focus on the spatial learning that takes place with HandMark menus – they compared HandMark menus only to toolbars at the edge of a table, rather than pop-up menus that are invoked at the user's work location. Therefore, it is still unclear whether HandMarks are fast because of the hand landmarks, or because of other factors such as the simple proximity of the commands.

In this paper we address these two limitations. We first present a new version of HandMark menus that works in a single-handed fashion, and is therefore appropriate for settings where a touch tablet is held in one hand and manipulated with the other. We then report on two studies: one that establishes a baseline for spatial learning with the one-handed versions of the technique, and one that compares the two HandMark techniques with a pop-up menu that does not provide hand-based landmarks.

Our results provide several new findings that argue for the use of hands as landmarks in touch interfaces. Our baseline study shows that both types of HandMark menus work well in single-hand operation, and both allow quick development of spatial memory. Second, our comparison study shows that both of the HandMark menus were significantly faster than the hidden popup menu (by more than 400ms per selection), and were strongly preferred by participants. In addition, the performance improvement arose from differences in the amount of time participants took to think about the spatial location of the item, not from the basic operation of the technique.

Our work makes two main contributions. First, our adaptation of bimanual HandMark menus provide two selection techniques for mobile tablets that are fast and that have high capacity. Second, our studies provide new evidence that using the hand as a landmark is feasible and effective for the development of spatial-memory based selection techniques, even with one-handed use.

RELATED WORK

Four areas of previous work influenced our design and analysis – multi-touch tablet interactions, rapid command selection techniques, use of hands as landmarks, and techniques support large command sets.

Interactions on Multi-Touch Tablets

Direct-touch interaction is the most common way to interact with multi-touch tablets [24]. Even though kinesthetic models suggest that humans are capable of using richer and more expressive forms of interaction with multiple fingers [12], most of the multi-touch gestures available in current tablets are typically limited to a small subset of one and two-finger gestures: tap, press, double tap, drag/flick,

pinch/spread, bezel swipe, and rotate gestures [3]. Research projects have attempted to improve the multi-touch functionality of touch-based systems [2, 3].

Although modern tablets support numerous simultaneous touch points [3], users typically cannot use all the fingers from both hands, as the non-dominant hand is required to hold and orient the device [13]. A few projects have attempted to improve tablet interactions by introducing limited touch interaction for the holding hand – for example, in Wagner et al.'s BiTouch [26] users can interact with thumb or fingers of the supporting hand along with a finger from the dominant hand. Other research has shown how the back of the tablet can be used for meaningful tablet interactions [28]. Moreover, interaction with pen or stylus is also available [13], and several projects use the combination of pen and touch for advanced interaction [13].

Rapid Multi-Touch Command Selection

Rapid command selection is a primary goal in HCI. There are several ways of improving selection, such as the use of memory-based invocation, using proprioceptive memory, and reducing invocation steps.

Memory-based command invocation is generally faster than visually-guided navigation once commands are learned [7, 9]. Many researchers have used memory-based techniques such as gestures [15], hotkeys [19], spatial locations [10], or multi-touch chords [8]. For example, studies have shown that spatial memory is built up through interactions with a stable visual representation [10], and as people gain experience with a particular location, they can easily retrieve that location from memory [10, 25].

Proprioceptive memory can provide new opportunities for rich interactions with multi-touch surfaces. For example, multi-touch marking menus [17], finger-count menus [5], and HandMark menus [25] allow users to associate menu categories with specific combinations of fingers; and with practice, menu invocation becomes fast. However, since a more-complex control action (often requiring both hands) may take more time to recall and execute, these methods do not always improve performance [14] and may be inappropriate for mobile tablet use.

CommandMaps [21], HandMark menus [25] and FastTap [10] try to *reduce the number of steps* required for command invocation and execution. For fast command selection, these techniques use an overlay method to display all the commands at once, as opposed to hierarchical organizations of commands in toolbars, tabs, or standard menus. However, some of these advanced techniques are also unsuitable for hand-held multi-touch tablets – because of the physical characteristics of tablets, such as small screen size, or because of the need to hold the tablet with one hand, or the "fat finger" problem [23]. In our extension to the HandMark technique, we investigate the potential of a proprioceptive memory-based selection method that minimizes the steps required for invocation.

Using Hands as Landmarks
In GUI-based systems, landmarks help users build up spatial memory of different command locations by providing a strong external reference frame that can anchor retrieval. For example, Gutwin et al.'s FastTap [10], and Hidden Toolbars [22] use the edges and corners of hand-held devices (e.g., tablets) as landmarks to organize a grid menu and toolbar. However, these techniques provide only a few landmarks, and with larger command sets, many commands are not near any landmark (e.g., the middle regions of a grid). In some techniques, researchers have looked at adding artificial visual landmarks (e.g., Footprint Scrollbar [1]) to support spatial memory [25].

