MorePhone: A Study of Actuated Shape Deformations for Flexible Thin-Film Smartphone Notifications

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ABSTRACT
We present MorePhone, an actuated flexible smartphone with a thin-film E Ink display. MorePhone uses shape memory alloys to actuate the entire surface of the display as well as individual corners. We conducted a participatory study to determine how users associate urgency and notification type with full screen, 1 corner, 2 corner and 3 corner actuations of the smartphone. Results suggest that with the current prototype, actuated shape notifications are useful for visual feedback. Urgent notifications such as alarms and voice calls were best matched with actuation of the entire display surface, while less urgent notifications, such as software notifications were best matched to individual corner bends. While different corner actuations resulted in significantly different matches between notification types, medium urgency notification types were treated as similar, and best matched to a single corner bend. A follow-up study suggested that users prefer to dedicate each corner to a specific type of notification. Users would like to personalize the assignment of corners to notification type. Animation of shape actuation significantly increased the perceived urgency of any of the presented shapes.

Author Keywords
Flexible Displays; Shape Changing Interfaces; Actuation; Notification; Organic User Interfaces.

ACM Classification Keywords
H.5.m. [Information interfaces and presentation (e.g., HCI)]: Miscellaneous.

General Terms
Human Factors; Experimentation.

INTRODUCTION
In the future, the physical form of computing devices might become as mutable as that of software data in terms of shape, behavior and movement, allowing devices to form a more dynamic relationship with the user's environment [15]. The reason for this is the emergence of new advanced technologies and materials for computer input and display that can be used for designing flexible computers. Thin-film electrophoretic displays (Flexible E Ink) [18], flexible organic light emitting diodes (FOLEDs) [16], and surface mountable thin film bend, pressure and touch sensors have resulted in a surging interest in exploring the possibilities of flexible, more organic [32] computer interfaces, such as Gummi [28], PaperWindows [13], PaperPhone [18] and Nokia's Kinetic [16]. A number of benefits have been attributed to flexible interfaces in literature, including: increased mobility, flexible screen real estate, better ergonomic fit to the body, increased robustness, light-weight multi-display operation for multitasking, and natural support for haptics. While one might debate the benefits provided by thin-film flexible computer prototypes over rigid form factors, the usability of flexible computer interfaces has become an active topic of research in HCI over the past few years [13,18,19,28].

Figure 1. MorePhone actuated shape changing phone.

Actuated Flexible Display Interfaces
While studies have been conducted on the use of actuation in rigid mobile bodies [11], input devices [30], pixelated actuated displays [20,24], actuated paper [25] and shape changing interfaces [5], one area that has received little attention to date is the actuation of flexible display surfaces.

Flexible displays provide a natural platform for actuation compared to rigid displays as they can be deformed with ease. The purpose of such actuated physical deformations is to communicate the state of the computer system through a change in the *visual* or *haptic* appearance of the device's shape.

Using Shape Change for Ambient Notifications

A common problem with auditory notifications is their general disruptiveness, both in terms of single user attention and in terms of interference with social interactions [29]. Visual notifications can be distracting [22] and easily missed when the user is not actively attending to the display. For this reason, vibro-tactile feedback has become a popular way of notifying users [4]. However, like visual notifications, vibro-tactile notifications are easily missed when the user is not in direct contact with the device. By contrast, actuated shape notifications provide a means for tactile notification that does have a distinct visual correlate [1]. Actuated shape notifications also provide a design space in between *visual* and *tactile* methods of feedback that is potentially rich in terms of communicating various states of the system.

Contributions

In this paper we present MorePhone, a prototype smartphone that uses shape deformations as its primary means of both *haptic* and *visual* notifications (Figure 1). We present a study of the semantics of a shape notification design language through a participatory study, matching urgency and notification types to full screen, 1 corner, 2 corner and 3 corner bends. An informal follow up study ascertains if shape actuation requires pairing with visual cues to convey information. We conclude with design recommendations for the presentation of actuated shape notifications on smartphones.

RELATED WORK

We will first discuss work related to *auditory*, *visual* and *tactile* notification cues. We will then discuss studies of actuated, shape-changing devices.

Auditory Notification Cues

Auditory notification cues can be attention demanding, intrusive, and often perceived as inappropriate. "Beeping and ringing is by nature an intrusive sound not unlike the sound of an alarm clock" [21]. According to Shell et al. [29], when many ubiquitous devices simultaneously demand full attention from the user, this may lead to attention overload. Hansson [10] describes attention overload as being obtrusive not only to the owner of the device, but also those in her vicinity.

Visual Notification Cues

Visual cues are useful in contexts that demand no disruption. However, they can be easily missed, as their effectiveness relies on users active engagement with the display device [10]. According to McCrickard [22], visual cues demand a high cognitive load and critical notifications may be lost over the users current activity.

Vibro-tactile Notification Cues

Vibro-tactile notifications effectively limit notification to one's own personal space. Brown and Brewster [4] evaluated vibro-tactile notification cues and their appropriateness to convey information when visual displays are not available. However, it is not always easy to distinguish between various vibro-tactile alerts, as they are invisible, thus hard to interpret, and their design space has been mostly limited to time-based vibration patterns [10,27]. Vibro-tactile notifications are also invisible to social contexts, increasing the risk for misinterpretations of a user's actions. Actuated shape notifications provide silent yet public notification cues that are visible to others. Because they offer a richer repertoire of visible shapes, they may also provide a larger semantic space for interpreting the type of notification.

