Understanding Affordance, System State, and Feedback in Shape-Changing Buttons

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ABSTRACT

Research on shape-changing interfaces has explored various technologies, parameters for shape changes, and transformations between shapes. While much is known about how to implement these variations, it is unclear what affordance they provide, how users understand their relation to the underlying system state, and how feedback via shape change is perceived. We investigated this by studying how 15 participants perceived and used 13 shape-changing buttons. The buttons covered several aspects of affordance, system state, and feedback, including invite-to-touch movements, two styles of transition animation, and two actuation technologies. Participants explored and interacted with the buttons while thinking aloud. The results show that affordances are hard to communicate clearly with shape change; while some movements invited actions, others were seen as a malfunction. The best clue as to button state was provided by the position of the button in combination with vibration. Linear transition animation for changes in button state was the best received form of shape-change feedback. We discuss also how these findings can inform the design of shape-changing interfaces more generally.

Author Keywords

Shape-changing interfaces; affordance; system state; feedback; empirical study.

ACM Classification Keywords

H.5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous.

INTRODUCTION

Shape-changing interfaces use physical shape change as input and output [33]. Their dynamic features offer new possibilities for interaction techniques. Shape change has been used in development of novel user interfaces such as shape-changing 2.5D displays [8,21,32], handheld devices that change in shape [6,14,15], and shape-changing input devices [17,22]. Most research into shape change in HCI focuses on introducing novel user interfaces that explore shape-change technologies [5,42], parameters for shape changes [19,35], and transformations between shapes [27].

While previous work provides a wealth of information on ways of implementing such interfaces, studies of how users perceive or interact with shape-changing interfaces are few (though exceptions do exist [18,19,31]). We know particularly little about the relation between the *shape-change mechanisms* (e.g., the technology, transformations, and parameters) and *what users perceive and act on* (e.g., the affordances they see and interpretations of shape change).

We present an empirical study of how users perceive and interact with shape-changing buttons. Buttons enable useful simplification: as a basic and ubiquitous user-interface element, they limit the complexity and novelty effects associated with shape-changing interfaces. Rather than puzzle users with completely new techniques or domains of application, we were able to focus on varying the shape-change mechanisms and learning about their effects. To do so, we created 13 shape-changing buttons, which varied in such mechanisms as actuation technique, movement, and shape-change feed-forward [39] (see Figure 1 for an example). Users' perceptions and reactions were then examined via detailed video analysis, in terms of three key button-design concepts introduced in earlier work by Janlert [16]: affordance, system state, and feedback. These three concepts aid in exploring how variations in buttons (and their associated shape-change mechanisms) affect users' perceptions and way of interacting with devices.

This paper contributes a) a set of variations of shape-change mechanisms in a ubiquitous interface type, b) an in-depth analysis of how users' perceptions and behaviors are affected by those mechanisms, and c) a discussion of what these findings mean for research and design and the extent to which they generalize.

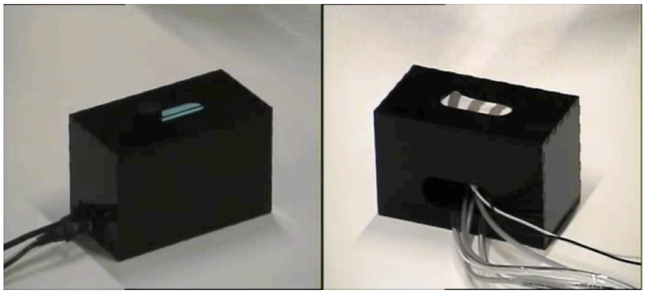

Figure 1: An instance of a mechanically actuated button (left) and a pneumatically actuated one (right).

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RELATED WORK

Shape-Changing Interfaces

Previous research into shape-changing interfaces has generated a host of novel user interfaces. Rasmussen et al. [15] and Roudaut et al. [16] have catalogued the various parameters affecting shape-changing interfaces. One of the main parameters is the type of shape change: is it a change in form, volume, or orientation? Another parameter is the type of physical animation or transformation between shape states. This can vary from a rapid mechanical transformation to a "soft" organic movement. The transformation type is composed of the velocity, direction, and path of the physical movement. The final parameter is a technical one that affects the design of shape-changing interfaces – the technology and materials used for implementation. Coelho and Zigelbaum [5] have provided an overview of smart materials and technologies that could be used to implement shape change. For instance, it can be achieved by means of pneumatic actuation [4,17], mechanical actuation [3,10,14], shape-changing materials [1], or even bacterial spores [13].

Common approaches in the development of shape-changing interfaces are mechanical and pneumatic actuation, used in diverse application scenarios. For example, Leithinger et al. [8,21] and Taher et al. [37] used mechanically actuated physical rods to create shape-changing displays. Leithinger and colleagues designed their displays for providing dynamic affordances and constraints [8], physical telepresence [20], and dynamic furniture [40], while Taher et al. explored supporting data analysis by means of interactions with dynamic bar charts. The pneumatic approach is represented by Kim et al. [17], who introduced the Inflatable Mouse, which uses change in volume for input and output. PneUI [42] and Sticky Actuators [23] employ soft composites and plastic pouches that can be pneumatically actuated to enable various types of shape-changing interface.

Previous work also has employed both forms of actuation specifically to develop shape-changing buttons. Harrison and Hudson [12] implemented dynamic physical buttons using air-filled chambers. They utilized air-based actuation, flexible latex, and clear acrylic sheets to produce concave and convex buttons on a multi-touch display. In addition, Métamorphe [2] used linear actuated keys to augment traditional keyboards with haptic and visual feedback.

