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User-defined Bend Gesture Completion Strategies for Discrete and Continuous Inputs

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Abstract. Bend gesture-based input on a flexible device requires a distinct indication of gesture completion. Existing research commonly used threshold-based strategies for discrete input, whereas releasing the bend is used to confirm continuous input. However, the simplest form of these strategies does not allow the rejection of unwanted or unintended input and bi-directional manipulation of the output parameter before confirming continuous input. This work aims to identify user-defined gesture completion strategies with the potential to overcome these drawbacks. Ten blind or low vision (BLV) and fifteen sighted students participated in the study. We identified four and three unique strategies for discrete and continuous inputs, respectively. We believe the reported implications and recommendations with potential application scenarios will help researchers and interaction designers take advantage of these strategies.

Keywords: Gesture completion strategy · Bend Gesture · Accessibility

1 Introduction and Background

A flexible electronic device allows input interaction through manipulation of the physical form factor of the device [12, 18, 21]. Researchers have explored and investigated bend gestures on flexible devices [29, 10, 12, 3] and found these interactions to be feasible, effective, and enjoyable [26]. The bend gestures are also studied with BLV users [6, 7] and found to be easy to learn and perform [8].

Bend gestures are naturally associated with bending the flexible device at different locations and in two directions (upward and downward) [20, 21, 29, 15]. This act of performing the bend on a flexible device (Figure 1) is dynamic in nature. Usually, a dynamic gesture involves three stages: start, update, and end stages [25]. For bend gestures, the initial neutral or relaxed state (Figure 1a) before bending the device is commonly the start stage [26, 16], and the gradual bending is the update stage. For continuous input, this gradual bend is detected by the system, and respectively the output parameter value changes until the end-stage indicate the gesture’s completion to confirm a value. For discrete input, the end-stage is detected by the system, and accordingly, the discrete output action is triggered. Although the end-stage plays a vital role in completing the gestures, based on our understanding, the existing research provide evidence of implementing gesture completion strategies that depend on reaching or crossing predefined thresholds [5, 26, 30, 27, 31, 16, 10, 17, 22] to provide discrete input and releasing the bend to confirm continuous input [26, 16].

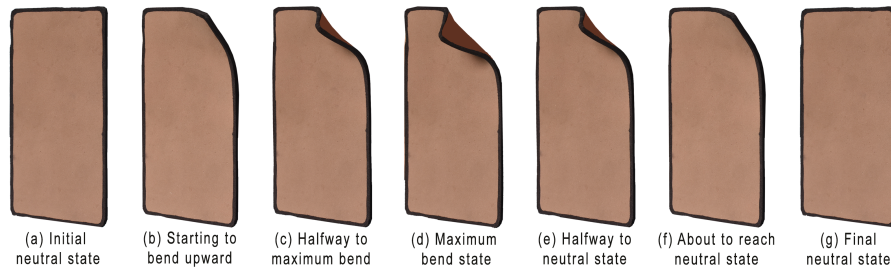


Fig. 1. Different intermediate states while bending a flexible device.

The major drawback of using only a threshold-based strategy in its simplest form is the lack of freedom to reject unwanted or unintended input as reaching or crossing the threshold triggers the output action immediately. Identifying a common threshold for different user groups also becomes challenging due to diverse manual dexterity and user expertise. On the contrary, a smaller threshold to support a wide range of user groups may adversely affect spurious input rejection. This indicates that applying only a threshold-based gesture completion strategy is insufficient. Similarly, for confirming continuous input, the simplest form of gesture completion on releasing the bend also has certain drawbacks. As soon as the bend is released (or starts to move back), the respective value for the most recent degree of bend gets confirmed for the output parameter. As a result, only uni-directional (either increase or decrease) manipulation of the output parameter is allowed before confirming a value. For instance, if an output parameter value increases on bending upward, the user will have the freedom to only increase (but not decrease) the value before confirming one. Since all bend gestures end up confirming a value on releasing the bend, this strategy also does not allow the rejection of unwanted or unintended input. This indicates that a controlled study that investigates bend gesture completion strategies is necessary to overcome these drawbacks. However, to the best of our knowledge, no prior research has investigated user-defined bend gesture completion strategies.

