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Hinge Gestures: Leveraging Foldable Phone Hinges to Enrich Dual-Screen Tactile Interaction

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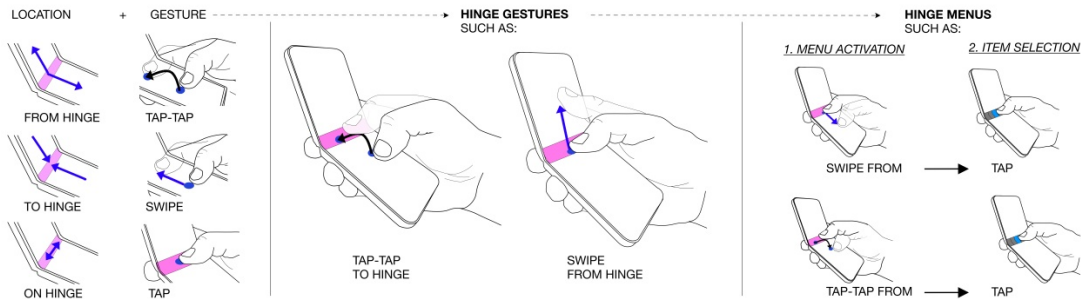


Figure 1: In this paper we explore touch inputs (tap-tap or swipe) executed fully or partially on the hinge (Left). We call them Hinge gestures, such as a *Tap-Tap to hinge*, or a *Swipe from hinge* (Center). We designed Hinge menus that combine hinge gestures for menu activation and item selection (Right).

Abstract

Foldable phones naturally support displaying two applications side by side on adjacent screens. However, one-handed interaction with this dual-screen configuration faces two challenges: first, users must change grip to reach each screen; second, menus displayed on each screen take valuable screen real estate and can be difficult to reach. To address this, we investigated how the hinge of foldable phones can enrich tactile interaction and provide access to hinge menus, unifying interaction across both screens. In a first experiment, we examined how users hold a foldable phone at different fold angles and identified the thumb-accessible screen areas, validating that a hinge-based grip enhances reachability. In two subsequent experiments, we evaluated the feasibility and performance of hinge gestures, defined as touch inputs (tap, tap-tap

or swipe) executed fully or partially on the hinge. Building on these findings, we designed hinge menus that combine hinge gestures for menu activation and item selection. Our final experiment identifies different hinge menus that outperform linear menus on adjacent screens. Our findings provide practical guidelines that can immediately inform and improve interaction on current foldable phones.

CCS Concepts

• **Human-centered computing** → Human computer interaction (HCI); Interaction techniques.

Keywords

Foldable phones, touch gestures, command selection

ACM Reference Format:

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1 Introduction

Foldable phones allow users to display two applications or views side by side on adjacent screens. One-handed interaction with each application can be challenging, as users often need to change their grip to reach different screen areas [7, 28]. Yet, we lack empirical knowledge about the specific grips and reachability limitations of dual-screen interaction on foldable phones. Moreover, each application typically includes its own menu, which both consumes valuable screen real estate and is often located in hard-to-reach areas. These challenges related to phone grips, thumb reachability and screen occlusion underscore the need to rethink traditional phone interaction paradigms in order to fully leverage the unique form factor of foldable phones.

Prior work has explored alternative interaction techniques for foldables devices [22, 27, 31, 48, 51], including fold- and touch-based gestures. Folding or unfolding the device can serve as an input gesture [22, 48] to trigger specific actions such as opening a menu. However, fold gestures are coarse, provide limited control and make it hard to view the screen while folding. Other research has explored touch gestures and mid-air interaction between the two screens to facilitate content transfer [24, 37]. However, these approaches did not investigate how the physical properties of the hinge could be leveraged to enhance interaction. Additional studies have explored touch gestures that cross the hinge – an area of fixed height centered on the physical separation between the two screens – on desktop-like devices or foldable tablets, showing that hinge curvature and thickness can affect both gesture accuracy and movement trajectories [9, 14, 43, 44]. However, much of this early research considered the hinge primarily as an obstacle that disrupts both input and output. To date, we still lack a systematic exploration of how the hinge can be leveraged as an interactive area to enrich interaction with foldable phones.

In this work, we introduce a novel approach that leverages the foldable phone hinge as a dedicated space for gestures and menus. Although often overlooked as an interactive area [9, 14, 53], the hinge offers unique advantages: physically located between the two screens, it reduces thumb travel distance and provides tactile feedback to guide gestures [35, 53]. Moreover, when two applications are displayed on adjacent screens, placing menus on the hinge preserves screen space, as menu content can adapt to the last active application. Hinge gestures can also start or end on either screen, providing a clear indication of which application the menu is associated with. By treating the hinge not only as a mechanical element but also as a dedicated interactive space, we aim to enhance the usability of foldable phones.

In this paper, we explore one-handed interaction with foldable phones using the dominant hand. In the first part of our work, we investigate how users interact with the hinge by examining hand grip, thumb reachability, and hinge gestures. We define hinge gestures as touch inputs (tap, tap-tap [15, 16, 32] or swipe) performed fully or partially on the hinge (see Figure 1left and center). This investigation involved three user experiments. In the first experiment, we studied how users naturally hold a foldable phone at various fold angles and assessed the resulting thumb reachable areas. Building on these results, a second experiment evaluated the execution time and accuracy of tapping on the hinge. In a third

experiment, we assessed the efficiency and user preference of hinge gestures composed of tap-taps or swipes performed on, toward, from, and across the hinge.

In the second part of our work, we build on insights from the first studies to design several hinge menus, i.e. menus displayed on the hinge that combine hinge gestures for menu activation and item selection (see Figure 1right). In a fourth experiment, we compared these hinge menus to a traditional linear menu. Results show that hinge menus outperform traditional linear menus in terms of speed and error rate. Additionally, linear menus were associated with higher physical demand, effort and frustration, as well as lower perceived performance, compared to hinge menus.

Our contributions are threefold: 1) we characterize the accessible areas of a foldable phone’s screen at various fold angles and analyze the grips adopted in each condition; 2) we define and analyze a range of hinge gestures in terms of speed, precision and user preference, highlighting their advantages and limitations; 3) we design and evaluate hinge menus, showing their benefits over traditional linear menus on foldable phones.

2 State of the art

2.1 Interaction with foldable phones

Foldable devices open new possibilities for both fold- and touch-based interactions, offering a richer input vocabulary than traditional smartphones.

The folding action is not merely a physical transformation and can serve as a direct input mechanism [22, 31, 48]. Folding can operate as a continuous control parameter, much like a slider, where the fold angle maps to specific functions such as zooming, timeline navigation, or mode switching. In 3D manipulation tasks, folding form factors provide alternative perspectives and viewing angles for spatial data, enabling users to apply filters on the 3D view [5] or manipulate 3D objects [25]. Varying the fold angle can also influence task distribution: specific configurations may facilitate independent activities on each screen [11, 17], while others allow content duplication across multiple screens [11, 51]. For example, in the first case, a partially folded device can act as a miniature laptop, with one screen displaying content while the other hosts tools or input controls. In the second case, two users can collaborate face to face using different screens. These examples illustrate that folding can support both continuous –folding to control a parameter – and discrete interactions, where a fixed fold angle determines a predefined interaction mode. However, fold gestures are coarse, provide limited control and make it hard to view the screen while folding.

Regarding touch-based interactions, foldable phones raise important questions about reachability. Their physical form factor can strongly affect which areas of the screen are easy or difficult to reach [44, 53]. Depending on the fold angle, the thumb’s comfortable reach area may vary, affecting touch accuracy and interaction speed. Prior work on grip posture and reachability has focused on conventional smartphones [45] or tablets [41, 46, 47], without accounting for foldable-specific characteristics such as hinge curvature, asymmetric screen orientations, or the dynamic changes introduced by folding. A preliminary study on a dual-screen phone prototype investigated how variations in the fold angle influence

the thumb-accessible areas of both screens [28]. They found that the reachability of one screen can be limited when the user is holding the other screen. However, the screen sizes and angles in this study were not representative of current foldable phones.

To sum up, while previous works have partially explored screen reachability on articulated devices, we still lack a deeper understanding of the relationship between fold angle, grip and reachability during dual-screen use of foldable phones.

2.2 Hinge interaction on foldable devices or desktops

The defining feature of foldable phones is the hinge, a physical separation between screens that may affect touch interaction. While essential mechanically, the hinge's role as an interactive area has received little systematic attention. Early mobile research mostly ignored the hinge or treated it primarily as a limitation, an obstacle disrupting input and output [9, 14, 26, 42, 53].

Some studies explored its interactive potential on other foldable devices, such as desktops or tablets. These works investigated touch gestures across the hinge for content transfer between screens [24, 37]. For example, Curve and BendDesk demonstrated that hinge curvature affects both gesture accuracy and movement trajectories [43, 44]. More recently, Zinck et al. [53] showed that hinge thickness reduced both speed and accuracy, although gestures performed along the hinge tended to be faster than those traversing it.

In collaborative scenarios, the hinge has been explored as a shared workspace: for example, when a foldable phone is placed folded on a table, with the screens facing outward, the hinge enables two users to exchange or temporarily store digital objects [35].

Despite these developments, the design space of touch gestures involving the hinge, which could exploit its physical affordances to guide interaction, remains largely unexplored.

2.3 Bezel interaction vs Hinge interaction

Related research has also explored how users can interact with physical boundaries surrounding mobile displays. In particular, bezel-based interactions have demonstrated that device edges can serve as reliable tactile landmarks to support input interaction without occluding on-screen content. Prior work on bezel swipes and tap-from-bezel gestures [36, 45] shows that users can perform quick, stable, and eyes-free bezel gestures. These techniques have also been used to trigger contextual commands or lightweight menus, leveraging the bezel as a non-intrusive interaction zone [20].

Hinge gestures share conceptual similarities with these bezel-based approaches, yet differ in important ways. Unlike the static and narrow bezels of traditional mobile devices, the hinge of a foldable device is a dynamic and large area that can display content (such as menu items). The hinge ridge is typically more pronounced than a conventional bezel, which can provide stronger tactile guidance for gestures such as swipes. Moreover, because the hinge is located between the two screens, it creates a central and symmetrically accessible interaction corridor, differing from external bezels. This position uniquely enables hinge gestures to coordinate interactions across multiple screens, extending the benefits of bezel interactions to dual-screen, or cross-application workflows. Hence,

exploring the hinge's potential as an interactive zone is critical for designing dual-screen interactions, particularly for higher-level components such as menus, and for identifying how they can be positioned and used on this area.