Empirical Studies of Shape-Changing Interfaces

As a supplement to the above research, a growing but still modest body of research has investigated users' experience with shape-changing technology [18,19,34]. Most studies on the topic focus on handheld devices [15,30,31]. Animate Mobiles [15], for instance, explored how animation based on proxemic interactions affect relations between users and handheld devices. Park and colleagues investigated how users use shape-changing handheld devices for communication and to convey emotions [28–30]. Pedersen et al. [31], in turn, measured user reactions to videos of a shape-changing handheld device. They systematically varied their shape-change parameters in line with Roudaut et al.'s [16] model and assessed the effect on users' perception of urgency, animacy, and affect. Rather than considering handheld devices, Kwak et al. [19] conducted a repertory-grid study to gauge participants' responses to a set of shape-changing artifacts with manipulation of volume, texture, and orientation. Finally, coMotion [18] is an actuated bench that was used in a study "in the wild." The researchers observed the effects of the dynamically shape-changing bench on social situations and contextual atmosphere.

Buttons

Buttons are among today's simplest and most ubiquitous user interfaces. The button in its most basic form is an ON/OFF switch that controls or triggers certain system functionality. A well-designed button should convey three key things to the user [16]: How does one interact with the button? What is the current state of the function controlled by the button? What effect does the action performed have on the button? For instance, a simple ON/OFF switch to a machine should tell the user how to press it, show whether it is currently ON or instead OFF, and indicate after pressing whether the machine is now ON or not. These three core elements are related to affordance, system state, and state-change feedback, respectively.

One way to answer the question of how to interact with a button is offered by the idea of affordance. According to Gibson, who introduced the notion [10], affordances are "what [the environment] *offers* the animal, what it *provides* or *furnishes*, either for good or ill." Norman [24] introduced affordances to HCI as the physical properties of an object that suggest how it might be used. Norman focused on perceived affordance [25] – what the user perceives as possible actions – as a very important factor for design. Later [26], he introduced the term "signifier" in an attempt to differentiate between perceived affordances and "cues or indicators that a certain affordance is present." Norman emphasized the role of designers in providing appropriate signifiers to guide users' interaction with physical objects. This need exists with most UI elements, and buttons have been highlighted as no exception [16]. Our paper uses the three concepts discussed by Janlert [16] and the aforementioned literature on affordances to uncover how users interact with buttons.

Summary

Given the scarcity of earlier work on users' perceptions of shape change, we developed a selection of shape-changing buttons and empirically evaluated them. We investigated the effect of using shape-change mechanisms as signifiers on users' interpretation of the buttons through the concepts of affordance, system state, and feedback.

We opted to use buttons for our study because, in addition to being ubiquitous, they represent a simple case combining affordance, system state, and feedback of a user interface. Buttons also made it easier to focus on exploring the effects of shape change rather than adding novelty factors that usually accompany shape-changing interfaces.

In the following sections, we explain the button designs used and then detail the procedure applied for eliciting users' reactions.

BUTTON DESIGNS

The key idea with the button designs used in the empirical study is to vary shape-change parameters and also the actuation technology applied for the buttons and see the effect on users' perception of affordance, system state, and feedback.

Our button designs mimic the *horizontal toggle button*. We opted to mimic a style of button that is ubiquitous and familiar to users. The general layout of the horizontal toggle button consists of a horizontal groove and a handle that can move along the groove as a controller for switching between the button's two states as shown in Figure 2. The two states of the toggle button are defined by the position of the handle when it sits at either of the two ends of the groove.

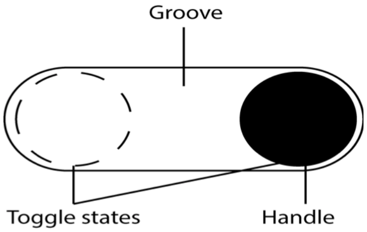

Figure 2: The layout of a horizontal toggle button.

Actuation Technologies

We used two actuation techniques: mechanical and pneumatic. These two techniques led to two handle designs (*knob* and *air*). Mechanically actuated buttons have a round handle (a knob) that is fixed in shape and can be moved or sent along the groove. The handle of pneumatically actuated buttons is formed from a dynamically shaped amplitude that results from blowing air underneath a piece of fabric. In our design, air could be blown at any of five positions along the groove (one at either end and three between), simulating movement of the handle. The amplitude of the handle was controlled by the amount of air blown beneath the fabric.

Having two handles gave us an opportunity to better explore and compare various button designs. The knob buttons were designed to be tactile, familiar to users, and have a mechanical feel to them. In the second design, we implemented air buttons by using air flow instead of air chambers [12]. This provided more possibilities for dynamic shape change. The air buttons were less familiar to users but, on the other hand, had a more organic feel.

The handle of knob buttons reacts to touch, swipe, push, and drag operations. If the knob is touched or swiped, it switches to the other state, at the other end of the groove. If a push or drag moves the knob beyond the midpoint of the groove, it enters the other state; if not, it returns to its original position. The handle of air buttons reacts to touch and swipe interactions. Switching states is indicated via an animation by blowing air across the five positions along the groove, in sequence from left to right or right to left.

The Overall Variety of Buttons

We developed 13 toggle buttons, divided into four groups:

- Non-interactive (three buttons: ⓐ ⓑ ⓒ)
- Shape change before touch (four buttons: ⓓ ⓔ ⓕ ⓖ)
- Shape change on approach (two buttons: ⓗ ⓘ)
- Shape change after touch (four buttons: ⓙ ⓚ ⓛ ⓜ)

The set consists of six pairs of buttons plus one singleton, where every pair is of similar buttons implemented with each of the actuation techniques, mechanical and pneumatic. The singleton, group 1's button ⓐ, was implemented by means of pneumatic actuation only.

Next, we explain the rationale behind each group and the details of its buttons.