As both BLV and sighted users can perform these bend gestures, the involvement of both the user groups will allow the interaction designers to draw more accessible and inclusive design decisions. The smartphones being the most commonly used and carried digital devices by BLV users [14], we conducted this study on a flexible smartphone-sized mock-up prototype. We identified four and three strategies for discrete and continuous inputs, respectively.

2 Study on User-defined Gesture Completion Strategies

This study aims to identify user-defined bend gesture completion strategies for discrete and continuous inputs on a flexible smartphone-sized prototype.

2.1 Participants

For BLV participants, we contacted an academic institute requesting students' voluntary participation. Participation criteria were: the degree of visual impair-

ment [1] should be 70% or more according to their medical certificates, no upper limb disorder, and minimum 3 years of experience using smartphones through screen reader (Google TalkBack). Ten students (8 male, 2 female, and 3 left-handed) with a degree of visual impairment 100% (except one has 80%) between the ages of 18-22 years (Mean = 19.4, SD = 1.58) participated in the study. For the sighted group, we asked first-year university students for their voluntary participation. The participation criteria were: minimum 3 years of experience using smartphones and no upper limb disorder. Fifteen students (9 male, 6 female, and 3 left-handed) between the ages of 18-25 years (Mean = 20.73, SD = 2.49) participated in the study. We have taken prior consent from all participants and followed the ethics of conducting research on human subjects.

2.2 Apparatus

We conducted the study with a flexible smartphone-sized mock-up prototype (154mm x 74mm x 6mm) measuring 6.7 inches at the diagonal. The prototype comprises a flexible 3D printed internal structure (thickness 1mm, shore 95A) sandwiched between two silicon layers (shore 25A) for higher flexibility [16, 19].

2.3 Task

We asked the participants to assume interacting with a flexible smartphone in two scenarios and propose bend gesture completion strategies to confirm discrete and continuous inputs. We selected the following scenarios, which are familiar to users, distinguishable as discrete and continuous inputs, and also been studied with bend gestures [2, 20, 26]. To reduce the effort in learning and performing bend gestures, we selected only the corners and asked them to perform bend gestures towards upward and downward directions. No external feedback was provided as the gestures' ends (completions) were proposed by the participants.

Scenario-1: This scenario was to provide discrete input to open a file or application. We asked the participant to assume that a selected file or application will open as soon as the participant indicates the completion of the bend gesture.

Scenario-2: This scenario was to provide continuous input to change the volume. We asked the participant to assume that the volume changes with respect to the degree of bend and the current value will be confirmed for the volume parameter as soon as the participant indicates the completion of the gesture.

2.4 Procedure

We conducted the study in a controlled environment. Before conducting the study, we organized two separate training sessions (one week before and immediately preceding the study) to help the participants effectively familiarize themselves with bend gestures to utilize the full potential of the device's flexibility and to reduce the effect of prior experience [23]. In the first training session, we demonstrated (by holding BLV participants' hands) the bend gestures at the corners, while one hand was holding the device and another hand was bending the corners towards upward and downward directions. Then the

participants practiced the gestures under the moderator’s observation and assistance (if required) until they found themselves ready. We followed the same procedure for the second training session before introducing the participants to the concept of gesture completion strategy. Irrespective of participants’ prior knowledge, we explained the need and role of gesture completion strategies for discrete and continuous inputs by referring to the scenarios. We introduced them to the threshold-based strategy for discrete input and releasing the bend gesture for continuous input and explained their drawbacks. This was done to help the participants propose new strategies that can overcome the drawbacks.

We referred to each gesture by combining the names of the bent location (corner) and direction as a pair [3] for example, “Top-Right-Corner Bend-Upward”. First, we asked the participants to perform bend gestures at one corner (for both directions) to provide discrete input (Scenario-1). Then we asked the participants to explore a set of gesture completion strategies that are intuitive [3, 4, 11], easy to perform, and do not involve other input modalities such as touch or voice. The exact process was repeated for the remaining corners, where we asked the participants to perform the previously explored strategies and explore new strategies. Then participants performed the final set of strategies for each location and direction. They finally proposed a sequence of preferences (maximum three) that are intuitive, easy to perform, and can overcome the drawbacks of existing strategies. After they proposed the strategies, we asked them to share their experience regarding confidence during input, scope of one-handed interaction, and potential application. Then we repeated this process for continuous input (Scenario-2). We randomized the sequence of scenarios and corners.

