Sketching Shape-changing Interfaces: Exploring Vocabulary, Metaphor Use, and Affordances

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ABSTRACT
Shape-changing interfaces allow designers to create user interfaces that physically change shape. However, presently, we lack studies of how such interfaces are designed, as well as what high-level strategies, such as metaphors and affordances, designers use. This paper presents an analysis of sketches made by 21 participants designing either a shape-changing radio or a shape-changing mobile phone. The results exhibit a range of interesting design elements, and the analysis points to a need to further develop or revise existing vocabularies for sketching and analyzing movement. The sketches show a prevalent use of metaphors, say, for communicating volume though big-is-on and small-is-off, as well as a lack of conventions. Furthermore, the affordances used were curiously asymmetrical compared to those offered by non-shape-changing interfaces. We conclude by offering implications on how our results can influence future research on shape-changing interfaces.

Author Keywords
Shape-changing Interfaces; Actuated interfaces; Organic interfaces; Design.

ACM Classification Keywords
H.5.2. Information interfaces and presentation (e.g., HCI): User Interfaces.

INTRODUCTION
Research on shape-changing interfaces is maturing, providing a wide range of examples that illustrate different interactions possibilities (e.g., [27,28]), uses of material (e.g., [13,33,37]), as well as studies of user experiences with shape-changing interfaces (e.g., [11,17,27,40]). Furthermore, work looking beyond single research prototypes is emerging in the form of frameworks [34,41], models [38,42], and studies across several designs [24,33], which illustrate how frameworks can drive systematic exploration of a design space. Yet, much of the design space of shape-changing interfaces remains underexplored. For example, we have only seen a few accounts of design processes of shape-changing interfaces, such as [23,46], both illustrating sketches from the design process and concepts beyond technical implementation. Furthermore, concepts such as *metaphor* and *affordance* have been widely used for understanding the design of and interaction with other types of interfaces. While the literature on shape-changing interfaces has frequently mentioned these concepts, there has been little *systematic* use of them to inform the design of shape-changing interfaces.

We suggest that further understanding of the *design of* shape-changing interfaces may help mature the research field of shape-changing interfaces. Concretely, we posit three approaches to do this: (i) using existing frameworks to analyze shape-changing interfaces can help identify weaknesses in and directions for frameworks that inform design; (ii) investigating the use of metaphors can assist in the design of shape-changing interfaces; and (iii) performing a principled investigation of affordances in shape-changing interfaces may inform future designs for user experience. The approaches are based on the belief that investigating designers' work with shape-changing interfaces is key to supporting richer and more ambitious designs by developing practice-based recommendations and to discussing and qualifying current recommendations on the design of shape-changing interfaces.

The design of shape-changing interfaces might be studied by cataloguing and analyzing existing designs. However, clearly such designs are shaped by technical feasibility and practical difficulties in construction, which likely overshadow the potential of shape change and the imaginations of designers. Consequently, to explore what shape-changing interfaces might become, rather than what they are, as well as to investigate approaches i-iii above, we have asked researchers in the field of shape-changing interfaces to perform two design exercises in the form of sketches. Twenty-one participants each spent about one hour generating ideas for either a shape-changing radio or a shape-changing mobile phone. For each case, we posed two scenarios, one for functional use (e.g., adjusting volume) and one for hedonic use (e.g., conveying emotions).

We present an analysis of the sketches made by the participants along three lines: the sketches were analyzed for types of shape change using (a) an established vocabulary framework [41], (b) analysis and reflection on

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metaphors using the categories of Barr et al. [1], and (c) analysis and reflection using the notion of instrumental affordance from Kaptelinin and Nardi [24].

The present study makes three contributions. First, we picture a design space through sketches of a mobile phone and a radio, mapped out by 42 answers to the design exercises. Second, we analyze the design elements used in terms of three principled approaches: vocabulary, metaphor use, and affordances. We provide a critical discussion on how designers may employ these elements for the design of shape-changing interfaces and how these elements may both inform the design process and expose concrete challenges to designs using shape change. Third, we use these insights to reveal future directions for the research and design of shape-changing interfaces.

RELATED WORK

In the following, we position this paper in relation to (1) frameworks for shape-changing interfaces; (2) metaphor use in shape-changing interfaces; and (3) affordances of shape-changing interfaces. Finally, given that our study uses graphical sketches as materials, we briefly outline previous work on empirical studies of designers.

Frameworks and Vocabularies for Shape Change

Research on shape-changing interfaces has sought to provide an understanding of the design space through frameworks [34,41] and models [38,42], contributing vocabularies to support designers and researchers in designing and reasoning about shape change. In 2012, Rasmussen et al. [41] reviewed 44 papers to describe eight types of shape change, according to purpose (e.g., functional and hedonic) and characteristics of movement, transformations, and types of interaction. Coelho and Zigelbaum identified three main design elements: topology, texture, and permeability [6]. Parkers and Ishii [38] provided a model of shape change, offering a design vocabulary for motion prototyping. Morphees [42] described ten features of shape change, such as area, granularity, and porosity.

In spite of existing work, the design space of shape-changing interfaces has yet to be fully investigated, and to our knowledge, no previous study has provided insights by asking researchers to sketch shape-changing interfaces.