In all touch-based systems, however, a rich and natural visual landmark is always present – the user's own hands and fingers. Previous work on the HandMark technique [25] showed how hands and fingers can be used as landmarks to support the development of spatial memory for command locations. The two versions of HandMark menus use the space around each hand and its fingers to place command items. People can remember those spatially-stable locations by using the knowledge of their own hands and fingers. However, the bimanual operation of HandMark menus means that they are unsuitable for tablets when the non-dominant hand is used to hold the device.

A few techniques also use proprioceptive knowledge of the hands. For instance, Arpège [8], Multi-finger chords [27], and Finger Count menus [5] use the memory of different finger patterns for better command selection.

Supporting a Large Number of Commands
Many existing memory-based techniques for touch devices support a limited number of commands. For example, Finger Count menus [5] support only 25 commands, while FastTap can only accommodate 19 [10]. Researchers have tried to increase the number of commands through various approaches. HandMark menus use finger combinations of both hands to maximize the number of commands (the HM-Finger technique allows 42 commands, and the HM-Multi technique allows 160) [25]; other techniques such as Marking menus [15], Polygon menus [29], Flower menus [4], Arpège [8], Augmented letters [20] and Octopocus [6] try to increase the command vocabulary by extending gesture range, or allowing chained hierarchies of gestures.

In our work, we adapt HandMark menus [25] so that they can be operated with the dominant hand while the non-dominant hand holds the tablet. Our adaptation maintains the large number of commands possible in the technique, and attempts to maintain the spatial stability that allows users to capitalize on their intimate knowledge of their own hands as a reference frame for spatial command selection.

DESIGN OF HANDMARK MENUS FOR TABLETS
We describe the two adapted HandMark menu techniques, and then consider questions of enabling rapid execution, identifying fingers, and using hands as landmarks. Our work is strongly based on the original HandMark design [25], but several changes were required to enable one-handed use.

Design 1: HandMark-Finger for Tablets
Similar to the original version of HM-Finger for tables [25], our version of HM-Finger for tablets provides modal access to a set of commands (Figure 1). The need to hold a tablet with one hand means that we must we deviate from the bimanual technique and enable command selection using one hand only. In our adapted technique, commands can be displayed by touching down all the fingers of one hand in any order, spreading the hand to provide space between the fingers. The user can rotate and move the menu in any direction by moving the fingers. Unlike the earlier technique, however, command selection is carried out by lifting the fingers from the screen and touching the desired item with any finger. Command icons remain displayed until a selection is made (or until the menu is dismissed by touching on another part of the tablet).

As with the previous version, the spaces around the hand and between fingers are used to display commands (Figure 1). We place one command at the top of each finger (except the thumb), and pairs of commands between fingers. We utilize the large space between the thumb and index finger by placing eight commands in a 2x4 grid (20 items total).

Design 2: HandMark-Multi for Tablets
We also adapted the earlier HM-Multi technique for use on tablets. HM-Multi uses a similar command selection mechanism as HM-Finger, but differs in the placement and number of commands. There are four sets of commands, invoked by placing a specific number of fingers (in addition
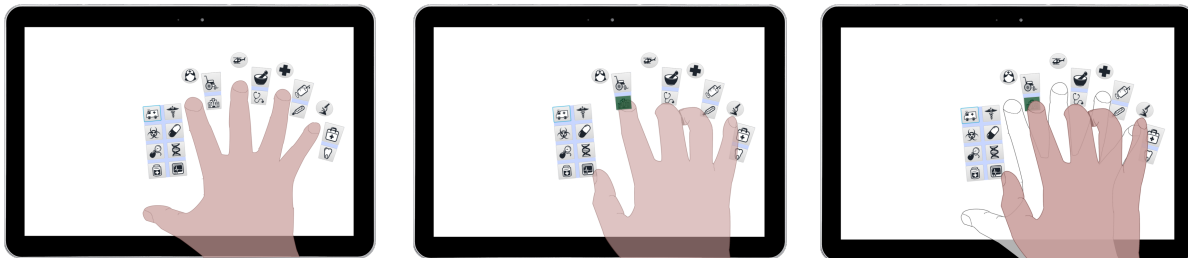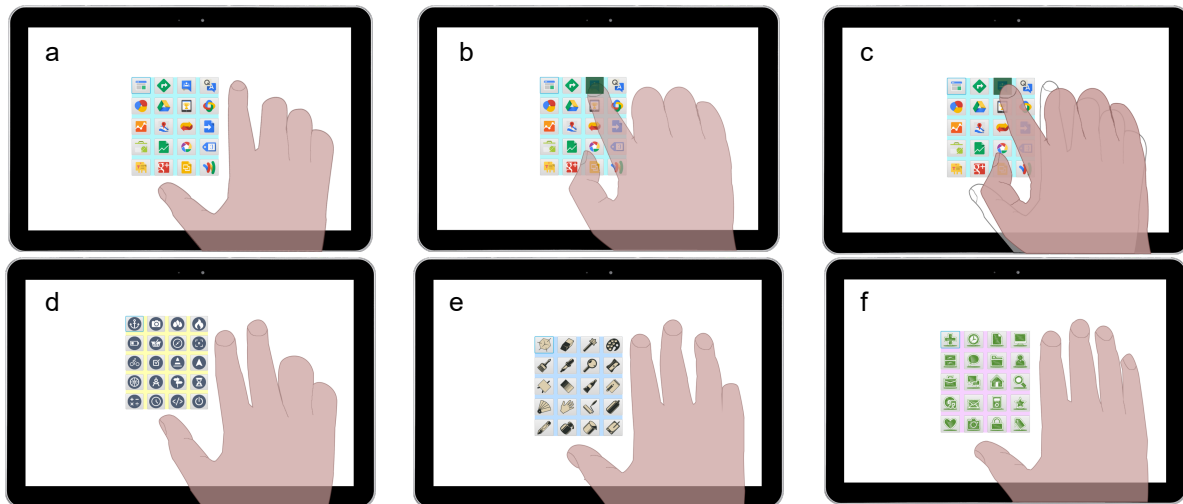

