Exploring Optimal Placement of Head-Based Hierarchical Marking Menus on Smartphones

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Abstract. Studies have shown that hierarchical marking menus, which allow for the navigation of menu items through a hierarchy, are faster at accessing items compared to traditional menus. Though hierarchical marking menus have been studied in non-touch-based input methods for smart devices (such as gaze-based input with VR), little is known about optimal menu placement in hierarchical structures for smartphones. In this paper, we investigate the optimal placement of subsequent marking menus within a menu hierarchy utilizing head-based input on smartphones. We examine how to position a second menu by considering the distances and directions from the first menu while examining two selection techniques: Dwell and Border Crossing. Results from a user study involving menu item selection tasks reveal that users are faster at selecting items when the second menu partially overlaps the first menu and appears in the direction where the target in the first menu is located. Furthermore, results showed that while Dwell was slower than Border Crossing, it resulted in significantly fewer errors in selecting items in the hierarchical menu. Based on these findings, we provide design guidelines for placing menus in the hierarchical marking menu setting.

Keywords: Marking Menus · Hierarchical Menus · Smartphones

1 Introduction

Hierarchical marking menus present a second menu with items relevant to the selected item in the initial menu after users select an item in the initial menu. Prior studies showed that hierarchical marking menus are effective in expanding the number of menu options available to users by allowing them to select items from multiple submenus through the use of compound strokes with a cursor [11]. These menus have demonstrated the potential to decrease selection time when compared to conventional menus [5] and support the gradual transition from novices to experts [11]. Though prior work investigated factors that can affect

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user performance such as the number of menus and items in each menu, little is known about the optimal menu placement of hierarchical marking menus.

Hierarchical marking menus have been implemented with both touch-based inputs [12,21] and non-touch-based inputs [17,23] on various devices. For example, touch-based marking menus have been used on desktops [9], and smartphones [21]. Prior work explored marking menus that are built for smartphones [7], using the smartphone screen for interaction in wearable devices [19], and using the touch facility to help learn mid-air gesture set [9]. However, little is known about the ideal placement of menus within a hierarchy.

Smartphones provide users with the ability to access information while on the move. As a result, people rely on smartphones in various situations, including when their hand is occupied with carrying objects. Previous studies indicated that touch input during such one-handed cases could have a negative impact on users' smartphone performance and experience [10] Consequently, researchers proposed alternative input methods, such as head-based input and eye-based input, for interacting with smartphones in such situations. In such a one-handed situation, people hold their smartphones in front of their faces to facilitate access to on-screen content. In this holding posture, the device's front camera can detect the user's face and track their head movements, which opens up possibilities for novel non-touch-based input for spatial interactions and user interfaces [24]. Despite previous research on marking menus with smartphones, there is still limited understanding regarding the optimal placement of hierarchical marking menus on smartphones for non-touch input such as head movement.

In this paper, we investigated the optimal placement of a subsequent marking menu within a hierarchical menu structure with head-based input on smartphones. Specifically, we studied menu placement techniques that involve positioning a subsequent menu by considering the distances and directions from the previous menu. Additionally, we explored the effectiveness of two selection techniques, Dwell and Border Crossing, within the context of a hierarchical menu structure. We conducted a user study where results showed that users could quickly and accurately select menu items when the second menu partially overlapped the first menu and was positioned in the direction of the target in the first menu. Furthermore, we observed that while Dwell was slower than Border Crossing, it resulted in significantly fewer errors when selecting items. Based on the results, we provided recommendations for the design and optimization of the placement and selection techniques that can significantly enhance users' experience accessing items on hierarchical menus.

2 Related Work

2.1 Marking Menu

The original marking menu, introduced by Kurtenbach and Buxton in 1993 [11] uses a "mark" to indicate the menu item to be selected. To choose an item, the user draws a mark through it. Researchers explored several extensions of the marking menu in the past. For instance, Wave menu [1] is designed to improve the novice mode of the traditional hierarchical marking menu by facilitating the sub-menu inside the previous menu. The Flower menu [2] and the Zone and Polygon menu [25] leverage the marking menu to contain a larger number of items, which can be accessed by straight and curved gestures. OctoPocus [3] extends the idea of marking menus for learning command sets that use gesture sets, making it faster than a hierarchical marking menu.