Metaphors in Shape-changing Interfaces

Metaphors are widely mentioned within research on shape-changing interfaces, but the work does not consider established *categories* of metaphors, such as the taxonomy provided by Barr et al. [1]. Despite the absence of a theoretical foundation for the use of metaphors, previous work has employed a varied use of the notion of metaphors, describing how it applies to shape, moment, and interaction.

Ninja Track [25] used shape change to evoke different metaphors; for instance, a bent shape denotes “saxophone” and a stick shape denotes “drumstick.” The design exploration of Jung et al. [23] used metaphors from living creatures, such as hedgehogs and potato bugs, as design inspiration for a computer mouse. Interaction metaphors are evident in Bendi [39], where a shape-changing mobile phone doubles as a joystick. SpeakCup [48] used the notion of physical substance as a metaphor for sound. Hemmert et al. [20] explored users’ experience with a shape-changing mobile phone, indicating how users described the shape changes of an abstract form using “animal metaphors,” for instance describing an approaching movement as “a cat that wants to be stroked.”

While ample work has shown that shape-changing interfaces can evoke different metaphors because of their physical and dynamic characteristics, it remains unclear how to interpret those metaphors and how they can be used to improve the design of shape-changing interfaces.

Affordance and Shape-changing Interfaces

Many papers have argued that shape-changing interfaces create new possibilities for addressing the notion of *affordance* in designing technology (e.g., [6,13,14,47]). However, the uses of the term “affordance” are diverse: Coelho [5] mentioned *interaction* affordances, Dawson et al. [10] *device* affordances, and Yao et al. [47] *dynamic physical* affordances and *haptic* affordances. A range of papers have argued that a key property of shape-changing interfaces is their ability to provide *dynamic* affordances (e.g., [14,21,30]). Yet, what particular authors see as dynamic affordances has differed. For instance, Rasmussen et al. [41] defined dynamic affordances as *“perceived action possibilities that change with changes in shape,”* while Ishii et al. [21] described dynamic affordances as the way in which an object communicates its transformational capabilities. Therefore, understanding the role of using shape change to create affordances within interaction design largely remains an open question.

Empirical Studies of Designers

Design studies [2,8] and design cognition [4,9] have a rich tradition of conducting empirical studies of how designers work. The key interest is to understand how designers think, as well as to generate skills and knowledge over time. In design studies, there are many examples of insights established from interviews with designers (e.g., [2,8]).

In HCI, such studies are much less prevalent, but are beginning to emerge. Zimmerman et al. [49] and Sas [43] conducted interviews with design researchers to investigate the sources and results of research through design [49] and how they deal with the transition from empirical studies to design implications [43]. More specific themes have been investigated through interviewing design practitioners, such as how practitioners use specific tools (e.g., moodboards [31]) and personas [32]. Investigations of specific design cases have included exploring how intended design qualities were evident in later designs [44] and documenting details of material explorations in a design process [22].

The difference between our work and the above is that, while design cognition and its associated work in HCI are interested in understanding the *processes* of the designer, we are interested in studying the *properties* of the resulting designs. However, we are inspired by the method of design cognition in developing empirical materials through asking designers to perform an artificial design task.

METHOD

We invited a group of researchers in the shape-changing interface field to complete two short design tasks, spending approximately one hour sketching ideas. Sketching was chosen because it is fast paced and frees participants from technical limitations of prototyping while being exploratory and suggestive.

Participants

To recruit participants, we invited researchers who have published papers at CHI or TEI within the last five years (2011-2015) on shape-changing interfaces, organic user interfaces, or actuated tangible user interfaces. We chose participants with these characteristics because they had previous experience with shape change. We compiled a list of 264 people, who were sent an email invitation; all positive responses were added to the pool of participants. This resulted in 21 participants from 16 countries, with an average age of 32 years (SD = 4.9).

Three-quarters of the participants have developed shape-changing interfaces, including shape-changing mobile phones, deformable interfaces, and flexible displays. Beyond shape-changing interfaces, participants had experience with the design of tangible user interfaces, actuated interfaces, and robots. Eighteen participants are active researchers on HCI, and 13 have published scientific papers specifically on shape-changing interfaces, either introducing technological advances and prototypes or presenting results of user studies with shape-changing interfaces. In addition, some of our participants had design experience in fields other than HCI, including digital arts, music, and embodied interaction. The participants were compensated with an Amazon gift card with a value equivalent to $25.

Design Tasks

We randomly assigned participants to generate sketches for either (1) a shape-changing radio or (2) a shape-changing mobile phone. The two artifacts were chosen to obtain information about how shape change could be applied to a simple and common artifact that has not been explored in research on shape-changing interfaces, the radio, and to obtain information on how sketching, rather than building, might extend the design space of a well-explored artifact within research on shape-changing interfaces, the mobile phone (e.g., [16,20,26,39,40]).

For each of the two artifacts, two tasks were developed, focusing on *pragmatic* use (A) and *hedonic* use (B), respectively. The tasks were chosen to be exploratory and are based on earlier work [41] that has shown how these foci can lead to very different shape-change designs. The tasks also aimed to strike a balance between a broad and a focused task, as a very broad task might not stimulate participants' creativity by introducing restrictions, whereas a highly focused task might lead to responses that are too homogenous. The instructions for the tasks were as follows.

1A Radio Volume (pragmatic)
Please sketch one or more examples of how physical changes in shape can be used to indicate the volume level on a radio. Your answer should explain how the user could see and change the volume level.