Figure 1. HandMark-Finger selection technique: (left) menu invocation, (middle) item selection after visual search, and (right) rapid selection with two sequential actions – one to invoke the menu, and another to select an item.

Figure 2. HandMark-Multi selection technique: (a) invoking the 1st item set by placing index and thumb in 'L' shape posture, (b) item selection after visual search, (c) rapid selection with two sequential actions – menu invocation, and item selection, and (d-f) invoking 2nd, 3rd, and 4th item sets with specific finger combinations respectively.

to the index finger and thumb) on the screen in an L-shaped posture (Figure 2). For example, to invoke the second set of commands, the index and middle fingers of one hand along with the thumb are placed on the tablet. The menu follows the user's hand as it rotates or moves. HM-Multi uses a spatially-stable 4x5 grid to show commands in the space between thumb and index finger (Figure 2). In total, HM-Multi supports 80 items (4 tabs, and 20 items in each tab).

Enabling Rapid Execution

Spatially-stable organization of commands helps users to build up spatial memory about those commands, and allows command execution by remembering their associated locations rather than searching for a command in the interface [16]. HandMark menus (both Finger and Multi) work on the simple principle of accelerating a basic interaction process. However, instead of the bimanual process used for the original HandMark menus (invoke the menu with one hand, and select with the other), our adapted menus require the user to invoke and select with the same hand (Figure 1, 2). Even though our adapted menus require two sequential actions rather than a bimanual parallel action, we hypothesize that as users become familiar with commands' locations, the two separate steps (menu invocation and command selection) will be integrated into a single learned motor chunk [16]. Chunking of sequential actions is well known in operations such as double clicking, which is considered as a single action for expert users.

Identifying Hand and Fingers

Current multi-touch tablets typically support only ten touch points, and the operating system typically only reports these as (X,Y) locations [3]. For accurate identification of hand and fingers, therefore, we have to rely on fingers' touch points. Previous research showed users' touch points based on distinctive geometric features of hands and comparative positions of different fingers can be used efficiently to

identify specific hand and fingers [25]. For example, when the hand is pointing upwards, the lowermost position always belongs to the thumb, and the leftmost finger is the thumb of right hand (and reversed for left). We adapt this simple hand and finger detection approach used in the original HandMark technique [25] in our work.

Using Hands and Fingers as Landmarks

We designed our HandMark tablet techniques to maintain the use of hands and fingers as landmarks, as well as visual structures in the display of the menu items themselves. Both HM-Finger and HM-Multi provide visual guidance to assist command selection, including the user's hand, the display menu, the selected item, and the menu's gridlines. First, the techniques assign command sets to specific fingers. To invoke a command set, the HM-Finger technique requires all fingers to be touched down on the screen, while HM-Multi requires a specific finger combination.

Second, after invoking a command set, the commands for that menu are displayed on the screen as long as the menu fingers are touch down. Once the fingers are lifted, however, we set a timeout so that commands remain visible for 600ms. As the commands are shown in specific places around the hand, our hypothesis is that these techniques still allow users to remember locations of commands with reference to hand and fingers, even though the hand is lifted from the surface before the actual selection is made.

Third, when an item is selected after visual search, it is displayed in its position with different color for 500ms. This feedback provides confirmation of selection, which helps users to develop spatial memory.

Fourth, we place items in grids for the HM-Multi technique. Previous studies confirmed that grid marks are helpful for spatial memory development [10, 16]. We test people's ability to make selections based on landmarks (only the grid

positions with reference to fingers are shown) in our studies, described below.
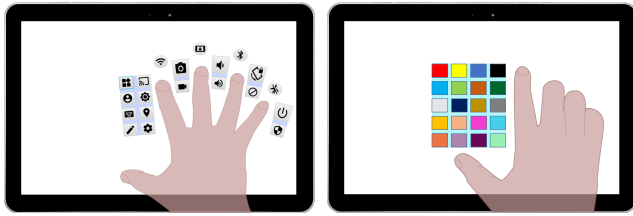
Figure 3. Mockup applications: Android system options in HM-Finger (left), and a drawing app in HM-Multi (right).