Actuated Mobile Shape-Changing Interfaces

While research in the domain of ambient user notifications has been extensive, we find few projects where actuated notifications where seamlessly integrated in a shape changing mobile device. Dynamic Knobs [12] evaluated the concept of a rigid mockup phone capable of changing shape in a small extension on one of its sides. Hemmert et al. [11] also explored the concept of a shape-changing device that uses two-dimensional tapering to display the directionality of off-screen contents. We believe actuated notifications in flexible mobile devices might also be useful for displaying this type of notification. Horev [14] investigated the use of actuated pixel matrices in mobile phones. Although these can provide the user with simultaneous tactile matrices, the interpretation requires high tactile attention, drawing on abstract languages that users need to learn how to decode. Coelho and Maes [6] presented Surflex, a programmable surface for the design and visualization of physical forms. Surflex provides a notification platform that inspired our design. Note that none of the above projects included a high resolution display in the actuation surface.

Actuated 3D Displays

Actuated 3D displays serve to provide 3D graphics by dimensioning the actual display through actuation. Poupyrev et al.'s [24] Lumen explored the design of an actuated pixelated information display. Lumen used light and shape memory alloys to lift pixels in the z dimension of the screen to display 3D movement and simple 3D shapes. Similarly, ShadePixel [17] demonstrated a foam skin actuated by solenoids to produce shadow effects that visualize pixels using ambient light. By contrast, Leithinger and Ishii [20]'s Relief's main purpose was to allow high resolution images to be visualized in 3D. Their system uses a series of rods that actuate a fabric display that is top projected with 2D images.

Studies of Actuated Shape Interfaces

To our knowledge, there are few empirical studies that explored effects of shape-changing in a flexible mobile device context. However, studies have been conducted on designing gestures for such devices and we borrow from their methodology. Lahey et al. [18] evaluated the effectiveness of bend gestures to execute tasks in a flexible mobile device. In this study, users designed bend gestures for common computing actions deployed on a flexible E Ink smartphone. They identified the most frequently used bend gesture pairs and observed that bend gestures that take directional cues into account are more natural to users. Lee et al. [19] conducted a study to generate a set of interaction gestures for mockup deformable displays as input devices. In this study, participants were given 11 specific interaction tasks, such as zooming or navigating, and were instructed to deform the displays in ways that would execute these tasks. They found that users preferred pairings of closely related but opposite actions and gestures. Rasmussen et al. [26] conducted a review of the design space of shape-changing materials and proposed guidelines for designing mutable interfaces.

DESIGN SPACE OF SHAPE CHANGING NOTIFICATIONS

To inform the design of a flexible mobile device that uses shape changes for the purpose of notifications, we used the following design criteria:

Lessen Reliance on Screen Real Estate for Notification

Visual notifications use valuable real estate on the display. While they provide easy access to contextual semantics of a notification, they are easily missed when eyes are off the display. When minimal pixels are used to provide notifications much of the semantics of notification is lost.

Lessen Reliance on Auditory Notifications

Auditory notifications demand immediate attention and are disruptive to others. Using alternate channels of notification provides means for designing notifications that are less disruptive.

Introduce Actuated Shape Changes for Notification

Vibro-tactile cues are easily missed when the user is not in contact with the device. Use of actuated shape notifications potentially allows for a notification platform that is simultaneously *tactile and visual*.

Design for Ambient-Foreground Transitions

The use of actuated shape notifications allows a device to communicate state from a distance or the periphery of interaction, and provide a smooth trajectory towards focused interactions with the notification source.

Richer Forms of Tactile-Visual Feedback

Vibro-tactile notifications provide minimal means of distinguishing between different notifications. As such, they often require visual notification to contextualize the semantics of the notification. Actuated shape notifications may offer a potential for exploring the sweet spot between visual and tactile notification design.

Kinetic Properties

Changes in the speed and intensity of an object's movement can be explored to express emotional connotations [26]. Surflex [6] used changes in tempo and intensity of its actuation to express dynamic emotional contexts. Thrifty Faucet [31] used random movements to express personality traits.

Expressive Properties

Repeated animation of any particular shape may increase its perceived urgency (i.e. a fast, pumping motion might be perceived as something that requires immediate attention). Changes in shape attract more attention in peripheral vision than do static notifications.

Mapping Shape Changes to Notifications

To inform our design of the semantic mapping between actuated shape changes and specific notifications, we designed a participatory study that allowed users to indicate the perceived urgency of various changes in shape, and associate them with common smartphone notifications to find patterns of semantic relationships. In general, we hypothesized that gross shape changes would be perceived as pertaining to more urgent notifications, such as phone calls. We also hypothesized that different shapes might convey different meanings to users in terms of their appropriateness for a particular notification. We were interested in understanding if the curling of more than one corners of the display would be perceived as indicating multiple, less urgent, simultaneous notifications.