1B Radio Genre (hedonic)
Please sketch one or more examples of how physical changes in shape can be used to indicate the genre of the music playing on a radio. Your answer should explain how the user sees and changes the mood of music playing.

2A Mobile Mode (pragmatic)
Please sketch one or more examples of how physical changes in shape can be used to indicate a mobile phone's mode (e.g., flight mode, silent, or normal). Your answer should also illustrate how the user changes the mode.

2B Mobile Emotion (hedonic)
Please sketch one or more examples of how physical changes in shape can be used to convey emotion in text messages on a mobile phone. Your answer should illustrate both how messages are created and received on a mobile phone.

The participants were asked to produce sketches (e.g., drawings, pictures, or videos) and supporting descriptions; they were free to choose any technique or material to complete the tasks. However, we asked the participants to use at least two or more images to illustrate the transitions from one shape to another and to illustrate users' interaction with the artifacts. In addition, we asked them to include clear written explanations of the design strategies and design elements used. Finally, we asked participants to emphasize creative solutions over technical feasibility.

Procedure

We communicated with each participant individually by email. After they agreed to participate in the study, they were sent a PDF file containing detailed instructions on how to complete to the tasks, a link to a questionnaire with questions on age and experience, and a link to an online folder for uploading sketches.

Material

We received answers from 21 participants, each submitting answers to two tasks, for a total of 42 answers. The full set of sketches is available in high resolution as supplementary material. A majority of the answers (39) used hand-drawn sketches to describe their ideas, augmented with handwritten descriptions, while one participant used a simple 3D model to illustrate a concept. Three participants used pictures of physical mock-ups, where different materials, such as paper, napkins, and clay had been used to communicate the concepts. Two responses used a collection of images, either close-ups of material textures or product

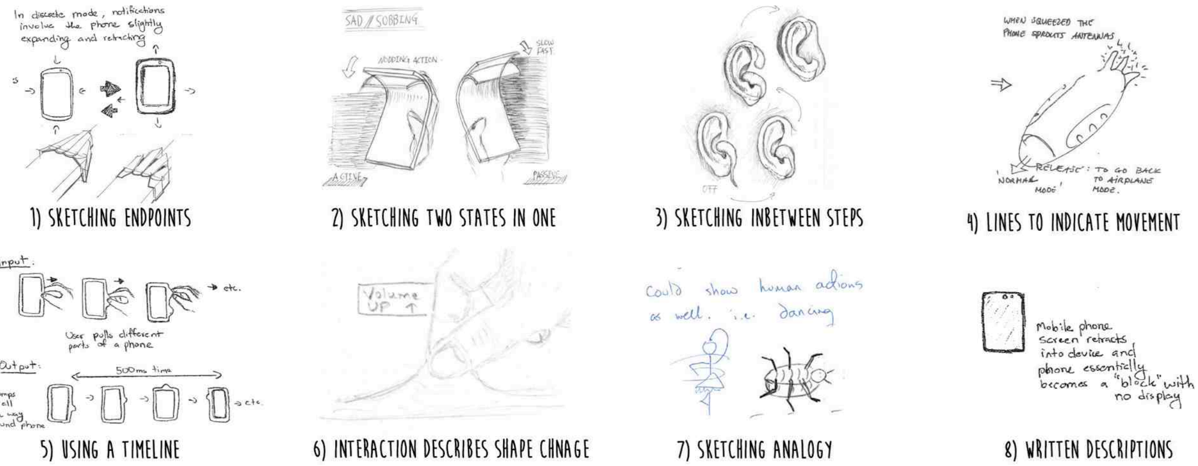

Figure 1: Eight strategies for communicating shape change

images, to illustrate different changes in texture and color. Sketching shape-changing interfaces is a challenge, as the dynamic qualities of the design must be conveyed in a static medium. Figure 1 illustrates eight different sketching strategies used by the participants. Participants generally used more than one strategy in their sketches (16 participants used two to four strategies), whereas five participants used a single strategy (sketching endpoints) to illustrate the transformations in shape.

Analysis

We analyze participants' sketches using thematic analysis [1] with three foci: (1) *vocabulary*, (2) *metaphors*, and (3) *affordances*. The following presents the theoretical framing of the analyses.

Vocabulary analysis

To understand the use of different types of shape change and transformations in the design tasks, we analyze the sketches using the vocabulary framework proposed by Rasmussen et al. [41]. The vocabulary consists of three parts:

(a) Types of shape change, which comprise changes that preserve the original topology of the artifact (*topologically equivalent*), *orientation, form, volume, texture, viscosity,* and *spatiality*, and those that do not (*topologically non-equivalent*), comprising changes in *permeability* and changes that *add or subtract* from the form.

(b) Types of transformation, classified according to *kinetic parameters* (*velocity, path, direction,* or *space*) or *expressive parameters*, either *adjectives* such as "soft" or *associations* such as a faucet resembling an elephant's trunk.

(c) Types of *interaction*, which include *no interaction, indirect interaction*, where implicit input is used together with shape-changing output, or *direct interaction,* comprised of both shape-changing input and output, which can occur locally or remotely.