2.4 Menus on regular and foldable phones

Menu placement has long been a key focus in mobile device interface design [23, 30, 40, 50, 52]. Menus can be difficult to reach due to their distance from the user's thumb [4, 21, 29] and often occupy a large portion of the screen, obstructing main content [8, 12]. While these challenges have been addressed on conventional smartphones, they are amplified on foldable phones. Indeed, the physical separation between screens increases menu reachability issues, reduces screen real estate, and raises new design questions about how menus should be distributed across screens.

Early studies examined dual-screen layouts in which one screen displays the primary application while the other hosts a persistent menu [22, 37], leveraging the device's form factor to assign distinct roles to each screen. Modern foldable operating systems allow independent applications on each screen [1], so menus are displayed on the same screen as their corresponding application, duplicating menu areas. In such dual-screen scenarios, persistent or system-level menus may occlude important content [8, 38], appear far from the user's focus [12, 18], or require excessive reach.

To address these issues, we propose using the hinge as a dedicated menu interaction zone. This concept echoes the work of Zinck et al. [53] who placed a radial menu along the hinge of a foldable laptop. While their study did not evaluate usability and targeted a different device, it illustrates how hinge-centered UI elements can reduce reach effort and spatial conflicts.

2.5 Summary

Foldable phones introduce new interaction opportunities through both folding actions and touch gestures. However, fold gestures are coarse, and the device's form factor affects thumb reachability, yet the relationship between fold angle, grip, and reachability remains underexplored. Furthermore, the hinge, a defining feature of foldables, has received limited attention, though studies on desktops, tablets, and laptops suggest hinge properties can influence gesture accuracy, speed, and collaborative interactions. Finally, menu placement on foldable phones poses additional challenges, as splitting the screen reduces real estate, limiting the space for displaying menus and raise reachability issues. In this work we propose to leverage the hinge itself as an interactive zone to enrich touch interaction and menu selection on foldable phones.

3 Study 1: hand grip and thumb-Reachable areas

Our goal is to explore how the hinge can extend the input vocabulary of foldable phones. To this end, we first investigated the relationship between fold angle, grip, and reachability. We focus on single-handed interaction, with the device held in the dominant hand and input performed using the thumb. We restricted our investigation to unimanual use, as bimanual interaction (using the index finger of the opposite hand) is not always feasible in mobile contexts.

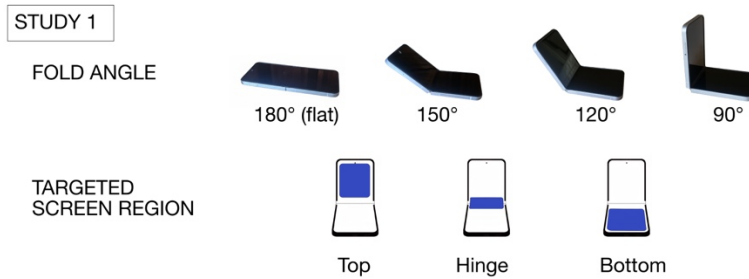


Figure 2: Illustration of two factors of our study 1: the fold angle and the targeted screen region for the hand grip.

3.1 Task Design

Participants held a foldable phone in their dominant hand. Since users may naturally adopt different grip postures depending on the screen being interacted with, we asked each participant to adopt the most appropriate grip for the *Top* screen, *Bottom* screen, or *Hinge* regions (see 2).

With a screen folded at 90°, the top screen is closer to the user’s thumb than when the phone is flat. To assess the impact of **fold angle**, we considered four angles: 90°, 120°, 150°, and 180° (flat, like a regular smartphone). We chose 180° and 90° as they are physical limitations beyond which the content displayed on both screens may be difficult to visualize. In-between these two limits, we chose to explore two angles (120° and 150°) because they represent alternative fold angles that users might adopt naturally while interacting with foldable phones (see 2).

For each **Region** × **Angle** combination, participants completed three **tasks**: two tasks consisted in outlining the contour of an area without changing grip, distinguishing between *Comfortable* or *Reachable* thumb areas (the reachable area being the largest area the user could reach). The third task required performing a *Swipe* along the hinge. The first two tasks identify usable interaction areas and assess hinge reachability for different interaction regions and fold angles. The third task examines how these factors affect hinge-based swipe gestures.

3.2 Participants, Apparatus, and Implementation

We collected and analyzed data from 12 participants (8 self-reported as male, 4 as female), with a mean age of 23 years (SD = 3.99). All were right-handed, recruited from a local university, and experienced smartphone users., but none had previously used a foldable phone. The average thumb length was 56.52 mm (SD = 4.48). Participants were seated during the study, holding the foldable phone in their dominant hand with the arm raised and unsupported.

The device was a Samsung Galaxy Z Flip 3 5G [34] with a 6.7” screen (1080 x 2640 px, portrait orientation), connected via local Wi-Fi to a laptop running the experimental conditions. We measured the hinge curvature $k_\alpha = 1/r$, where r is the curvature radius, for each fold angle α . Curvature is reported in inverse millimeters (mm^{-1}). The resulting hinge curvatures were $k_{90} = 0.35 \text{ mm}^{-1}$, $k_{120} = 0.13 \text{ mm}^{-1}$ and $k_{150} = 0.06 \text{ mm}^{-1}$. In all experiments, the folding angle was mechanically constrained using a small custom insert

placed inside the hinge on the back of the foldable phone. This insert prevented any angle changes during the tasks while preserving the phone’s natural grip and appearance. Participants could hold and interact with the phone normally, while the fold angle remained fixed and stable throughout the trials. The device was disinfected between participants, and all university health and safety guidelines were followed. Participants gave informed consent in accordance with the institution’s ethical policies.

3.3 Experimental Protocol

We adopted a 4×3×3 within-subject design with **Fold angle** (90°, 120°, 150°, 180°), targeted screen **Region** (Top, Hinge, Bottom) and **Task** (Comfortable, Reachable, Swipe) as factors. Fold angle order was counterbalanced using a 4×4 Latin square. For each angle, participants selected a grip that maximized access to a specific screen region in the following order: *Bottom*, *Hinge*, then *Top*. They could take as much time as needed to choose the appropriate grip. Once the grip was selected, the three tasks were performed in a fixed order: (1) Outline the *Comfortable* area, (2) Outline the *Reachable* area, and (3) *Swipe* along the hinge.

In total, we collected: 12 participants × 4 angles × 3 regions × 3 tasks = 432 trials, and 12 participants × 4 angles × 3 regions = 144 grip posture photos. Before each set of the three tasks, participants were allowed to rest. Each experimental session lasted approximately 38 minutes.

3.4 Data Collection and Analysis

For each trial, we recorded all touch points detected over the phone’s touchscreen at a sampling rate of 20 ms. To characterize the comfortable and reachable areas, we applied a surface reconstruction algorithm (gift wrapping algorithm) [10], calculated the total area (in mm^2), and generated heatmaps. We also computed the centroid of each area, defined as the mean of all (x, y) points within the corresponding area [33]. Participants were also invited to provide qualitative feedback on the grips, tasks, and fold angles at any moment during the experiment. At the end of the session, they ranked the four fold angles in order of preference.

We used repeated measures two-way ANOVA to analyze the results (F, p, η^2). Post-hoc pairwise T-tests with Bonferroni correction were used when needed. When the normality assumption was violated (Shapiro-Wilk normality test), we transformed the data using a log function. If the normality assumption was still violated,

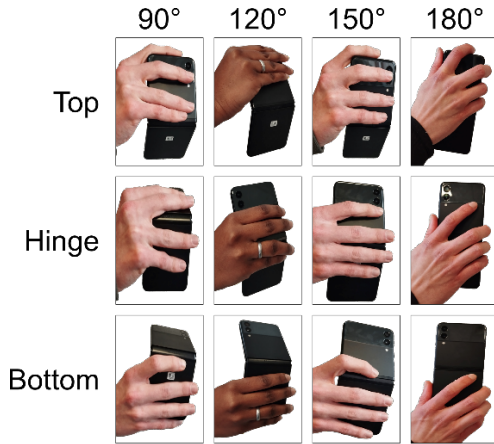


Figure 3: Examples of grips for interacting with the Bottom (Left), Hinge (Center) and Top (Right) regions.

we conducted a Friedman test (χ^2 , p , n), followed by a pairwise Wilcoxon test with Bonferroni correction.

3.5 Results

3.5.1 Grip Postures. We did not observe a clear impact of the Fold angles on the user’s grip of the phone. On the contrary, grip varied with the targeted screen Region, as illustrated in Figure 3. For the Bottom region, users typically placed three fingers behind the lower part of the phone and one finger near the hinge to stabilize the device. For the Hinge region, the grip included one finger at the bottom, two along the hinge, and one at the top—offering strong device stability. For the Top region, participants predominantly adopted a grip symmetrical to the Bottom region: three fingers at the top and one near the hinge.

3.5.2 Comfortable and Reachable Areas. An Anova established that the size of the **comfortable area** is significantly influenced by the Region ($F(2, 132)=3.3, p<0.05, \eta^2 = 0.05$). A grip on the *Hinge* region yielded a larger comfortable area (42.27 cm^2) than on the *Bottom* region ($32.88 \text{ cm}^2, p = 0.015$), see Figure 4 - Left. No significant difference was found with the *Top* region (35.05 cm^2). We found no impact of the Fold angle on the comfortable area. Regarding the centroid of the comfortable area, an Anova showed that the Region had a significant impact on the centroid’s Y-coordinate, i.e. the vertical position of the comfortable area on the screen ($F(2, 132) = 205.6, p < 0.001, \eta^2 = 0.757$). The phone Y-axis ranges from 0 px (top) to 2640 px (bottom). The centroid of the comfortable area for the *Top* region ($Y=799 \text{ px}$) was located significantly above the centroid of the comfortable area for the *Hinge* region ($Y=1106 \text{ px}, p < 0.001$). The centroids of the comfortable areas for the *Top* and *Hinge* regions were situated significantly above the centroid of the comfortable area for the *Bottom* region ($Y=1532 \text{ px}, p < 0.001$ in both cases).

For the **reachable area**, a Friedman test revealed a significant difference in terms of Region ($\chi^2(2) = 9.5, p < 0.01, W = 0.396$), see Figure 4 - Center. The *Hinge* region led to a larger reachable area

(55.30 cm^2) than the *Bottom* region ($50.88 \text{ cm}^2, p = 0.048$) and the *Top* region ($49.19 \text{ cm}^2, p = 0.043$).

A Friedman test also showed that the size of the **reachable area** was significantly influenced by the Fold angle ($\chi^2(3) = 20.3, p < 0.0001, W = 0.564$). The 90° angle resulted in a bigger reachable area (61.01 cm^2) than the 150° ($48.35 \text{ cm}^2, p = 0.006$) and 180° angles ($44.16 \text{ cm}^2, p = 0.009$). No significant difference was observed with the 120° angle (53.64 cm^2). Regarding the centroid of the reachable area, a Friedman test found that the Region had an impact on the centroid Y coordinate ($\chi^2(2) = 24, p < 0.001, W = 1$). The centroid of the reachable area for the *Top* region ($Y=891 \text{ px}$) was situated significantly above the centroid of the reachable area for the *Hinge* region ($Y=1083 \text{ px}, p = 0.0005$). The centroids of the reachable areas for the *Top* and *Hinge* regions were situated significantly above the centroid of the reachable area for the *Bottom* region ($Y=1363 \text{ px}, p = 0.0005$ in both cases).