Usage Contexts

Our adapted HandMark techniques can be easily integrated with interaction paradigms and applications currently available on tablet platforms. For example, Figure 3 (left) shows a mock-up of an Android options menu with commonly used system settings and applications (using the HM-Finger method). Figure 3 (right) shows a color picker for a simple drawing application using HM-Multi. Other commands sets (accessed with different finger combinations) could be used for tools, shapes, or styles.

STUDY 1: SPATIAL LEARNING AND PERFORMANCE OF HANDMARK MENUS ON TABLETS

Changing HandMark menus from a bimanual to a single-handed technique means that selections are not made with the hand as a permanent reference frame. Since this may compromise people's proprioceptive spatial memory, we carried out a study to determine the baseline performance for the two adapted versions of HandMark. We designed the study to answer three questions:

- Does spatial learning occur when HandMark operation uses two serial touch actions with the same hand?
- What is the speed and accuracy of the adapted menus?
- What is the effect of overlapping item positions from different command sets (in HandMark-Multi)?

Tasks and stimulus. The study consisted of a series of trials, each involving the serial touch actions for both HM menus. In each trial, the participant pressed a start button, and then a stimulus icon appeared on the screen. The participant then invoked the HandMark menu and selected the item with any finger of the right hand (Figure 1, 2). Command icons were organized into sets by color and visual style.

HM-Finger shows 20 commands, of which six were used as study targets. HM-Multi shows four sets of 20 commands (in 4x5 grids); twelve of the 80 commands were used as targets (three from each set).

Procedure and study design. The study used a within-participants design, with order of menu counterbalanced. The menus were introduced to participants and they performed 36 sample selections using HM-Finger and 54 for HM-Multi. Participants then completed several blocks of trials with the same target items (random order, sampling without replacement).

The 15 blocks were grouped into three stages. At the end of each stage, participants performed a "blind" memory test with no feedback, where only the grid lines were visible, but not the icons. The aim of these blind blocks was to test the participant's spatial memory of the items. After each stage, participants were allowed to rest, and after finishing all the stages of each interface they completed a NASA-TLX [11] questionnaire.

Each selection was confirmed by visual feedback – changing the button background to green for correct, and red for incorrect. Incorrect selections could be corrected by simply selecting another item (except in the blind memory tests). Participants were instructed to complete trials as quickly and accurately as possible. For each trial, we recorded task completion time, errors, the number of incorrect sets opened (for HM-Multi only), and data describing individual touches.

Participants. We recruited 20 people (19 right-handed, and 1 ambidextrous) from a local university campus. We could not collect one person's data due to technical difficulties, leaving 19 participants (10 males, 9 females), ages 19-40 (mean 25.7). The same participants also took part in the second study discussed below. The two studies took ~60 minutes, and a $10 remuneration was paid to each participant. Eleven participants reported of owning and regularly using a tablet (> 10 hours per week).

Apparatus. The experiment was conducted on a Microsoft Surface Pro 4, with a 12.3-inch multi-touch 2736 x 1824 screen, and running Window 10. The interfaces were written in JavaFx. During the studies, we removed the physical keyboard, and participants held the tablet in landscape mode with their left hand and operated the system with right hand.

Study 1 – Results

Here we present completion time and error rates for both versions of the adapted HandMark menus without any comparison. We analyzed the 15 feedback-enabled blocks and the three 'blind' memory-test blocks separately.
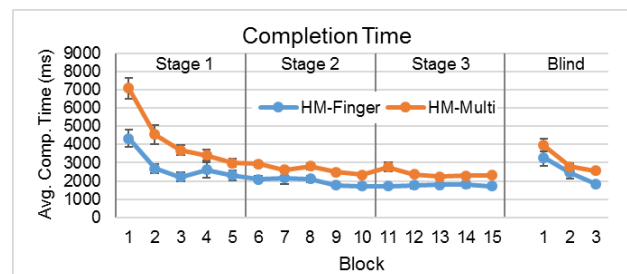
Figure 4. Average trial completion time by method and block.

Selection performance: HM-Finger

Average trial completion times for HM-Finger are shown in Figure 4. For the 15 feedback blocks, mean completion time was 2187ms (s.d. 1228ms); for the blind blocks, mean time was 2531ms (s.d. 1600ms). RM-ANOVA showed significant effect of *block* on completion time for both the

feedback blocks ($F_{14,252}$=8.52, p<.0001) and for the blind blocks ($F_{2,36}$=5.08, p<.0001). Figure 4 clearly shows that trial completion time decreased significantly. In addition, completion time for the final memory-test block was similar to that of the feedback blocks (1848ms).

Selection performance: HM-Multi
Mean completion times for HM-Multi also decreased significantly for the feedback blocks ($F_{14,252}$=29.61, p<.0001) and the blind blocks ($F_{2,36}$=19.62, p<.0001) (see Figure 4). Average completion time with feedback was 3127.ms (s.d. 1648.ms).

Performance with both techniques closely followed the power law of learning: fitting power-law curves to the data in Figure 4 gives R-squared values of 0.88 for HM-Finger, and of 0.94 for HM-Multi. This correspondence suggests that participants were quickly developing spatial memory.