Metaphors analysis

In traditional user-interface design, metaphor has played a considerable though controversial role [3]. To understand how metaphors could be used in shape-changing interfaces, we analyze the sketches and explanations for instances of metaphor use. We use the taxonomy of Barr et al. [1]. This taxonomy builds on work by Lakoff and Johnson [29], who describe the use of metaphors as "understanding and experiencing one kind of thing in terms of another" (p. 5 [29]). The taxonomy identifies three primary categories of metaphors: orientational, ontological, and structural metaphors. In brief, *orientational* metaphors use concepts of spatial orientation, such as up, down, left, and right, to leverage our everyday understanding of spatiality to convey useful information. *Ontological* metaphors use a basic category of existence in the physical world, such as "substance," "object container," or "entity," to explain concepts. Finally, *structural* metaphors use a detailed real-world concept or object to describe an abstract concept, similar to how the trashcan icon in modern operating systems illustrates file deletion.

In addition, we consider *metaphoric means* [19] and *metaphoric entailment* [1]. Metaphoric means are the ways in which the source cues are transferred to the target, such as form, sound, movement, material/texture, smell/taste, name, or graphics. *Metaphoric entailment* is a description of what the signifier implies about the signified [1]. For example, a trashcan icon used for file deletion may, though not intended by the designer, might imply that the lid can be removed or must be emptied by a garbage collector.

Affordances analysis

According to Gibson's notion of *affordance* [15], as popularized in HCI by Norman [35,36], affordances are "the fundamental, actual properties of an object that define how it can be physically interacted with." To understand the ways in which shape change can be used for supporting or augmenting affordances in interfaces, we employ the framework by Kaptelinin and Nardi [24], which suggests that *instrumental* affordances more adequately describe

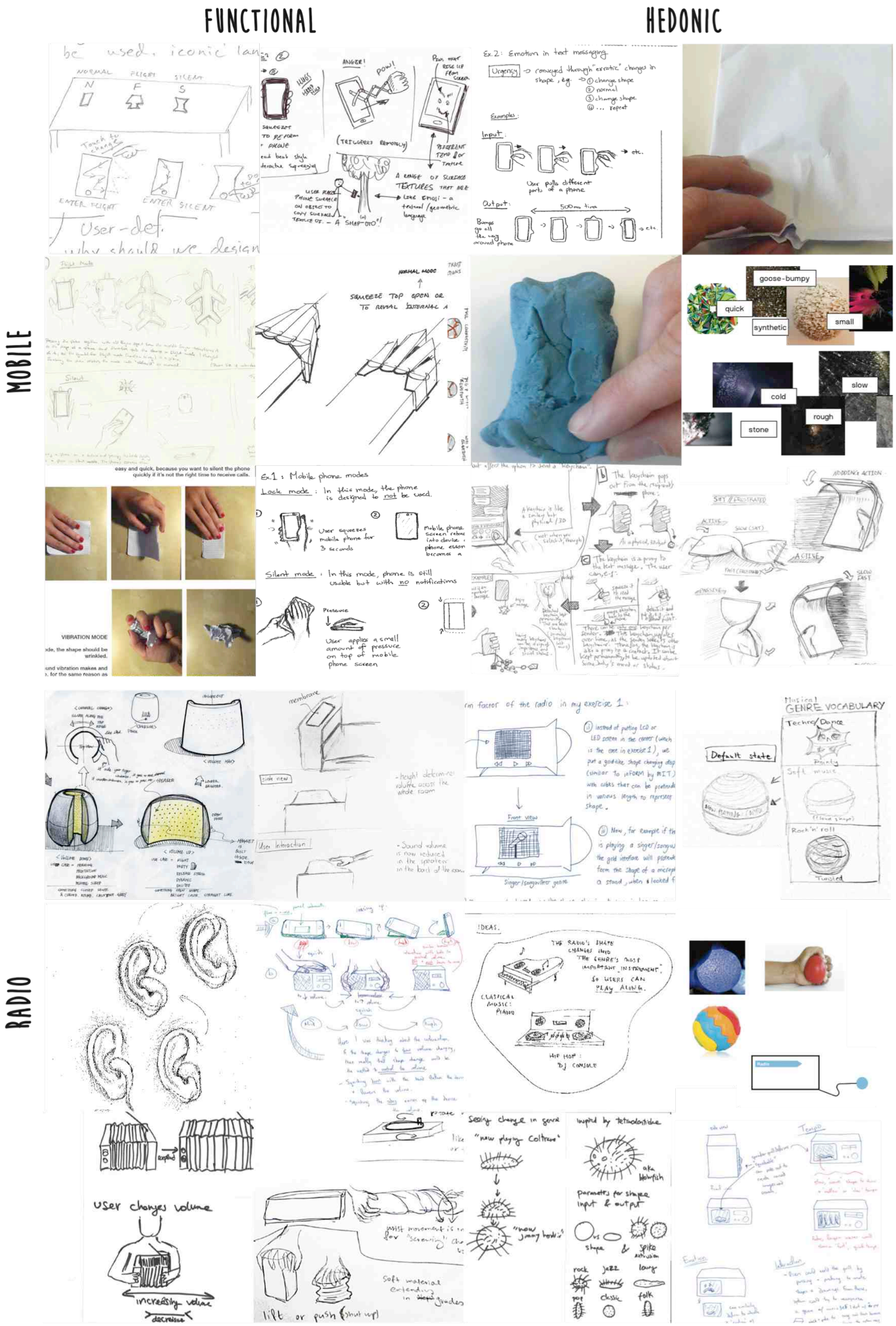

Figure 2: Excerpts from sketches. The sketches are available as supplementary material.

