BendAide: A Deformable Interface to Augment Touchscreen Mobile Devices

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ABSTRACT

The uses of handheld mobile devices are diverse, yet interaction is not; touchscreens are the singular primary interface on most mobiles. Touch interaction has usability issues (e.g., the "fat fingers problem") which impair the fine control of small interface elements, such as when working with text. Beyond text entry, this includes tasks like placing the in-text cursor (caret), text selection, and copy/paste. Current solutions for touch usability issues do not address complex uses like working with text. We propose deformable interaction, specifically bend, added alongside touch to support working with text on mobile. We explore this through a study of BendAide, a novel deformable 3D printed case for mobiles that adds bend interaction to the device. We found that people perceive different advantages between bend and touch and that they will alternate between these inputs based on task demands and their personal abilities. Adding alternate input options to mobile could reduce the complexity of on-display interfaces and interactions and give people more choice in how they use their devices.

CCS CONCEPTS

• **Human-centered computing** → Human computer interaction (HCI); Interaction devices; Human computer interaction (HCI); HCI design and evaluation methods; User studies.

KEYWORDS

multimodal interaction, deformable interface, touch interface, mobile device, handheld device, prototype, bend, text editing

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Figure 1: BendAide is a 3D printed case that is fitted around a touchscreen mobile device. Its deformable bezel detects bend input, providing an alternative interaction modality to touch in support of complex text tasks.

1 INTRODUCTION

Current handheld mobile devices (mobiles) have dropped hardware interfaces (e.g., keyboards) in favour of larger touchscreens with software user interface (UI) equivalents. Touch is the dominant interaction modality but has poorer performance versus hardware [2, 52], as well as usability issues [6, 8, 9, 23] that are difficult to resolve through touch-centric designs. These limitations affect working with text, which comprises a large portion of daily app use [13, 30] and is present in many mobile applications. Working with text is a complex use case which involves more than text entry; it can include placing and moving the caret (i.e., the in-text cursor) [3, 4], text selection [53], and actions like copying, cutting, pasting, and deleting text [31].

Adopting an additional input modality, like bend interaction, is an alternative approach to supporting complex mobile use cases, such as working with text. We explore how touch and bend interaction can aid text-related tasks on mobile with BendAide (Figure

1), a 3D printed mobile case and deformable interface with a flexible bezel that adds bend interaction to touchscreen devices. Unlike detached input accessories (e.g., Bluetooth keyboards or styli), BendAide is held like a mobile, which allows using bend and touch together. Our study is one of only few works (e.g., [26, 47, 55, 62]) that evaluate simultaneous touch and bend interaction, and working with text is among the most complex use scenarios evaluated for a deformable interface to date.

We offer the following contributions. First, we present the BendAide prototype, a deformable interface that augments a consumer mobile with bend interaction, to emulate keyboard commands. BendAide illustrates how 3D printing can be used to fabricate deformable interfaces. Second, through quantitative and qualitative data that we gathered from a usability study of 22 participants, we evaluate the user experience and performance of bend, touch, and a combination of both on mobile text tasks. We found that bend can work alongside touch inputs, that each interaction type has its own advantages, and that people who struggle benefit from multiple interaction modalities. We present our recommendations for devices that use touch and deformation.

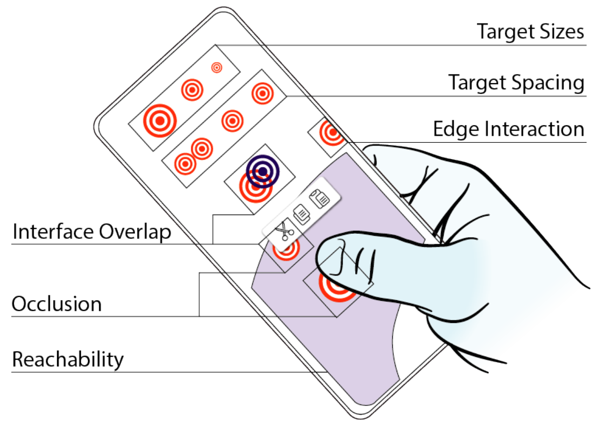

Figure 2: Touch usability issues that affect text tasks include small touch targets, crowded or overlapping UI, occlusion by UI/thumb/fingers, and targets out of reach or close to edges.

2 RELATED WORK

We describe the challenges of touch for complex tasks like text editing and outline proposed touch-centric solutions. We discuss mobile deformable interfaces that inform our design of a bendable interface to augment a touchscreen mobile device with bend input.