Group 1: Non-interactive

The three buttons in the first group (ⓐ ⓑ ⓒ) were used to investigate how the design and technical implementation of the toggle buttons affect affordance. They helped us explore how users interact with shape-changing buttons when given only limited visual cues and feedback (see Figure 3).

Air No Affordance, ⓐ, has no handle, which renders it neither interactive nor responsive at all. *Knob Handle*, ⓑ, and *Air Handle*, ⓒ, have non-responsive handles that offer no feedback upon interaction. *Air No Affordance* (ⓐ) consists of just a groove in a planar surface covered by a piece of fabric similar to pneumatically actuated buttons, while *Knob Handle* (ⓑ) is a mechanically actuated button whose handle can be moved freely along the groove but with no resistance or feedback. *Air Handle* (ⓒ) is a pneumatically actuated button with an amplitude handle formed by constantly blowing air in a fixed position that is not responsive to interaction.

Group 2: Shape Change Before Touch

The second group consists of four buttons (ⓓ ⓔ ⓕ ⓖ in Figure 4). These buttons implement affordance signifiers using shape change, for investigating how the signifiers

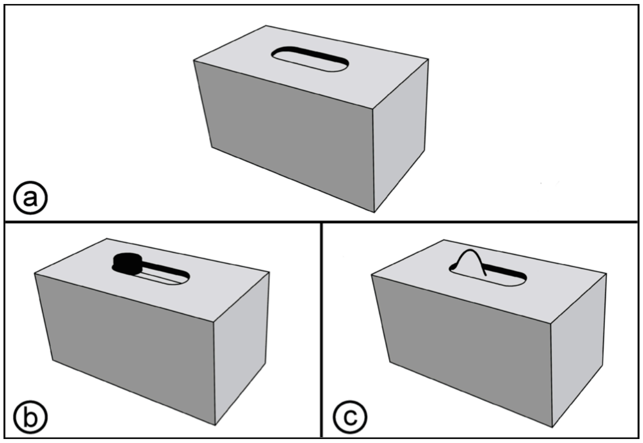

Figure 3: Non-interactive buttons. ⓐ = Air No Affordance, ⓑ = Knob Handle, ⓒ = Air Handle.

affect the interpretation of the affordance. Inspired by previous work [3,4,9,11,36], we chose to use vibration (ⓓ ⓔ) and feed-forward (ⓕ ⓖ) as affordance signifiers.

Vibration movements

Knob Jiggle (ⓓ) and *Air Pulsate* (ⓔ) use vibration as a signifier that the button is active in order to stimulate interaction with it. The handle of these two buttons performs small vibration movements, horizontally in the case of *Knob Jiggle* (ⓓ) and vertically for *Air Pulsate* (ⓔ). The knob of the mechanical button jiggles left and right repetitively. This jiggling motion is inspired by iOS apps' animation in deletion mode. The air handle pulsates up and down with a constant frequency, in a pulsation movement inspired by the up-and-down movement of a jackhammer.

Feed-forward

The handle of *Knob Feed-Forward* (ⓕ) and of *Air Feed-Forward* (ⓖ) signals the direction of interaction by moving towards the other-state position before returning to the initial-state position. This movement is repeated continuously. The handle of the *Knob Feed-Forward* button (ⓕ) moves slowly from its initial-state position towards the other position until two thirds of the way along the groove, then returns to its initial position at normal speed. Similarly, the handle of the *Air Feed-Forward* button (ⓖ) starts moving from its initial-state position with a high amplitude, moves at lower amplitude towards the other-state position until it gets two thirds of the way along the groove, then goes back to its initial-state position with a high amplitude.

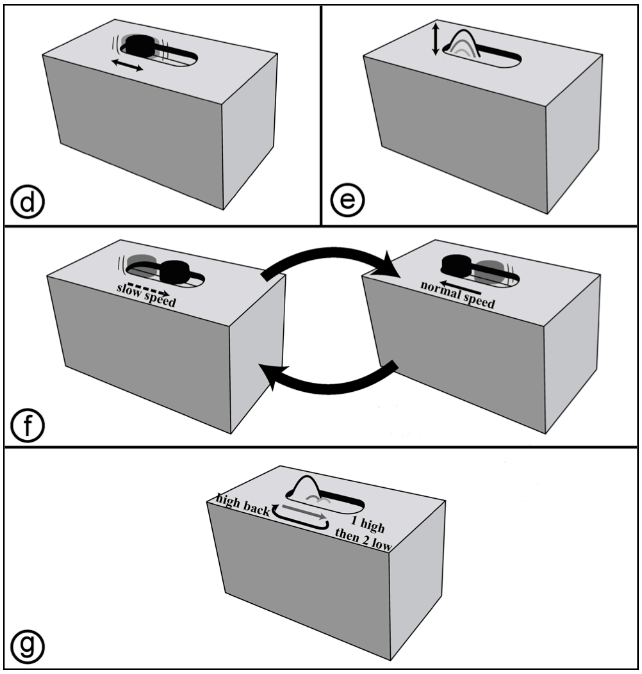

Figure 4: Buttons for before-touch shape change. ⓓ = Knob Jiggle, ⓔ = Air Jiggle, ⓕ = Knob Feed-Forward, ⓖ = Air Feed-Forward.

Group 3: Shape Change on Approach

Group 3 consists of two buttons: *Knob On-Approach* (ⓗ) and *Air On-Approach* (ⓘ) (see Figure 5). The *Knob On-Approach* (ⓗ) and *Air On-Approach* (ⓘ) buttons are similar to *Knob Jiggle* (ⓓ) and *Air Pulsate* (ⓔ), but in group 3 the vibration movements are triggered only when the user's hand approaches the button. In a similarity to the before-touch group, the vibration stimulus is used for investigating affordance signifiers, with the difference being that the signifier is triggered by user actions. Moreover, these buttons shed light on movement-based output that is triggered by hand approach [15,31] as a means of giving feedback about the state of a button.