different facets of the human use of tools. An instrumental affordance comprises (a) a *handling* affordance, a possibility for interacting with a tool and (b) an *effector* affordance – a possibility for using the tool to cause an effect on an object. As an example, consider a single button situated at an elevator door. A user perceives the *handling* affordance of pressing the button and the *effecter* affordance of calling the elevator. As indicated in [18], the instrumental affordance may have associated *signifiers* or visual cues (e.g., the button being raised from the surrounding surface or text saying "press here to call elevator"). The instrumental affordance may have *feedback*, cues that alert the user to whether the action was successful (e.g., a sign illuminating or an audible ping when it arrives). In this view, Norman's notion of affordance corresponds to handling affordances with its associated signifiers. In an instrumental affordance, the handling and effecter affordances may be *tightly coupled* (i.e., the relationship between the handling and effecter affordance is clear to the user) or *loosely coupled.* Loosely coupled handling and effecter affordances may result in poor usability. For example, if the button is situated too far from the elevator doors, without clear visual cues to associate it, it is an example of poorly integrated handling and effecter affordance.

RESULTS

The following presents the results from the analysis of the sketches through three lenses: *vocabulary*, *metaphor use,* and *affordances*.

Vocabulary

Types of shape change

Among the 42 answers received, participants used all types of shape change described by Rasmussen et al., except *viscosity*. *Topologically equivalent* shape changes were highly predominant, while *topologically non-equivalent* changes were used in only two answers.

The sketches showed a varied use of the different types of shape changes, illustrating both input shape change (e.g., folding the phone in half to engage silent mode) and output shape change (e.g., a mobile phone bending downwards to express sadness). Changes in *orientation* were used in 17 answers, such as a mobile phone that twists to express frustration or stress (two answers) or a mobile phone that changes its angular position to express volume loudness (one answer). Participants illustrated how changes in *form*

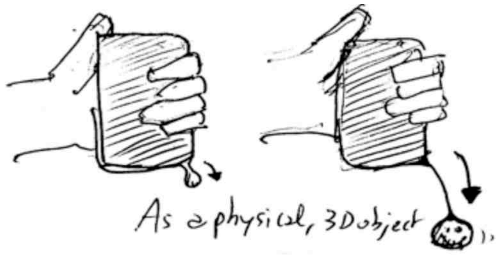

Figure 3: An example of adding/subtracting shape change

(21 answers) could be used to convey specific information to the user, such as when the shape of a radio conveys information about the music, generating a spiky shape when techno music is playing or a cloud shape for classical music. Changes in *form* were also used for iconic representation (e.g., a mobile phone that shifts to an airplane shape when set in flight mode). Twenty answers used changes in *texture,* such as expressing emotion using a coarse texture to indicate anger on a mobile phone or using changes in texture to inform the user about the tempo of the music and allowing the user to mold the texture to retrieve particular musical genres. Physical changes in *volume* were used in 12 answers, using, for example, size to indicate the sound volume on a radio or the urgency of an incoming message on a mobile phone. *Spatiality* was used in one answer, where the user could raise or lower floating spheres containing different musical genres.

Two answers used topologically *non*-equivalent shape change. One used *permeability*, where the number of pinholes in a mobile phone's speaker would increase/decrease according to the volume level, and one example of *adding/subtracting* in the case of a mobile phone that pops out a message as a physical keychain (see Figure 3).

Types of transformation

The sketches used both *kinetic* parameters (e.g., velocity) and *expressive* parameters (e.g., adjectives or association) to explain the movements of the shape change. The participants used expressive parameters slightly more frequently (used in 38 answers) than kinetic parameters (used in 35 answers) to describe the shape changes.

For *expressive* parameters, participants often used different *adjectives* to describe the movement of the shape change, such as text describing the qualities of the movement (e.g., quick, mellow, or smooth). The personality traits of the shape and movement were also described in that they displayed, for instance, anger, sadness, and happiness. Furthermore, the *association* between shape and movement was also described through zoomorphic traits, such as a phone curling up like a bug, or through anthropomorphic traits, such as expressing sadness through a human-like sobbing pose or describing the movement as dancing. No written associations were made to nature or mechanical characteristics. Given the prevalent use of abstract forms, however, the transformations portray more *mechanical* transformations (26 answers) than *organic* transformations (12 answers).

The *kinetic* parameters of the sketches were less clear from the descriptions; however, some participants did seek to describe the velocity of the movement (seven answers) through describing the speed or with a diagram sketching the movement over time (see Figure 1).

Figure 4: A sketch of a shape-changing mobile phone that can be shaped like a "mouth" to send a kiss via message

Types of interaction

Among the 42 answers, *direct interaction* was used the most (34 answers), encompassing a range of different types of interactions, such as *squeezing* (e.g., squeezing a mobile phone at a certain rate to change the emotional content of messages), *pressing* and *squeezing* in combination (e.g., to turn the volume on a shape-changing radio up or down).