Error rates: HM-Finger and HM-Multi
We analyzed errors per trial by tracking incorrect selections for both techniques. Interestingly, participants made zero errors in the feedback blocks with HM-Finger. For blind blocks, mean errors per trial for HM-Finger were 0.28 in the first block, 0.05 in the second, and 0.03 in the third (overall 0.12 errors/trial, s.d. 0.21). RM-ANOVA showed a significant effect of *block* on errors ($F_{2,36}$=12.94, p<.0001).

HM-Multi had a slightly higher error rate in feedback blocks (mean 0.02 errors/trial, s.d. 0.04), but with no significant effect of block ($F_{14,252}$=0.63, p=.84). However, blind trials showed a significant effect of *block* ($F_{2,36}$=27.64, p<.0001). Means were 0.43 for the first block, 0.2 for the second, and 0.11 for the third (overall 0.25 errors/trial, s.d. 0.23).

Menu	Pos.	No Overlap	Overlap	Overall
Correct	Correct	896 (96.34%)	447 (97.17%)	1343 (96.62%)
Correct	Wrong	22 (2.3%)	8 (1.74%)	30 (2.26%)
Wrong	Correct	0	0	0
Wrong	Wrong	12 (1.29%)	5 (1.09%)	17 (1.22%)

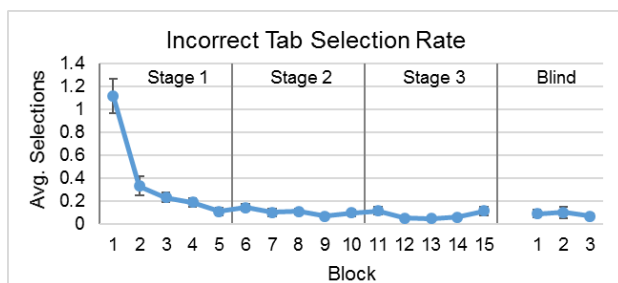**Table 1. Error analysis for HM-Multi in few final blocks.**

Figure 5. Average incorrect tab selection rate by block.

Impact of overlapping item positions in HM-Multi
We analyzed selection errors in HM-Multi to consider overlapping target positions (i.e., targets that were in the same grid location but different sets). Four of the 12 targets overlapped. We analyzed selections from the final stage (blocks 11-15) and last blind block (Table 1). Most errors

occurred by tapping the wrong location in a correct menu (2.26% of selections). There were zero errors with the correct position but in the wrong menu, suggesting that overlapping targets are not a major source of errors.

Incorrect set selections: HM-Multi
There were four command sets in HM-Multi, each assigned to specific combinations of fingers. We recorded the number of times participants invoked an incorrect command set. For the 15 feedback, RM-ANOVA showed a significant effect of *block* on incorrect set selection ($F_{14,252}$=28.27, p<.0001) with 0.19 sets/trial (s.d. 0.34). Figure 5 shows that incorrect set selections reduced substantially by block three. The effect of *block* was not significant for blind trials ($F_{2,26}$=0.27, p=.77).

Subjective responses
Participants' gave positive responses for both HandMark interfaces in NASA-TLX scores (see Table 2). We did not perform a statistical comparison on these data (because of the large difference in the number of items), but it is clear that participants saw the HM-Multi technique as requiring additional effort – likely because of the increased capacity.

HM-Finger	Questions	HM-Multi
3.94(2.37)	Mental	5.52(2.44)
3.68(2.58)	Physical	4.58(2.69)
3.47(2.14)	Temporal	4.68(2.14)
8.21(1.13)	Performance	7.00(1.6)
4.89(2.31)	Effort	6.16(2.27)
2.11(2.02)	Frustration	3.00(2.4)

Table 2. Mean (s.d.) effort scores (0-10 scale, low to high).

In summary, our study showed that people were able to quickly and correctly learn both types of HandMark menus, even with single-handed use and serial (rather than bimanual) operation. Selection errors were very low, and overlapping targets did not cause additional errors.

STUDY 2: EFFECT OF LANDMARKS
Previous studies of HandMarks provide only limited evidence about the value of the hands as landmarks for anchoring spatial memory. In this study, we compared HM-Finger and HM-Multi against a version of the technique that does not strongly orient the grid menu to the position of the hand (the menu is posted underneath the user's hand). We were interested in which version of HandMark menus would perform best, and whether the two versions that are oriented towards the location of the hand performed better.

Study 2 – Method
This study tested three menu systems – HM-Finger, HM-Multi-1Tab (with only one tab of 20 items), and a pop-up menu called HM-Under. We restricted the HM-Multi technique to one tab to equal the number of commands available in HM-Finger. In this variant, all five fingers of the hand were required to display the menu (again, to equalize the invocation to that of HM-Finger). HM-Under was similar, with one set of commands in a 4x5 grid, but

the menu was posted beneath the user's hand so that there was no clear association between the visual image of the hand and the location of items in the grid (Figure 6). We note, however, that this technique had a shorter average distance to commands than the other techniques.
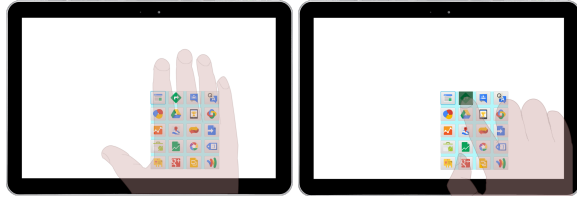
Figure 6. HandMark-Under method used in Study 2: menu invocation (left), and item selection (right).