2.1 Usability Problems with Touch Interaction

Working with text on mobile is aggravated by touch usability issues [3, 4, 7, 21, 31, 53], as shown in Figure 2. Our fingers occlude our view as we touch, press, and drag on the display and their size, relative to UI targets, can make interaction difficult and imprecise; this the "fat fingers problem" [9, 37, 59]. Offset magnifier pop-ups display content hidden by the finger and aid interaction with small touch targets [5, 59] but these and other UI (e.g., cut/copy/paste pop-up) also create occlusion. When working with text the content is integral to our task and occlusion from any source can cause difficulties (e.g., pop-ups can occlude text we want to read or block us from placing the caret in text).

The location and size of the text workspace also impairs interaction. Soft keyboards and other UI allow text entry, but they reduce and shift the text workspace to the upper, hard to reach [36], part of the display. Margins further reduce this area but help avoid difficult edge interactions [6]. Thus, interacting with the text workspace from a one- or two-handed typing position can be difficult [36, 37], require grip changes, or cause us to drop our mobiles [29, 64]. UIs for the thumb [29, 39, 48, 64] extend access to the upper display without reaching or re-gripping but may not work for tasks where the soft keyboard occupies their interaction space.

2.2 Solutions for Mobile Text Manipulation

Innovations in software and interaction design for touch input have improved working with text on mobile. Some improve text input, like gestural typing [40, 65], predictive text [63] and text completion [7], which minimize text entry, speed it up, and reduce targeting inaccuracy.

Even so, working with text involves more than text entry. The placement and repositioning of the caret is central to all text tasks. Small corrections, inserted words, and other edits rely on the caret to mark where changes should occur (two, for text selection). Both Android™ and iOS™ use caret anchors (larger touch-targets set below the caret) to reduce the fat fingers problem and make positioning easier, albeit while contributing to UI text occlusion. Even with anchors, caret positioning can be slow and error prone [3, 4]. Alternatively, Gboard [40] supports left-right caret navigation via swipe gestures along the spacebar. While addressing the problem of reach, caret positioning with the spacebar can cause accidentally inserted spaces and words [34].

Multiple works address caret positioning and text selection. Gboard [40] can switch to a Text Editing keyboard with dedicated controls for navigation, selection, copy, paste, and delete; but this interrupts text entry. Others, like Fix and Slide [53] and TouchTap [21], use gestures that overlay the keyboard to interact in the text workspace without reaching. However, they compete with other UI in a crowded interaction space where rushed or imprecise gestures can lead to erroneous or unintentional input [7, 9, 31, 33]. Likewise, gestures in the text workspace could interfere with scrolling, caret placement, text selection, and other UI pop-ups.

Some of these issues may be avoided by shifting interactions off the display. Approaches that forego touchscreen interaction avoid usability issues like reach or the fat fingers problem altogether, e.g., back of device input [35], audio input [60], tactile brain keyboards [11], and deformable interactions. The latter, we discuss in depth, while the others are outside the scope of this work.

2.3 Deformable Interfaces and Interactions

Multimodal interaction via touch and deformation could overcome the current limitations of mobiles. Deformable interfaces can support interactions like bending, twisting, stretching, and squeezing on or around a display [22, 38, 56, 58]. Deformation can pair with touch to form novel interaction paradigms [14, 25, 26, 55].

Some research explores use cases and prototypes that combine deformable and touch interactions. WhammyPhone [25] uses touch to play a musical note while concurrent bend gestures control the note's pitch. HoloFlex [26] uses bend to move a 3D object on the z-axis (perpendicular to the display) and touch for x, y translation. Flexcase [47] adds a bendable case to a touchscreen mobile and uses bend to navigate through content and touches on the display for tasks like selection. These works use continuous bend input that, when paired with touch, supports precise interactions.

Other works add deformable interfaces to touch devices but focus on demonstrating aspects of deformable interaction. Fares et al. [20] attach a silicone case with bend-sensors to a smartphone to evaluate mobile gameplay with bend interaction. Skin-On [55] wraps the sides and back of a mobile with a deformable skin and proposes, but does not evaluate, compelling use cases like expressive gestures (e.g., tickling) to communicate emotions or squeezes to activate touch-menus on the display. These works show how deformable interfaces on mobile can support diverse use cases.

Deformation for text has seen little attention since Gummi [50], a foundational work on deformable interaction, evaluated bend input for text entry and found it to be a poor fit. Since then, works exploring other uses for bend have presented devices with greatly expanded interactivity. These works considered edge [15, 20, 32, 42] and corner [15, 20, 23, 25, 32, 47] interactions and cross-device bends at different locations [24] or along different axes [42]. These diverse bend interactions could support working with text on mobile or other complex use cases [14, 15, 22, 50], mitigating or avoiding touch interaction issues. In particular, a deformable interface on a touchscreen mobile can avoid touch usability issues by moving interactions off the display [61] and providing tangible support of fine motor control [42, 61]. Bend gestures are learnable without extensive training [20, 50] and interaction designs can benefit from metaphor [27, 32, 50, 54], directionality [10, 32, 50], and quickly formed mental models [42].