Pinching, pressing, and *pulling* were used as transitional interactions to show how users can *mold* shape-changing mobile phones into smiling, sad, or kissing phones (see Figure 4), giving them an anthropomorphic look. Classical multi-touch input was used to show how users could slide or touch either to provide textual input with a mobile phone or to control the volume on a radio. Finally, one participant sketched an extreme case of shape change, where stretching a mobile phone would be used to “break” the display and have two separate screens to interact with simultaneously. Among these examples, 29 answers used both *shape-changing input and output* in the same shape, while only a few answers used *shape-changing input and remote output* (five answers). Finally, four answers did not show any interactions.

Summary and analysis

While great variation in the frequency of types of shape change was seen, all types except viscosity were represented across the four tasks. However, some particular types of shape change were used only in the radio exercise (i.e., spatiality) or in the mobile phone exercise (i.e., adding/subtracting and permeability). Furthermore, the sketches show that changes in form were used almost solely for iconic or symbolic representation; we also see a prevalence of sketches using mechanical features over organic features, especially in shape transformations. This suggests that researchers still rely more on mechanical and technical transformations to represent shape change, even though shape-changing interfaces have been regarded as a chance for HCI to make interactive interfaces more organic or lifelike [40].

Metaphors

Among the 42 answers received, a majority used orientation metaphors (18 answers) and structural metaphors (17 answers); ontological metaphors were more rarely used (seven answers). A selection of answers grouped into the three types of metaphors can be seen in Figure 5.

Orientational metaphors

Orientational metaphors were primarily used in the **radio pragmatic** task for showing volume (used in nine out of ten answers). The prevalent use of metaphor for volume shows how existing metaphors, such as sliders, have influenced the sketches. It also illustrates how simple orientational metaphors, particularly loud-is-up, helped participants in this task. While “up” was often used as a way to portray volume, less familiar orientational metaphors, such as open-is-more, were also used (e.g., the speaker aperture opening to show increased volume).

Orientational metaphors were also used in five answers to give shape to emotion in the **mobile emotion** answer, such as linking a direction to an emotion, such as happy-is-up. Metaphors were also used to communicate the state of the mobile phone, for instance, by opening or closing the shape to reveal an antenna-like structure that indicates whether the phone is in regular or flight mode (see Figure 5). The size of a message was also used to indicate its importance, as shown in Figure 5 (left).

Structural metaphors

Structural metaphors use real-world objects as metaphors, such as smile-is-happy, shape-is-function, or radio-is-accordion. Structural metaphors were divided relatively equally between the four tasks (three to five uses each) and employed a varied range of real-world objects.

Six answers based their structural metaphors on animals or

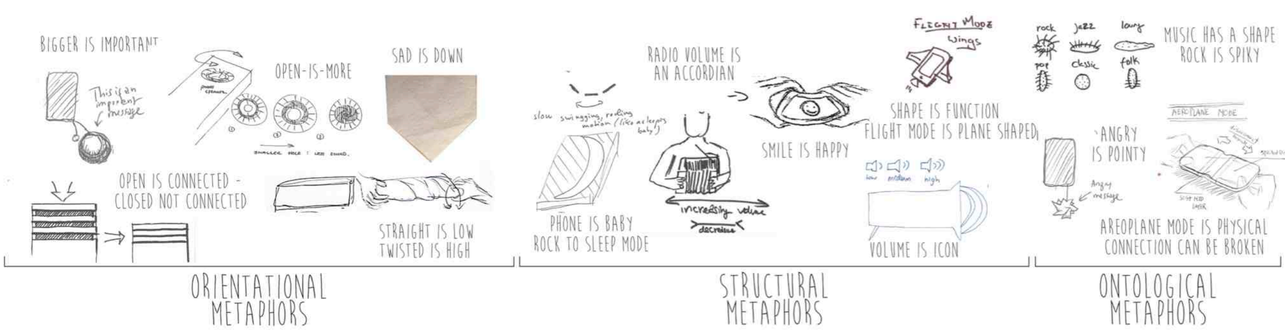

Figure 5: Three categories of metaphors

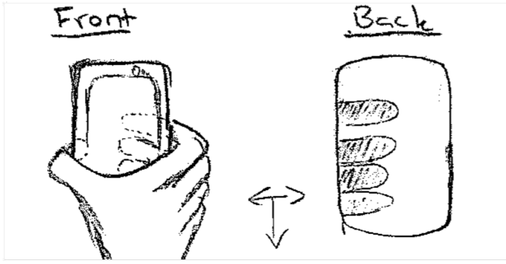

Figure 6: Imprinting directly, rather than by metaphors

humans, such as mapping emotion to a sobbing pose or happiness to the form of a smile or likening the radio to a body and using body language to express the volume level.

The use of structural metaphors varied from very literal use, such as using a plane shape to indicate flight mode (see Figure 5), or creating a radio shape that imitates the shape of the speaker icon used on computers. Others pursued a more symbolic use, such as using a moon shape to indicate “do not disturb” mode. Whether symbolic or literal, these metaphors help map from user interface features to physical form. However, some participants, particularly for the **mobile emotion** task, decided against any such mapping and instead used the direct imprinting of shape manipulations from a sender’s phone to a receiver’s phone, as shown in Figure 6.

Ontological metaphors

Ontological metaphors give abstract concepts a substance, such as angry-is-pointy, or seeing a wireless connection as a material that can be pulled apart to be disconnected. Ontological metaphors were not used in any of the **radio volume** answers, but occurred in two to three answers for each of the other three tasks.

