Visual Feedforward Guides for Performing Bend Gestures on Deformable Prototypes

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ABSTRACT

As a novel input techniques for deformable devices, bend gestures can prove difficult for users to perform correctly as they have many characteristics to master. In this paper, we present three bend visual guides which use feedforward and feedback mechanisms to lead users to correctly perform bend gestures on a flexible device. We conducted an experiment to evaluate the efficiency and preference for our visual feedback designs. Our results show that users performed faster when the visual guidance appeared at the location where the bend gesture is to be performed instead of always at a fixed location on the screen. While feedforward improved users' performance, using feedback had a negative effect. We propose a set of design guidelines for visual systems for bend gestures.

Keywords: Bend gesture; visual guidance; feedback; feedforward; deformable user interface

Index Terms: H.5.2. User Interfaces–*Design, Interaction styles*

1 INTRODUCTION

Due to the large demand for handheld computing devices, there is an increase of interest in research on new methods for their fabrication and interaction. One technology capturing the interest of many scientists is handheld flexible devices that allow users to use bend gestures as a form of interaction. We classify research on deformable devices in two general groups: hardware prototyping and interaction design. For research focusing on hardware challenges and problems, scientists are searching for suitable materials to fabricate flexible displays, batteries, sensors and electronic components for applications in flexible displays [1,2]. Researchers are also studying interaction with flexible devices to find methods for better and simpler interaction [8,9,23,24].

Designing a proper interaction for communication with a device with small display such as smartphones and tablets has always been a major challenge for human computer interaction (HCI) researchers. In such devices, the use of traditional methods such as buttons and menus is less efficient due to the reduced space for interaction and real estate to display patterns and shapes [23]. As flexible devices offer a new way of interaction (bending), many researchers used bend gestures as their main interaction style with flexible devices [8,10,15,23].

Upon reviewing the deformable device literature, we found little information about educating and guiding users in the correct application of a bend gesture. Suppose that a user wants to take a photo with her/his flexible handheld device, which offers bend gestures as its only interaction method. To do this, the user must access the camera application via one or more bend gestures; achieve the proper zoom by means of several bends; and, finally, take the photo using a final bend. To perform all these steps correctly, the user must know which part of the device she/he should bend, then learn the correct direction (downward or upward), and the correct angle of the bend. As bend gestures could differ in their location, direction, size, angle, and speed for example [27], learning and performing several bend gestures could be challenging for users, as it is sometimes difficult to even repeat an identical gesture [15].

This research identifies the problems and difficulties a user might experience during her/his interaction with a flexible device, proposes and compares two visual feedback guides that offer bend gesture information in a simple manner. Our goal is to guide users into correctly completing bend gestures. We study how such information should be displayed for the user by evaluating the efficiency and preference for different elements of our designs.

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2 RELATED WORKS

Flexible devices are a rapidly growing research domain. We reviewed related works on flexible devices interactions, and visual feedback and feedforward for gesture-based interactions.

2.1 Flexible Devices

We separate prior works on studying flexible devices into two general groups: physical properties and fabrication of the flexible prototypes and devices, and interaction styles and user experiences with flexible devices.

2.1.1 Prototyping Deformable Devices

Although flexible displays are not yet commercialized, the technology is advancing rapidly. A few researchers have accessed functional flexible displays and built prototypes with them, such as Kinetic device [10], and PaperPhone [15]. In the absence of commercialized flexible displays, other researchers have come up with novel ideas to create flexible prototypes for use in different studies on such devices. Some researchers fabricated their flexible prototypes with an input device without a screen, using instead an external display [7,9]. Other researchers built prototypes with rigid display affixed to the flexible device [23,30]. Finally, many researchers use projection to display a screen on the surface of prototypes [6,12,17,22,28].

2.1.2 Interactions with Flexible Devices

The majority of previous studies on interaction styles for flexible devices focused on bend gestures as the primary interaction style. Pioneering the flexible device research, Schwesig et al. [23] introduced a set of interaction techniques using bend gestures. They integrated single and double bends and used the flat state to distinguish between actions. Following, many researchers have investigated the use of bend gestures on devices with different sizes and flexibility [7,11,15,16,30]. Warren et al. [27] proposed a classification scheme for bend gestures. Their study identified two levels of magnitude for bend gestures that had optimal distinction with their users with their prototype. We applied the prior work's findings by leveraging Warren's classification scheme, as it was important to take into account different factors of a bend gesture.

2.2 Visual Feedback and Feedforward

Research on visual feedback exists since the beginning of the computers, and the early days of psychology [21]. We discuss prior works on visual feedback and feedforward on rigid and flexible devices. Our goal is to use some techniques designed and implemented for touch gestures for bend interactions.