Group 4: After-Touch Shape Change

The final button group consists of four buttons: ⓙ ⓚ ⓛ ⓜ (see Figure 6). Each implements two variations of physical transition animation for toggling between states: linear (ⓙ ⓚ) and decaying (ⓛ ⓜ). These four buttons are used to investigate the effect of varying transition animation on the perception of state-change feedback.

Linear transition animation

Knob Linear (ⓙ) and *Air Linear* (ⓚ) perform a linear transition animation toggling between states after user interaction. The handle of *Knob Linear* (ⓙ) makes a linear motion between the groove's ends to indicate switching between states, while *Air Linear* (ⓚ) simulates a linear smooth transition with the air flowing between two ends of the button toggling state. Air is blown in the five positions in sequence along the groove (one at either end and three between the ends). The transition animation starts at one end of the groove with large amplitude. Afterwards, three smaller amplitudes appear in sequence from left to right or right to left. The animation ends with another large amplitude, at the opposite end. The large amplitudes at the ends emphasize the two states of the button, while the three smaller ones along the middle indicate the direction of movement of the air handle in toggling between states.

Decaying transition animation

Knob Decay (ⓛ) and *Air Decay* (ⓜ) perform a decaying transition animation towards their destination position that represents toggling between states. The transition animation of *Knob Decay* (ⓛ) is inspired by the motion of a bouncing ball when it falls to the ground. When the button changes its state, the handle moves back and forth in a decaying

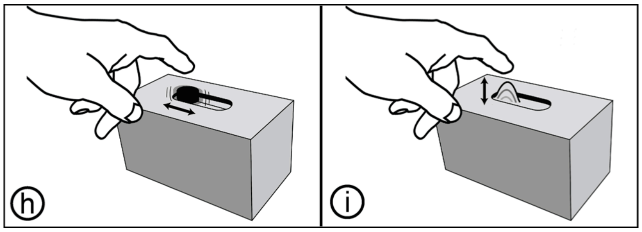

Figure 5: Shape change on approach. ⓗ = Knob On-Approach, ⓘ = Air On-Approach.

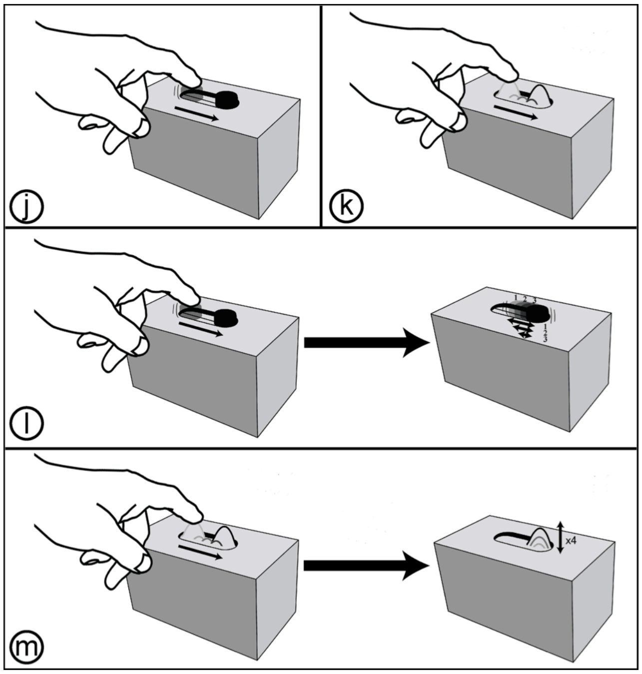

Figure 6: Buttons for shape change after touch. ⓙ = Knob Linear, ⓚ = Air Linear, ⓛ = Knob Decay, ⓜ = Air Decay.

manner towards the destination position as if it is hitting the end of the groove as shown in the left panel of Figure 7. The transition of *Air Decay* (ⓜ) is inspired by the sound of a mechanical engine when it is turned OFF and cools down. The air-handle animation starts from the initial position and passes the middle, moving towards the other end of the button, in a parallel to *Air Linear* (ⓚ). When the air handle reaches the destination position, it pulsates up and down four times with a decelerating frequency as shown in the right-hand panel of Figure 7. Afterwards, the air handle remains static, with high amplitude and no pulsation, as usual.

Implementation Details

Mechanically actuated buttons

The core of our knob buttons consists of a motorized linear potentiometer that provides position calculation, linear actuation, and touch detection. A 3D-printed cap covers the potentiometer's handle to act as a knob. This cap is coated with conductive ink for augmentation with touch-sensitivity.

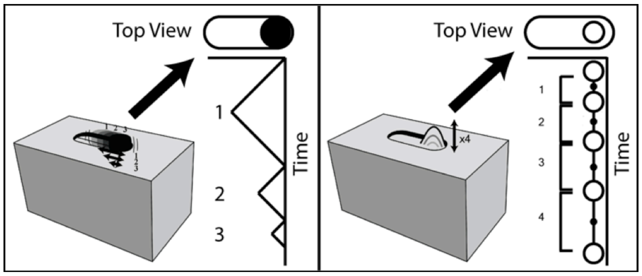

Figure 7: Illustration of decay transition animation, with Knob Decay (ⓛ) at the left and Air Decay (ⓜ) at the right.

The sensory interface and actuation of the potentiometer are controlled with an Arduino UNO board. All the electronic components are enclosed in a laser-cut acrylic box casing, as shown in the left panel of Figure 8.