Importantly, in all 36 conditions (4 angles x 3 regions x 3 tasks) the hinge region was consistently located within both the comfortable and reachable zones, underlining its potential as a reliable region for always-available interaction, see Figure 4.

3.5.3 Swipe Along the Hinge. When performing a swipe along the hinge, we computed the mean swipe deviation as the average distance between each touch point and its projection onto a hinge-centered horizontal line (hereafter referred to as the hinge line). This metric can be used to distinguish hinge gestures from on-screen gestures by capturing where users actually perform swipes along the hinge. Based on this, the hinge area should be sized to accommodate the maximum mean swipe deviation observed in this experiment.

An Anova revealed a significant effect of Fold Angles on swipe deviation ($F(3, 132)=15.08, p<0.001, \eta^2 = 0.26$). The 90° angle produced a larger deviation (11.15 mm) than the 120° (6.99 mm, $p < 0.001$), 150° (8.55 mm, $p < 0.001$), and 180° angles (7.70 mm, $p < 0.001$). This suggests that at 90° , users perform hinge swipes farther away from the hinge line, likely because the narrower angle creates a more constrained interaction space around the hinge. We did not find any significant effect of the targeted screen Region on swipe deviation.

3.5.4 Ranking of angles and user feedback. We asked participants to rank the Fold angles to identify the ones that they would prefer to use in real usage of the foldable phone to better inform our following studies. Participants most frequently ranked the 120° and 150° angles as their top choices (five times each). Only two participants ranked the 180° angle as their top choice, whereas seven participants placed it third. The 90° angle was unanimously ranked last by all participants. This result is confirmed by the participants’ feedback: “I don’t like when the phone is flat, first it makes the foldable part of the phone useless, but it also means it is harder to reach the top of the screen”, (P3). Participants also stated: “When the phone is in a right angle, it is hard to hit the hinge properly, I often go from above the hinge to directly under and miss the middle part”, (P5) or “There is nothing shown here, but I think I had trouble seeing content on the phone if it was folded like that [90°]”, (P11).

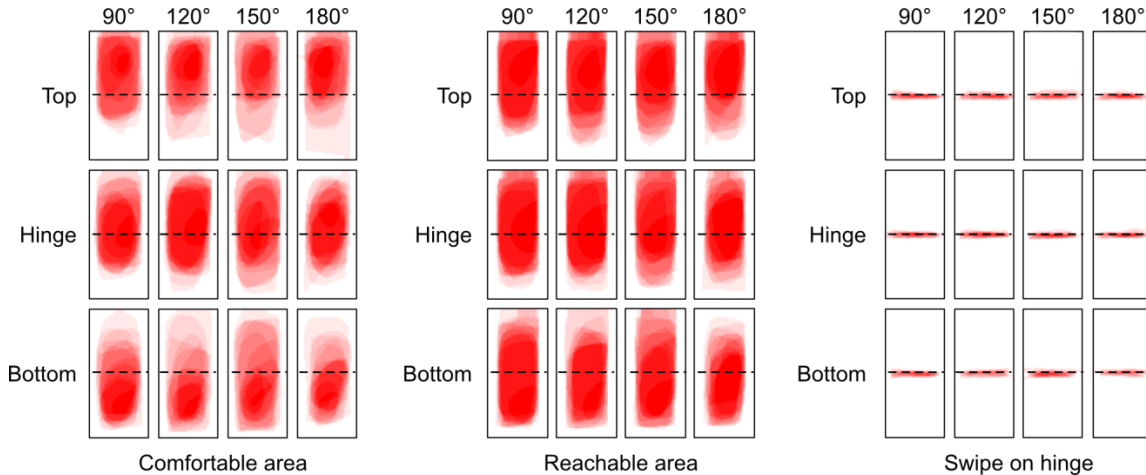


Figure 4: Heatmaps for the comfortable area (Left), reachable area (Center) and swipe on hinge (Right). The scale goes from white (no user reached that area) to dark red (all twelve users reached that area).

3.6 Summary

Our results highlight the impact of screen region (inducing a specific grip) and fold angle on the reachable and comfortable areas of a foldable phone. A grip optimized to interact with the hinge region yielded a larger reachable area than a grip focused on the bottom region. Interestingly, the hinge region consistently fell within both the comfortable and reachable zones across all conditions. Fold angle also affected interaction: a 180°-fold angle reduced screen reachability, while a 90° angle impaired thumb positioning and increased swipe deviation from the hinge center. Preference rankings indicated that users disliked the 90° angle and found 180° less favorable. Accordingly, we retained only the 150° and 120° angles for the following studies. To sum up, this first study demonstrates that the hinge is a relevant interactive zone, that a hinge-based grip better supports dual-screen interaction, and that certain fold angles are more suitable for the following studies.

4 Study 2: Pointing performance on the hinge

After characterizing the reachable areas of the foldable phone, we investigate the interaction with the hinge. As discussed in the introduction, in a dual-screen use of the device, a user might interact with the content of one of the two screens before interacting with a menu located on the hinge. The goal of this study is to validate if users are able to reach and accurately tap on the hinge, a fundamental hinge gesture, in different fold angles and from different starting screens. Our second study, therefore, focuses on an item selection on the hinge, starting from one of the two screens. We focus on other hinge gestures in a third study.

4.1 Formative study

Before conducting study 2, we ran a formative study to identify the minimal item height and width required to keep errors low when selecting items placed along the hinge. Following the same rationale as conventional guidelines for minimum widget size on flat touchscreens (which account for finger width) [3, 39], we aimed to establish an equivalent measure for the hinge (to account for

finger width and hinge curvature) to ensure that the targets in our later gestures and menus designs could be reliably selected.

Task design: Each trial started with an initial tap on a circle (7.7 mm diameter [39]) displayed at the center of one of the two screens (*Top* or *Bottom*). Trials ended with a tap on a cross located on the hinge. Eight crosses were displayed on the hinge, four of which were used as **targets** (0, 2, 5, 7 with 0 being the leftmost target and 7 the rightmost). As motivated in section 3.6, we considered only two **fold angles** (120° and 150°). The eight crosses were displayed in grey, with one of them highlighted in blue (the target).

Participants, Apparatus, and Implementation: We collected and analyzed data from 12 participants (6 self-reported as men and 6 as women), with an average age of 20 years (SD = 3.26). All participants were right-handed, recruited from the local university, and were familiar with smartphone use. None had previously used a foldable phone, and none had participated in study 1. During the study, participants were seated and held the foldable phone in their dominant hand with the arm raised and unsupported. Because each trial started with a touch on one of the two screens, participants were allowed to adopt the grip of their choice depending on the starting circle position (*Top* or *Bottom* screen).

The equipment (phone, laptop, etc.) was identical to the first study, and we followed the same health and safety guidelines. Participants gave informed consent in accordance with the institution’s ethical policies.

Experimental Protocol: We adopted a within-subject 2x2x4 design with **Fold angle** (120°, 150°), starting **Screen** (*Top*, *Bottom*), and hinge **Target** (0, 2, 5, 7) as factors. The fold angle was counter-balanced between participants using a 2x2 Latin square. For each angle, participants completed training trials followed by the full set of measured trials, presented in random order. For each trial, the position of the final tap was recorded. In total, we collected 12 participants × 2 angles × 2 screens × 4 targets = 192 training trials and 1152 measured trials (same structure × 6 repetitions). Before each trial, the participants were free to take a break. The experiment lasted 41 minutes on average.

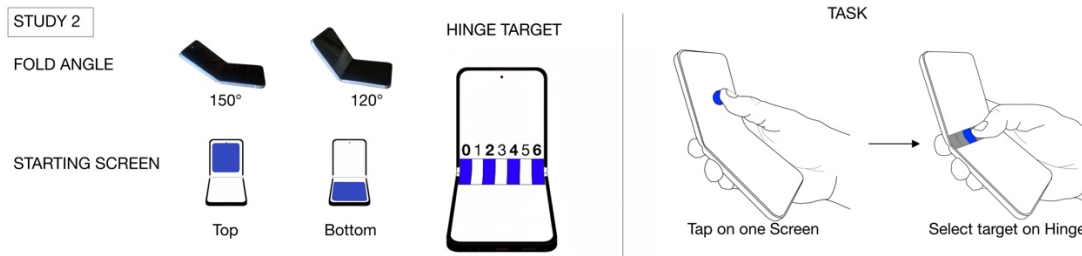


Figure 5: Illustration of the experimental factors (Left) and illustration of the task to perform in our first study (Right).

Results: To identify suitable target dimensions we applied an algorithm that computed, for each fold angle, the minimal hinge menu item height and width to achieve at least 95% accuracy (i.e., <5% error). The algorithm yielded a hinge-item width of 9.02 mm across both fold angles. This result implies that only seven targets can be placed along the hinge. Furthermore, the algorithm yielded a height of 16.96 mm for 120° and 11.43 mm for 150°. We used the results from this formative study to define the hinge target sizes in our subsequent studies.

To facilitate comparison with prior work on target sizes for smartphones, we computed the error rate for the optimal target size proposed by Tu et al. [39] (7.7 mm). Across all fold angles, the error rate for selecting a 7.7mm hinge target ranged from 7% to 40%. We also found that error rates were higher at the 120° fold angle than at 150°. This finding confirms the need for distinct heights at different fold angles and demonstrates that existing flat-screen recommendations cannot be directly applied to the hinge context.

4.2 Task design

Based on the results of the formative study, we conducted study 2. It used the same task design as the formative study, but with two differences. First, the hinge contained seven rectangular items, as illustrated in Figure 5. Four of these were used as **targets**: 0, 2, 4, 6, with 0 being the leftmost target and 6 the rightmost. Second, the heights of the menu items displayed on the hinge were different for each fold angle (16.96 mm for 120° and 11.43 mm for 150°).

4.3 Participants, Apparatus and Implementation

We collected and analyzed data from 12 participants (7 self-reported as men and 5 as women), with an average age of 21 years (SD = 2.87). All participants were right-handed, recruited from the local university, and familiar with smartphone use. Only one participant had previously used a foldable phone. None of the participants in this study took part in the study 1 or the formative study. The apparatus and implementation were identical to the formative study.