Our work is the first since Gummi [50] to evaluate deformable interactions for text tasks and is among the few that combine deformation and touch interaction [25, 26, 47].

3 DESIGN RATIONALE

We propose deformation, alongside touch, for working with text on mobile and draw the following broad guidance from the literature:

- Alternative interaction modalities can support mobile tasks affected by touch interaction limitations.
- The on-screen interaction space is crowded with overlapping UI, which alternatives could shift off-screen.
- Touch is the primary interaction modality on mobile and additions should avoid impairing touch interaction.

From these considerations, we derive two research questions which we explore through the qualitative evaluation of working with text using our deformable prototype.

RQ1: Can touch and deformable interactions work alongside each other on a handheld mobile device?

RQ2: What are the advantages and drawbacks of a multimodal handheld mobile device that uses deformation and touch?

To explore RQ1, we derive initial guidance from the literature to inform our design. We outline these guidelines and how they inform the design of our prototype, interactions, and evaluation.

Deformable Interaction and Bend Input: We chose deformation for its tangibility, directionality, and flexibility as an interaction modality. It supports discrete or continuous input [10, 32, 42, 50]. Continuous input with directionality can map to tasks like navigation, whereas deformations for actions like cut, copy, and paste can be read as discrete input. Other inputs like buttons are exclusively discrete or, like pressure sensors on rigid substrates, lack tangible feedback without added haptics. Our interface uses bend, as it offers diverse and complex interactions [15, 20, 24, 25, 32, 42, 47]. Deformations like squeeze, stretch, and pinch have not been so extensively explored.

Interface Location: For a deformable interface that works with a rigid mobile device, we drew from the complex edge and corner interactions of Fares et. al. [20], Eady and Girouard [15] and others [32, 42]. Our off-display deformable interactions allow text tasks to be executed without on-screen UI and avoid occlusion from fingers.

Orientation: Our device is portrait oriented, which supports one- and two-handed text input [7] and is how people predominantly hold their mobiles [28, 37]. Mobile writing tasks are often tested in this orientation [7, 37].

Gripping: Our device is held and used with two hands. Changing grip is not desirable mid-task in touch or deformable contexts [19, 42, 57]. A two-handed grip is stable, allows bending with less risk of dropping the device [16], and supports a larger set of possible gestures [38]. On touch devices, one- and two-handed use while typing are both common [7]. The device must be comfortable for most hands, and easy to grip and to bend.

Interaction Mapping: Like how we consider grip, bend interactions for text tasks must be positioned to avoid interfering with how touchscreen mobiles are currently held and used during text entry. Grips or bends that require re-gripping, or that make the screen unreachable, should be avoided [19, 42, 57], except in high-cost task flows, where this might avoid accidental input.

4 BENDAIDE

BendAide (Figure 3) is a 3D printed deformable smartphone case that we fit to a touchscreen mobile. We locate bend interactions off-display on a 23mm wide, 1mm thick flexible bezel with embedded Flexpoint™ bi-directional bend sensors (23mm x 5mm). BendAide is held vertically and used with two hands, which allows interaction with the bezel and the touchscreen display.

Bezel deformations are read through the embedded bend sensors and interpreted by an Arduino™, connected to the smartphone as a human interface device (HID) and emulates a keyboard. The HID translates bend gestures into keyboard commands, thereby using Android's built-in keyboard to interface with many applications.

4.1 Prototype Hardware

BendAide is 165 x 100 x 20 mm, with a bezel 23 mm wide and 1 mm thick (Figure 3B). It fits around a Xperia™ XZ1 Compact (XZ1) measuring 129 x 64 x 9.3 mm. BendAide is phablet sized (e.g., the Samsung™ Galaxy S22 Ultra is 163.3 x 77.9 x 8.9 mm).

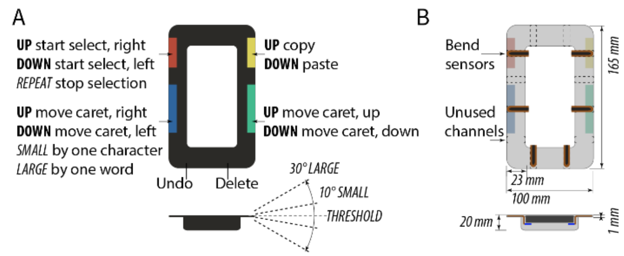

Figure 3: (A) We map frequent actions to the lower portion and less frequent/high-cost actions to the upper portion and bottom edge. (B) BendAide dimensions and sensor layout.