2.2.1 Visual Feedback/Feedforward on Rigid Devices

We investigate two concepts: feedforward and feedback. We reviewed research taking a deeper approach of them, and to the fundamentals of guiding users to interact with computer devices.

Feedforward is a mechanism that informs the user about what the result of their action will be, whereas they defined feedback as a mechanism that informs the user about the process of an action [4]. According to Djajadiningrat et al. [4], feedforward and feedback would have far-reaching effects for the look and feel of the future electronic products. Kurtenbach et al. [14] proposed an early example of the use of feedforward in gestural interaction. They designed circular menus to help both novice and expert users perform a menu selection by either popping up a pie menu, or by making a straight mark in the direction of the desired menu item without popping up the menu. Their feedforward system proved to be three times faster than ordinary pull down menus [13], adaptable for text entry [20], and multiple command entry. Lastly, Vermeulen et al. [26] investigated the importance of feedforward as a powerful tool to bridging Norman's Gulf of Execution (the difference between the user's intentions and the allowable actions) in designing interactions.

We also reviewed research that implemented feedforward and feedback mechanisms to help users learn gesture-based interactions [3,5,25,29]. Bau and Mackay [3] described a dynamic guide that combines on-screen feedforward and feedback to help users learn, execute, and remember gestures. Their concept consisted of dynamic guidelines for performing a set of gestures on a touch-screen display that uses dynamic feedforward and feedback to directly guide a novice user's performance. Wigdor et al. [29] presented Ripples, a system to visualize every contact point on a touch-screen display. Ripples included six visualizations spanning fourteen states and transitions that place the information beneath and around users' fingertips. Within these visualizations, their users could see the feedback about successes and errors of their touch interactions

2.2.2 Visual Feedback/ Feedforward on Flexible Devices

To the best of our knowledge, there are no prior studies focusing specifically on providing visual feedback that serves to guide users in performing bend gestures on handheld flexible devices. Previous studies mainly provided verbal feedback to educate their users about the interaction styles. Additionally, most prior work had a specific visual feedback system, designed to show users the information they needed to complete the tasks of their experiments. For example, Girouard et al. [6] showed information about the completion of each bend gesture to their users by using a green check mark that appears after successfully completing a bend gesture; and an empty circle that would become green after performing a bend gesture. In a study on evaluating use of bend gestures for authentication on mobile devices, Maqsood et al. [19] visualized the activation of performed bend gestures by showing an asterisk in the password field and an LED light on the screen. In a second study, she displayed pictures of gestures to guide users, and the pictures were highlighted once performed. Additionally, Lo [18] used a simple visual feedback system to educate the users about correctly performing bend gestures, where the quadrant of the bent corner would become orange for downward bends, and blue for upwards.

3 PERFORMING BEND GESTURES

An important feature of bend gestures is their large degrees of freedom [27]. Yet, in the majority of studies, bend gestures are solely defined by their location and direction [7,10,15,23]. In this work, we augmented the basic classification of bend gestures to include the bend angle, to explore additional levels of complexity and provide more detailed information to the user. We applied two angle levels: half-activation and full-activation angle. Half activation indicates the midpoint of the angle for activating the bend gesture, and full activation indicates the completed angle. We chose the four corners of our flexible prototype, each corner having an upward and downward flexibility, respectively towards and away from the user. We also used two device-spanning complex bends: vertical and horizontal, both upwards, downwards. Eight corner gestures and four middle gestures totalled twelve unique bend gestures.

3.1 Potential Problems

To perform a correct bend gesture, it is critical that users know the different components of the gesture (location, direction, angle, size, etc.). We began our research by identifying possible problems that might arise during users' interactions with flexible devices. Difficulties include bending a wrong location of the device, in the wrong direction, or in the wrong angle. To prevent such problems, the user should be provided with simple and understandable instructions, covering two components: the information before performing a bend, and the information during or after the bend action. These align with the two mechanisms for showing the users information and guiding them to correctly perform the gestures in a gesture-based interaction: feedforward and feedback. Feedforward is the mechanism that presents the required information for starting a command before the user starts to perform it. Feedback is the mechanism that presents the information about the recognition to the user during or after performing the command.

Imagine a novice user trying to use a deformable device for the first time. After determining what action they want to complete in an application, the first challenge in interacting with a flexible smartphone is finding the location of the bend associated with this action. Then, users need to determine the correct direction of the bend gesture (up or down). Once the user starts a bend, they must know is how much pressure to exert on the device to activate or terminate a bend. Simply put, the user needs to know how far the device must be bent. This parameter is called angle of the bend.