4.4 Experimental protocol

We adopted a within-subject 2x2x4 design with **Fold angle** (120°, 150°), starting **Screen** (*Top*, *Bottom*), and hinge **Target** (0, 2, 4, 6) as factors. The fold angle was counterbalanced between participants using a 2x2 Latin square. For each angle, participants completed training trials followed by the full set of measured trials, presented

in random order. In total, we collected 12 participants × 2 angles × 2 screens × 4 targets = 192 training trials and 1152 measured trials (same structure × 6 repetitions). Before each trial, the participants were free to take a break. The experiment lasted 34 minutes on average.

4.5 Data collection and Analysis

For each trial, we recorded the location of the first touch (screen) and the second touch (menu item). We also measured the time between the two touches. We used the same statistical analysis as in the previous study.

4.6 Results

4.6.1 Completion time. We did not observe a significant difference between the two starting screens (*Top* vs. *Bottom*). However, a Friedman test showed a significant difference between targets ($\chi^2(3) = 24, p < 0.001, W = 0.667$). Selecting the target 0 (on the left, furthest from the thumb) required more time (425ms) than targets 2 (378ms, $p = 0.003$), 4 (384ms, $p = 0.006$) and 6 (398ms, $p = 0.03$, closest to the thumb), see Figure 6 - left. Moreover, selecting target 2 (left side of the screen) took less time than target 6 ($p = 0.006$, right side, closest to the thumb). Although comparing performance among the two fold angles is not our primary goal, as users will adopt their preferred angle when using the foldable phone, a Wilcoxon test revealed a significant difference in completion time between the two fold angles ($p = 0.034, r = 0.12$). The 120° angle (407ms) required more time than the 150° angle (385ms), see Figure 6 - right. We did not find any interaction between the experiment's factors.

4.6.2 Errors. We found no significant differences in error rates between fold angles, starting screens, or targets along the hinge. All error rates were below 5% and the general average across all condition was 1.74% (CI: [0.98, 2.49]).

4.7 Summary

This study validates that users can reach and accurately tap on the hinge across different fold angles and starting screens. Although 150° yielded faster completion times than 120°, both fold angles allow users to point at any hinge item with less than 5% error. No performance differences were found between the initial screens, confirming that the hinge can serve as a unified interaction area while using both screens of a foldable phone. The target position analysis revealed faster completion time for central positions while peripheral positions showed degraded performance, particularly

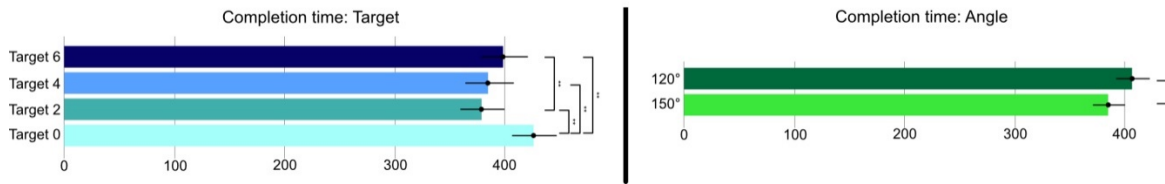


Figure 6: Completion time depending on the target (Left) or fold angle (Right) in ms (95% CI).

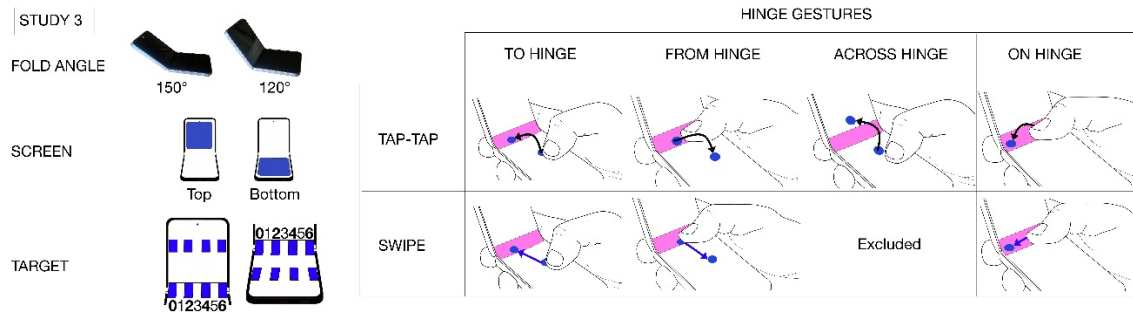


Figure 7: Illustration of the experimental factors of the study 3.

targets on the extreme left (farthest from the thumb). These results suggest three design guidelines for hinge interactions: 1) limit hinge menus to a maximum of seven items on a 6.7" foldable phone to preserve accuracy; 2) adjust item height to the fold angle to ensure at least 95% success; 3) encourage users to adopt a wider fold angle (around 150°).

5 Study 3: Characterizing Hinge gestures

The previous study confirmed that users can accurately tap on the hinge. In this third study, we investigate how more complex gestures, such as tap-tap [15, 16, 32] or swipes directed toward, from, or along the hinge, perform in terms of speed, precision, and user preference. The goal of this study is to explore more precisely the gesture vocabulary enabled by the hinge and identify which gestures are robust enough to be integrated into practical UI components. Moreover, this study considers gestures that start or end on the hinge, extending prior work [53] that focused mainly on gestures along or across the hinge.

5.1 Hinge gestures

We define a hinge gesture as a touch input executed fully or partially on the hinge. In this study, we focus on two types of touch inputs: tap-tap and swipe. The starting or ending points of these gestures can be situated on either screens or on the hinge itself, creating combinations that distinguish hinge gestures from tap-taps or swipes performed entirely on a single screen.

For **tap-tap** gestures, we explored four gesture **categories** (*To Hinge*, *From Hinge*, *On Hinge*, and *Across Hinge*). For example, a tap-tap *To Hinge* starts with a tap on one of the two screens (*Top* or *Bottom*) followed by a tap on the hinge; A tap-tap *Across Hinge* starts with a tap on one of the two screens followed by a tap on the other screen, without any direct contact with the hinge.

For **swipe** gestures, we considered three gesture categories (*To Hinge*, *From Hinge*, and *On Hinge*). For example, a *Swipe To Hinge* starts with the thumb on one of the two screens, followed by a movement toward the hinge. We excluded the *Across Hinge* category, as it was explored in previous studies and considered non-optimal due to longer completion times and lower accuracy than gestures along the hinge [53]. The resulting hinge gestures investigated in this study are illustrated in Figure 7.

5.2 Task design

As in the previous study, for gestures *On/To Hinge*, seven targets were displayed on the hinge, four of which were used as actual **targets**: 0, 2, 4, and 6.

With tap-tap gestures *To/From/Across Hinge*, the tap away from the hinge was placed at one of three predefined **distances** from the hinge (one, two, or three target circles away), corresponding to 12.33, 20.03, and 27.73 mm at 120°, and 9.57, 17.27, and 24.97 mm at 150°. For tap-tap gestures *Across Hinge*, the second tap was performed on the second screen (at the corresponding distance) instead of on the hinge. We had to adopt different distances for the 120° and 150° angles because the hinge height differs according to the fold angle (16.96 mm and 11.43 mm respectively). The tap-tap or swipe gestures were performed perpendicularly to the hinge. Finally, tap-taps *On Hinge* involved two taps at the same position on the hinge.

With swipe gestures, we defined two swipe **distances** and **positions** based on heatmaps generated in our first study. These **positions** (*Left*, *Right*) correspond to a third and two-thirds of the average length between the start and end locations of swipes along the hinge. The **distances** used were 16.90 mm and 33.81 mm, and were applied across all gesture categories (*To Hinge*, *From Hinge*, *On Hinge*).

Each trial began when the participant performed the initial touch (first tap for **tap-tap** or touch-down for **swipe**) and ended with the second tap (for **tap-tap**) or finger lift (for **swipe**). If the second tap/finger lift was not on the correct target, the trial was counted as an error.

5.3 Participants, Apparatus and Implementation

We collected and analyzed data from 12 participants (6 self-reported as men, and 6 as women), with an average age of 20 years (SD = 3.68). All were right-handed, recruited from the local university, and experienced smartphone users (none had previously used a foldable phone). None had participated in any of our earlier studies. The experimental setup and procedure were the same as in the previous study.

5.4 Experimental protocol

For tap-tap gestures, we adopted a within-subject design with **Fold angle** (120° , 150°), gesture **Category** (*To Hinge*, *From Hinge*, *Across Hinge*, *On Hinge*), **Screen** (*Top*, *Bottom*), **Distance** to hinge (for 120° : 12.33, 20.03, 27.73 mm; for 150° : 9.57, 17.27, 24.97 mm) and **Target** (0, 2, 4, 6) as factors. All factors were combined except for the *On Hinge* category, that was only combined with the fold angles. The total number of trials was thus: 2 angles \times (3 categories \times 2 screens \times 3 distances + 1 category (*On Hinge*)) \times 4 targets \times (1 training + 3 measured trials) = 608 trials per participant.

For swipe gestures, we adopted a within-subject design with **Fold angle** (120° , 150°), gesture **Category** (*To Hinge*, *From Hinge*, *On Hinge*), **Screen** (*Top*, *Bottom*), swipe **Direction** (*Left*, *Right*), swipe **Distance** (16.90, 33.81 mm) and **Target** (0, 2, 4, 6) as factors. The total number of trials was thus: 2 angles \times (2 categories \times 2 screens \times 4 targets + 1 category (*On Hinge*) \times 2 directions) \times 2 distances \times (1 training + 3 measured trials) = 288 trials per participant.

A block consisted of a combination of a tactile **Gesture** (tap-tap or swipe) and a **Fold angle**. Blocks were counterbalanced across participants using a 4 \times 4 Latin square. For each block, participants completed a set of training trials followed by randomly ordered measured trials for one gesture **Category**. Once the gesture **Category** was completed, a new one was randomly selected.

In total, we collected: 12 participants \times (608 tap-tap trials + 288 swipe trials) = 10752 trials. The average session duration was 86 minutes.

5.5 Data collection and Analysis

For each trial, we recorded all touch points (sampled every 20ms), along with the time between the initial and final touch (second tap for tap-tap and release for swipe). For tap-tap gestures, a trial was considered an error if the second tap landed outside the target area. For swipe gestures, success was determined solely by the release location at the end of the swipe; participants could deviate from a straight path without being penalized. At the end of the experiment, participants ranked their preferences for **Fold angles**, **Gesture** (*tap-tap*, *swipe*) and gesture **Categories** for tap-tap (*To Hinge*, *From Hinge*, *On Hinge*, *Across Hinge*), and for swipe (*To Hinge*, *From Hinge*, *On Hinge*). Participants were also invited to provide

qualitative feedback on the experimental factors. We used the same statistical methods as in the previous study.