Visual vs. Shape-only Notifications

We were also interested in understanding whether users would prefer to dedicate a particular corner of the display to a particular notification, or whether they would prefer to use a single corner for notifications in conjunction with visual notifications. This question is particularly relevant in the case of multiple simultaneous notifications. We designed a second, more informal, study with a fully functional prototype to determine appropriate design recommendations in this regard.

MOREPHONE IMPLEMENTATION

Before we discuss our first study, we will discuss the implementation details of our shape changing smartphone prototype. MorePhone (Figure 1) is a 14.4 x 9 *cm* flexible smartphone prototype that actuates its display as a means of providing user notifications. Our prototype consists of 3 layers: a flexible E Ink display augmented with a layer of bi-directional bend sensors and an actuation layer with Flexinol shape-memory alloys (Figure 2**Error! Reference source not found.**) [25]. MorePhone bend and actuation layers are tethered to an Arduino board [2] that is connected to a MacBook Air laptop running a simple Processing application allowing the laptop to send actuations to the prototype, and respond to user bend inputs.

Flexible Display

The first layer of our prototype consists of an Arizona State University 3.7" Bloodhound flexible electrophoretic display (Figure 2a) [3]. This display is driven by an E Ink Broadsheet AM 350 Kit [8] connected to a MacBook Air laptop running a Processing application that provides full screen gray scale images to the AM 350. The flexible

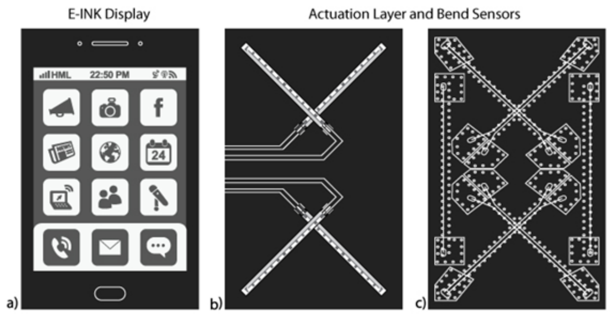

Figure 2. MorePhone layers of flexible cardboard circuitry.

display is glued to cardboard substrates containing the bend sensing and actuation layers (Figures 2b and c).

Bend Sensor Layer

Figure 2b shows the second layer, containing 4 Flexpoint 2” bidirectional bend sensors [9] that are used to gauge user responses to shape actuation notifications. These bend sensors are glued to a 14.4 x 9 *cm* 110 *lbs* cardboard substrate and soldered to a printed circuit. Bend data is processed by an Arduino, and interpreted by a Processing application on the laptop to control actuation.

Shape Actuation Layer

Figure 2c shows the third layer, which contains an actuation circuitry made of Flexinol [7] shape-memory wire. Flexinol wire contracts upon heating, which is achieved by putting a current on the wire. The wire was sewed with Kevlar threading to a second layer of cardboard substrate via small lasercut holes, allowing for its expansion and contraction (Figure 3) [25]. We used 0.006’ low-temperature Flexinol wire using a current of 410 *mA* to produce a full contraction in 1 *s*. We controlled the degree of actuation as well as the velocity of actuation by altering the voltage via the Arduino board. Use of a single 0.006’ wire provides a maximum pulling force of 321 *g*, which is not enough to provide a noticeable change of shape in our flexible phone prototype. We therefore used 2 parallel wires for each actuated section, allowing it to produce distinct and reliable curls of up to 1.5 cm at each of the four corners, as well as the entire display.

Shape Notification and Visualization

Figure 1 shows MorePhone actuating the entire screen up to 1.5 *cm* on each side. MorePhone also can actuate each of the 4 corners of the display independently from one another, providing a total of 17 possible shape combinations (including flat). Figure 4 shows MorePhone actuating the top right corner of the display. To provide additional feedback on the type of notification, MorePhone can pop up a visual notification balloon in the actuated corner. In the example shown in Figure 4, actuation of the top-right corner also pops up a notification balloon that contextualizes the notification as a text message. Users can open the text message and cancel the notification by pressing the actuated corner. The current prototype allows any shape actuation to be animated with .5 *s* pulses, e.g., to convey urgency.

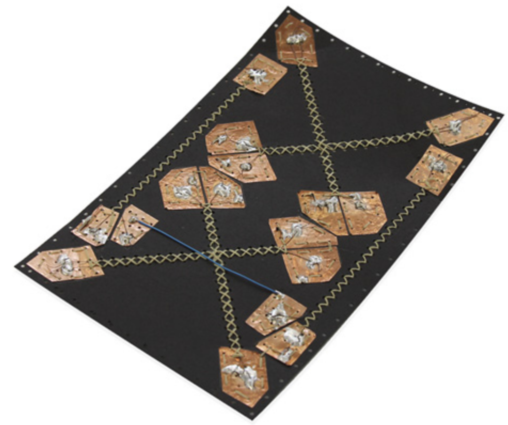

Figure 3. Cardboard actuation layer with Flexinol wires affixed to a copper substrate.

Figure 4. MorePhone displaying shape actuation in the top right corner, with on-screen notification popup.