Pneumatically actuated buttons

The air buttons are made up of two parts: a touch-sensitive interface and a pneumatic control system. The former consists of a conductive zebra fabric (a fabric that is divided into conductive and non-conductive strips to achieve separated areas of conductivity). Capacitive sensing is used to augment the zebra fabric with touch-sensitivity by means of an Arduino UNO board. The pneumatic control system consists of an air compressor, electrically controlled solenoid valves, and tubing. A tubing layout is mounted underneath the zebra fabric. Using flexible tubing and 3D-printed tubing holders (see Figure 8, right panel), this segment allows the air flowing from the air compressor to be blown beneath the zebra fabric: at five positions, along the groove of the button. The behavior, position, and animation for the air flow are controlled by opening and closing of the solenoid valves, which are controlled with the same Arduino board as the touch-sensitive interface. Similarly to knob buttons, the zebra fabric and tubing layout are enclosed in a laser-cut acrylic casing. The rest of the pneumatic control system and the Arduino board are in a separate cardboard box so that the knob and air buttons are presented in the same casing.

THE USER STUDY

The study described next was performed to elicit participants' perceptions of the affordance, system state, and state-change feedback provided by the buttons presented above. Perceptions were obtained via a think-aloud protocol focusing on each of these three aspects. The assumption was that we would thereby learn something about how shape-change mechanisms affect perceptions. That, in turn, should inform future designs.

Study Design

The study was designed to elicit participants' perception and interaction with each button in turn. The 13 buttons were presented to each participant in an order determined at random, so as to distribute learning and boredom effects evenly across the buttons. Each button was presented individually, and participants were asked a fixed set of questions designed to elicit information about the three

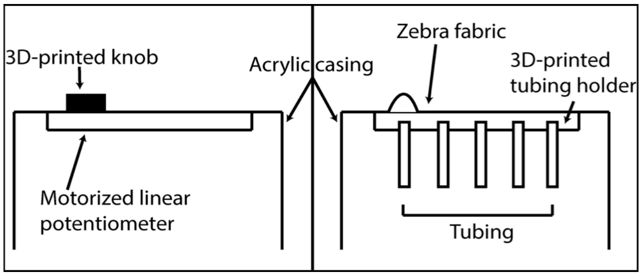

Figure 8: Implementation details for knob buttons (left) and air buttons (right).

characteristics of buttons discussed earlier (*viz.*, affordance, state, and state change).

The questions were the following:

- First, we asked each participant to explain which state the button was in. This question was intended to elicit information about perception of the current state of the button. Specifically, we asked, "Is the button ON or OFF?"
- Second, we asked about the affordance of the button. The participant was not allowed to interact with it but was merely to watch it and explain how he or she would interact with it. This type of question is similar to those asked in many guessability studies [38,41]. Our initial question was "How would you use the button?"
- Third, the participant was asked to toggle the button to its other state while explaining what he or she was doing. The intent was to elicit information about interaction and feedback accompanying state change. We asked, "Could you please try using it?"

The first two questions were asked before touching the button or interacting with it. Afterwards, participants were able to interact freely with the button.

While interacting with the button, participants were asked to think aloud [7]: we asked, "What do you think is happening?" and, if they were silent, we reminded them to "keep talking" [7]. Finally, they were asked to rate the button by using a Likert scale on a sheet of paper that contained the question "How much do you like this button?" (from "not at all" to "very much"). This rating item was intended to elicit information about the overall experience with each button.

The rationale behind these questions is that they should a) generate think-aloud data about the perception of the various shape-change elements and b) generate behavioral data about how participants interact with the buttons.

Random assignment was used for the initial state of each button, whether left or right. Random assignment was also used to determine on which side of the button shape-changing movements occurred. Movements occurred either on one side (left or right) or on both sides.

Participants

We recruited 15 people to take part in the study (6 female), aged 23 to 34 ($M = 28$, $SD = 4.1$). None of the participants (most of whom were students) had previous experience with shape-changing technology, while all had prior experience with smartphones. Participants were given €13 as compensation for use of their time.

Procedure

We first welcomed the participants and explained the study setup. They then gave informed consent and were introduced to the purpose of the study. Next, each participant was stepped through the buttons in turn, answering the questions introduced above and, for each button, completed the rating item on how much they liked it.

Figure 9: Study setup.

The protocol concluded with a semi-structured interview about the participant's opinion of the best buttons in terms of affordance, interaction, and feedback, followed by a debriefing. In total, the study took about 40–50 minutes per participant.

Data Collection and Analysis

The primary data sources were video and audio recordings of the participants as they interacted with the buttons. We used four cameras to capture users' interactions with the buttons and record their thinking aloud. These produced, in all, approximately 12.5 hours of recordings. From each session, the recorded material pertaining to a particular button was compiled into a set of clips on that specific button. Afterwards, comprehensive notes were taken on the set of clips to capture the participants' interactions. In addition to that, the audio from the sets of clips was transcribed, as were the answers in the semi-structured interviews. We performed thematic analysis [1] of the clips and the corresponding transcripts. The first step in this was to assign codes to individual clips (e.g., participant answered "button is ON," participant commented "button movement is like a shaking head," or interaction: "participant stopped button movement"). After this, categories were created to span similar codes, across buttons and participants (we report the findings from the coding process in the results section). We also collapsed codes across clips so as to identify trends and patterns emerging from considering all buttons at once.

RESULTS

In this section of the paper, we present the results, using the concepts of affordance, system state, and state-change feedback. We discuss how each was affected by the shape-change mechanisms. These themes correspond to the three key concepts of button design discussed by Janlert [16]. After this, we present some general observations regarding the buttons and users' ratings of them.

Affordance

Our analysis shows that using physical movements as affordance signifiers is hard. For instance, users found before-touch vibration movements the most inviting to interact with the buttons, but feed-forward movements were not successful in inviting users to interact or in showing the direction of interaction. Most participants interpreted feed-forward movements as an indication of system state. Direction of vibration movement and actuation technology showed the greatest effect on affordance.