Ontological metaphors use form to express a concept rather than drawing on parallels to a source domain. For example, when communicating music and emotion, four answers mapped music to abstract shape representations (e.g., techno-is-spiky, classical-is-round-and-soft). Another ontological metaphor viewed the wireless functionalities on the phone as a physical material that can be broken to switch from normal to flight mode (see Figure 5).

Metaphoric means

Mostly, metaphors are shown in the form of an object, such as a giving music a shape (rock-and-roll-is-twisted; classical-music-is-a-piano) or emotion a shape (happy-is-a-smile). However, in two answers, the metaphor is linked not to the shape of the interface, but instead to movement. Consequently, the metaphor would only become apparent through movement, such as using a nodding movement to express sadness. *Hiding and revealing* parts of the object were a particularly interesting strategy (see Figure 7).

Two answers used interaction to support or even create the metaphor. One sketch showed the use of a rocking gesture to put a phone to sleep, as if it were a baby, or seeing sending messages as throwing a ball. The message-as-a-ball metaphor uses the characteristics of balls, namely that they can be thrown to somebody, roll around, be thrown with different force, and used for playful interaction with others.

Metaphoric entailment

Metaphoric entailment is particularly relevant for structural metaphors, where not all parts of the source metaphor are transferred to the target. Take the example of an accordion shape being used to set the volume of a radio (see Figure 5, middle). By turning the frequently used loud-is-up metaphor on its side, it resolves an interaction challenge of the metaphor, namely that pulling is more difficult than pushing. However, the metaphoric entailment of the shape (the accordion) suggests that the user has to pump in and out for the music to play or could even play along – none of which seems intended with the sketch. Another sketch similarly altered the shape of the radio to familiar musical instrument shapes, a piano shape when playing classical music and a DJ console when playing hip-hop music. However, here, the metaphoric entailment is resolved by allowing the user to play along with the music, consequently, altering the functionality of the radio and making it more than just a device for listening.

Summary and analysis

The answers show a very prevalent use of metaphors, as 37 answers used one or more metaphors. Because all three types of metaphor seek to make abstract concepts physical, either through spatial or artifact relations or by giving them a physical substance, metaphors are an obvious approach for designing shape-changing interfaces. What is clear from the sketches is that, while a majority of answers for the **radio volume** task uses an up-is-louder metaphor similar to the one found in tangible controls or UI design, the rest of the answers show less conformity. Consequently, a challenge for shape-changing interfaces is a lack of conventions, and the question is how much shape-changing interfaces should follow existing metaphor conventions used in other types of interfaces or whether new conventions should be developed.

Affordances

In the analysis of affordances, it was clear that a majority of

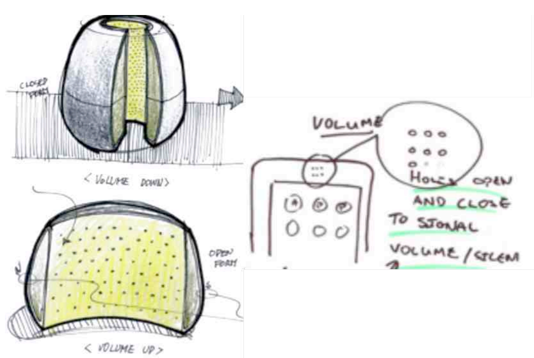

Figure 7: Hiding and revealing as a design metaphor for the entire shape (left) and for holes in a shape (right).

the sketches contained either handler or effector affordances. Only a minority managed to make these well integrated into the design.

Handling affordances

Twenty-four answers use shape change for handling affordances but not for the associated effecter affordances, such as using *corner* or *edge* folding where the effect of manipulation is not accompanied by a shape change. For example, in the two hand-drawn sketches in Figure 8, it is clear that the corners can be bent. However, in the first example, the lower corner must be bent to enter silent mode, and in the second, it is the top-right. The corresponding effecter affordance (entering silent mode) in the two cases is not accompanied by a shape change; indeed, no feedback is indicated at all. In the third sketch, the phone is folded in the middle to achieve silent mode, but again, no association between the handling affordance (folding the phone) and effecter affordance (entering silent mode) is evident to the user. These examples illustrate a common theme among most of the sketches, namely that the mapping between manipulation (handling affordance) and effect relies on UI mechanisms that are not yet common or agreed upon.

Effecter affordances

Thirty-three answers use shape change for effecter affordances but not for handling affordances. For 10 answers to the **radio volume** task, the effect of an adjusted sound volume is immediately clear from the adjusted volume level itself, and there is no need to deliberately design for it in the same way as handling affordances. For two answers, shape change is integrated as part of the feedback of effecter affordances for volume level, in addition to sound level. One of these shape changes is used both for handling (physically “closing” or “opening” a loudspeaker) and effecter (closing/opening lowers/raises volume) affordance as part of a single manipulation.