USER STUDY 1: SHAPES AND NOTIFICATION TYPES

Our first user study had a two-fold objective: First, we wanted to determine how users perceive the urgency of shape configurations provided by MorePhone. Second, we were interested in determining whether and how users would relate particular shape configurations to specific types of notifications. Our design was based on studies by Lee et al. [19], who studied the participatory design of bend interactions with mockup displays, Morris et. al. [23], who designed multitouch gestures to perform operations in a Microsoft Surface table based on user agreement, and Lahey et al. [18], who studied participatory design of bend interactions with flexible smartphones.

Overview

We showed participants the subset of MorePhone shapes illustrated in Figure 5 for two cases: where MorePhone was held in the hand, and where it was placed on the table. We

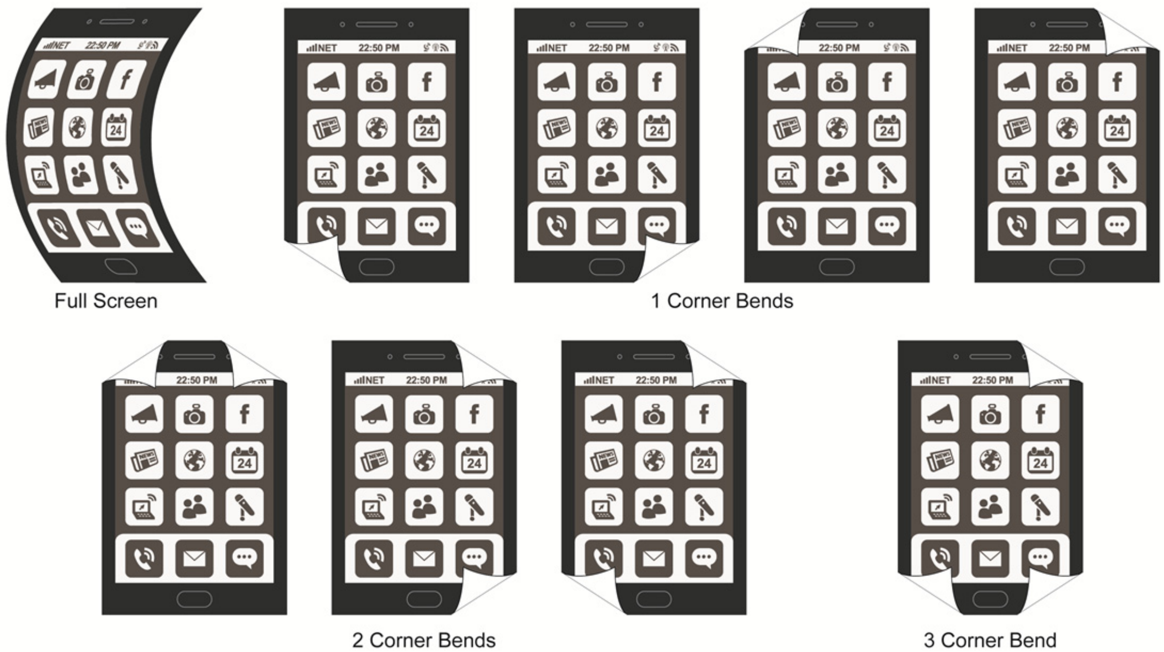

Figure 5: Subset of MorePhone shape actuations as experienced by participants of our experiment.

subsequently asked them to rate the perceived urgency of each shape, after which we asked to rate the correspondence of each shape to a set of notification types.

Participants

14 participants volunteered for this study (5 females, 9 males). The participants were between the ages of 19 and 37 (mean 26 years). All participants were students, and received $10 for 1 hour of participation.

Experimental Design

We used a within-subjects design for our study, in which each participant was asked to evaluate each shape in both conditions: where the device was handheld (VT: visuo-tactile) and where it was on a table (VO: visual-only). Shapes were presented in random order. Condition order was counterbalanced between subjects.

Shape Condition

The 9 shapes presented during the study, in addition to flat, are shown in Figure 5. To limit the amount of time required per trial, we removed the 4-corner bend, and only showed one 3-corner bend and half of all possible 2-corner combinations. The first shape was the baseline of a flat display with no actuation (not shown). The second shape, Full Screen, was a bending of the entire display along its horizontal axis. The next set of four shapes, 1 Corner Bends, curled each of the four corners of the device. The next set of three shapes, 2 Corner Bends, simultaneously curled two opposing corners of the device. In the final shape, 3 Corner Bend, three corners of the device were curled. In all shape conditions, the display was bent into a concave shape with the tip of the display curling 1.5 *cm* upwards, as measured vertically from the flat shape. The shape was actuated from flat to shape in 1 *s*.

Shape Animation

We animated each shape group to evaluate whether this would increase the perceived urgency of the shape. Each animation consisted of 5 pulses from flat to shape, each of 0.5 *s* duration. We then asked subjects how appropriate animation was for each notification type, using a 5 point Likert scale.

Visuo-tactile vs. Visual-only Condition

To ascertain the effect of visual-only versus visual-tactile feedback of MorePhone, shapes were presented in two different conditions, one where the prototype was held in the non-dominant hand, and one where it was placed on the table. In the visuo-tactile condition, users were asked whether they could see and feel the shape after actuation. The users held the prototype such that all shapes were able to touch the skin. In the visual only condition, they were only asked if they could see the shape after actuation.