2.2 Selection on Marking Menu

Prior work explored touch and non-touch *Selection Techniques* with marking menus. For instance, Francone et al. [7], Salkanovic et al. [26], Zheng et al. [21] leverage touch input on the screen to interact with marking menus. Researchers also explored extended-input capabilities to interact with marking menus. For instance, Lepinski et al. [12] proposed a technique that goes beyond a single-touch input, leveraging multi-touch input where five fingers are used to determine the command. Non-touch based input has also been investigated with marking menus. A popular selection method for any gaze-based navigation system is Dwell [18], where users need to keep the pointer (e.g., cursor) static for a certain amount of time. Border Crossing [23] selection is another technique that lets users select an item by crossing the border of an item in a pie menu. However, overshooting, false activation or incorrect selection can occur if they are not handled properly. To this end, we looked into the Dwell and Border Crossing *Selection Techniques* while keeping the marking menu size and depth constant.

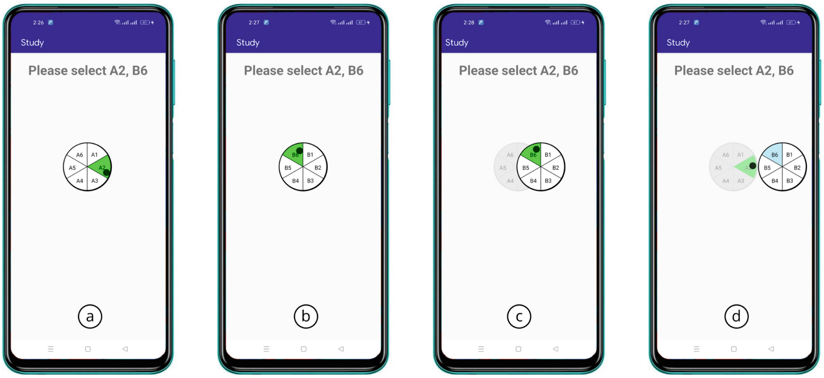

Fig. 1. (a) The cursor is moved on top of a target item in the marking menu. (b) In *In place* condition, the second menu appears on top of the first menu. However, in the (c) *Partial overlap* condition, the center of the second menu appears on the border of the first menu, thus partially overlapping the first menu. (d) In the *Disjoint* condition, the second menu appears in a location without overlapping the first menu.

2.3 Head Based Interaction

Head-based interaction has been explored in various fields. For instance, head-based controls have been studied as keyboard inputs for extremely small key sizes [8]. Gaze-based interactions, as well as gaze and head combined interactions, have also been explored [16]. With a study, Qian et al. [20] found that head-pointing worked faster than the combined eye and head input in wearable virtual reality. Prior work also explored head-based interaction for people with disabilities [14]. Although many studies have explored head gesture interaction techniques on smartphones, to the best of our knowledge, no study has investigated head-based interaction for marking menu navigation on smartphones. Therefore, in our work, we have explored head-based interaction to navigate marking menus.

3 Design Space

There are several factors that affect the placement of the subsequent menu within a hierarchical menu structure, which we discuss below:

3.1 Menu Distance

Distance refers to the relative position of the second menu to the first menu when the menus are displayed one after another. We discuss the possible *Distance* options below:

In-Place: The in-place menu placement style ensures that the second-depth menu appears exactly where the first menu appeared. We included this style in our study since no prior work had explored its use with head-based inputs. With this style, we anticipated that users would require less cursor movement to make selections as the second menu appears on top of the first menu (Fig. 1b).

Partial Overlap. The partial overlap style of menu placement is characterized by the appearance of the second-level menu in a way that partially overlaps with the first-level menu. Specifically, the center of the second menu appears on the circumference of the first menu, resulting in the second-level menu touching the center of the previous menu, as illustrated in Fig. 1c. We anticipate that this style minimizes the cursor movement between menus since the second-level menu overlaps with the prior menu.

Disjoint. The Disjoint menu placement style ensures that the second marking menu appears without overlapping the first menu. Here, the border of the second menu touches the border of the first menu (Fig. 1d). We anticipate that this style will help in reducing the error rate for the head-based input as well.