3 Results and Discussion

The BLV and sighted participant groups proposed a total of 42 strategies (26 for discrete and 16 for continuous inputs) and 75 strategies (44 for discrete and 31 for continuous inputs), respectively. The demonstrations and the verbal descriptions of the strategies enabled us to identify the functionally similar strategies. Finally, we identified four unique strategies (D1, D2, D3, and D4) for discrete input and three unique strategies (C1, C2, and C3) for continuous input (Table 1). We calculated the total number of participants from both BLV and sighted groups who reported the strategies as their first, second, and third preferences and presented in Table 1 as the sum of the two groups (Number of BLV participants + Number of sighted participants = Total). These preferences are based on intuitiveness, ease of performance, and the ability to overcome the drawbacks of existing strategies. The majority of the BLV participants reported the On-Hold strategies (D1 and C1) as their first preferences for discrete (80%) and continuous (88.89%) inputs. The majority of the sighted participants reported the On-Release strategy (D2) and the On-Hold strategy (C1) as their first preferences for discrete (76.92%) and continuous (66.67%) inputs, respectively.

During the analysis of participants’ verbal feedback, we noticed that confidence during input was a major deciding factor for the BLV group. Since they solely relied on tactile and kinesthetic perception, their preferences were inclined

Table 1. The unique strategies proposed by BLV and sighted participants.

| Strategy codes | Strategy names | Input types | Preferences of (BLV + sighted) participants | | | Total Count out of 25 (10+15) |
|----------------|----------------|-------------|---|-------------------|------------------|-------------------------------|
| | | | First preference | Second preference | Third preference | |
| D1 | On-Hold | Discrete | 8+2=10 | 1+10=11 | 1+2=3 | 10+14=24 |
| D2 | On-Release | Discrete | 2+10=12 | 3+2=5 | 0+1=1 | 5+13=18 |
| D3 | On-Relax | Discrete | 0+2=2 | 1+1=2 | 4+6=10 | 5+9=14 |
| D4 | On-Double-Bend | Discrete | 0+1=1 | 5+2=7 | 1+5=6 | 6+8=14 |
| C1 | On-Hold | Continuous | 8+10=18 | 1+4=5 | 0+1=1 | 9+15=24 |
| C2 | On-Second-Bend | Continuous | 2+3=5 | 4+2=6 | 0+2=2 | 6+7=13 |
| C3 | On-Quick-Relax | Continuous | 0+2=2 | 0+6=6 | 1+1=2 | 1+9=10 |

towards strategies (D1, D4, C1, and C2) that not only allow them to continue the grip on the device, also offer rejection mechanisms. The grip on the bent location allowed participants to perceive the innate tactile and kinesthetic feedback of bend gestures. In contrast, the ease of performing the strategies was often a major deciding factor for the sighted participants during discrete input. However, during continuous input, the confidence during input was a major deciding factor due to the difficulty in measuring the degree of bend only through visual perception. The continuous grip on the bent location offered them higher confidence. We also noticed that participants often refer to their prior experience with button and touch-based [28, 13, 24] interactions. Considering legacy-inspired interactions to be easily guessable and learnable [32, 23], we believe these strategies can help touchscreen users easily adapt to bend gestures of flexible devices.

We also noticed participants' inconsistency in performing degrees of bend, especially a few participants who performed very small degrees of bend for discrete inputs. This may result in unintended input, hence leading to poor user experience. We believe using a bend angle-based activation threshold [22] in combination with the proposed input strategies can address this issue. Crossing the activation threshold does not trigger actions rather confirms the current bend as a valid bend and informs the user to go ahead with the proposed strategies.