5.6 Results

5.6.1 Completion Time. For the tap-tap gestures, we found a significant effect of gesture **category** on the completion time using a Friedman test ($\chi^2(3)=19.9$, $p < 0.001$, $W = 0.55$): *On Hinge* (163.7ms) required less time than *To Hinge* (214.3ms, $p = 0.006$), *From Hinge* (215.9ms, $p = 0.009$), and *Across Hinge* (232.9ms, $p = 0.006$), see Figure 8 - Left. Additionally, *To Hinge* required less time than *Across Hinge* ($p = 0.009$). Unsurprisingly, a Friedman test ($\chi^2(2)=24$, $p < 0.0001$, $W = 1$) revealed that for all categories and angles, increasing the **distance** to the hinge increased the completion time (from 188.5ms with the smallest distance to 248.4ms with the biggest distance, $p = 0.001$ in each case). Furthermore, a Wilcoxon test revealed that gestures involving the *Bottom* screen (216ms) led to faster interactions than the *Top* screen (226ms, $p = 0.0005$). Finally, a Friedman test showed that the target also had an effect on completion time ($\chi^2(3)=10.9$, $p = 0.01$, $W = 0.3$). Selecting the target 6 (the closest to the thumb, 224.2ms) took longer than target 2 (middle-left of the screen's width, 212.4ms, $p = 0.0005$). As expected – due to the increased distance associated with different hinge heights - a Wilcoxon test showed a significant difference in terms of completion time between **Fold angles** ($p = 0.005$, $r = 0.18$), with 120° taking longer (227.6ms) than 150° (208.6ms).

For the swipe gestures, a Friedman test showed a significant effect of the gesture **category** on completion time ($\chi^2(2)=12.7$, $p = 0.002$, $W = 0.53$): *From Hinge* (367.5ms) took longer than both *On Hinge* (321.5ms, $p = 0.02$) and *To Hinge* (321ms, $p = 0.007$), see Figure 8 - Right. As expected, a Wilcoxon test ($p = 0.0005$, $r = 0.16$) showed that longer swipe **distances** also increased completion time (16.90 mm: 304.3ms; 33.81 mm: 381.8ms). A Wilcoxon test ($p = 0.034$, $r = 0.15$) revealed that swipes using the *Bottom* screen (340.4ms) took less time than those using the *Top* screen (348.2ms). A Wilcoxon test ($p = 0.0034$, $r = 0.17$) also showed that swiping to the *Right* (307.5ms) required less time than to the *Left* (335.5ms). Finally, a Friedman test showed that the target had a significant effect on completion time ($\chi^2(3)=15.9$, $p = 0.001$, $W = 0.44$): target 6 (closest to the thumb, 353ms) required more time than target 2 (middle-left of the screen's width, 332.9ms, $p = 0.0005$). Finally, as swipe distances were the same for both **fold angles**, we did not find a significant difference between **fold angles**.

5.6.2 Error rate. Errors were either due to a too long time between the two taps or a final tap on an erroneous target item.

For tap-tap, a Friedman test showed there was a significant effect of gesture **Category** on errors ($\chi^2(3)=30.3$, $p < 0.001$, $W = 0.84$). *Across Hinge* (8%) produced more errors than *From Hinge* (4%, $p = 0.02$), *To Hinge* (3%, $p = 0.015$), and *On Hinge* (0%, $p = 0.015$), see Figure 9 - Left. A Friedman test ($\chi^2(2)=8.47$, $p = 0.015$, $W = 0.353$) revealed that error rate also increased with gesture **Distance** (from 2% to 8%, $p < 0.02$ in all cases). A Wilcoxon test ($p = 0.009$, $r = 0.25$) also revealed that the error rate was higher when using the *Bottom* screen (6%) than the *Top* screen (4%). No significant differences were found between hinge positions.

For swipe, there were no significant differences in errors across **Fold angles**, gesture **Categories**, **Distances**, or hinge **Positions**,

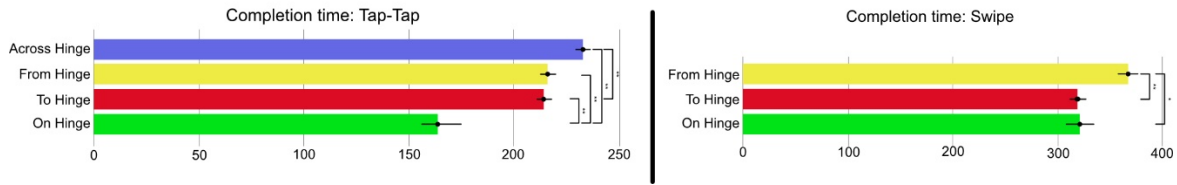


Figure 8: Completion time for gesture categories for tap-tap (Left) and Swipe (Right) in ms (95% CI).

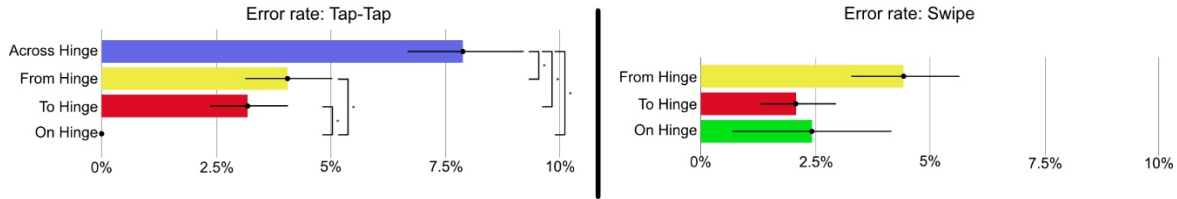


Figure 9: Error rates for gesture categories for tap-tap (Left) and Swipe (Right) in percentage (95% CI).

see Figure 9 - Right. However, a Wilcoxon test ($p = 0.006$, $r = 0.41$), *Bottom* screen led to more errors (4%) than *Top* screen (2%). This result remains true for both *From Hinge* and *To Hinge* gesture Categories.

5.6.3 Ranking and informal feedback. For tap-tap, ten participants preferred *On Hinge*, two preferred *To Hinge*, and *Across Hinge* was ranked last by all participants, as explained by informal feedback: “When I do the across hinge tap-tap, the two targets are really far away and it seems I’m not doing a simple gesture anymore”, P1.

For swipe, eight participants favored *On Hinge*, followed by four who preferred *To Hinge*; *From Hinge* was least favored, underlying that the physical properties of the hinge are appreciated by the users: “When I go to the hinge, I’m stopped by the hinge because of the curvature”, P4.

Although comparing tap-tap and swipe gestures was not our goal as both gestures can be used for complementary reasons, nine participants preferred swipe over tap-tap: “When I swipe on the hinge, it is easier because I follow the curvature. For tap-tap, whether the hinge is here or not does not matter”, P11.

5.7 Summary

This study allowed us to characterize tap-tap and swipe gestures involving the hinge, in terms of completion time, error rate, and user preference. All tap-taps were executed in under 300ms, validating that they conform Android’s definition of a double tap: such gestures could thus be added as a new input gesture on foldable phones. *Across Hinge* gestures were slower and more error-prone, and we therefore exclude them from our subsequent work. All gestures *From/To/On Hinge* were performed with low error rates, indicating that they can serve as new input gestures, extending the traditional touch gestures of non-foldable phones. Furthermore, the lower completion times observed for the *To Hinge* swipes may be explained by the physical constraint created by the hinge, which acts as a natural endpoint, similar to how sliding toward a boundary on a touchscreen can enhance precision [19]. The *On Hinge*

swipes are both quick and accurate, likely because the movement is guided along a narrow corridor between the two screens, similar to path-steering mechanisms that encourage users to follow a central trajectory [1, 6]. These findings indicate that the hinge itself shapes swipe execution, influencing both speed and precision. Finally, although gestures involving the *Bottom* screen induced more errors, they required less time than those involving the *Top* screen. We hypothesize that this effect is due to the thumb’s resting position being on the *Bottom* screen, allowing faster hinge gestures. To confirm this hypothesis, we decided to measure thumb rest position in our next study.

6 Study 4: Exploiting the hinge gestures to design a hinge menu

The previous study established which hinge gestures are fast, accurate, and preferred by users. The goal of the fourth study is to investigate how these gestures can be combined into complete interaction techniques. We focus on scenarios where the user interacts with two applications or views displayed simultaneously on both screens: in this situation it is crucial to determine which hinge gestures are most appropriate for 1) menu activation and 2) item-selection. This study therefore examines how hinge gestures can be used for menu techniques and evaluates whether such hinge-based menus provide benefits over traditional on-screen linear menus. By doing so, we assess the practical value of hinge interaction under realistic dual-screen usage conditions. Furthermore, while some prior work considered placing menus on the hinge of other foldable devices [35, 53], this study is the first to propose and evaluate using the hinge for menu interaction on foldable phones.

6.1 Menu design

One advantage of placing a menu on the hinge is its proximity to both screens. A single hinge menu can therefore be associated with applications or views displayed on both the top and bottom screens. However, it is essential to explicitly indicate which screen the hinge

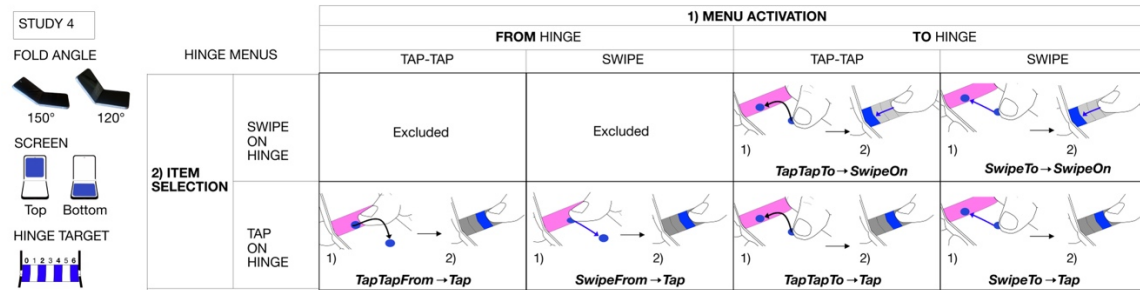


Figure 10: Illustration of the experimental factors, with the hinge menus explored in our study 4.

menu is associated with. Selecting a hinge menu item thus involves a two-step process: an activation step followed by a selection step. The activation step specifies the screen for which the menu opens (*Top* or *Bottom*) and triggers its display on the hinge. Then, the selection step allows the user to select one of the displayed menu items. In this study, we focus exclusively on single-level menus. Since the first level is located on the hinge, implementing a second level would require placing it on one of the two screens, which falls outside the scope of our focus on hinge interaction.

To perform these two steps, we relied on the hinge gestures studied earlier: tap on the hinge, tap-tap and swipe gestures (*From / To / On Hinge*). However, not all of these are suitable for every interaction step.