3.2 Menu Direction

Menu Direction refers to the positioning of the second menu in a diagonal direction from the first menu. We considered the following two menu directions:

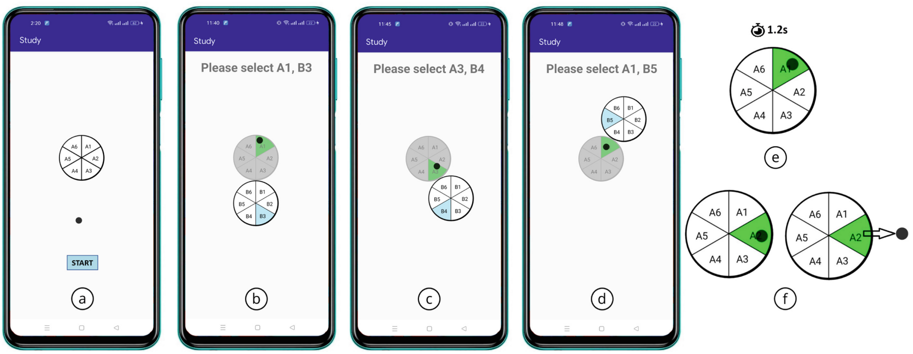

Fig. 2. (a) A trial begins when the start button is selected by moving the cursor on top of it. The fixed menu direction (b) shows the second menu in a specific direction from the first menu. The dynamic approaches (c-d) show the second menu appearing in a direction based on the previously selected item. In (c), the bottom-right item was selected in the first menu, and the second menu appeared in the same direction. In (d), the top-right item was selected in the first menu and the second menu was displayed in the corresponding direction. (e) Dwell selection technique, where the cursor is required to remain on a menu item for 1.2 s for selection, and (f) Border Crossing, where the cursor moves from inside the menu to the outside through a menu item for selection.

Fixed. In a fixed direction condition, the second menu is always displayed at a predetermined position, regardless of the selected item in the first menu. For our study, we placed the second menu at the bottom of the first menu for the fixed placement condition (Fig. 2b). However, the separation between the first and second menu displays is determined by the *Distance* condition.

Dynamic. In the dynamic direction, the second menu appears dynamically based on the item selected in the first menu. In this condition, the second menu is positioned with an angle so that its center is aligned with the angle bisector of the angle formed by the borders of the selected menu item. The separation between the first and second menus is determined by the distance choice, which can be either Disjoint or Partial Overlap. Note that the dynamic direction does not affect when the distance method is set to In Place (Fig. 2 (c–d)).

3.3 Selection Techniques

Selection Technique refers to invoking a specific item from the menu. It plays an essential role in any task to execute an action (e.g., opening a browser with a click). We chose two of the most popular selection techniques that do not rely on any external hardware to make them feasible on smartphones.

Dwell. In this *Selection Technique*, users are required to keep the cursor inside a marking menu item for a certain amount of time in order to select it. We found that eye gaze- and head-based systems typically use a dwell time ranging between 0.5 s and 1.5 s [22]. After a pilot study, we kept the dwell time at 1.2 s. To trigger a selection with dwell, we used a timer that started when the circular cursor entered a menu item, and the item was selected when the cursor remained within the item for the predefined dwell time (i.e., 1.2 s).

Border Crossing. In the Border Crossing *Selection Technique*, a menu item is selected when the cursor moves out toward the outer border of the item of the marking. We anticipate that the technique would be useful compared to Dwell considering the fatigue and discomfort that can arise from a prolonged head fixation on a single menu item (Fig. 1f).

4 User Study

Our study has two main goals: (G1). Explore the most suitable positioning strategy for the second marking menu concerning the first menu when an item in the latter is selected. (G2). Identify appropriate *Selection Technique* for invoking items from hierarchical marking menus.

4.1 Participants and Study Implementation

Twelve participants (8 males, all right-handed), aged between 20 and 25, were recruited from the local university. The average age of the participants was 22.75 years (SD. 1.05). They had little or no prior experience with head-based interfaces; however, had an average of 9.42 years of experience using smartphones.