Knowing these three parameters — location, direction, and angle — the user can perform correctly a bend gesture from beginning to end. However, while performing a bend gesture, users might apply the incorrect pressure which may lead to the wrong angle, or select the wrong location or direction. To resolve such problems, users should have additional information to educate the user about their mistakes.

3.2 Brainstorming Session

Once we reviewed the literature and identified potential issues in performing bend gestures correctly, we decided to collect insightful data on first impressions with bend gestures and deformable prototypes, to start the design process by collaborating

Figure 1: Central Circle Design: location and direction of each arrow represent location and direction of a bend.

with possible future end users of the visual guides. We gathered a group of 5 HCI and industrial design graduate students. They were novices with regards to bend gestures but they were experienced in design. This brainstorming session provided us with basic information and ideas to start the process of designing our visual feedback systems. Four stronger ideas emerged: participants proposed simple shapes to indicate the location and direction of bend gestures. They doubled these shapes to indicate gestures to be performed in two locations simultaneously. They used arrows to indicate the direction of bend gestures. Finally, participants' designs also often used two colors to show bend direction. We selected these to inform our designs, as these concepts is easy to understand, to distinguish, yet powerful enough to indicate a complex gesture with diverse attributes, hence they it could be a meaningful alternative for using text.

4 Designing Visual Feedforward and Feedback Guides

We developed three visual feedback guides: 1. Central circle design, 2. Arrows design, and 3. Cheat sheet design. We proposed a novel feedforward and a feedback mechanism for the first two designs. We developed the cheat sheet design with a minimal, basic feedforward, and no feedback, to serve as a baseline for comparison. Our designs are meant for users who already have some information about bend gestures. We did not focus on giving very basic information such as what is a bend gesture.

4.1 Central Circle Design

The Central circle design presents all required information to complete an interaction with a flexible device in a single location on the screen. The central circle design contains a circle with a 58 mm diameter (30% of our prototype's screen), and has two types of arrows: simple and double (Figure 1, left). The bend direction is indicated using 3 methods: the arrow direction and the arrow color. We use text to indicate the result of performing each bend gesture, and the mapping between bend and action is reinforced through the location of the text and its color. The whole design is transparent, as there will be an overlap with the interface of the application below (Figure 1, right).

This design is always located in the middle of the display, and all information from the feedback and the feedforward mechanisms always appear in this circle. In this concept, the user always knows where to look to find the information needed. We chose to place the circle in the middle of the display as we wanted the distance between the circle and each bend gesture to be somewhat close and equidistant. We aimed for users to easily see the information in the circle and the location of the bend gesture at the same time, since performing any bend gesture on a flexible device occludes part of the screen (under the thumb, for instance, or too curved to see). In our prototype, the only place always visible is the center of the screen.

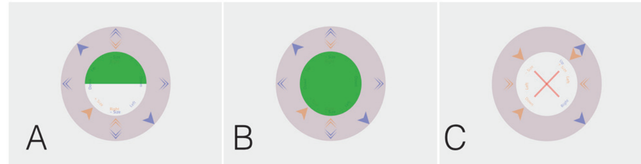

Figure 2: Feedback mechanism in the Central Circle design. A. Half activation B. Full activation. C. Incorrectly performed bend gesture.

Feedforward: We used arrow tips to show the location and direction of each bend gesture. These arrows are located at the edge of the circle, and each arrow represents an available bend gesture. Their location represents a bend gesture's location, and the orientation and color of the arrow indicates the gesture's direction. To show the direction of each gesture, we used arrows pointing inward as related to the circle's center, which indicated an upward bend, and outward, indicating a downward bend. The outward arrows were blue, and the inward arrows were orange. For instance, to show a bottom-right-upward bend, we used an inward-pointing orange arrow located at a 45° angle.

For device-spanning gestures, we used a second type of arrow, to indicate locations to be bend simultaneously. We designed these arrows using two thin lines, to differentiate them from the other arrow. Similar to a normal bend gesture, the location, direction, and color of each double arrow represent the location and direction of a bend gesture. For example, to show a vertical-downward gesture, we used two double outwards blue arrows, one at 0° and one at 180° angles.

We inform the user of the gesture results using text. Words are placed near the corresponding arrows, in the same color.

Feedback: Once users become aware of all three pieces of information in the feedforward mechanism (location, direction, and resulting action), they start to perform a bend gesture. At this stage, the feedback mechanism helps users finish a correct bend gesture, or to stop them from performing an incorrect one. This helps the user complete the gestures in the best and most accurate manner. While making a correct bend, the feedback mechanism provides information about the bend gesture angle.