For the activation step, an *On Hinge* gesture does not clearly associate the menu with a screen. Therefore, only tap-tap and swipe gestures *From* or *To Hinge* were considered for activation.

Since the selection step has to be performed on the hinge (where the hinge menu is located), a tap or a swipe *On Hinge* are more appropriate than any *From/To Hinge* gesture. We also excluded a tap-tap *On Hinge*, as it would take longer than a single tap.

Furthermore, considering the sequence of gestures across the two steps, certain combinations introduce unnecessary actions, increasing completion time. We identified two such combinations: performing a tap-tap *From Hinge* followed by a swipe *On Hinge*, and performing a swipe *From Hinge* followed by swipe *On Hinge*. In both cases, selecting the final menu item with a swipe *On Hinge* first requires a hover to the hinge, then a press, followed by the swipe. This sequence is unnecessarily long compared to directly tapping on the hinge to select the item. As a result, we did not include these two combinations from our study.

In summary, interacting with our hinge menus involves two steps: 1) performing an activation gesture (tap-tap or swipe *From / To Hinge*) to associate the menu with a screen and trigger its display; and 2) selecting a menu item displayed on the hinge via a tap or swipe *On Hinge*. For clarity, we refer to the combination of an activation gesture and an item selection gesture as an **hinge Menu**. We adopted the following naming convention: <Gesture for menu activation><To or From>→<Gesture for item selection>. Thus, six **Hinge Menus** were evaluated in our study, illustrated in Figure 10 *TapTapFrom→Tap*, *SwipeFrom→Tap*, *TapTapTo→SwipeOn*, *SwipeTo→SwipeOn*, *TapTapTo→Tap*, and *SwipeTo→Tap*.

6.2 Task design

Each trial involves two steps: performing the activation gesture and selecting a menu item. However, we also aimed to measure the user’s thumb rest position as it can have an impact on the total duration of the task: starting from a different thumb rest position will induce a different distance to the target, thus a difference in the time required to perform the task. Therefore, before performing the two steps, participants were asked to tap once on the screen at their natural thumb rest position. Each trial thus proceeded as follows: the participant tapped at their thumb rest position (trial start), performed the activation gesture, and then selected the target menu item (trial end). If an error occurred (e.g., incorrect item selection, activation gesture performed on the wrong screen, etc.), the trial was immediately aborted, counted as an error, and added back into the remaining set of trials to ensure that every condition was completed correctly once. As in the previous study, seven menu items were displayed on the hinge.

To provide a baseline for comparison, we designed two reference menus: a vertical linear menu placed on the left side of the screen (*LinearLeft*) and one on the right (*LinearRight*), see Figure 11. After the initial tap, a menu icon was displayed in the upper-left (or upper-right) corner of one of the two screens. A simple tap on this icon displayed on the same screen seven vertically aligned menu items. The items dimensions were identical to the those on the hinge. The user then selected the target item to complete the trial.

For all menu techniques, the six hinge menus and the two linear menus, we used the same targets as in previous studies (0, 2, 4, and 6).

In this study, we did not constrain the distance or starting position of tap-tap or swipe gestures as we wanted to assess the validity of our menu techniques in a more realistic context. For example, to perform a tap-tap *From Hinge*, the user could start anywhere along the hinge and complete the gesture with a second tap (within 500ms) wherever the user wanted on the designated screen.

6.3 Participants, Apparatus and Implementation

We collected and analyzed data from 12 participants (8 self-reported as men, and 4 as women), with an average age of 28 years ($SD = 4.55$). All were right-handed, recruited from the local university, and experienced smartphone users (none had previously used a foldable phone). None had participated in any of our earlier studies. The

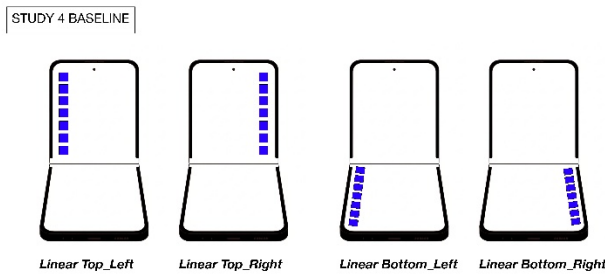


Figure 11: Illustration of the LinearLeft and LinearRight menu techniques.

participants were seated, held the foldable phone in their dominant hand with the arm raised and unsupported, and were free to adopt any grip.

Before each trial, the participants could take a break. The device and equipment setup were identical to those in the previous studies. We followed the same health and ethical procedures as in previous studies.

6.4 Experimental protocol

We adopted a within-subject $8 \times 2 \times 2 \times 4$ design with **Menu technique** (*TapTapFrom*→*Tap*, *TapTapTo*→*Tap*, *TapTapTo*→*SwipeOn*, *SwipeFrom*→*Tap*, *SwipeTo*→*Tap*, *SwipeTo*→*SwipeOn*, *LinearLeft* and *LinearRight*), **Fold angle** (120° , 150°), **Screen** (*Top*, *Bottom*) and **Target** (0, 2, 4, 6) as factors. Menu techniques were counterbalanced using an 8×8 Latin square. For each technique, the Fold angle was randomly selected. For each Fold angle, screen and targets were randomized, and participants completed the full set of trials under these conditions.

In total, we collected: 12 participants \times 8 menu techniques \times 2 angles \times 2 screens \times 4 targets = 1,536 training trials and 4,608 measured trials = same structure \times 3 repetitions. The average session duration was approximately 78 minutes.

6.5 Data collection and Analysis

For each trial, we recorded all touch points (sampled every 20ms), along with the total time of each trial. We also recorded the first tap position (thumb rest position) on the screen. At the end of each menu technique, participants were asked to fill a NASA-TLX form [13]. Participants were also invited to provide qualitative feedback on our experimental factors (e.g. **menu techniques**, **fold angle**, etc.). We used the same statistical methods as in the previous studies.

6.6 Results

6.6.1 Completion time. A Friedman test showed a significant difference between **menu techniques** ($\chi^2(7)=87.4$, $W=0.78$, $p<0.001$). *SwipeFrom*→*Tap* (910ms) and *SwipeTo*→*Tap* (954ms) took less time than *TapTapTo*→*Tap* (1030ms), *SwipeTo*→*SwipeOn* (1078ms), *TapTapTo*→*SwipeOn* (1145ms), *LinearRight* (1147ms), and *LinearLeft* (1236ms), see Table 25 for detailed p values. No difference was found between these two techniques and *TapTapFrom*→*Tap*

(961ms). Additionally, *LinearLeft* and *TapTapTo*→*SwipeOn* required more time than *SwipeTo*→*Tap*, *SwipeFrom*→*Tap*, *TapTapTo*→*Tap* and *TapTapFrom*→*Tap*, see Figure 12.

No significant difference was found when considering Fold angle or Screen. However, a Friedman test showed a significant effect of target ($\chi^2(3)=35.7$, $W=0.74$, $p<0.001$): targets 2 (1031ms) and 4 (1027ms) took less time to be reached than the extreme targets 0 (1073ms, $p = 0.005$ for target 2 and $p = 0.003$ for target 4) and 6 (1099ms, $p = 0.003$ in both cases).

6.6.2 Errors. We found a significant difference, using a χ^2 test, in error rates between **Menu techniques** ($\chi^2(7)=41.02$, $p<0.001$). *SwipeTo*→*Tap* (0.5%) and *TapTapTo*→*Tap* (0.8%) resulted in fewer errors than *LinearLeft* (3.1%) and *TapTapTo*→*SwipeOn* (4.0%, the highest error rate among all techniques), see Table 28 for detailed p values. Overall, all **Menu techniques** induced less than 5% of errors, and we did not find any significant difference between the two **Fold angles**.

6.6.3 Thumb rest position. Our experimental results confirm that the resting thumb is most often located on the upper part of the Bottom screen, see Figure 12. This finding supports our earlier analysis in section 5.6, stating that gestures involving the *Bottom* screen required less time than those involving the *Top* screen due to the thumb's rest position being on the *Bottom* screen.

6.6.4 NASA-TLX and informal feedback. Multiple Anovas showed a significant differences across **Menu techniques** for physical demand ($F(7, 120)=61.5$, $p<0.001$, $\eta^2=0.78$), performance ($F(7, 120)=35.4$, $p<0.001$, $\eta^2=0.67$), effort ($F(7, 120)=72.6$, $p<0.001$, $\eta^2=0.80$), and frustration ($F(7, 120)=23.4$, $p<0.001$, $\eta^2=0.58$). For all four measures, *LinearLeft* and *LinearRight* induced greater physical demand (and respectively lower performance, greater effort, and greater frustration) than the six hinge-based menu techniques, see Table 31, Table 34, Table 36 and Table 38 for detailed p values. This result is confirmed by informal feedbacks from participants: “With the linear menus, I have to bend my grip to access the menu button or the bottom menu items, it hurts a little after some time.”, P3 and “I thought the linear on the right would be easier because its closer to my thumb, but some angles are really hard to achieve, it makes some targets really hard to hit”, P7.

6.7 Summary

This study compared six hinge menus with two linear menus positioned on the left or right of the two screens. Our findings show that three hinge menus (*TapTapFrom*→*Tap*, *SwipeFrom*→*Tap* and *SwipeTo*→*Tap*) require less time than traditional linear menus (*LinearLeft*, *LinearRight*). In addition, we found that *TapTapTo*→*Tap* and *SwipeTo*→*SwipeOn* require less time than *LinearLeft* (but not than *LinearRight*). Finally, both linear menus induced higher physical demand, effort, frustration, and lower perceived performance than all six hinge menus, confirming the advantages of the hinge gestures refined in our earlier studies.