We developed an Android application for the user study, which was run on a Realme 9 Pro+ smartphone (screen resolution 1080×2400 pixels). To track a user's head, we used MediaPipe Face Detection [15], which can extract 3D face landmarks from a camera input in real time. We leveraged OpenCV Perspective-n-Point (PnP) [4] pose computation libraries to determine head rotation angles in horizontal and vertical directions. The horizontal head movement is then mapped to control the cursor to the left and right on the screen and the vertical head movement to move the cursor up and down - thus allowing users to move the cursor horizontally, vertically, and diagonally. The cursor movement is mapped to move 6 dp (i.e., 18 px) horizontally for each degree of head movement. In contrast, the smaller range of vertical angles and the larger number of pixels in that direction result in a higher amount of cursor movement per degree of head movement, specifically 24 dp (i.e., 72 px) for each angle in the vertical direction. A similar mapping was used in a prior work [24].

4.2 Menu Placement and Selection Techniques

We devised the following placement techniques for the second marking menu based on two directions and three menu distances. (a) *Fixed + Disjoint (FD)*: The second menu appears right below the first menu. The position of the second menu always remained fixed in this condition. (b) *Fixed + Partial Overlap (FPO)*: The second menu appears below the first menu, as we saw in FD. However, in this case, the center of the second menu is located at a distance equal to the radius of the menu r, resulting in partial overlap with the previous menu. (c) *Fixed + In Place (FIP)*: The second menu appears at the same position as the menu from the previous depth. The position of the second menu remains fixed in this combination, thus, completely overlapping the first menu. (d) *Dynamic + Disjoint (DD)*: The second menu appears at a fixed distance of $2r$ from the previous menu, and its center is oriented towards the direction of the selected target item in the first menu. and (e) *Dynamic + Partial Overlap (DPO)*: With this technique, the center of the second menu appeared at a distance of r. The second menu always appeared in the direction of the previous targeted item, partially overlapping the previous menu. Importantly, Dynamic + In-Place was not investigated as it would behave exactly like Fixed + In-Place. As mentioned before, we investigated two *Selection Techniques*: Dwell and Border Crossing. We anticipate that the selection time with Border Crossing will be shorter than Dwell because Dwell requires additional 1.2 s for selection. However, Border Crossing requires users to be cautious when moving the cursor and might be more susceptible to errors than Dwell.

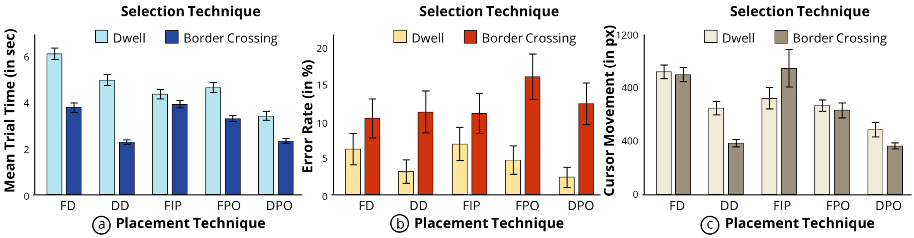

Fig. 3. Mean (a) trial time (in sec), (b) error rate (in %), and (c) cursor movement (in px) for *Placement Techniques* clustered by *Selection Techniques*.

4.3 Task, Procedure and Design

Our study involved tasks in which participants had to select items from marking menus. Wenmin Li et al. [13] suggested using a maximum of eight items on marking menus and having two depths to yield the best performance. Consequently, we had 6 items in a marking menu in two depths. Initially, the first menu was visible without displaying any target item. We decided to use a menu with a 120dp diameter to ensure that a second menu can be placed to the sides in Dynamic directions - ensuring that no part of the second menu extends beyond the screen. A start button was placed below the target close to the edge of the screen (Fig. 2a). Participants could initiate a trial by selecting the start button using a circular cursor controlled with the head movement. This action makes the target item highlighted in sky blue on the menu. We also included textual instructions (e.g., "Please select A1, B3") on top of the screen. If a participant selected a wrong item, an error message ("Wrong Selection") appeared at the top of the screen. Conversely, if the correct target items were selected, a "Successful Trial" message was displayed. When the cursor was placed over a non-target or the target item, it was highlighted with red or green color, respectively. The menu items were arranged in a 360° circular layout in both depths as shown in Fig. 2. Thus, each item on the menu had an angle of 60°. The labels for the menu items started with a letter ('A' and 'B' for the two depths) and ended with a number, ranging from 'A1' to 'A6' and 'B1' to 'B6'. A trial started once participants selected the *Start* button by moving the cursor over it. A trial ended when either the participants selected both of the target items correctly (i.e., successful trial) or they selected a wrong target item in any of the menus (i.e., error trial). The error trials were then re-queued into the remaining trial pool. We instructed the participants to keep their hands steady while allowing head movement, as we were specifically interested in utilizing head movement for the interaction.