Notification Types

We selected notification types commonly present in standard smartphone devices: *voice call, text message, email, voicemail, alarm/reminder, social notification* and *software update*. Prior to the session, users were asked to rate each notification type on urgency using a 5-point Likert scale (strongly agree-strongly disagree), evaluating the statement *“A [notification type] is urgent and requires my immediate attention”*. They also ranked the urgency of calls, text messages and emails by specific people.

No Visual or Auditory Notifications

The goal of our experiment was to discover possible mappings between various shapes and various notification types, rather than comparing the efficacy of shape notifications versus *visual*, *auditory* or *tactile* notifications. To avoid confounding effects of display design on the outcome of this experiment, the flexible display showed a neutral and static home screen in all conditions.

Task and Questionnaire

During the session, subjects were presented with a random shape for 2 *s*, after which they were asked to rank this shape for agreement with statements using a 5-point Likert scale (strongly disagree–strongly agree), pertaining to a) the perceived *urgency* of the notification, and b) the *appropriateness* of the shape for a particular notification type.

Ranking Urgency of the Shape

The first question evaluated the perceived urgency of the shape, measuring agreement with statement *"This shape indicates something urgent has happened that requires my immediate attention"*.

Mapping Shape to Notification Type

The remaining 7 questions evaluated the perceived appropriateness of the shape for each of the notification types. We measured agreement with the statement *"This shape indicates [notification type]."*

Personalization

To examine whether shape actuations might provide participants with associations of individual persons, participants were asked to evaluate the statement *"I think this shape signifies an incoming email from someone specific"* using the same Likert scale format, and were then asked to specify whom they were referring to.

Responding to Notifications

For each shape, users were asked how they would respond to the notification.

Usefulness

At the end of the session participants were asked: (1) *"In what ways do you think actuated notifications are useful?"* (2) *"In what ways do you think actuated notifications are not useful?"* and (3) *"Would you use an actuated mobile device if it was widely available?*

Training and Procedure

After completing the information and consent forms, participants were shown a subset of random shapes to allow them to become familiar with the MorePhone prototype. We demonstrated these actuations asking participants to *"Imagine this is your future phone: it does not just notify you by ringing and vibrating – but by changing shape."* We instructed users to avoid folding or twisting the device, due to the fragile nature of the prototype. We guided the participants to hold the display as if it was wireless, and to ignore the single connector cable. Aside from this, we did not instruct participants on shape changing notifications. Throughout the experiment, participants were encouraged to think aloud, so as to verbalize their thought processes, which were noted by the experimenters.

RESULTS

All subjects taking part in our study stated they were able to distinguish all 10 variations in shape that they were presented with, both with the device resting on a table (visual-only) or handheld (visuo-tactile). In the visuo-tactile condition, all participants indicated they were able to feel and see the shapes. In the visual-only condition, all participants indicated they were able to see the shapes.

Statistical Analysis

We analyzed results from our questionnaire data using a one-way Friedman's non-parametric analysis of variance based on ranked order of the questionnaire items, and with Bonferroni corrected one-tailed Wilcoxon Signed Rank post-hoc tests. Bonferroni correction was applied by evaluating the standard alpha level of .05 divided by the number of comparisons.

Grouping of Shapes

In both visuo-tactile (VT) and visual-only (VO) conditions, there were no significant differences between shapes with a single corner (VT: Friedman's χ^2 (3)=1.679, p=.642; VO: Friedman's χ^2 (3)=2.305, p=.512). There were no significant differences between shapes with two corner bends in the visual-only condition (Friedman's χ^2 (2)=.867, p=.648). There was a small but significant difference between shapes with two corner bends in the visuo-tactile condition (Friedman's χ^2 (2)=9.091, p=.011). To simplify analysis and reduce the chance of Type II errors upon posthoc analysis, we subsequently grouped shapes into five groups: Flat, Full Screen, 1 Corner Bend, 2 Corner Bend, and 3 Corner Bend. Because we focused on the visual-only condition for further analysis, the significant difference between 2 Corner Bends in the visuo-tactile condition did not affect further results.

Visuo-tactile vs. Visual-only

In the present scenario, differences between visuo-tactile and visual-only conditions were very small, and not significant for any shape group (2-tailed Wilcoxon Signed Rank at alpha of 0.05): Flat: Z=-1.732, p=.083; Full Screen: Z=-.289, p=.773; 1 Corner: Z=-1.655, p=.098; 2 Corner: Z=-1.706, p=.088; 3 Corner: Z=-.730, p=.465. Since results were very similar between VT and VO on all measures, we chose to present further statistical analyses for the visual-only condition only. There appeared to be little effect of tactile feedback on the choice of notification style. This limitation might be caused by the usage of an actual display. Alternative methodologies and materials could lead to different results.

Flat vs. Shape Notifications

A planned comparison showed a large and significant difference in ratings on all questionnaire items between the mean baseline flat condition and the average score over all

Shape	1 Corner	2 Corner	3 Corner	Full Screen
Urgency	3.07 *(0.15)*	3.40 *(0.17)*	3.71 *(0.29)*	4.43 *(0.17)*

Table 1. Mean *(s.e.)* urgency score for each shape group .

shape groups (Z=-3.298, p<.001). The flat condition was rated the lowest on all items, with a mean score of 1.3 across items. We subsequently discarded this flat baseline condition from further analysis, so as to avoid biasing results between shape groups. This means all subsequent comparisons were between shapes other than flat.