7 Discussion, Limitations and Future work

Our research contributes to a better understanding of how the hinge of foldable phones can be leveraged as a functional interaction zone for extending their input vocabulary. Through four empirical

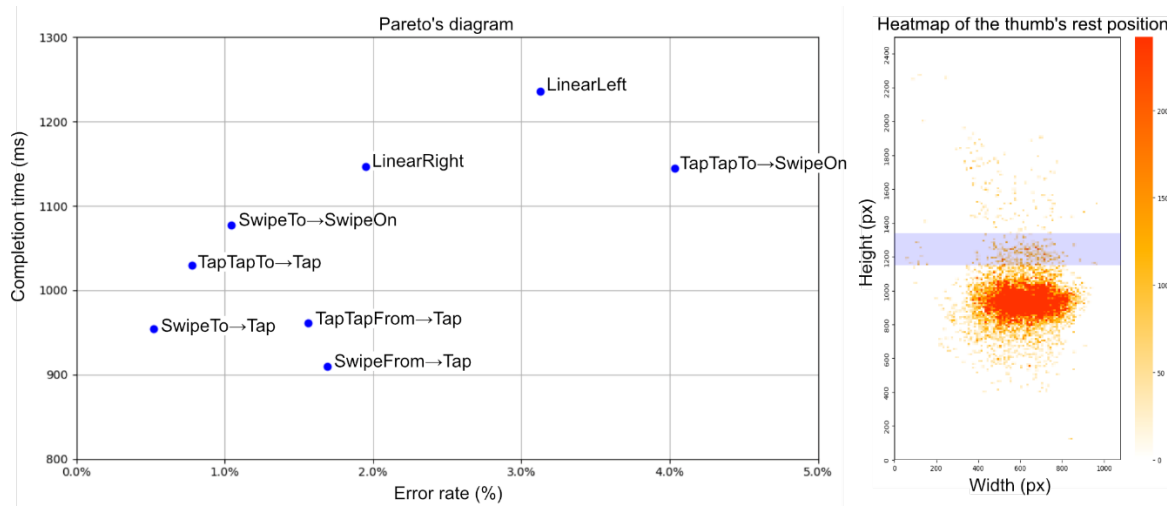


Figure 12: Pareto's diagram of the completion time and error rate per Menu Technique (left). Heatmap of the thumb rest position (right).

studies, we demonstrated that the hinge is both reachable and usable for interaction gestures including taps, tap-taps, and swipes, as well as for interaction tasks such as menu selection. We also identified how grip, fold angle, and gesture category influence performance and user preference. We further discuss these findings within the context of related research.

7.1 Link between grip and reachability on foldable phones

Our first study investigated the impact of grip and dual-screen touch on reachability in foldable phones. Regarding grip, our findings align with those of Pecchioli et al. [28]: our participants often adopted a “junction grasp”, which provided a more secure grip of the foldable phone. Regarding fold angle, our results also corroborate this previous study which was performed on a smaller device, showing that on larger foldable phones a narrower fold angle increases both the reachable and comfortable areas. Beyond these findings, our work extends prior studies by showing that the reachable and comfortable areas additionally depend on which screen the interaction is performed. Our findings indicate that users adjust their grip according to their primary area of focus (hinge area, top or bottom screens), which in turn modifies the thumb's reachable and comfortable areas. Interestingly, when randomly interacting with both screens, as in our study 4, our results show that the resting thumb is most often located on the Bottom screen. Overall, these findings are consistent with recent work [49], which emphasized the strong influence of grip strategies on thumb reachability, reinforcing the importance of considering contextual hand postures when designing interaction for foldable phones.

7.2 Impact of the fold angle on hinge interaction

Our second study extended this analysis by systematically examining the reachability and performance of taps on the hinge across

different fold angles. Consistent with Dengyun et al.'s work [24], we showed that fold angle directly influences completion time and gesture precision. Our first study also revealed that fold angle affects the deviation of swipe gestures on the hinge. These findings align with the work of Roudaut et al. [33] on concave touch surfaces, which showed that touch gestures are more error prone because “concave surfaces hug the user's finger”, increasing the contact area and thus the offset with higher curvature. We contribute with a novel proposal to adapt the height of hinge items to the fold angle to preserve accuracy: hinge items should be larger for narrower angles (e.g., 120°) than for wider ones (e.g., 150°). Our studies demonstrate that, when hinge items height is adapted, users can interact accurately with the hinge across a range of fold angles, highlighting its viability as an input area even in non-flat configurations. This contrasts with earlier perspectives that primarily treated the hinge as a limitation [9, 14, 26, 42–44].

7.3 Hinge gestures as a novel input vocabulary on foldable phones

Our third study focused on hinge gestures, defined as a novel type of touch gestures (tap-tap or swipe) involving the hinge in different ways: the gestures can be performed on or along the hinge (On Hinge), cross the hinge from one screen to the other (Across Hinge), or start or end on the hinge (From and To Hinge respectively). Our results on the tap-tap gesture — specifically its high precision and completion time below 300ms — confirm that consecutive distant taps involving the hinge on a foldable phone can effectively expand the interaction vocabulary. This extends prior work by Heo et al. [16], who demonstrated the feasibility and interest of consecutive distant taps on a flat surface. Our results on the swipe gesture demonstrate that a swipe To Hinge does not require more time than On Hinge, extending Zinck et al.'s [53] finding that gestures along the hinge perform better than gestures across it. Leveraging the physical properties of the hinge to guide the gesture allows for faster completion time. Overall, hinge gestures expand the tactile

interaction vocabulary beyond what is possible on conventional flat smartphones. In particular, the hinge-enabled tap-tap shares similarities with bezel tap interactions [36], as both exploit screen borders to introduce new input opportunities. By demonstrating that such hinge gestures can be performed efficiently and distinctly from traditional touch actions, our results suggest that foldable phones can support an enriched set of input modalities without requiring additional hardware.

7.4 Hinge menus to improve dual-screen usage

Finally, our fourth study built on our prior results to explore the use of the hinge to display and interact with a menu in dual-screen scenarios. We showed that hinge menus can reduce reach effort and better align with the user’s thumb comfort area, compared to traditional common menu placements, i.e. in the top corner of the screen. In a way, our hinge menus can be seen as an extension of bezel menus [20, 36] conveniently placed inside the thumb comfort area: indeed the hinge can be seen as a bezel generated by folding the phone. Furthermore, while our implementation focused on multitasking contexts with one application per screen, the same design principles could apply to single-application scenarios—for example, using the hinge as a toolbar for quick shortcuts. Our approach could thus improve usability by minimizing reach to distant UI elements in single app scenarios. However, we acknowledge that swipe To Hinge gestures may be prone to confusion with standard swipes on the screen, potentially triggering unintended actions such as scrolling. In contrast, tap-tap To Hinge gestures appear more robust for regular menu activation. These insights demonstrate that hinge menus are a relevant alternative to current linear menus on regular foldable phones.

7.5 Usage scenario: Dual-screen interaction with a map and a restaurant booking platform

To ground our findings in a realistic scenario, this section illustrates how hinge menus support dual-screen workflows on foldable phones. The following scenario demonstrates how the hinge can serve as a central, always-available interaction zone when two applications are displayed simultaneously, one per screen, reducing reach effort and helping users fluidly coordinate tasks across apps.

Alex is planning an evening out. The foldable phone displays a mapping application (e.g., Google Maps) on the top screen (Figure 13 – A). Alex begins by exploring the map to find a restaurant for dinner. Thus, they perform a *SwipeFrom* gesture to the top screen to activate the hinge menu (Figure 13 – B). On this menu, Alex selects the “restaurant” category of points of interest using a tap to highlight them.

After browsing the highlighted POIs on the top screen, Alex selects a specific restaurant on the map. This action opens a restaurant booking platform on the bottom screen, displaying the restaurant’s detailed view, allowing Alex to check opening hours, location, or reservation options (Figure 13 – C). For instance, to access the restaurant’s menu, they use a *SwipeFrom* gesture on the bottom screen to activate the hinge menu, this time associated with the restaurant booking platform displayed on the bottom screen (Figure 13 – D), and select the “Menu” item with a tap on the hinge.

Throughout this process, the hinge menu plays a central role in coordinating interactions across the two applications. Because it is positioned at the fold, equally accessible from both screens, the user can trigger contextual commands without shifting their grip. In addition, using a hinge menu preserves valuable screen real estate on each screen for displaying either the map (top screen) or the POI information (bottom screen).

7.6 Limitations and future work

While these results open up promising design opportunities for foldable phones, several limitations remain, which pave the way for future work.

First, our studies involved a homogeneous sample of participants—right-handed, young adult university students—who were familiar with smartphones but had little to no prior experience with foldable phones. This limited diversity may affect the generalizability of our findings. Future work should include a broader participant base, including left-handed users or older adults, in order to assess whether the hinge remains reachable and efficient across diverse user groups.

Second, all interactions were performed in a controlled environment using thumb input with the phone held in the dominant hand. Although this reflects common mobile use, it does not cover alternative input modalities, such as bimanual interaction, index finger input when the phone is on a surface, or stylus-based interactions. Performing additional studies to include these interaction styles could help further generalize our findings and uncover new use cases.

Finally, we conducted our experiments on a single commercial foldable phone (Samsung Galaxy Z Flip 3). Although representative of current foldable hardware, our results may be influenced by device-specific characteristics, such as screen size or touchscreen sensitivity. Replicating these studies across a variety of foldable form factors (e.g., tablets, dual-screen laptops) and hardware configurations might be advisable.

Regarding target size and task difficulty, our intention in this work was to explore whether hinge gestures and hinge menus can be considered viable interaction techniques. For this reason, we defined the minimal target sizes to achieve high accuracy ($\geq 95\%$). While our present work focuses on establishing a robust interaction vocabulary, understanding how performance evolves under more demanding conditions is an important direction for future research. In particular, to better support designers’ options, future studies could systematically decrease target size, increase item density, or introduce mobility and distraction, in order to characterize the boundaries of hinge-interaction robustness. Additional work with extended training could also reveal whether users can achieve reliable performance with smaller targets once hinge gestures are more practiced and become more familiar.

Other promising ideas for future research include investigating adaptive menus that respond to fold angle and grip, exploring other combinations of hinge gestures, and examining the long-term usability of UI components on the hinge. Together, these efforts can inform the design of foldable phones that make full use of their unique physical affordances, ultimately enhancing mobile interaction beyond the flat screen paradigm.

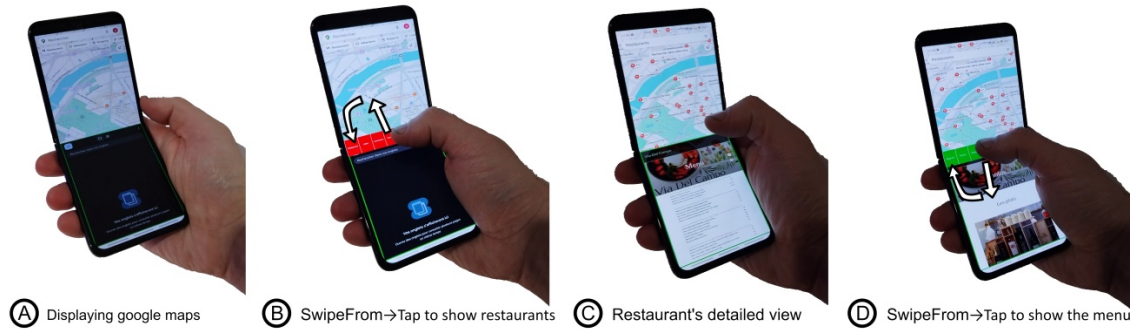


Figure 13: Usage scenario: a user interacts with a map on the top screen (A). A *SwipeFrom→Tap* allows filtering on restaurants (B). After selecting a restaurant, its detailed view is displayed on the bottom screen (C). A *SwipeFrom→Tap* allows navigating through the website and find the restaurant's menu (D).