Tasks and stimulus. Similar to the study discussed above, each participant performed a series of selection trials with each of the three menu systems. In each trial, a stimulus item was displayed on the screen, and participants selected the corresponding item to complete the trial. Correct and incorrect selections were confirmed with color feedback. For incorrect selection, the trial continued until the correct item was selected. To avoid learning effects, we used new command icons for this study.

Procedure and study design. The study used a within-participants design. Each menu consisted of 18 blocks of trials (using 6 items as targets), divided into three stages (5 blocks of regular trials, followed by one blind block), as described above. Participants went through a practice session before starting each menu.

The order of the menu system was counterbalanced, and items of each block appeared in randomized fashion. At the end of each menu, participants took a break and filled out a NASA-TLX [11] questionnaire; after finishing all three menus, they gave their overall preferences.

Participants and apparatus. All 19 participants from our first study participated in this study as well, and the study was conducted with the same multi-touch tablet.

Study 2 – Results

Selection performance of the three techniques
We analyzed average trial completion time for the 15 feedback blocks and 3 blind blocks separately. For feedback blocks, HM-Multi-1Tab performed best (mean 1776ms, s.d. 1048ms) compared to HM-Finger (1960ms, s.d. 1182ms) and HM-Under (2365ms, s.d. 2257ms) (see Figure 7).

RM-ANOVA showed a main effect of *interface* ($F_{2,36}$=3.26, p=.05). As shown in Figure 7, completion times decreased across trial blocks for all the interfaces; RM-ANOVA showed a significant effect of *block* ($F_{14,252}$=19.16, p<.0001), and significant interaction effect between *interface* and *block* ($F_{28,504}$=2.03, p=.002). Performance with HM-Under was not as consistent as the other two methods, and was slower overall because of the occlusion. However, we suggest that although the menu was occluded

by the fingers and hand, users could use the hand as a landmark to aid development of spatial memory.
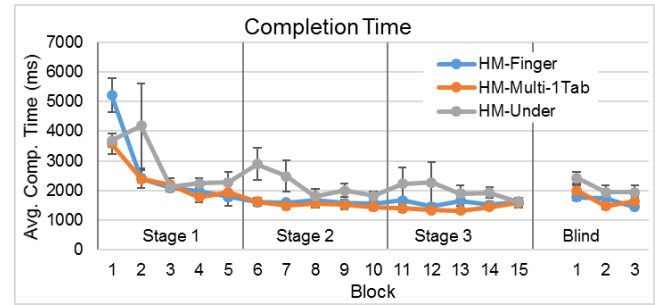
Figure 7. Average trial completion time by method and block.

We explored the issue of spatial-memory development for the three different techniques by again fitting the data to power-law curves corresponding to the classical power law of learning. The R-squared values were 0.90 for HM-Multi, 0.78 for HM-Finger, but only 0.64 for HM-Under – suggesting that participants were not able to learn item locations as well in the hidden pop-up menu.

For blind blocks, HM-Finger performed best (1653ms (s.d. 464ms), and the effect of *interface* was significant ($F_{2,36}$=5.4, p=.009). RM-ANOVA also showed significant effect of *block* ($F_{2,36}$=10.17, p<.0001), but no interaction between *block* and *interface*.
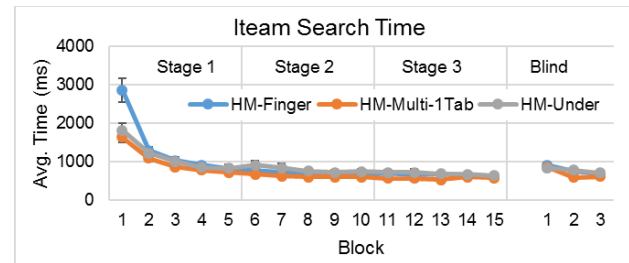
Figure 8. Average item search time by method and block.

We further analyzed performance by calculating the time from invocation of the menu to the selection (i.e., the time from stimulus appearance to menu invocation was removed). RM-ANOVA showed a significant effect of *interface* ($F_{2,36}$=8.19, p=.001); as shown in Figure 8, HM-Multi-1Tab was the fastest technique (mean 735ms, s.d. 390). HM-Finger was slow at the beginning (when users need to visually search for items) but by the second block performance with this technique was similar to the others.

This analysis shows that the additional time needed for the HM-Under technique (shown in Figure 7) arises primarily between stimulus appearance and menu invocation – and again we suggest that this indicates that users were having more difficulty remembering where the item was before starting the process of selection.