We used the empty space in the middle of the circle to show the angle of the bend parameter in the central circle design. When the user starts to bend the device, the internal space of the circle remains empty until the exerted pressure reaches the half-activation level. At that point, half of the central circle turns green (Figure 2a). Subsequently, when the user increases the pressure, he or she ultimately reaches the full-activation stage. At this stage, the entire inner space of the circle turns green (Figure 2b).

In addition to the feedback mechanism for correct bend gestures, we developed one for incorrectly performed bends. When a user attempts to perform a bend gesture, it is possible that he or she has made the wrong choice and is attempting to perform an incorrect bend or an unavailable bend. In this design, the display of a red X at the center of the circle would convey to the user that he or she is performing an incorrect bend (Figure 2c).

4.2 Arrows Design

The Arrows design presents required information to complete interactions at the actual location of the bend gesture. We use similar single and double arrows, with text (Figure 3, left).

We hypothesized that a direct manipulation technique, showing the information exactly where the user has to take the action, will improve the user's performance. The user can see the information

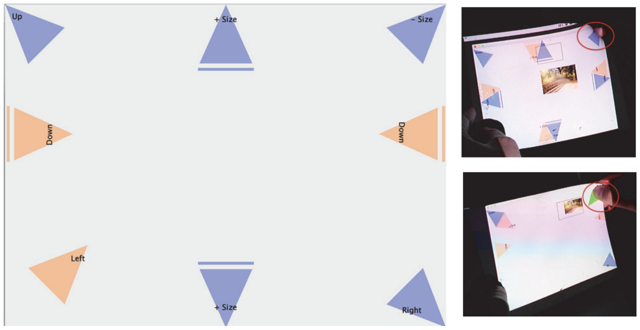

Figure 3: The arrows design: location and direction of each arrow represent location and direction of a bend gesture

and perform the bend gesture all in one location, resulting in a faster interaction. Finally, the concept of showing information at the location where the action is to be performed is popular in most commercial devices such as touch smartphones and tablets. A downside is that fingers can occlude the information displayed (Figure 3, right).

Feedforward: In the arrows design, similarly to the central circle design, an arrow's direction and color represent the direction of the gesture. The arrows point in two directions, inward (up) is blue and outward (down) is orange. To show a device-spanning gesture, we added a line at the base of the arrow. For each dual bend gesture, there are double base arrows at the locations to be bent simultaneously. For example, to show a vertical-downward gesture, we used two base-lined blue arrows at the top and bottom of the screen. Text, again, indicated the results of each instance of bending. We overlaid it on top of the arrows, closer to the thinnest part of the arrows. It was always black for easier readability.

Feedback: We used arrows displaying the location and direction of the bends to illustrate feedback. As users start to perform a bend correctly, they are guided to complete the bend using the same two levels of angle. At half activation, the widest half of the arrow turns green (Figure 4a), to indicate to users that they need to increase the curve to activate the gesture completely. When users bend the device to such an extent, the arrow becomes completely green (Figure 4b). In addition, when a user begins the wrong gesture, the arrow turns completely red, indicating an error. A user trying to create a bend that is unavailable will also see a red arrow in this same location (Figure 4c).

4.3 Cheat Sheet

To compare our two designs, we created an additional design that would provide the user with information about the action-to-bend-gesture mapping without any localized feedforward or feedback information. We present the required information via text.

Feedforward: The objective of this design was not to present a new, innovative pattern; rather, it aimed to be a baseline by which evaluating the two previous designs. As a result, the cheat sheet

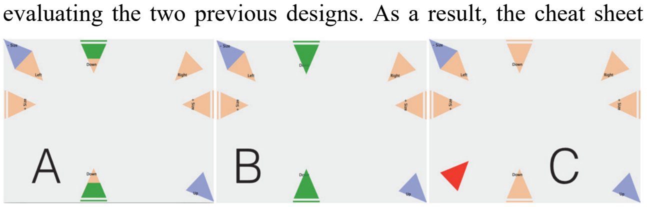

Figure 4: Feedback mechanism in the Arrows design. A. Half activation. B. Full activation. C. Incorrectly performed gesture.

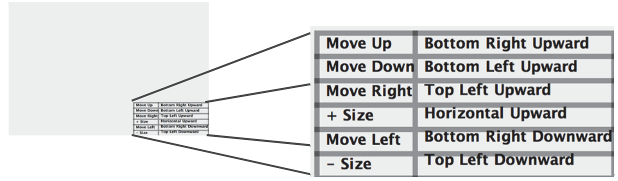

Figure 5: Cheat sheet design (left), with the text blown up (right).

design is our most basic design, without geometrical shapes or colors. In this design, we present the information in a two-column table at the right corner of the display. The first column indicates the action (result of the bend), and the second contains the location and direction of each gesture (Figure 5). As detailed in the upcoming experiment, the gesture-action mappings in all designs are random to ensure and enable an adequate comparison of the designs. We also randomized their order in the table.