3.1 Gesture Completion Strategies for Discrete Input

Gesture completion On-Hold (D1): This strategy indicates the bend gesture's completion on holding the bend in the same state (without any change in the degree of bend) for a predefined interval of time (hold-time). As soon as the predefined interval ends, the associated action gets triggered. As a result, this strategy offers the freedom to reject unwanted or unintended input by avoiding the hold-time. However, this hold-time does not allow quick input. Although the hold-time between 1 - 1.5 Sec was preferred by the majority of the BLV (70%) and sighted (64%) participants, further investigation is required to identify one or multiple appropriate values. According to both participant groups, this strategy can be applied during one-handed interaction. The higher confidence during input reported by the BLV participants resulted in maximum BLV participants under the first preference (D1 row in Table 1). In contrast, the associated hold-

time resulted in maximum sighted participants under the second preference. One BLV participant said, “When I bend, I can feel the device all the time, I will not hold this bend unless I am confident about the action”. Literature [28] also discussed a similar touch input strategy of Android devices.

Gesture completion On-Release (D2): This strategy indicates the completion of a bend gesture on releasing the bend. As soon as the bend is released (or starts to move back), the associated action gets triggered. As a result, it allows the user to decide the precise moment of discrete input. However, this strategy alone does not offer the freedom to reject unwanted or unintended input. According to both participant groups, this strategy can be applied during one-handed interaction. The ease of performing the strategy and its intuitiveness resulted in maximum sighted participants under the first preference (D2 row in Table 1). In contrast, the reduced confidence during input reported by the BLV participants and the lack of rejection mechanism resulted in a lower (less than or equal to 50%) number of proposals by this group. One sighted participant mentioned, “It is easier than threshold-based strategy in terms of reduced cognitive load as I don’t have to focus on bending the device to trigger an action”. Literature also reported similar strategies for touch [24] and bend gesture-based [9] input.

Gesture completion On-Relax (D3): This strategy indicates the bend gesture’s completion on reaching the final neutral state (Figure 1g) after releasing the bend. As soon as the bent location reaches the final relaxed or neutral state, the associated action gets triggered. Although this strategy alone does not offer the freedom to reject unwanted or unintended input, according to the participants, bending the device in the opposite direction (without stopping at the neutral state) can serve the purpose. However, they also reported that the application of this strategy would be difficult during one-handed interaction due to the rejection mechanism. The less intuitive rejection mechanism at the cost of more effort resulted in maximum sighted participants under the third preference (D3 row in Table 1). In contrast, the reduced confidence during input reported by the BLV participants and the less intuitive rejection mechanism resulted in a lower number of proposals by this group. A similar strategy was reported in the literature [18] to provide bend input during bi-manual interaction.

Gesture completion On-Double-Bend (D4): This strategy indicates the bend gesture’s completion on quickly performing double (two identical) bend gestures with the same location and direction. After performing the first bend gesture, the user quickly starts the second bend gesture, and as soon as the second bend gesture reaches the previous gesture’s maximum degree of bend, the associated action gets triggered. As a result, this strategy offers the freedom to reject unwanted or unintended input by avoiding the repeated bend. According to both participant groups, this strategy can be applied during one-handed interaction. The higher confidence during input at the cost of more effort reported by the BLV participants resulted in maximum BLV participants under the second preference (D4 row in Table 1). In contrast, the additional effort required

to perform repeated bends resulted in maximum sighted participants under the third preference. Kane et al. [13] reported a similar strategy for touch input.

3.2 Gesture Completion Strategies for Continuous Input

For continuous input, a user starts a bend gesture, and based on the degree of bend, the output parameter value increases or decreases. This manipulation of the parameter is temporary until the user confirms a respective value for a degree of bend by indicating the gesture's completion at that degree of bend.

Gesture completion On-Hold (C1): This strategy indicates the bend gesture's completion on holding the bend in the same state (without any change in the degree of bend) for a predefined interval of time (hold-time). As soon as the predefined interval ends, the respective value for the degree of bend gets confirmed. As a result, this strategy allows the rejection of unwanted or unintended input and bi-directional manipulation of the output parameter before confirming a final value. However, this hold-time does not allow quick input. Since, unlike discrete input, a user has to try the manipulated value before confirming it, the majority of the BLV (78%) and sighted (60%) participants preferred a higher hold-time between 1.5 - 2 Sec. According to the participants, this strategy can be applied during one-handed interaction. The higher confidence during input reported by both groups and the ability to overcome the drawbacks resulted in maximum participants under the first preference (C1 row in Table 1).