Shape and Urgency
Table shows the means and std. errors for each questionnaire item, per shape group, for the visual-only condition. Differences in urgency ratings were highly significant between shape groups (Friedman's χ^2 (3)=25.272, p<0.001). Bonferroni corrected post-hoc comparisons (evaluated at an alpha level of 0.0083), show Full Screen Bends were rated significantly more urgent than 2 Corner Bends (Z=-3.204, p<0.0002) and 1 Corner Bends (Z= -3.308, p<0.002), but not 3 Corner Bends (Z= -1.263, p=0.02). When Bonferroni corrected, there were no significant differences in urgency ratings between any other shape groups.

Shape and Notification Type
Table shows the means and std. errors for each notification type, per shape group, for the visual-only condition. Differences between shape groups in matching scores for text (Friedman's χ^2 (3)=7.639, p=.054), email (Friedman's χ^2 (3)=1.439, p=.696), voicemail (Friedman's χ^2 (3)=1.950, p=.583) and social network notifications (Friedman's χ^2 (3)=7.421, p=.060) were not significant.

Call Notifications and Shape Group
Differences between shape groups in matching scores for voice call notifications were highly significant (Friedman's χ^2 (3) =22.451, p<.001). Bonferroni corrected post-hoc comparisons (evaluated at an alpha level of 0.0083) show Full Screen Bends were rated significantly higher in terms of matching Voice Call notifications than 1 Corner Bends (Z=-3.329, p<.0002), 2 Corner Bends (Z=-3.084, p=.0002) or 3 Corner Bends (Z=-2.041, p=.0035). 1 Corner Bends were rated significantly higher than both 2 Corner Bends (Z=-2.374,p=.0015) and 3 Corner Bends (Z=-2.249, p=.002). There were no significant differences between 2 Corner Bends and 3 Corner Bends (Z=-1.069, p=.024).

Alarm/Reminder Notifications and Shape Group
Differences between shape groups in appropriateness ratings for Alarm/Reminder notifications were highly significant (Friedman's χ^2 (3) =18.139, p<.001). Bonferroni corrected post-hoc comparisons (evaluated at an alpha level of 0.0083) show Full Screen Bends were rated significantly higher in terms of matching Alarm/Reminder notifications than 1 Corner Bends (Z=-2.938, p=.0003), 2 Corner Bends (Z=-2.812, p=.0003) and 3 Corner Bends (Z=-2.588,

Notification Type	Shape			
	1 Corner	2 Corner	3 Corner	Full Screen
Alarm	2.05 *(0.28)*	2.38 *(0.25)*	2.71 *(0.41)*	3.57 *(0.33)*
Call	2.89 *(0.20)*	3.33 *(0.23)*	3.71 *(0.29)*	4.43 *(0.14)*
Voicemail	3.32 *(0.23)*	3.40 *(0.22)*	3.50 *(0.25)*	3.14 *(0.27)*
Text	3.66 *(0.15)*	3.48 *(0.16)*	3.50 *(0.27)*	3.86 *(0.25)*
Email	3.52 *(0.17)*	3.33 *(0.19)*	3.21 *(0.26)*	3.14 *(0.29)*
Social	3.41 *(0.21)*	2.90 *(0.22)*	3.00 *(0.31)*	2.71 *(0.24)*
Software	2.88 *(0.23)*	2.50 *(0.23)*	2.29 *(0.22)*	1.79 *(0.19)*

Table 2. Mean *(s.e.)* score for matching each shape group to each notification type .

p=.00083). There were no significant differences between 1 Corner Bends and 2 Corner Bends, (Z=-1.483, p=.0115), 1 Corner Bends and 3 Corner Bends (Z=-1.610, p=.009), and 2 Corner Bends and 3 Corner Bends (Z=-.827, p=.034).

Software Update Notifications and Shape Group
Differences between shape groups in matching scores for software update notifications were highly significant (Friedman's χ^2 (3) =21.690, p<.001). Bonferroni corrected post-hoc comparisons (evaluated at an alpha level of 0.0083) show 1 Corner Bends were rated significantly higher in terms of matching software notifications than 2 Corner Bends (Z=-2.533, p=.001), 3 Corner Bends (Z=-1.933, p=.0045) and Full Screen Bends (Z=-3.187, p=.0002). 2 Corner Bends were rated significantly higher than 3 Corner Bends (Z=-.680, p=.0041) and Full Screen Bends (Z=-2.542, p=.0018). 3 Corner Bends were rated significantly higher than Full Screen Bends (Z=-2.942, p=.00034).

Animation and Urgency of Notification Types
Figure 6 shows the results for matching animated shapes with notification types. Results show a significant and strong correlation (r^2=0.85, p<0.001) between the notification type matching scores for animated shapes, and the pre-session notification type urgency scores. By contrast, correlations between non-animated shape group matching scores and pre-session notification type urgency scores were not significant for any of the shape groups.