Feedback: To keep the cheat sheet design basic, we did not develop a separate feedback for this design. For the experiment, we will borrow each feedback of the other designs.

5 EXPERIMENT

Our experiment is designed to evaluate the efficiency, advantages, and disadvantages of each proposed design. We created a flexible prototype, and developed two tasks in which the user had to perform several bend gestures using each visual feedback designs.

5.1 Prototype

To conduct the user study and test the efficiency of the designs, we developed and fabricated a flexible prototype to emulate a real product. We selected a prototype size larger than the commonly used smartphone, the size of a notebook, measuring 190 mm x 140 mm x 1 mm. We used a plastic sheet, flexible enough to deform easily but that could retain its shape after extended trials. We attached six 2 in bidirectional Flexpoint sensors to the back of the device (Figure 6). We located one bend sensor in each corner of the device, and attached two bend sensors at the middle, one vertically and one horizontally. With them, we were able to detect the 12 gestures considered. We painted the front of the device white. We connected the sensor to an Arduino microcontroller and used a Pico projector to display the interface on the prototype.

The Arduino program received and processed the raw bend sensor data and mapped the smoothed data to a range of 0 to 100. The thresholds for full up and down activation were +10 and -10 from the neutral state, and we set the half up and half down activation to be +5 and -5 of the neutral state. To obtain these thresholds, we tested several values to indicate the smallest value that could be consistently recognized for setting the thresholds. A Java program received the sensor data, randomly assigned functions to bend gestures, showed the relevant information about tasks and visual guides on the display, and recorded the quantitative data (duration of tasks and number of errors).

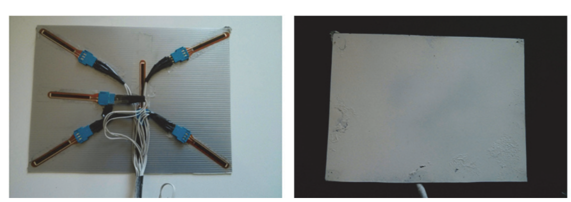

Figure 6: Front and back side of the prototype.

5.2 Experiment Design

Our main research goals were to determine an overall preference for visual bend guides, evaluate the usefulness of different aspects of each design, and observe behavioral patterns of users during performing each task. To compare the different aspects of the three guides, we evaluate each design with and without feedback. For the cheat sheet, we tested it as is, without feedback, as well as with the arrows feedback, and the central circle feedback. In total, this means seven conditions: the central circle design without feedback, and with feedback; the arrows design without feedback, and with feedback; and the cheat sheet design without feedback, with the arrows feedback, and with the central circle feedback.

We tested these conditions with two applications, an image docking and a simple game, which we call tasks. Due to time constraints, participants performed the first task twice for every condition, and the second task once for every condition, for a total of 21 trials per participant (7*2+7*1).

We randomized the set of gestures used in every trial, to complexify the task (6 gestures out of a possible 12). The remaining gestures became unavailable. The set of actions per task was always identical. We randomized all bend to action mappings at every trial to prevent users from memorizing the mappings. This means that participants had a different set of gestures and gesture-to-action mappings for each trial performed. This prevented the user from memorizing the gestures during the experiment. If all the gestures and their functions were the same in every trial, the user would not have to notice the designs after a period of working with the device, which could not allow us to assess the design in a within subject experiment. We also randomized the mapping to avoid users guessing or doing the gestures by chance. For example, for moving down in a menu, users might guess they have to bend somewhere in the bottom of the device. Our goal here was not to test the mappings between gestures and actions, only to test the visual designs. We are aware that randomly assigning functions to the gestures is not ecologically valid. However, most previous studies about bend gestures attempt to find the ecologically valid bend gestures to the functions mapping [6,8,10,15,24,27], so we feel it appropriate to avoid focusing on this type of validity here.

Each session lasted approximately an hour. Prior to starting the experiment, participants completed a brief tutorial designed to teach them how to correctly perform the gestures and presented briefly each feedback designs. We measured trial completion time and number of errors. We gathered subjective data through 5-point Likert scale questions about usefulness of each design in showing different information such as direction, location, angle, wrong bends and half/full activation. We administered the questionnaires after each task with each design. At the end, we asked them to complete a final questionnaire about their overall experience to compare designs in general.

5.3 Participants

24 participants (11 women) were on average 24.0 years of age (between 18 and 50 you). 3 of them had worked with a flexible prototype during a prior research study. We compensated them with a $10 gift card for their participation.