The study used a within-subjects design with two primary independent variables: *Placement Technique* with 5 levels (FD, FPO, FIP, DD, DPO) and *Selection Technique* with 2 levels (Dwell, Border Crossing). Each trial was repeated 10 times for each participant - yielding a total of 5 *Placement Techniques* × 2 *Selection Techniques* × 10 *Repetitions* × 12 Participants = 1,200 trials in total. We counterbalanced the *Selection Techniques* across participants and randomly selected the *Placement Techniques* to conduct the study.

4.4 Measures and Results

The application recorded user performance-related metrics, including trial time, error rate, and cursor movement for all the trials. The trial time was measured from the time when the users clicked the start button to the time when the trial ended successfully. An error was recorded when the participants selected a non-target item in the first or second menu. Cursor movement was calculated by measuring the total path covered by the cursor during a trial. Additionally, we obtained subjective feedback from participants regarding the techniques.

We removed 16 outliers (1.3%) from the data where the trial times were 3 SD away from the mean. We then performed repeated measures ANOVA and Bonferroni adjusted post hoc pairwise comparisons to analyze trial time and cursor movement. Post-hoc pairwise comparisons were Bonferroni adjusted (α-level = 0.05). Friedman tests with Wilcoxon tests were used for post hoc pairwise comparisons to analyze error rates. We define the error rate by the number of trials with an incorrect selection divided by the total number of trials.

Trial time. RM-ANOVA showed a significant effect of placement technique on trial time ($F_{4,36} = 16.44$, $p < 0.001$, $\eta^2 = 0.65$) We found that DPO ($M = 2.74s$) was the fastest, followed by DD ($M = 3.65s$), FPO ($M = 3.83s$), FIP ($M = 4.25s$) and FD ($M = 5.05s$). Post hoc pairwise comparisons showed that DPO was significantly faster than all other techniques, and DD and FPO were significantly faster than FD. There were no other pairwise statistically significant differences. RM-ANOVA also showed a significant effect of the *Selection Technique* on trial time ($F_{1,9} = 32.41$, $p < 0.001$, $\eta^2 = 0.78$) Post hoc pairwise comparisons showed that Border Crossing ($M = 3.15s$) was significantly faster than Dwell ($M = 4.66s, allp < 0.001$). This is understandable as Dwell was taking an additional 1.2 s for selection, while Border Crossing does not need a further delay to select an item from the marking menu.

Error Rate. The overall error rate was 9% (i.e., the percentage of trials that contained one incorrect selection in the first or the second menu). Figure 3b shows the mean error rates across different *Placement Techniques* and *Selection Techniques*. We observed error rates of 8%, 7%, 9%, 11% and 8% for FD, DD, FIP, FPO, and DPO placement techniques, respectively. However, we didn't find any significant effect of placement technique on the error rate ($\chi^2(4, N = 12) = 8.021, p = 0.08$). Results showed that the *Selection Technique* had an effect on the error rate ($\chi^2(1, N = 12) = 8.33, p < 0.01$). Pairwise comparisons showed that Dwell (5%) caused significantly fewer errors than Border Crossing (12%).

Cursor Movement. Results of the RM-ANOVA revealed a significant effect of placement techniques on cursor movement ($F_{4,36} = 20.13$, $p < 0.001$, $\eta^2 = 0.69$). DPO ($M = 379.57px$) was found to be the placement technique with the least cursor movement, followed by DD ($M = 517.76px$), FPO ($M = 606.79px$), FIP ($M = 699.32px$). FD was the technique that required the most cursor movement to select items on the marking menus ($M = 895.77px$). Post hoc pairwise comparisons indicated that DPO required significantly less cursor movement than all other techniques except for DD. Results also revealed that DD and FPO needed less cursor movement than FD (all $p < 0.05$). No other statistically significant differences were observed between the techniques. RM-ANOVA on the *Selection Techniques* showed no significant effect of the *Selection Technique* on cursor movement ($F_{1,9} = 2.56$, $p = 0.15$, $\eta^2 = 0.21$).