Personalization of Shape
There were no clear results with regards to personalization of shapes or shape groups to persons. 70% of participants had no preference for a person they would associate with 1 Corner Bends, 79% of the responses indicated no

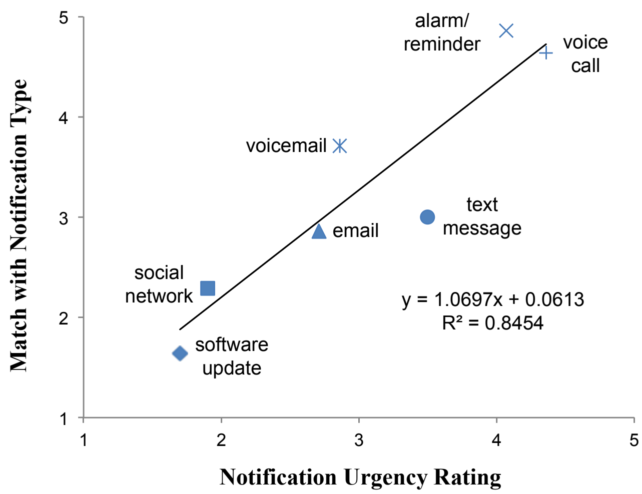

Figure 6. Match scores against pre-study ratings of notification types for animated shape notifications.

preference for 2 Corner Bends, 64% for 3 Corner Bends, and 54% for Full Screen Bend.

Responding to Notifications

Most participants, when asked how they would respond to a shape notification, answered that they would simply touch the screen of the device. One participant remarked they would touch the shape changing corner(s) of the device.

Usefulness and Participant Comments

13 of 14 participants said they would use this technology if it was widely available, and seek it out. 1 participant indicated no preference. Some concerns were voiced about the durability of the current prototype.

Silent and Noisy Usage Scenarios

Participants said the actuated shape notifications would be useful in situations where silence is necessary. Scenarios mentioned included: meetings, movies, or when concentrating. Another benefit identified is the ability to receive notifications in noisy environments. *"I listen to music all the time, and I usually miss notifications even if my phone is on high volume. If this was beside me while I worked I would notice my phone moving, and probably respond to people a lot more frequently."*[P13].

Visual Communication at a Distance

A common useful feature participants noted was the ability to receive notifications from a distance. Due to the device's capacity to hold shape, participants noted they could identify the notification and decide whether to attend to this notification or ignore it, without ever going to the phone. Participants commented that shape notifications would not be useful if the phone was in another room: *"I would want to pair the movement with the sounds phones have now."* [P3]. The addition of sound was a popular comment among participants, as: *"For really demanding notifications, I do not think movement would be enough."* [P2,P7,P11].

Shape Animation

All participants were enthusiastic about animating the phone, but the majority mentioned the desire to personalize these animations: *"Pulsing very gently would be more suitable for secondary notifications."*[P6]; *"I'd like to specify contacts and associate pulsing with a very close friend or a very urgent notification."*[P8]; *"Different pulsing patterns could provide information in a similar sort of way that the shapes provide information."*[P12].

Corners and Notifications

Participants commented on the shapes presented, mentioning an affinity for the shapes that moved one corner, and the shape that actuated the full-body of the device: *"The single corners are very clear, they're simple; I would want to assign a notification to each one. Simultaneous corners are a bit confusing: it's more like it's saying I've received two or three notifications. But it did get my attention."*[P4]

DISCUSSION

Results suggest that generally speaking, tactile feedback appears to have little effect on the appreciation of particular shapes for various types of notifications. We believe there are a number of explanations for this. Firstly, all deformations of the device were away from the hand (the corners pointed upwards). While users reported to be able to feel these deformations, this meant there was no positive pressure exerted on the hand during the presentation of any of the shape notifications. Secondly, the forces exerted by this MorePhone prototype are insufficient to provide significant kinesthetic cues. Thirdly, comments indicated that participants considered shape deformation as a means of visually drawing their attention (as opposed to tactilely). The latter can be explained by the fact that movement in the user's peripheral vision upon shape actuation provides a powerful yet subtle and ambient means to signify a status change in the phone's notification state. Although there was a significant difference between notification type matching scores for various 2 Corner Bends in the visual-tactile condition, this was not significant in the visual-only condition, and this was not significant in either condition for 1 Corner Bends. We believe that, while subtle, this effect was due to participants perhaps experiencing more of the shape change through tactile sensations in 2 Corner conditions.

Shape and Urgency

Our hypothesis that different shapes would be rated with different urgency was partially confirmed. While there were significant differences in urgency ratings between Full Screen, 2 and 1 Corner bends, there was no significant correlation between pre-study urgency and notification type match for shape groups. While Table suggests a small but insignificant trend between urgency rankings and surface area of shape groups, this is not substantiated by a clear association between pre-study urgency scores and notification type matches for shape groups. Any connection between urgency and area in shape groups appears largely associated with full screen actuation as opposed to other, smaller, surface area actuations.