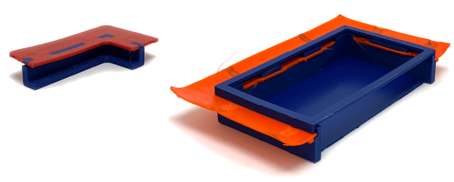

Figure 4: Early 3D printed variations of case and bezel designs.

We printed BendAide on a dual extrusion 3D printer using flexible filament (2.85mm Ninjatek™ Cheetah TPU 95A) and water-soluble filament (2.85mm Ultimaker™ PVA). We varied the bezel thickness to give it a thin flexible span and a thicker rigid edge. This way the bezel does not deform under its own weight but does not impede bending. We used the water-soluble filament to print dissolvable pockets for the bend sensors. We embedded two sensors on each side and two on the bottom of the prototype.

Through 3D printing, we iterated through materials, variations of bezel designs (shape, width, thickness, and infill), see Figure 4, and sensor locations more quickly than with silicone casting, a common method of prototyping deformable interfaces [20, 41, 44]. With silicone, each variation requires mold making, de-gassing, and curing. Since hardware, like sensors, is embedded during casting, modifications and troubleshooting are difficult [44] and it cannot always be recovered from discarded versions.

4.2 Interactions

Our mapping choices build from the design rationale. Since the device is held with two hands, both sides are interactive. We placed frequently used interactions (caret navigation) where we anticipated people would hold the device. We located infrequent actions (start/stop selection, copy/paste) above, where people can stretch to reach them, and high-cost actions (undo/delete) on the bottom of the device, where people must loosen their grip and twist their wrists to access.

We use 20 bend interactions to work with text on mobile which cover navigation, selection, and actions (e.g., copy, paste). We mapped these bends by location and direction on BendAide, see Figure 3A, and assigned them keyboard equivalents, as shown in Table 1. We color-coded the interaction locations to help participants to identify and learn them during the experiment.

4.3 Prototype Software

Bend gestures are classified using sensor location, direction, magnitude, and repetition state. Our software recognizes a total of 32 states: 4 sensors (one in each corner) * 2 bend directions (up or down) * 2 magnitudes (small or large) * 2 repetition states (repeating or not). An up bend is towards the user, while a down bend is away from the user. We read sensor data and map the range of resistance values produced as a percentage; a resting state is 0 and a maximum up bend is 100% (a down bend is -100%). We set a >10% threshold to recognize a bend in either direction. This threshold avoids unintended input from holding or changing grip, but introduces a response latency of 0.15 seconds. From initial prototyping, we determined that a threshold of 30% worked well to distinguish between small bends (between 10% and 30%) and large bends (>30%).

For example, the caret moves right and left via up and down bends on the lower left edge of the device, and the caret moves up and down via up and down bends on the lower right edge of the device. Small bends from those sensors are output as directional arrow key commands. A sustained (i.e., repeating) bend, small or large, moves the caret until it is released. Sustained bends do not repeat actions like copy and paste.

5 EVALUATION OF DESIGN, INTERACTION, AND USABILITY

In our study, people used bend, touch, or both to work with text. We assessed participants' experiences and performance to understand what it is like using these interaction modalities. We obtained clearance from our institution's research ethics board.

5.1 Methodology

We asked participants to perform variations of a copy and paste task where they reorder content in a document. In the task (Figure 5), participants first navigate a multi-paragraph text to locate a marked portion. Then they position their caret, select the text, and perform a copy action. Finally, they find a marked target (curly braces, {}) and perform a paste action. We marked targets in orange for its high colour and value contrast against black text.

Our study had 3 test conditions that varied by input: bend, touch, and free use of both (bend + touch). Each condition had 3 tasks that vary by content: select a portion of a word, a whole word, or a sentence. Each task contained 3 trials which vary the copy/paste targets. Each person experienced 27 trials (3 conditions * 3 tasks * 3 trials). We mitigated learning effects by counterbalancing the order of the conditions and randomizing the task order.

Task design: Our text tasks presented usability issues like working with small or crowded targets, near display edges, occlusion, and reaching. To do so, we varied the sample text size, target locations in text, and the amount of text to copy (word portion, whole word, or sentence). We did not remove Android supports like caret anchors or auto-word selection with double-tap or touch & hold gestures.

Table 1: Listing text tasks, gesture location on prototype and directions, and the HID keyboard commands.