Subjective Feedback. We asked participants to provide us with their feedback on the menu *Placement* and *Selection Techniques*. We received positive feedback on the Dynamic + Partial Overlap (DPO) as it requires less cursor movement to select items compared to the disjoint condition. One participant commented, *"Selecting items (with DPO) is faster and requires less head movement"*. Another participant expressed preferring Dynamic + Partial Overlap (DPO) as he could leverage continuous cursor movement to make item selections on both menus: *"Partial overlap because it allows the user to keep the cursor in the same direction for item selection"*.

5 Discussion and Future Work

G1 Placement Technique: The results of our study indicated that the Dynamic + Partial Overlap (DPO) *Placement Technique* outperformed other techniques in terms of trial time, cursor movement, and error rate. This was due to the fact that DPO rendered the second menu in the same direction and partially overlapped where participants had selected the target item in the first menu. This resulted in less cursor movement and faster access to the target item in the second menu compared to other techniques. It was also evident to the participants that with DPO, the second menu would partially overlap the previous one and be in the same direction, requiring minimal cursor adjustment. Our study revealed that the Fixed Disjoint (FD) *Placement Technique* resulted in higher trial time and cursor movement compared to other techniques. This was because the second menu appeared in a fixed direction, below the first menu, which might not align with the targeted item in the first menu, leading to more cursor adjustment.

The in-place menu placement technique (i.e., FIP) positions the second menu in the same location as the first menu, which was expected to decrease cursor movements and improve item selection time. However, throughout our study, we observed that participants found this placement problematic when using both selection techniques. Similarly, with Border Crossing, participants had to move the cursor out of the menu for item selection, back inside, and then outside again for item selection in the second menu, leading to a higher mean trial time.

The dynamic menu *Placement Techniques*, namely DD and DPO, generally performed better than other techniques regarding trial time and cursor movement. As previously discussed, with dynamic placement techniques, the subsequent menu is placed adjacent to the selected item in the previous menu. This factor leads to less cursor movement and hence a shorter trial time.

G2 Selection Technique: Our results showed that while Border Crossing is faster on average, Dwell is significantly more accurate for item selection. It is worth noting that the trial time includes an additional 2.4 s required for the Dwell technique to select target items in two depths (1.2 s in each depth). This result differs from the findings of a previous study [23] that utilized eye movement for menu selection. We believe that head movement is faster and more stable than eye movements, which helps Border Crossing to be faster than Dwell.

Our study results demonstrate that the Dwell technique has a lower error rate than the Border Crossing technique. Firstly, participants were observed to be more careful when using the Dwell technique, as it required them to keep the cursor static on the target item. Secondly, the Border Crossing technique involved moving the cursor from the inside of the menu to the outside, and we observed that participants occasionally moved the cursor a significant distance, unintentionally triggering the selection in both the first and second menus. Our results align with prior work [6] that showed the Dwell technique to be less error-prone than other hands-free selection techniques. We had anticipated that the Dwell technique would involve less cursor movement than the Border Crossing. However, our study tasks required participants to move from the first menu to the second, resulting in a comparable amount of movement for both techniques.

We here suggest potential areas for future research. Firstly, to investigate menu placement and selection techniques, we only examined two menus, each containing six items based on [13]. Future studies could explore ways to increase the number of menus and menu items in the menu hierarchy. Secondly, we focused on head-based inputs as a type of non-touch input. Other non-touch input methods, such as eye-based or voice inputs, could be investigated in the future. Finally, further research is needed to explore the potential of head control-based marking menus with placement techniques for common applications including as gaming, texting, or others.

6 Conclusion

In this paper, we explored the optimal placement of subsequent menus within a hierarchical marking menu structure on smartphones. Our results indicated that partially overlapping and dynamically placed second menus could improve user performance in selecting items. Moreover, we observed that although the Dwell selection technique had a longer selection time, it led to fewer errors in comparison to Border Crossing. The results of this study can benefit the design of marking-menu based user interfaces for small-screen mobile devices, such as smartphones, and improve their efficiency and usability.

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