Shape and Notification Type

Our hypothesis that different shapes convey different meanings to users in terms of their appropriateness for a particular notification was confirmed. Participants, however, indicated no particular preference of any one shape group for text, voicemail, social or email notifications. Comments by participants suggested that all message notifications were best matched with a single corner bend, using multiple corners for multiple simultaneous notifications. As such, for these categories, we believe they interpreted the shapes differently, and rather than using shape to identify what message type they would receive, they were more interested in determining how many simultaneous notifications there would be.

Animation of Shapes

Results for animation of actuated shape notifications strongly suggest that animation is aligned with urgency. Approximately *85%* of the variance in matching of notification types with animation was explained by pre-study urgency rankings alone.

USER STUDY 2: DISPLAY VERSUS SHAPE

In our second, more informal study, we used MorePhone with an active display providing visual popup notifications in two corners of the flexible display: top right and bottom right. 6 participants volunteered for this study (3 females, 3 males, mean 27.5 years). The purpose of this follow-up study was to ascertain if users would require visual notifications to ascertain notification type, and whether they would touch the actuated corner to attend to the notification. We were also interested to know whether they wanted to dedicate particular corners of the display to particular notifications, as suggested by their comments in the first study, or whether they would prefer to have the entire display signify the notification type. We used the same apparatus as in the first study, but with active graphical notifications.

Task

We first showed a shape actuation in the top right corner, with a visual notification popup of a text message, and asked participants where they would touch the display upon a shape notification. We subsequently also actuated the bottom-right corner with a visual notification popup of a Facebook update. After this, we showed them the same sequence, without visual notification, and asked participants what they thought these notifications meant, and whether they thought the visual popup was helpful. We again repeated the sequence with visual notification, this time reversing the corners for each visual notification type. We subsequently asked them if they preferred dedicating corners to a notification type, and if so, whether they wanted to personalize which corner. Finally, we repeated the same sequence without visual notification, telling participants that a one-corner bend indicated a text message, and a two corner bend a Facebook message. We asked them if they preferred to be able to tell from a distance by the number of actuated corner what kind of notification they received.

Results and Discussion

Results from the follow-up study showed 4/6 participants touching the display on the curled tip to address the notification. The remaining participants simply touched the display. After having been shown which corner pertained to which notification, all participants were able to determine the notification type based on shape-only notifications. 5/6 participants preferred notifications in a dedicated corner as they found arbitrary corners confusing. *"There should be an option allowing user to set for each corner which alerts should be displayed."* [P2]. 4/6 Participants indicated they saw little to no value in determining the type of notification by the shape of the screen. Results clearly point in the direction of the use of customizable dedicated corners with visual notifications for actuated shape notifications. All participants wanted to be able to personalize in which corner each notification type would appear. There were also benefits identified for using shape notifications without visual cues. *"I see this being useful in social contexts, because it is less disruptive and favors privacy. I don't like keeping my phone face up in public as I don't want people to be able to read every text I receive."* [P1].

DESIGN RECOMMENDATIONS

From the above discussion, we derived a number of design recommendations for actuated smartphone notifications:

1. Use Animation to Increase Urgency of Notifications

We recommend that animation of actuated shape notifications is used to increase the urgency of any type of notification. This may be particularly appropriate for alarms and urgent voice calls.

2. Full Screen for the Most Urgent Notifications

We recommend that in static cases, actuation of the full surface of the display is best used for the most urgent category of notifications. This includes alarms and reminders, as well as voice calls.

3. Multiple Corners for Simultaneous Notifications

Notifications other than alarms and voice calls best rely on 1 Corner bends. Multiple corners are best used to indicate multiple parallel notifications, by type.

4. Dedicate Corners to Notification Type

Corners are best dedicated as pertaining to a particular notification type, and should be personalizable by users.

5. Provide Visual Notification Popups

Actuated shape notifications are best augmented with co-situated visual notifications. This supports learning which notification pertains to which corner, and allows for cases in which there are more alerts than corners available.

6. Filling the Gap between Visual & Tactile Notifications
Flexible smartphones support new notification paradigms that can use deformation to convey information. While more research is needed to ascertain the efficacy of shape actuation for tactile feedback, the capacity to actively change shape provides an extra design vocabulary that fits between current visual and vibratory notification methods.

LIMITATIONS AND FUTURE DIRECTIONS

While we expect future MorePhone prototypes to be highly customizable, allowing users to design their own actuated shape vocabulary, current hardware limitations prevented such customization. The current prototype is limited in terms of the amount of force it can exert on the body which constrained the expression of shape actuation for kinesthetic feedback. These limitations may be due to present display technology and results may vary with different actuation or display methods and materials. There appears to be a tradeoff between visual and tactile actuated shape notification design: in order for shapes to be clearly visible, they are best actuated outwards. Haptic perception is, however, best served through inward actuation. Our results may, as such, be limited by the choice for our prototype to actuate outwards. We aim to reduce the need for power cables in future designs.

CONCLUSION

In this paper, we presented MorePhone, a prototype flexible smartphone that changes shape to provide notifications. We studied how users perceive the urgency of full screen, single corner and multiple corner shape notifications. Results suggest full screen notifications are best used for the most urgent notifications, such as phone calls and alarms. Single corner notifications were best matched to notifications that were ranked as less urgent, such as emails and messages. Users preferred using multiple corner actuations to service multiple notifications, dedicating each corner to a particular notification type.

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