Text Tasks	Location and Bend Gesture	Keyboard Output
Place caret [a]		
Caret up/down	lower right bezel up/down	arrow key UP/DOWN
Caret left/right	lower left bezel up/down	arrow key LEFT/RIGHT
Select text to left	upper left bezel, down	shift key HOLD + LEFT
Select text to right	upper left bezel, up	shift key HOLD + RIGHT
Text select end	upper left bezel up/down	shift key RELEASE
Move left selection anchor	if selection activated to left, same as caret navigation	shift key + arrow keys
Move right selection anchor	if selection activated to right, same as caret navigation	shift key + arrow keys
Copy selection	upper right bezel, down	CTRL + C
Paste	upper right bezel, up	CTRL + V
Delete	bottom bezel, right up/down	Delete
Undo	bottom bezel, left up/down	CTRL + Z

[a] In our experiment, the caret is placed automatically at the start of the text in each trial, like in a word processor.

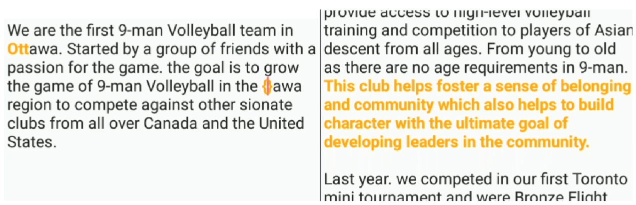

Figure 5: Two conditions, portion of a word (left) and sentence (right). Participants locate the marked text, select and copy, then find the target, {}, and paste.

Assessing User Experience and Usability: We administered a qualitative survey after each condition, where participants rated their experiences of bend, touch, and the prototype. Our questions use a 5-point Likert scale (1 strongly disagree to 5 strongly agree). We asked participants to think aloud during tasks and our surveys contain open-ended questions to collect experiences, reasoning, and motivations. In tasks, we counted errors as when the copied text or paste locations did not match their targets. We allowed participants to restart tasks, though we counted errors cumulatively. We do not report completion times, as the data would be biased by our participants' compliance with our think aloud protocol.

Study Devices: We chose different mobiles to optimize user experience in each condition. The bend and bend + touch conditions used BendAide with the XZ1 and, for touch, an HTC™ 10 (HTC), measuring 145.9 x 71.9 x 9.0mm. Both use the Android Oreo operating system, providing identical UI and functionality.

Software: We developed a simplified text editing app for the study and for training that uses Android's built-in text editing UI and functionality, but no advanced word processing features. It loads a sample text with marked copy and paste targets, randomizes task and trial orders, and logs errors.

Training: We trained participants to complete copy and paste tasks using bend (BendAide) and touch (HTC) with our software. Upon completion, participants could choose to repeat training for practice or proceed with the study. All declined further training.

Table 2: Participants' interaction preferences by context.

Context	Bend	Touch	Both	Neither
Navigation	2	7	13	0
Text Selection	7	6	9	0
Actions	10	4	8	0
Overall	5	5	12	0

5.2 Participants

We recruited 22 participants and administered a demographic entry survey. They self-identified as 11 male, 11 female and their ages range from 18 to 63 ($\bar{x} = 28$, $M = 25$, $SD = 12$). 19, were right-handed, with only 2 left-handed, and 1 ambidextrous. We measured handbreadth and hand-length following Le et al. [36]. Their handbreadths ranged from 7.0cm to 10.5cm ($\bar{x} = 8\ cm$, $M = 8\ cm$, $SD = 1$) and hand-lengths range from 16.0cm to 20.0cm ($\bar{x} = 18\ cm$, $M = 18\ cm, SD = 1$). Our participants hand sizes were comparable to previous works [36, 46], suggesting that our sample was distributed similarly to the general population.

All participants reported owning touchscreen phones, and 15 had other touchscreen devices, like tablets. All said that they could read and type on mobile, though 2 said that typing is frustrating. All participants said that they use their mobiles for informal writing (e.g., SMS texts or social media) every day and 17 said that, at least weekly, they write formally (e.g., emails). Every day participants made small ($n = 17$) or large edits ($n = 12$) in their text and selected text for various purposes ($n = 20$). However, 17 found one or more of those tasks frustrating (small edits, $n = 7$; large edits, $n = 9$; selection, $n = 9$). Frustration may be unavoidable, as 10 people still performed tasks that they found frustrating every day.

6 RESULTS

After all they experienced all conditions, we asked participants to choose their preferred interaction (bend, touch, both, neither) for navigation, selection, actions, and overall (Table 2). Bend + touch

Table 3: Median rating for bend (*Mb*) and touch (*Mt*) by question (1 strongly disagree, 5 strongly agree). Rankings (N = 22), Z and raw and Holm-Bonferoni adjusted p-values from Wilcoxon Signed-Ranks test (Bend - Touch), significance (*) at alpha < 0.05. Ranks count how individual participants evaluated touch versus bend on each question, i.e., P_N rated bend higher than touch (+), lower (-), or the same (=).