8 Conclusion

In this paper, we explored how to leverage the hinge of foldable phones to enrich interaction. To this end, we conducted four user studies. In the first study, we analyzed how users naturally hold a foldable phone at various fold angles and assessed the resulting thumb-reachable areas. Building on this, a second study evaluated the reachability and performance of tapping on the hinge of a foldable phone. The results validated that users can reach and accurately tap on the hinge across different fold angles and starting screens. The third study evaluated the performance and user preference of hinge gestures, defined as tap-tap and swipe gestures performed On, To, From, or Across the hinge. The results showed that all gestures From/To/On Hinge were performed with low error rates, demonstrating they can serve as new input gestures. Finally, the fourth study applied these insights to inform the design of hinge menus that we compared against a traditional linear menu. Results revealed that hinge menus are more efficient, with the best performance achieved through a tap-tap or a swipe to the hinge, followed by a simple tap on the hinge to select a menu item. Taken together, our findings provide both empirical evidence and practical guidelines for designing interactions with current foldable phones, demonstrating that the hinge is not merely a structural element but a promising input area that can enrich interaction on foldable phones.

Acknowledgments

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Table 1: Comfortable area according to the region factor (in mm²).

	Mean (mm ²)	Ci low	Ci high
Bottom	3288.32	2710.03	3866.62
Hinge	4226.54	3713.91	4739.16
Top	3505.16	2961.37	4048.94

Table 2: Y coordinate of the centroid of the Comfortable area (in pixels), With Y = 0 at the top border of the foldable phone's screen.

	Centroid Y	Ci low	Ci high
Bottom	1531.97	1462.74	1601.21
Hinge	1106.75	1075.35	1138.15
Top	799.33	753.83	844.83

Table 3: Reachable area according to the region factor (in mm²).

	Mean (mm ²)	Ci low	Ci high
Bottom	5088.41	4591.48	5585.34
Hinge	5529.74	5066.24	5993.24
Top	4919.31	4494.37	5344.25

Table 4: Reachable area according to the fold angle factor (in mm²).

	Mean (mm ²)	Ci low	Ci high
90°	6100.81	5585.76	6615.86
120°	5364.49	4830.56	5898.42
150°	4835.07	4315.89	5354.24
180°	4416.24	3973.59	4858.88

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A APPENDICES

In this section, we detail all statistical results we provided in the experiments.

A.1 A.1 STUDY 1: HAND GRIP AND THUMB-REACHABLE AREAS

A.2 STUDY 1: Comfortable area

A.1.2 STUDY 1 : Reachable area

A.1.3 STUDY 1: Swipe deviation

A.2 STUDY 2: POINTING PERFORMANCE ON THE HINGE

A.3 A.2.1 STUDY 2: Completion time

A.3 STUDY 3: CHARACTERIZING HINGE GESTURES

A.4 A.3.1 STUDY 3: Tap-tap - Completion time

A.3.2 STUDY 3: Swipe - Completion time

A.3.3 STUDY 3: Tap-tap – Error rate

A.3.3 STUDY 3: Swipe – Error rate

A.4 STUDY 4: EXPLOITING THE HINGE GESTURES TO DESIGN A HINGE MENU

A.5 A.4.1 STUDY 4: Completion time

A.4.2 STUDY 4: Error rate

A.4.3 STUDY 4: NasaTLX

Table 5: Y coordinate of the centroid of the Reachable area (in pixels), With Y = 0 at the top border of the foldable phone's screen.

	Centroid Y	Ci low	Ci high
Bottom	1363.25	1307.09	1419.40
Hinge	1083.35	1056.77	1109.92
Top	891.53	847.16	935.90

Table 6: Swipe deviation according to the fold angle factor (in mm).

	Mean (mm)	Ci low	Ci high
90°	11.15	8.91	13.39
120°	6.99	8.76	8.04
150°	8.55	6.77	10.33
180°	7.70	5.46	9.95

Table 7: Completion time according to the target factor (in ms).

	Mean (ms)	Ci low	Ci high
0	425.25	405.20	445.30
2	378.00	358.15	397.86
4	384.49	362.92	406.06
6	397.66	377.06	418.27

Table 8: Completion time according to the fold angle factor (in ms).

	Mean (ms)	Ci low	Ci high
120°	407.13	392.33	421.92
150°	385.58	371.33	399.82

Table 9: Completion time according to the category factor (in ms).

	Mean (ms)	Ci low	Ci high
Across Hinge	232.95	229.32	236.59
From Hinge	215.94	212.08	219.80
To Hinge	214.34	210.91	217.78
On Hinge	163.68	154.34	173.02

Table 10: Completion time according to the distance factor for 120° (in ms).

	Mean (ms)	Ci low	Ci high
12.33 mm	206.67	201.45	211.89
20.03 mm	227.20	221.51	232.90
27.73 mm	248.43	242.82	254.04

Table 11: Completion time according to the distance factor for 150° (in ms).

	Mean (ms)	Ci low	Ci high
9.57 mm	188.54	184.35	192.74
17.27 mm	208.89	204.41	213.38
24.97 mm	228.41	223.97	232.86

Table 12: Completion time according to the screen factor (in ms).

	Mean (ms)	Ci low	Ci high
Bottom	216.02	212.92	219.11
Top	226.14	223.27	229.02

Table 13: Completion time according to the target factor (in ms).

	Mean (ms)	Ci low	Ci high
0	217.11	213.02	221.21
2	212.43	208.34	216.52
4	218.50	214.44	222.55
6	224.19	219.72	228.66

Table 14: Completion time according to the fold angle factor (in ms).

	Mean (ms)	Ci low	Ci high
120°	227.56	224.31	230.80
150°	208.56	205.96	211.16

Table 15: Completion time according to the category factor (in ms).

	Mean (ms)	Ci low	Ci high
From Hinge	367.50	357.97	377.04
To Hinge	321.03	314.33	327.73
On Hinge	321.50	308.21	334.79

Table 16: Completion time according to the distance factor for 120° (in ms).

	Mean (ms)	Ci low	Ci high
16.90 mm	304.29	296.99	311.58
33.81 mm	381.82	374.27	389.37

Table 17: Completion time according to the target factor (in ms).

	Mean (ms)	Ci low	Ci high
0	338.87	328.85	348.88
2	332.93	323.34	342.53
4	345.11	332.99	357.24
6	352.95	340.49	365.41

Table 18: Completion time according to the screen factor (in ms).

	Mean (ms)	Ci low	Ci high
Bottom	340.38	332.02	348.73
Top	348.16	339.82	356.49

Table 19: Error rate according to the category factor (in percent).

	Mean (%)	Ci low	Ci high
Across Hinge	7.87	6.60	9.14
From Hinge	4.05	3.12	4.98
To Hinge	3.18	2.35	4.01
On Hinge	0.00	0.00	0.00

Table 20: Error rate according to the distance factor for 120° (in percent).

	Mean (%)	Ci low	Ci high
12.33 mm	3.65	2.43	4.88
20.03 mm	3.40	2.22	4.58
27.73 mm	8.26	6.48	10.04

Table 21: Error rate according to the distance factor for 150° (in percent).

	Mean (%)	Ci low	Ci high
9.57 mm	1.53	0.73	2.32
17.27 mm	4.28	2.96	5.59
24.97 mm	7.49	5.77	9.20

Table 22: Error rate according to the screen factor (in percent).

	Mean (%)	Ci low	Ci high
Bottom	5.79	4.89	6.69
Top	4.28	3.50	5.06

Table 23: Error rate according to the screen factor (in percent).

	Mean (%)	Ci low	Ci high
Bottom	4.43	3.24	5.62
Top	2.08	1.26	2.91

Table 24: Completion time according to the menu technique factor (in ms).

	Mean (ms)	Ci low	Ci high
LinearLeft	1236.20	1215.81	1256.58
LinearRight	1146.66	1131.68	1161.65
TapTapFrom→Tap	961.05	947.48	974.62
TapTapTo→Tap	1029.71	1018.05	1041.38
TapTapTo→SwipeOn	1144.55	1132.70	1156.39
SwipeFrom→Tap	909.97	897.87	922.07
SwipeTo→Tap	954.03	941.74	966.31
SwipeTo→SwipeOn	1077.58	1065.90	1089.27

Table 29: NasaTLX’s mental load according to the menu technique factor (in 0-100 score).

	Mean (%)	Ci low	Ci high
LinearLeft	21.87	19.72	24.02
LinearRight	21.56	18.53	24.59
TapTapFrom→Tap	21.25	18.97	23.53
TapTapTo→Tap	20.94	17.98	23.89
TapTapTo→SwipeOn	26.56	23.23	29.89
SwipeFrom→Tap	18.13	14.77	21.48
SwipeTo→Tap	20.62	18.48	22.77
SwipeTo→SwipeOn	26.25	23.97	28.53

Table 30: NasaTLX’s physical load according to the menu technique factor (in 0-100 score).

	Mean (%)	Ci low	Ci high
LinearLeft	62.19	56.69	67.69
LinearRight	59.38	51.66	67.09
TapTapFrom→Tap	21.56	18.53	24.60
TapTapTo→Tap	25.31	22.65	27.97
TapTapTo→SwipeOn	25.00	22.43	27.57
SwipeFrom→Tap	24.38	21.17	27.58
SwipeTo→Tap	22.50	19.93	25.07
SwipeTo→SwipeOn	23.75	20.91	26.59

Table 31: P values for NasaTLX’s physical load for each pairwise combination of the menu techniques. NS means no significant difference was found ($p > 0.05$).

	Linear-Left	Linear-Right	TapTapFrom→Tap	TapTapTo→Tap	TapTapTo→SwipeOn	SwipeFrom→Tap	SwipeTo→Tap	SwipeTo→SwipeOn
LinearLeft		NS	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
LinearRight			<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
TapTapFrom→Tap				NS	NS	NS	NS	NS
TapTapTo→Tap					NS	NS	NS	NS
TapTapTo→SwipeOn						NS	NS	NS
SwipeFrom→Tap							NS	NS
SwipeTo→Tap								NS
SwipeTo→SwipeOn								

Table 32: NasaTLX’s temporal load according to the menu technique factor (in 0-100 score).

	Mean (%)	Ci low	Ci high
LinearLeft	22.81	19.05	26.58
LinearRight	21.25	16.43	26.07
TapTapFrom→Tap	18.44	16.32	20.55
TapTapTo→Tap	25.31	21.49	29.14
TapTapTo→SwipeOn	21.25	18.77	23.73
SwipeFrom→Tap	20.00	17.43	22.57
SwipeTo→Tap	25.00	22.08	27.92
SwipeTo→SwipeOn	21.25	17.95	24.55