In the following subsections, we show how a) before-touch and on-approach shape change and b) actuation technology affected the affordance provided by buttons.

Shape change before touch

Users reacted differently when the buttons moved without being touched or interacted with. The fact that the buttons moved before touch succeeded in grabbing users' attention and signaling that something was happening with the button that requires user action. However, differences in interpretation of why the button was asking for attention caused reactions to vary between participants. This is discussed next.

Vibration-type movement: In 11 encounters, participants associated the vibrating motion with the affordance: the button was inviting them to interact with it. Participant 5 commented, "It is moving; it is trying to get attention. It is trying to say it has to be used." However, in some cases the movement was interpreted as a malfunction or a danger signal. Participants thought that the handle of *Knob Jiggle* (ⓓ) was stuck and needed a push to move to the other side of the button. With *Air Pulsate* (ⓔ), P1 thought the button was giving a signal of overheating: "I just assume that there is something wrong that needs my attention because if I didn't interact with it in the first place then it shouldn't react unless I interact with it." In short, vibration movement was difficult to use for affordance.

The direction of the vibration movement affected how participants interpreted the affordance of the buttons. Most participants, among them P8 and P10, agreed that the vertical pulsating motion of *Air Pulsate* (ⓔ) invited interaction. In contrast, the horizontal jiggling done by *Knob Jiggle* (ⓓ) was a sign of a warning or a malfunction. Participant 8 said, "I can see that there is something wrong here [with *Knob Jiggle*]. I must change something, but air [*Air Pulsate*], it is more just 'press me.'" In contrast, P12 associated the vertical pulsating with blinking warning lights. Therefore, he concluded that the vertical pulsation is a warning sign while the horizontal jiggling invites interaction.

*Feed-forward: F*eed-forward buttons were rarely seen as affordance signifiers. The majority of participants (nine participants with the knob and nine with the air button) interpreted the feed-forward movement as indicating system state. They assumed that the button was in ON state and actively processing something. This led P9 and P12 to not want to touch it at all during its motion. Participant 9 commented, "I don't think I would interfere. I think it would be working on its own without me interacting with it," while participant 12 said, "It is moving, and if I make it stop I may break it."

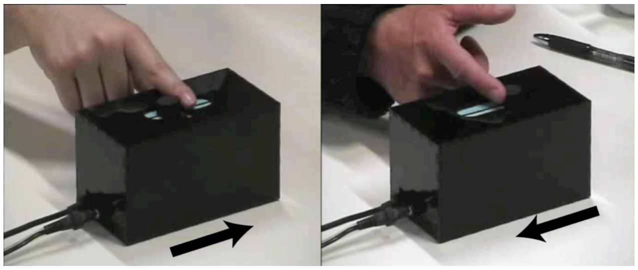

Figure 10: Two participants trying to stop the motion of *Knob Feed-Forward* (ⓕ). Arrows show the direction of motion of the knob. At left, the participant puts his finger in the way of the motion. At right, the participant locks the knob to the side of the button.

It was surprising also that participants did not follow the direction of movement suggested by *Knob Feed-Forward* (ⓕ) when interacting with it. Users wanted to stop the movement of the handle instead of pushing or swiping in line with its direction of motion, as shown in Figure 10.

On-approach shape change

The on-approach technique received mixed reactions from participants. Some considered it to be inviting touch or asking, "Are you sure you want to touch it?" However, for other participants, the on-approach interaction technique was not clear.

In six encounters, participants thought that the movement was intended to grab their attention for interaction with the button when their hand was approaching or nearing it. However, participant 10 concluded that this catching of attention is not needed in most digital scenarios. He commented, "If the button can tell me already if there was something wrong, then it should fix it by itself. Instead of saying 'please switch me,' it should be able to do it itself." He deemed grabbing attention useful only if the button is coupled to a physical machine that needs user action to fix the problem at hand.

In seven encounters, participants thought the button was warning them about touching it. In six cases, participants assumed that they should not do so. Participant 7 said, "The button is flicking me away like a cat," while participant 1 found the warning similar to "are you sure?" prompts, verifying that the user is aware of the consequences of this action.

The on-approach interaction technique was unclear to some users. In three encounters, participants thought that the buttons were trying to get attention after not being interacted with for a while. In five other encounters, participants toggled between states quickly, which made the on-approach triggering of the vibration less obvious. This resulted in the assumption that the vibration movements were a malfunction rather than triggered as a hand approached.

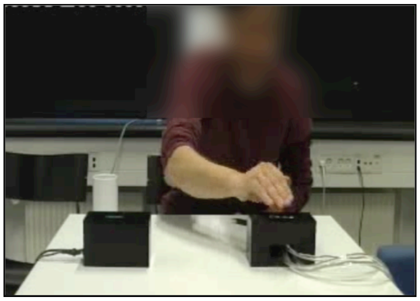

Figure 11: P2: "I'm just trying to see how the air feels on my hand. I'm trying to curl my hand upwards because it is like being in a car when it goes really fast and you put your hands outside the window. It feels like a wing of an airplane, maybe it starts to interact, maybe it takes the shape of my hand."

Actuation technology

Participants' interpretation of the affordance of the buttons differed, depending on the technology used for implementation. Knob and air buttons use similar interaction techniques for switching states after being touched or swiped. However, actuation using air elicited other interactions and gestures, which we did not anticipate. Participants tried to cut off the air flow not just by pressing the protruding part of the fabric but also by covering it with their palm/hands. Participants 2 and 12 waved and moved their hands upward, downward, left, and right over the button, trying to interact with the air flow, and P8 even suggested, "I would blow air into it" for *No Affordance* (ⓐ), which had no air flow.