Gesture completion On-Second-Bend (C2): This strategy indicates the currently performing bend gesture's completion on performing a second bend gesture at a different location. When a user is manipulating the output parameter by performing a bend gesture, as soon as the user decides to confirm the respective value for a degree of bend, the user performs a second bend gesture at a different location to confirm the value. As a result, this strategy allows rejection of unwanted or unintended input, user-decided precise moment of input, and bi-directional manipulation of the output parameter before confirming a final value. Bi-manual interaction is required for this strategy. Despite the higher confidence during input reported by both participant groups, the bi-manual interaction and associated effort resulted in maximum BLV participants under the second preference and the lack of intuitiveness resulted in a lower number of proposals by the sighted group (C2 row in Table 1). Kane et al. [13] reported a similar touch input strategy (Second-Finger Tap) for BLV users.

Gesture completion On-Quick-Relax (C3): This strategy indicates the completion of the bend gesture on reaching the final neutral or relaxed state (Figure 1g) quickly. As soon as the user decides to confirm the respective value for a degree of bend, the user allows the bent location to quickly reach its final relaxed state (freely or manually) without any intermediate delay. Quickly reaching the neutral state acts as confirmation. As a result, this strategy allows bi-directional manipulation of the output parameter before confirming a final

value. According to the participants, the rejection of unwanted or unintended input can be achieved by slowly moving the bent location back to its relaxed state, which could be difficult during one-handed interaction. We believe implementing this strategy will require sophisticated hardware support and pattern recognition algorithms. The less intuitive rejection mechanism with reduced confidence resulted in maximum sighted participants under the second preference (C3 row in Table 1). In contrast, the lack of intuitiveness and reduced confidence resulted in a lower number of proposals by BLV participants.

4 Implications and Recommendations

For both BLV and sighted users: On-Hold (D1), On-Double-Bend (D4), On-Hold (C1), and On-Second-Bend (C2) strategies are the most appropriate while designing for both BLV and sighted users and eyes-free interaction by sighted users, as these strategies offer higher confidence during input.

For quick input: On-Release (D2), On-Relax (D3), and On-Double-Bend (D4) strategies are appropriate for quick discrete input. While On-Release (D2) strategy is more suitable when a precise moment of input is demanded (for example, pause audio at a specific moment on the timeline). During continuous input, On-Second-Bend (C2) strategy is more suitable for quick input during bi-manual interaction (for example, change volume and content zooming).

Discrete input for critical actions: On-Hold (D1) and On-Double-Bend (D4) strategies are appropriate for critical actions, where triggering the action can lead to significant or irreversible changes in the outcome (for example, close an application and delete a file). On-Hold (D1) is also suitable for shortcuts and input without shaking the device (for example, start camera and capture image).

Multiple actions with the same bend gesture: Mapping multiple actions to the same bend gesture can reduce frequent re-gripping. This can be achieved by mapping different actions to different discrete input strategies of the same bend gesture. Multiple actions can also be mapped with different hold-times of On-Hold (D1) strategy and different degrees of bend of On-Release (D2) and On-Relax (D3) strategies. Also, two related actions can be mapped with the update-stage and end-stage (completion strategy) of the same gesture.

5 Conclusion

This work aims to identify user-defined bend gesture completion strategies for discrete and continuous inputs on a flexible smartphone-sized device. Ten BLV and fifteen sighted participants proposed a total of 117 strategies. We identified four unique strategies (On-Hold, On-Release, On-Relax, and On-Double-Bend) for discrete and three unique strategies (On-Hold, On-Second-Bend, and On-Quick-Relax) for continuous inputs. We noticed that the participants' prior experience is a major source of inspiration, which in exchange may help users quickly adapt to bend gestures. We believe the proposed strategies can be applied to other sizes of flat flexible devices. However, further investigation to compare the strategies and explore the effect of device size may produce promising results.

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