5.4 Task 1: Image Docking

We implemented an image docking application [9]. In this task, users repositioned a photo inside a frame by moving it up and down, right and left, and scaling it (Figure 7). The users' goal was to put the image inside the frame as quickly and accurately as possible. The user interface contained a black photo frame and a photo on top of a grey background. We randomly defined the initial position and size of the photo, with the center of the image always outside the target frame, and the image scaled up to a minimum 1.5 times the size of the frame. The user could move and scale the image by performing bend gestures. There were 6 movements in this task: up, down, right, left, +size, and –size. Holding a bend gesture active fired the action continuously.

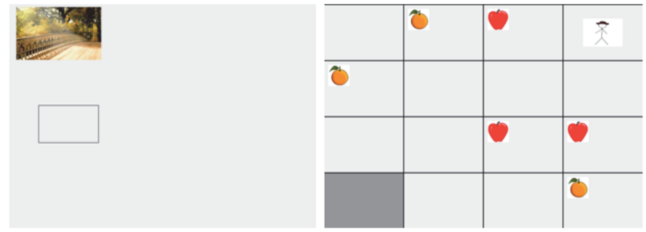

Figure 7: Task 1 (Image docking) and Task 2 (Game).

5.5 Task 2: Game

We created a simple game in which user had to move a character from the origin to the target block in a 4x4 board, and, along the way, eat all the randomly distributed apples and oranges (Figure 7). The origin block and target block locations were randomly selected in two opposite corners in each trial. Eating all apples and oranges was mandatory to finish the task. In this task, character moved one block at a time: for each movement, the user had to activate, and then deactivate a bend gesture. In this task, there were 4 movements (up, down, right, left); an "eat apple", and an "eat orange" function for a total of in 6 bend gestures.

5.6 Hypotheses

We hypothesized that the central circle design and arrows design would be more efficient compared to the cheat sheet, yielding faster completion times and fewer errors, based the use of graphical properties to display information. We hypothesized a higher rating for these two designs on their usefulness in the subjective ratings. We hypothesized that providing feedback would decrease task completion time and error rate as it gives users more information about bend gesture. Finally, we predict similar performance with the two main designs, as each make use of different but valuable and functional factors for guiding the users.

6 Results

6.1 Objective data

First, we analyzed the two version of feedback on the cheat sheet design using a 1-way analysis of variance. We did not find significant differences in either time and error rate difference between the cheat sheet design with circle feedback and the cheat sheet design with arrow feedback. Since these two groups were almost identical in both tasks, we selected one of the two feedback with this design (cheat sheet design with arrows feedback) to create a factorial experimental design: 3 designs (circle, arrow, cheat sheet) * 2 feedback presence (with, without).

6.1.1 Image Docking

We compared the duration and the number of errors in each task by performing a 3*2 repeated measure analysis of variance test on design by feedback. We found a significant effect of design ($F(1,47) = 12.908$, $p<0.05$) and feedback ($F(1,47) = 17.499$, $p<0.05$) on duration for task one. We used Bonferroni corrected pairwise comparisons to investigate the design factor. The arrows

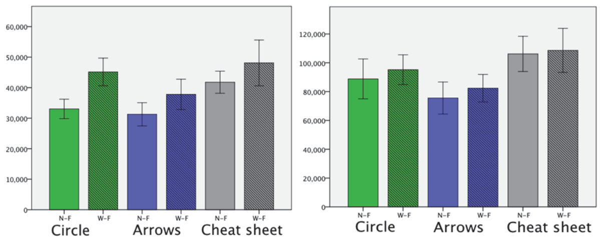

Figure 8: Completion time (ms) of image docking task (left), and game task (right). (N-F= No Feedback, W-F= With Feedback).
Error bars represent confidence interval.

design is the fastest (M = 34531 ms, SD = 1765), and significantly faster than the cheat sheet design (M = 44948, SD = 2403). On average the users performed task one by using arrows design 23% faster than they did by using the cheat sheet design and 11% faster than central circle design. We also found that users performed the task 19% faster without having feedback. Figure 8, left, shows the duration for this task.

We ran a Tukey test to evaluate the effect of the feedback on each individual design on duration. We found a significant ($F(1,94) = 19.312$, $p<0.05$) difference between the central circle design with feedback (M = 45153, SD = 15639) and without feedback (M = 33020, SD = 11011). We did not find significant factor or interaction with the number of errors for the first task.