System State

Movements conveyed richer cues about the state of buttons beyond simply being either ON or OFF. Users commented that movements signaled that buttons were waiting, processing data, and notifying of errors in the system.

In the following subsections, we discuss how shape change before touch and on approach affected participants' perceptions of system state.

Shape change before touch

On one hand, for the simple case of ON/OFF state, shape-change movements provided participants with sufficient feedback. All participants apart from P2 assumed that the buttons were active or ON when they were moving. Making an interesting observation about *Knob Jiggle* (ⓓ), P2 assumed that the button movements meant it was OFF because it grabs attention and wants to be turned ON. On the other hand, the absence of movements and the symmetry of the handle movements between the two button-state changes confused the participants. This might be due to the abstract use context of the buttons – for instance, the fact that they were not connected to a device. In these two cases, participants relied more on convention and the handle being at the left or right than on movements to identify the ON/OFF state of the button. The handle being on the left was considered to mean OFF, and on the right to mean ON.

The relation between the position of a button and its movements affected participants' interpretation of the button state. Consistency between the two gave the clearest feedback about system state. This was seen, for instance, when the button was on the right side and moving. When they conflicted, however, as in the case of a moving button at the left (in OFF state by convention), there were three distinct interpretations. In the first interpretation, convention wins out: participants said that, while it is strange because the button is moving while on the left side, they would still consider it OFF. In the second interpretation, the motion is prioritized: participants changed opinion and said that the button was in the ON state because of the motion. The third interpretation involves something in between, as in P4's conclusion: "It is in a standby state waiting for me to do something about it."

Feed-forward

In 20 encounters, participants commented that the feed-forward movement gave them feedback about the system state rather than inviting them to interact with the button. This was surprising to us because we designed the feed-forward movements as an affordance signifier. Users commented that the buttons conveyed processing of something or that something was wrong with them. We think that this misconception may have been due to two factors in the design of the feed-forward movement. First, the movement of the button handle was continuously looping, in a repetitive manner. This yielded the intuition "It is processing something" or "It is constantly handling data," as P11 and P1 stated, respectively. Second, the range of movement of the handle was rather long (the handle moved until two thirds of the way along the groove, then came back). This was obvious with the *Knob Feed-Forward* (ⓕ) handle on account of its rigid nature, which made it inconvenient for the participants to follow the movement of the handle and touch it. Therefore, they thought something was wrong with the button and preventing it from moving to the other side of the groove. Participant 7 said, "It is like a printer that will not print: it is stuck."

Shape change on approach

On-approach interaction elicited feedback scenarios with information richer than ON/OFF state alone. In seven encounters, participants commented that the button could be used as a motion sensor that detects their hand near the button. On the basis of this observation, they described some feedback scenarios using this button feature. Participants 6 and 7 said that the button could signal its state and location in eyes-free usage or when it is hard to find. Participant 3 assumed the button state to be controlled by hand approach: the button is moving and ON when a hand approaches and is not moving and OFF when there is no hand near it.

Feedback on State Change

Linear transition animation was beneficial in providing participants with state-change feedback and even enhanced the look and feel of the buttons. However, the usefulness of the decaying transition animation as state-change feedback depended on which button state the motion was coupled with. In the following subsections, we describe participants' reactions to shape change after touch: linear and decaying transition animation.

Linear transition animation

Linear transition animation between states provided good feedback on state change for participants. Participant 4 said, "The movement in between states could indicate that it takes time to switch between A and B. So it is not immediate, because this kind of shows progress." Moreover, for some participants it enhanced the look and feel of the buttons. It was more noticeable in *Air Linear* (ⓚ) because of the handle's dynamic nature. Participants 7 and 15 commented that they liked the animation transition since it made the air button feel more realistic and tangible. Participant 15 said, "It is like the flow of water or electricity from one side to the other." Users commented that the speed and resistance of *Knob Linear* (ⓙ) switching between states could be used as a means of feedback. Participant 14 thought of it as a circuit-breaker with which one direction of switching is faster and easier than the other.

Decaying transition animation

According to participants' comments, the utility of employing decay animation as state-change feedback depended on the button state the animation was coupled with. It was more beneficial when associated with a change to the OFF state. Participant 7 said, "It is making sure that I know it is OFF, like shutdown in Windows or something." For the ON state, participants did not mind it but found it unnecessary. They assumed that when the button is used in context it would be connected to a device. In this case, they could clearly see from the device turning ON that the state has changed.

The symmetry between the two directions of state-change animation added ambiguity to the feedback on changes in state. This resulted in negative comments from participants, that they could not see the animation transition as beneficial at all. For instance, P15 was even annoyed by it, saying, "I would be annoyed because I may switch it OFF by mistake and I want to switch it back ON but then I need to wait for it to finish the oscillations to be able to switch it back ON, which will take time." These negative comments occurred mostly when the animation was coupled with both states (ON and OFF), in contrast to just the aforementioned "shut-down" case. This highlights the importance of choosing an appropriate coupling of animation transition feedback and state.

Miscellaneous Observations

Most participants liked touching and interacting with the buttons. From the non-interactive group, *Air No Affordance* (ⓐ) and *Air Handle* (ⓒ) received low ratings because they gave no feedback after actions, which annoyed most of the participants. *Knob Handle* (ⓑ), however, received higher ratings, since participants thought it was a slider that they could use to choose a value along a continuum. Still they were missing feedback on their actions and about which value they had chosen. *Knob Linear* (ⓙ) and *Air Linear* (ⓚ) were rated highly because, according to participants, they were simple to interact with and gave clear feedback.