Questions	Bend (Mb)	Touch (Mt)	Rankings (N)			Z	p (raw)	p (adjusted)
			(+)	(-)	(=)			
1: The caret moves as I intend	4	3.5	8	8	6	-0.185	0.853	1
2: The caret is responsive to my inputs	3.5	4	9	10	3	-0.312	0.755	1
3: I can navigate through large sections of text	4	4.5	8	7	7	-1.269	0.204	1
4: I can move the caret precisely	4	2	14	3	5	-2.6	0.009	0.15
5: I am comfortable using this input for cursor placement	4	3.5	8	9	5	-0.171	0.864	1
6: I can activate text selection	5	4	10	4	8	-2.232	0.026	0.36
7: I can modify my selection to include only the text I want	4	4	11	3	8	-1.652	0.099	1
8: This works well for small text selections	4	2	18	2	2	-3.105	0.002	0.039*
9: This works well for selecting words	4	4.5	9	8	5	-0.122	0.903	1
10: This works well for large text selections	4	4	9	5	8	-0.835	0.404	1
11: I made few, or no, errors during these tasks	3.5	2.5	10	8	4	-0.727	0.467	1
12[a]: It is easier to select text in the middle of the screen vs. the sides	3	4.5	2	13	6	-2.852	0.004	0.051
13[a]: I am comfortable using this method of text selection	4	4	6	10	5	-0.686	0.493	1
14: I can tell which text manipulation actions are available to me	4	5	2	12	8	-2.956	0.003	0.059
15: I have enough information to perform an action	4	5	3	13	6	-2.639	0.008	0.14
16: I can do the action I intend, without mistakes	4	3	11	4	7	-1.103	0.27	1
17: I have enough information to know that I did my intended action	5	5	3	7	12	-2.067	0.039	0.35
18: I am comfortable using this for text manipulation actions	4	4	5	9	8	-0.842	0.4	1
19: Using this to interact was physically difficult	3	2	12	8	2	-0.609	0.543	1
20: I often had to change my grip	5	2.5	18	3	1	-3.225	0.001	0.027*

[a] N = 21, as one participant did not respond. **Actions** in this study include switching in and out of text selection mode, copy, and paste. Participants could perform their intended actions comfortably with both inputs (Q6, Q16, Q18). Using touch, participants benefited from guides like popups and feedback from notifications. However, 6 thought that pop-ups at undesired times (e.g., while positioning the caret) were an obstacle. Conversely, the pop-up for paste could disappear if participants re-positioned the caret during the task. When this happened, some felt stuck.

was the most preferred overall (n = 12), for navigation (n = 13), and selection (n = 9). Bend was preferred for actions (n = *10*). We deepen this understanding through our analysis of participants' responses to our survey of bend and touch interactions. Alongside this analysis, we report our observations and participant quotes. These provide context and insight into participants' thinking, strategies, and experiences with bend and touch interactions.

6.1 Participants' Experiences of Bend and Touch

We asked participants to score bend and touch using 20 Likert-style questions (1 = strongly disagree, 5 = strongly agree). Table 3 reports Median scores for bend (*Mb*) and touch (*Mt*) as well as signed ranks for each question. Signed ranks are useful because they account for how each person's touch and bend scores compare: a positive rank (+) when bend scored higher than touch, a negative rank (-) when bend scored lower, or a neutral rank (=) when they tied. Using the signed ranks, we computed Kendall's coefficient of concordance to measure inter-rater reliability. We found that there was fair agreement across participants (W=0.36, $p < 10^{-20}$). We tested for differences between touch and bend using a Wilcoxon Signed Ranks test at a 5% significance level (*alpha* < 0.05). After Holm-Bonferroni adjustment, we found significant differences between touch and bend on 2 of 20 questions: Q8 and Q20.

When navigating, participants felt they could move and place the caret with bend or touch (Q1, Q5), that both were responsive (Q2), and that each worked for gross navigation (Q3). During the touch and bend + touch conditions, 14 participants said scrolling with touch is easy and they moved quickly through the sample text using touch. 6 participants said navigating with bend is slow and hard to control. Some overshot their targets and had to readjust. P8 said it is "very hard to know how much to bend" and 10 people said that bend is not responsive, while 11 others found it too sensitive. When bending, latency was introduced, where commands to move 'forward' continued beyond the moment a participant decided to stop, until the bezel passed its threshold, returning to neutral state.

Participants struggled using touch to position the caret on target. We noted that, rather than make slight adjustments, many chose to move the caret far from the target and restart. In explanation, 12 said small movements are hard; P12 said "Well, I guess my fingers are just fat." 15 thought bend was easier for small adjustments; P5 likened it to "a keyboard with directional arrows." During the bend + touch condition, we observed participants using touch to roughly place the caret near the target and then using bends to shift it into position. People can navigate with both, but they value touch for speed and bend for precision. P3 said "they cover each other's flaws and give you an option" and P1 said it is the "best of both worlds."