Error rates
Participants made zero errors in the feedback blocks. For the blind blocks, RM-ANOVA showed a similar pattern to

study 1: HM-Finger had 0.053 errors/trial, s.d. 0.1, HM-Multi-1Tab had 0.099 errors/trial, s.d. 0.19, and HM-Under had 0.11 errors/trial, s.d. 0.16, with no main effect of *interface* ($F_{2,36}$=2.44, p=.101). There was a significant effect of *block* ($F_{2,36}$=17.73, p<.0001), and a significant interaction between *interface* and *block* ($F_{4,72}$=2.94, p=.026). These results also suggest that the presence of the hand as a landmark made the HM-Finger technique in particular less error-prone.

	HM-Finger	HM-Multi-1Tab	HM-Under	χ_r^2	*p*
Mental	3.47(2.04)	3.21(2.07)	4.0(2.65)	3.18	.2
Physical	3.79(2.88)	3.63(2.77)	5.21(2.74)	8.71	**.01**
Temporal	3.53(2.06)	3.37(1.92)	4.16(2.22)	5.08	.08
Performance	8.32(0.95)	8.53(1.17)	7.32(1.67)	9.03	**.01**
Effort	4.32(2.83)	4.68(3.13)	5.47(2.82)	8.84	**.01**
Frustration	1.58(1.8)	1.58(2.01)	3.21(2.66)	10.45	**.01**

Table 3. Mean (s.d.) effort scores (0-10 scale, low to high).

Subjective responses
Friedman tests on NASA-TLX responses showed several significant differences (see Table 3) in physical demand required, perceived performance, effort required, and level of frustration. In all cases, HM-Finger and HM-Multi-1Tab scored better than HM-Under.

Preference counts (see Table 4) showed that most participants (58%) preferred the HM-Finger and HM-Multi techniques. HM-Finger also preferred for facilitating easy memorization. Only one participant of the 19 preferred HM-Under on any measure.

	HM-Finger	HM-Multi-1Tab	HM-Under	None
Speed	8	10	0	1
Accuracy	8	8	0	3
Memorization	9	6	0	4
Comfort	8	10	1	0
Overall	11	8	0	0

Table 4. Count of participant preferences.

Participant comments
Participants preferred the HM-Finger and HM-Multi-1Tab almost equally, and these preferences were also reflected in the comments. HM-Finger method had more landmarks, allowing more opportunity to use proprioception: as one participant said, *"I can see every icon easily in the gaps between my fingers, and it requires an easy hand gesture."* Another person commented how their fingers facilitated memorization: *"I could use their location as reference."*

Others preferred HM-Multi as it required less visual search. One participant said *"everything was packed into one spot so I had to look only one spot."* Others commented about the occlusion problem with other methods: one stated that in HM-Finger *"I had to stretch my fingers apart to see all the icons."* Another participant commented that with HM-Under, *"I had less confidence in the location of icons."* Finally, all participants indicated that they used the hand and fingers as landmarks for all the three methods, even if the icons were partially occluded (HM-Finger and HM-Under).

STUDY 3: OVERLOADING SPATIAL MEMORY
When memory-based techniques are used in real life, there is a possibility that one application's command associations could interfere with another's commands. Because participants learned one set of icons for Study 1, and a different set for Study 2, we saw an opportunity to test this real-world issue.

As a final test at the end of the experiment, we asked our 19 participants to perform one final 'blind' memory test using all of the targets from both Study 1 and Study 2 (HM-Finger version). The 12 targets were used as stimuli in random order for the memory test. We were interested in whether participants' memory of the Study 1 command locations decayed after learning the locations in Study 2.

Study 3 – Results
As shown in Table 5, participants were able to recall a large majority of both command sets. However, items from Study 1 were recalled less accurately (72% overall) than items from Study 2 (91% overall). These results do not indicate whether the reduced accuracy is because of interference or simply the passage of time (participants had not used the Study 1 icons for about 20 minutes, whereas they had just used the Study 2 icons). However, this finding suggests that further research is needed on the issue of decay in memory-based techniques.

	No Overlapping		Overlapping		Overall	
Selection	**Study 1**	**Study 2**	**Study 1**	**Study 2**	**Study 1**	**Study 2**
Correct	60(79%)	69(91%)	22(58%)	35(92%)	82(72%)	104(91%)
Wrong	16(21%)	7(9%)	16(42%)	3(8%)	32(28%)	10(9%)

Table 5. Error analysis for Study 3.

DISCUSSION
Past research indicated that proprioceptive knowledge of hands and fingers can be used as landmarks for better bimanual multi-touch interaction on tabletops [25]. Our results suggest that the same approach can be used effectively for single-handed interactions on tablets:
- Study 1 showed that both HM-Finger and HM-Multi allowed rapid selections (completion time: ~2 seconds).
- Study 2 showed that using hands as landmarks improved performance: HM-Finger and HM-Multi outperformed HM-Under and were strongly preferred.
- Studies 2 and 3 showed that overlapping targets are not a main source of errors, but that location memory can degrade because of time or because of interference.