6.1.2 Game

We found a significant effect of design ($F(1,23) = 26.375$, $p<0.05$) on duration for task one (Figure 8, right). Feedback did not have a significant effect on duration. Our Bonferroni corrected pairwise comparison showed that arrows design (M = 78971 ms, SD = 3725) was significantly faster than both central circle design (M = 92025 ms, SD = 4662) and cheat sheet design (M = 107402 ms, SD = 6292), with the central circle design being significantly faster than cheat sheet design.

We found a significant effect for design in the number of errors in this second task ($F(1,23) = 3.572$, $p<0.05$). Pairwise Bonferroni corrected estimated margin means comparisons did not show significance, though the difference in the number of errors between the arrows design (M = 2.896) and the circle design (M = 4.271) is close to significant (p=0.063).

6.2 Subjective Data

We applied the Friedman test to analyze the Likert questions in our questionnaire. For the image docking, when asked about efficiency of each design in indicating the gestures location, users found the arrows design to be significantly better than the others ($x^2 = 7.467$, $p < 0.05$). Concerning the efficiency of each design in indicating the gesture direction, the arrows design was also significantly better than the others ($x^2 = 6.562$, $p<0.05$). The central circle design arrived second in both. The users found the arrows design to be significantly less distractive ($x^2 = 7.345$, $p<0.05$). We also found that users significantly preferred the central circles design without feedback better than the central circles design with feedback ($x^2 = 5.937$, $p<0.05$). Finally, on the question of the clarity of the feedbacks in showing the errors, we did not find any significant difference in user responses.

We found similar data in the game task. The users found the arrows design to be significantly better in indicating location ($x^2 = 6.267$, $p<0.05$) and direction ($x^2 = 6.767$, $p<0.05$). But we did not find any significant difference in the answers to questions about the designs' distraction features, nor in showing the errors.

In the final questionnaire about users' overall experience with each design, users were asked to rank the designs. 83% of the users expressed that arrows was their preferred feedforward design. 70.5% of the users selected central circles as their second preferred feedforward design. User's selected the cheat sheet design as their least favorite feedforward design (82.5%). No user select arrows as the least preferred design.

When asked to rank the visual appeal of the designs, 50.5% of the users put the central circles design in first place. For the second rank, 49.5% chose central circle design. 70.4% put the cheat sheet design to be the third-ranking design. When asked to classify the designs in terms of useful information, 58.3% selected arrows design for the first rank, 45.8% selected central circle design for the second rank, and 62.5% voted for the cheat sheet design in third rank.

When asked about the feedbacks in regards to showing errors and incorrect bends, 28.7% preferred the red arrow in arrows design, and 58.8% preferred the red cross sign in the middle of the display in the central circle design. Only 12.5% preferred a no-feedback state. Our Wilcoxon Signed-Rank test determined that users significantly preferred central circle design's error feedback over the arrows design error feedback ($z = .008$, $p < 0.05$).

7 Discussion

Overall, our results supported our first hypothesis about arrows design and central circle design improving users' performance in both tasks. Participants performed better using these two designs, in comparison with cheat sheet design. Additionally, our results showed that users performed tasks faster with the arrows design without feedback in both tasks. We also found that most users (83%) chose the arrows design as their preferred design. These results support our second hypothesis: participants' ratings were higher for arrows and central circle design. However, our quantitative results do not support our hypothesis about the usefulness of the feedback design: we observed that the presence of our type of feedback deteriorated users' performance. Finally, the arrows design performed better than the central circle design. Combined with users' preference for the arrows design, our last hypothesis is not supported.

7.1 Comparing Designs

Overall, the arrows design proved to be better than the central circle design in terms of both quantitative and qualitative data. Users performed the game task significantly faster with arrows design, which yielded a lower number of errors than the central circle design. Our result showed that 75% of participants found that it was easier to see the information and perform a bend gesture at the same time when the information appeared at the actual location of the bend gesture. Interestingly, 28% percent of participants made comments about the size of each design. According to them, the fact that the arrows design occupied a smaller area of the screen (14%) than the central circle design (30%) had a positive effect on their performance.

As we hypothesized, performance with the arrows designs and the central circle design was better than the cheat sheet design both in time and ratings. We observed that most users had problems recognizing the horizontal and vertical bend gestures when using the cheat sheet design; the same users did not have that problem using the central circle and arrows designs. These two designs were also better at indicating the dual bend gestures, and reduced the problems related those gestures significantly.

In the central circle and cheat sheet designs, users looked at one display location to gain information, then perform the bend a second location, i.e., two locations were required for one bend.

Some participants indicated it might have had a negative impact on their performance. Conversely, one user stated, "one of the best features of this design is that because the place of the circle is always fixed, the user knows where to look to find information". This comment indicates that the fixed shapes, despite their negative aspects, could prove useful in some applications.