To select text, participants scored both inputs as comfortable (Q13), working well for word and sentence selection (Q9, Q10) and being good for modifying selections (Q7). 14 disliked using touch near the edges of the screen and we noted that, when selecting text, nearing the top or bottom edge of the display could cause out of control scrolling and disrupt their efforts. P10 noted "Touching elsewhere on the screen can mess up the process." Participants liked Android's built-in ease-of-use features for touch, like double-tapping a word to select it, though some noted that this interfered with selecting word-portions. Indeed, 18 people scored bend higher than touch for selecting small portions of text (Q8: Mb = 4, Qt = 2, p = 0.039), suggesting that precision is a factor for tasks not well supported by software.

Using bend, 6 people liked a screen free of occlusion but others (5) wanted feedback and 9 said it was difficult to remember everything with bend. Without feedback for actions, one participant doubted whether they had successfully copied or accidentally cancelled text selection. 8 participants liked copy and paste, which are always available as they are mapped to the bezel. P11 said it is like "having copy/paste button which makes it easier." However, 9 people repeatedly confused the bend gestures for copy and paste during the tasks. P15 said "when. . .copying, I think of picking up and paste as putting down so these [actions] seem reversed to me." P22 said it is "intuitive to copy lifting up instead of down. . .like you are cutting out. . .and to paste it should be down because it feels like placing it on the screen." Thus, a third of our participants formed an inverse mental model of the copy and paste actions.

Working with text is hard. Neither interaction scored well for avoiding errors (Q11). Participants using touch expressed surprise and frustration when struggling. P14 shared that they would never be good at touch because their fingertips have limited sensitivity. They, and others, said swapping modes when they struggled made tasks less frustrating and encouraged them to persevere.

Interactions were not physically difficult for participants (Q19), but people using bend re-gripped more often (Q20: Mb = 5, Mt = 2.5, p = 0.027). We saw participants re-grip for text selection, copy and paste, and upward gestures in general. P7 said "there was no grip I could comfortably hold." 15 participants found that BendAide was too big, and some wanted softer edges and materials.

When bending, 6 people found the prototype too sensitive and 5 said that it was not sensitive enough. This may relate to how they held and used the device. P5 said "I do not always know how much force to use, and it seems to be different depending on the position of my thumb." Others said the interactions did not feel consistent or that the responsiveness of the prototype was slow.

Table 4: Frequency of mismatch when copying and when pasting by content and input type, P14 removed.

Task Step		Bend	Touch	Both
Mismatch on Copy	Word portion	0	1	1
	Full Word	3	0	4
	Sentence	13	4	5
Mismatch on Paste	Word portion	0	2	1
	Full Word	4	1	2
	Sentence	5	4	4

6.2 Measures of Performance

Although our analysis is not focused on performance, we tracked the frequency of task errors using our software. We defined errors as: copied text mismatch and missed paste targets. Table 4 shows the frequency of errors across conditions. The software ignored issues like caret positioning errors or accidentally canceled text selection, though we observed these (see previous section).

Most participants completed the tasks with few errors; the overall mean error rate was 0.8 ($SD = 1.0$). Separated, the interaction modes performed similarly. The Bend mean error rate was 1.6 ($M = 1.0$, $SD = 2.8$). The touch error rate was 0.9 ($M = 0.0$, $SD = 2.1$). The Bend + Touch error rate was 1.2 ($M = 1.0$, $SD = 1.0$). Two participants struggled: P13 and P14 account for 40% of the total errors, 91% of touch errors, 25% of bend, and 29% of bend + touch. We removed P14 as an outlier, as their error rates in each condition exceed three standard deviations from the mean.

Participants made the most mismatching errors when selecting sentences, though they were marked the same way as full words and word-portions. The low error frequency on those and when pasting suggests that selecting sentences presents a challenge to participants. Sentences differ in that they span more than one line, meaning that sentence selection includes vertical caret movement.

7 DISCUSSION

In our study, participants used bend, touch, or a combination of both for text tasks. Our analysis shows that, overall, participants found both favourable. It is through this data and participants' discussions of their experiences that we learned how neither interaction modality is optimal on its own. We discuss how mobiles can use bend and touch together to overcome their limitations as singular modes of interaction to improve user experience.