What Makes HM-Finger and HM-Multi Perform Well?
Study 1 and 2 showed that both HM-Finger and HM-Multi facilitate rapid command selection once participants are familiar with item locations (Figure 4, 7). The main reason for this performance is in the menu arrangement and item selection mechanism. For both techniques, menu items are placed in spatially-stable positions. When they are unfamiliar with the locations, users must visually search for a desired item (and explore multiple tabs with HM-Multi). After practice, users can use fingers as landmarks to

remember item positions, and perform a "chunked" invoke-and-select sequence that is similar to double-clicking.

Overall, the adaptation of the HandMark menus to one-handed use was highly successful. The final performance of our serial version of the technique was very similar to results from previous studies (both versions of HM-Finger take approximately 2.0 sec/selection, and both versions of HM-Multi take approximately 2.5 sec/selection). It is worth noting that for each trial, we analyzed the completion time that started with the appearance of a stimulus, and stopped after a successful command selection.

In memory-based selection techniques, some errors are inevitable [10, 16]. However, our studies showed that the adapted HandMark menus had extremely low error rates. We believe that the low error rate arises from the switch from parallel bimanual to serial operation – the latter enforces a short period between invocation and selection where the visuals of the menu can be used to check the selection.

Relative Merits of HandMark Menus for Tablets

In general, both techniques have relative strengths and weaknesses depending on the usage situation. HM-Finger has the potential of higher performance in situations where fewer commands are used, as it can support only 20 items. However, sometimes items were partially occluded by parts of the hand (as reported by few participants); this was not a major problem, however, as the menu's display can be adjusted by moving the hand. A main advantage of HM-Finger technique is that each finger is very close to some of the locations – in future, we plan to test menus where frequently-used items are placed in easier-to-reach locations (such as around the index finger).

The HM-Multi technique is more suitable for interfaces where larger command sets are required. Our current design supports 80 items (20 in each set). The multiple tabs can be difficult to learn at first, because there is no clear indication of which finger combination is required (thus leading to the incorrect tab selection errors discussed in Study 1). However, our participants quickly overcame this limitation (and we note that moving between tabs is fast enough that even when users make tab errors it does not greatly slow the technique).

Another advantage of HM-Multi is that all the items are placed in one general location, making initial visual search easier. Additionally, HM-Multi does not suffer from the occlusion problem, and involves a simpler hand posture when invoking the menu. Even though HM-Multi does not have as rich a set of landmarks compared to HM-Finger, the modified single-tab version of it performed as well or better than HM-Finger in Study 2. Therefore, HM-Multi can also be used as a single menu for a small number of items.

Finally, more research is required with both single-handed HandMark techniques to explore integration with current multi-touch tablets or use in smaller touch devices.

Spatial Menus for Multi-Touch Tablets

Although some previous research has used spatial memory for tablet interactions [10, 22], our work is the first attempt to using the rich landmarks of hands and fingers on handheld touch devices. In addition, our work provides additional evidence for the value of spatial-memory-based interactions for touch screens. In future work, we plan to also compare learning rates and overall performance with other spatial and proprioceptive techniques such as Finger-count menus [5], Marking menus [15], and FastTap [10].

Limitations

We investigated only a subset of the likely issues present in real-life use. First, we designed and tested the prototype for right-handed people only; however, with simple changes the techniques can be used by left-handed users. Second, partial occlusion is an issue for HM-Finger, as some people with smaller fingers faced problem occasionally in the early stages of use. In future, we plan to explore this issue by exploring different arrangement of items or automatic scaling of items with finger size. Third, there is a limitation with the hand and finger detection process, in that our method assumes the origin of the user's hand; further work is required to allow HandMark menus with any hand orientation. Finally, advanced sensing could enable further exploration of HandMark-style interactions on and around the tablet, including the back or bezel of device.

CONCLUSIONS AND FUTURE WORK

The original HandMark menus were introduced as a way to provide both a large number of commands and a mechanism for spatial-memory-based acceleration. Two limitations of previous work were that the technique required bimanual use, making it unsuitable for handheld tablets, and that previous studies provided only initial evidence about the value of using hands as landmarks (in addition, the bimanual approach was considered to be an integral part of the landmarking in the original technique). We addressed both of these limitations in this paper – we adapted the technique to single-handed use by serializing the bimanual operation of the menu, and we carried out three studies to test the value of hands as landmarks (as well as several other practical aspects of the technique). Our results provide clear evidence that HandMark menus are a feasible and useful technique for tablets, and that they support development of spatial memory and fast performance even when used with a single hand. In addition, we clearly showed that having the hand as a reference frame for the menu contents provides significant performance and preference advantages.

In future work, we will continue the development of the HandMark approach, and will test the technique in real-world settings and compare it to other memory-based selection methods. We are developing an Android component to allow the use of HandMark menus in real tablet interfaces, and are building several example systems (including the applications mocked up above). We are also

interested in improving the assignment of commands to the different spaces around the hand – for example, to put frequently-used commands around the index finger. We are also interested in comparing HandMark menus to systems that introduce artificial landmarks on the display surface, and potentially combining the two approaches. Finally, we will run studies that focus on issues of decay and interference in memory-based methods, to better understand how techniques like HandMarks can be deployed in the real world.

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