We recommend showing the information at the actual location of the bend gesture as the best approach to take in handheld flexible devices, and minimizing the amount of space used by the visual feedback designs.

7.2 Effect of the Visual Guides for Each Task

In the image-docking task, the user had to perform several small movements with bend gestures to correctly place the image inside the frame, which required detailed attention. Participants performed faster with the arrows design during this task. This shows that the arrow design can be useful for applications that require much of the user's attention, and in which accuracy of bend gestures is important. For instance, performing a bend gesture password requires several small and accurate gestures. These designs can also be helpful for applications that require zooming in and out while taking a picture.

In the game task, the user interface contained many elements (16 blocks, 3 apples, 3 oranges, and a character), making it a more realistic interface than the first task. Our results show that these designs are appropriate for applications that contain busy interfaces. However, further research is required to confirm this.

7.3 Feedback

One of the most interesting results from our work related to the presence or absence of feedback in the designs. Contrary to our hypothesis, we observed that, for all designs, the presence of feedback, increased on average the time needed to complete the image docking task, a significant result for the central circle design. Feedback distracted users instead of helping them perform their tasks better. In the central circle design in particular, the feedback appeared in the middle of the screen, as a large, green circle. Thus, it may have caused some distraction. However, the results of our questionnaires showed that the majority of the participants (66%) acknowledged the usefulness of feedback in the guides. This result suggests that, while feedback had a negative effect on users' performance, it had a positive effect on users' confidence that they were performing correct bend gesture.

In the case of showing user errors during interactions with the prototype, we again observed no significant difference in the number of errors committed in the presence or absence of feedback. These results suggest that users did not require feedback to recognize their mistakes. One user declared, "I needed no feedback for understanding that I had made a mistake. When I didn't see the desirable result in the interface, I looked more closely into the feedforward, then performed the bend correctly." The results themselves provided some sort of feedback for users. Although error feedback did not improve users' performance during our experiment, when asked to choose which feedback type would be best for wrongly performed bend gestures, only 12% of participants chose no feedback, which tells us that participants felt better when they had some kind of feedback to indicate their mistakes. The preferred wrong gesture feedback was that of the central circle design, a red X in the middle of the circle. One explanation for this might be that, in the case of a wrongly performed bend gesture, the only thing that users needed was a small hint to warn them to stop.

This result is interesting, yet a bit contradictory. Further analysis is required to determine whether this is a general observation or one specific to bend interactions with the applications tested. However, if the designers believe feedback is necessary, a small hint at the center of the display is helpful to indicate the wrong bend gestures.

7.4 Limitations

A limitation of our work is the physical engineering of the prototype. We used bend sensors that were not perfectly responsive to the small bends that users made, and this had a negative effect on the recognition process of the program. We ran our study with a mock-up display using projection instead of a real flexible display. Though we tried to keep the position of the display on the prototype, we were unable to reduce distortion during bend interactions, which could have a negative effect on participants' completion time.

The brainstorming session's results were limited. The size of the group was limited (five), and the absence of expertise of the participants in the flexible displays area lead to ideas that were simple and lacked depth. We also used of simple tasks in our evaluation. It would be worth testing our design on more practical and complex tasks such as typing or browsing the Internet.

Finally, the graphical design of the guides could be improved. While participants did not mention problems understanding the double arrow explicitly, it is not clear that a true novice would interpret those without training.

8 Conclusion

In this paper, our main goal was to help users perform bend gestures correctly on a flexible device. We informed users about the correct location, direction and angle of each available bend gesture. We also guided users in case of performing wrong bend gestures, to correct their mistake. We began our exploration by conducting a brainstorming session where designers were asked to present novel ideas about bendable visual guides. From the sessions' results, we developed three visual feedback designs using feedback and feedforward mechanisms: the central circle design, the arrows design, and the cheat sheet design. We conducted an experiment to examine the effect of visual designs on performance while working with our flexible prototype. Our result showed that the two main designs (central circle design and arrows design) had a positive effect on users' performance, and improved users' interaction speed. We observed, however, that feedback had a negative effect on users' performance. In addition, there was a strong agreement among participants that showing the feedforward information at the location of the actual bend made performing bend gestures easier, but they preferred the feedback in a central location.

For future work, it is important to evaluate our guides in an ecologically valid experiment, to determine how they perform when the gestures are correctly associated with actions. It will be valuable to evaluate the impact of the visual feedback designs on screens with different sizes, and to expand the design to other bend variables such as speed or edge. Finally, we suggest the investigation of other feedback mechanisms, such as audio or tactile feedback, to avoid occlusion or sensory competition.

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