Participants anchored the buttons and their movements to objects from their day-to-day life. For *Knob Linear* (ⓙ), P6 said, "That is very similar to the one in the iOS settings, like setting something ON and OFF," and participant 7 commented that *Knob Decay*, ⓛ), "is like a bouncing ball like when you drop a ball from somewhere and it bounces." Moreover, during the experiments they suggested other application scenarios wherein shape-changing buttons could be useful. Participant 2 said, "It looks like a chess clock […]. I have a friend who plays chess. He would really like it." Participant 3 offered another suggestion: "If you have two cameras, then the position of the button shows which camera it is controlling and the movement of the button shows whether the camera was ON or OFF."

DISCUSSION

Our study has generated some insights into the use of shape change for affordance, system state, and feedback, for the specific designs explored but also for shape-change technologies more generally. Below, we discuss findings across the button types, as well as some open questions and some limitations.

Shape Change and Affordance

Our study has shown that turning shape-change mechanisms (e.g., transformations) into affordances that users can correctly perceive and act upon is difficult. This surprised us for two reasons. First, some prominent works on shape-changing interfaces (e.g., the paper on inFORM [8]) discuss dynamic affordances, suggesting that the use of movement and transformation may be particularly suited to communicating affordance. Although the buttons used in our study are very simple, it seems that affordances through movements are much more difficult to design than expected. Contributing to this supposition is the observation that some movements were perceived as "do not touch" warnings or as indications of malfunction.

Second, affordance is widely discussed and illustrated for graphical user interfaces and even mechanical interfaces. Affordance signifiers, in contrast, could not be mapped readily to physical shape change. Vibration and feed-forward are used with great success in grabbing users' attention and hinting to interaction in digital systems. However, they did not perform as well in the context of physical shape-changing interfaces, on account of misinterpretations.

One reason for the two forms of difficulties mentioned above is that affordance, system state, and state-change feedback are intertwined. This was evident in the design process for the buttons and during the analysis. It was hard to design shape change that targets just one of the three elements without affecting the others. Analysis confirmed this challenge and showed that most of the shape-change movements, even when targeted at just one of them, affected the other two. The general lesson of this is that we lack design principles for shape change that aid in distinguishing good indicators of affordances from good indicators of, in particular, state.

Shape Change to Show State

Buttons usually show state by their position, normally clearly identifiable and static. In contrast, our attempts to show state by means of shape change were much more complex to interpret: for instance, participants saw more information in the movement than intended (e.g., that the system was waiting, was processing data, or had encountered an error). This shows that shape-change feedback may not be beneficial for conveying simple feedback, since it could lead to misinterpretations due to complexity in interpretation.

Shape Change to Give Feedback

Feedback and feed-forward are crucial for successful interactions. Feedback worked well in our study. Transition animation between states provided clear feedback about state change. Moreover, the animation parameters (e.g., speed and smoothness) supplied additional information about the system during the process of changing its state. Participants associated the speed of the animation with showing progress – for instance, slowness as denoting delay while jittery and non-uniform animation showed that the system had problems switching between states.

However, feed-forward was very hard to implement with motion in the study described here. Most participants perceived it not as an affordance signifier but as a malfunction or processing-state feedback. The key issue seems to be that it is unclear whether the movement is state information, feedback information, or something else (e.g., indicating malfunction). We suspect that clear communication via feed-forward might be even more difficult in more complex systems.

An additional reason feed-forward did not work well was that we based the designs mainly on following movement, not on restricting it. Most participants commented that they wanted to stop the movement rather than follow it. This shows an interesting clash of metaphors of understanding how a system works (restrict-to-interact vs. imitate-to-interact). We are interested in exploring further what this difference might mean for other shape-changing interfaces.

Creating further difficulty for the accurate interpretation of feedback were symmetric non-stop movements. These confused participants and added ambiguity. Alternatively, movement for only a limited amount of time could be used to show feedback. Another option may be to design on-demand feedback triggered by user actions.

Implications and Future Work

Our study has shown that the duration and repetitiveness of the physical movement form a key design parameter. If the duration is too short, it is unnoticeable, and too long and repetitive a movement is annoying and encourages misunderstandings. Brief-duration movements with few repetitions seemed more suitable for proxemic interactions. For longer durations and more repetition cycles, interactions based on stopping the movement are more suitable than following it.

The study was focused on showing affordance, system state, and feedback via shape change. However, some participants' comments raised the issue of when a physical movement is best and when an LED or a simple label or some other mechanism suffices. The benefits and drawbacks of physical shape change in comparison to visualizations, and vice versa, remain under-explored. Further work could investigate this tradeoff and how they could be combined to provide better affordances and feedback.

We observed that designing physical transition animation for toggling state is a challenging and interesting problem. Even with limited distance and duration of the transition (arising from the short interaction with the toggle button), parameters of the transition animation (such as speed, path, and position) clearly affected perceptions and feedback for the participants. Further work could target developing a set of design guidelines for physical transition animation.

Ethnographically based further work could investigate using shape-changing buttons in a practical context. In our study, the buttons were in an abstract context and several participant comments made reference to using the buttons tethered to other devices or machines. One intriguing case is that in which system-state and state-change feedback from shape changes conflicts with the device's other feedback.

Limitations

The key limitation of the study is that we chose to use buttons, for simplicity. While this is a benefit – earlier work has looked mainly at single interfaces, precluding specific conclusions as to the influence of variations of shape-change mechanisms – buttons are abstract and give limited context.

Our study did not fully cover user experience (in the sense, for instance, of separating stimulation and identification, as done by, for example, Hassenzahl [13]). Therefore, some aspects of the user experience were not explored.

CONCLUSION

We have presented a set of shape-changing buttons that we used to investigate the effect of various shape-change mechanisms on users' perception of affordance, system state, and feedback.

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