Participants rated both bend and touch favourably for navigation during text tasks, but they found bend too slow for navigation, a departure from previous works [45, 50]. When navigating with bend, participants used large deformations and they overshot their targets, due to a latency or ramping effect. This felt simultaneously over-sensitive and unresponsive. In comparison, participants using touch transitioned with ease from fast movement into rough caret placement. When touch users mistargeted, corrective adjustments were difficult. When given the option, participants used touch for fast navigation and then switched to bend to precisely target. Bend avoids the crowded display and offers dedicated controls which can help reduce the need for precise touch interactions [17, 19, 26]. While this did not alter performance and either mode is sufficient for the entire task, alternatives allow people to optimize their approach to meet their perceived needs across changing contexts.

Participant experiences using singular inputs for actions like text selection and copy/paste are similarly divided. Using touch, participants could easily select words or sentences. They felt bend did better with smaller portions of text and, in general, initiating text selection. Selecting large portions of text with touch can bring people in content with the upper and lower edges of the display, causing problematic movements. This is an issue of working with text that designs like margins [6] do not address. Our device and software support for text selection was limited to one mode of input throughout (e.g., if started with bend, switching to touch would cancel selection). In addition to more discrete opportunities to swap between interactions and supporting parallel interaction paths for tasks, we are eager to use interconnected deformation and touch interaction (e.g., [25, 26]) and chorded gestures [43], much like you can CTRL + Click with a mouse and keyboard.

In the action stage, some participants using bend missed the UI of touch, others did not. But UI for feedforward [12] and feedback designed for multimodal interaction and incorporating on- and off-display supports [17–19] could balance experiences. We encourage designs that offer more support for deformation while reducing the crowded display space for touch.

While touch has many on-screen guides for actions, our bend interactions did not and people struggled to remember some, while others misremembered. While arbitrary mappings are learnable with time [1, 51], Girouard et al. [24] encountered similar issues with reversed mental models and even noted that participants overlooked on-screen feedback that offered corrections. Likewise, tangibility, directionality and embodied feedback of deformation are useful [20] but may not overcome all the challenges of working with text on mobile.

Support for RQ1: People used both modes of interaction interchangeably on text tasks and our results do not indicate that bend interaction to mobile impeded touch. Participants made few errors and scored both interactions well across all conditions, except where those modes are undermined by their own limitations.

Support for RQ2: Multiple interaction modalities on mobile present opportunities to design advantageous alternative interactions that support a robust and accessible user experience, rather than use a singular mode to mitigate its own weaknesses.

An improved deformable interface: Our prototype was too big and pushed the limits of usability and comfort for our participants. We did not avoid re-gripping, as intended, and bend interactions lacked useful guidance and feedback. We suggest the following opportunities for deformable interfaces on touchscreen mobiles:

- Explore device forms that minimize reach and re-gripping, perhaps even reconfiguration [49].
- Devise parallel interaction paths for deformation and touch, that support swapping between modes.
- Allow simultaneous deformable interaction off-screen with touch interaction on screen and interconnected interactions, including chorded gestures.
- Methods to activate and end continuous deformable inputs aside from the deformation itself, thereby avoiding unwanted latency or ramping.
- Consider how on-screen UI can support off-screen interaction and how off-screen interaction can reduce on-screen UI.

8 LIMITATIONS

While multimodal interaction on mobile with bend and touch appears to support working with text, our study did not include text entry, which is a critical task. It is unclear how our proposed interactions might fit into everyday text workflows or common scenarios (e.g., browsing, making/receiving calls).

We used an XZ1 (in BendAide) and HTC in the study which, while differently sized, provided a prototype and control device comparable to current phones and phablets. This is a constraint of works exploring different interaction modalities or interface forms (e.g., [2, 42]). The bend and touch conditions each used a device optimized to that interaction modality, which support the qualitative aims of our study.

However, differences between the HTC and XZ1 could influence how people experienced touch in the bend + touch condition, particularly with regards to performance. The XZ1's smaller display could make touch tasks harder [9, 50] and the flexible bezel increases reaching distance to the display [9]. We did not control novelty or limit any inference of the purpose of the 'bend + touch' condition and, as a result, participants may have made greater effort to use both types of interaction. Nevertheless, we are encouraged that participants' expressed motivations for switching between bend and touch were based on the usefulness of these interactions.

9 CONCLUSION

We evaluated BendAide, a deformable interface that adds bend interaction to a touchscreen mobile and used it to explore a complex mobile use case, working with text on tasks like navigation, selection, and copy/pate. We found that touch and bend interactions work well alongside each other.

Each mode of interaction has strengths and weaknesses and, even in scenarios where all options are usable, people want to choose one that supports the demands of the task. Multimodal devices can offer complementary modes of interaction that suit people's changing interaction needs across diverse contexts. We saw evidence of this when people switched between bend and touch for precision and speed, respectively, at different stages in their text tasks. With singular interactions, there may be no ideal design or usability solution for people who struggle using their mobiles. Alternative interaction options could help people to persist through tasks where they might otherwise be blocked or lose motivation.

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