Coupling of handling and effecter affordances

Eight answers show tightly coupled handling and effecter affordances. One example is shown in Figure 9, where the

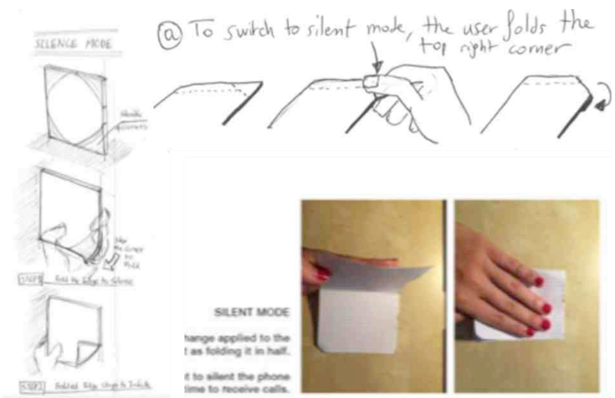

Figure 8: three examples of handling affordances using folding to enter "silent mode" on a mobile phone

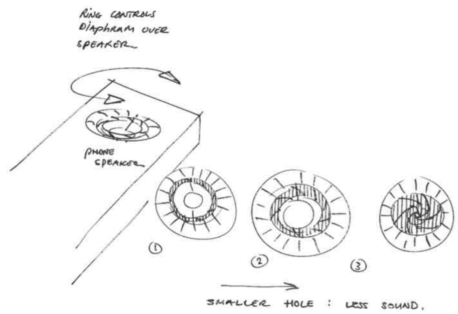

Figure 9: Tightly coupled handling and effecter affordance

control of the volume of the phone and the radio is tightly connected to the effect of manipulating the object. To adjust the volume, a ring around the speaker can be turned, hiding or revealing the speaker. The remaining 34 sketches show a loose coupling between handling and effecter affordances and in general contain very little information or sketching on signifiers (that could make users aware of a handling affordance if it is not obvious) or feedback. However, this may be due to the nature of some of the tasks – in the **radio volume** task, there is immediate auditory feedback – or the fact that the participants were asked to sketch with a focus on shape change, which may have led to a lack of details concerning traditional cues such as those given effectively on displays.

Summary and analysis

The answers show a dominant focus on *either* handling *or* effecter affordances. Furthermore, shape-changing interfaces are not a panacea for good design, and designing for well-integrated handler and effecter affordances should be encouraged. Complementing shape-change design with traditional modes of interaction (e.g., displays or other visual or auditory means) should be considered. This observation is particularly pertinent, as the mappings between a user's manipulation of a shape-changing device, the designer's intended consequence of this manipulation, and the output or feedback in the design sketches are often tenuous. Shape-changing interfaces are also challenged in that designs cannot in general rely on learned habits or supposedly commonly accepted metaphors that do not yet exist among researchers in the shape-changing device field, let alone among users.

DISCUSSION

In the following, we discuss our results and analysis and describe their implications for design and research on shape-changing interfaces.

Vocabulary, Metaphor Use, and Affordance

While several frameworks and vocabularies exist for shape-changing interfaces, it is notable that applying one of the richest, the vocabulary by Rasmussen et al. [41], indicated areas where the vocabulary is insufficient and needs to be further developed. First, while simple changes in shapes are easily described using the shape vocabulary, more complex changes in shape, such as changes in shape from a piano into a DJ console, are difficult to describe using the vocabulary. However, according to the vocabulary used, this change in shape is categorized together with much less rich changes, such as changing from a square to a round shape. Consequently, while the vocabulary might serve to describe the simple shape transformations in existing shape-change research, for more complex shape changes, the vocabulary either needs further conceptual development or must be accompanied by explanations of (i) the dynamic physical properties of its changes in shape, (ii) what the new shape entails for the user, and (iii) how the actual interaction with the interface occurs (as also suggested in [34]). The sketches provided by the participants showed many varied forms of interaction, such as twisting, pinching, squeezing, bending, stretching, or crumpling, which are not well accounted for by [41] or by other frameworks.

As a concrete example of the inadequacy of existing frameworks, the four answers in our study that use a *hide/reveal* approach (as in Figure 7) employ a strategy that has neither been covered in research on shape change nor is clearly present in the vocabulary of [41]. However, as evidenced by the design sketches, the strategy can be employed to great effect using shape change and presents new opportunities for design.

While there are many discussions of *metaphor use* for GUIs and TUIs (e.g., [3,7,12]), we are unaware of any specific analysis for shape-changing interfaces. With respect to shape-changing interfaces, the term has primarily been used simply as a means to describe features of an interface. Nonetheless, our results point to several areas of interest for considering metaphors. First, orientational metaphors are physically instantiated and can be physically dynamic (happy-is-up; louder-is-larger). Second, structural metaphors all draw on real-world objects as metaphors, but the metaphors may be implemented at very different levels, ranging from hyper-literal (flight-mode-is-an-airplane) to very abstract (disconnected-is-divided).

A different argument for using principled analyses is seen in our analysis of affordances. While the notion of affordance has been widely mentioned with respect to shape-changing interfaces (e.g., [13,14,47]), there exists no analysis of how affordances can be designed using shape change. Our use of *instrumental affordances* revealed a lack of examples of *tightly coupled* affordances in the sketches, suggesting that these might need to be supported by design mechanisms other than shape change. It is conceivable that similar principled approaches may be useful for revealing design challenges in concrete designs of artifacts that employ shape change.

The sketches show an extensive use of metaphors in the design of shape-changing interfaces, as 37 answers out of 42 used metaphors; this was not required by the tasks. Consequently, the sketches illustrate a potential for employing metaphors in the design of shape-changing interfaces. However, as the sketches also revealed, there is presently a lack of well-established *conventions,* which results in the same means of manipulation (e.g., corner folding) being mapped to many kinds of behaviors. While the sketches showed familiar metaphors, such as up-is-more, they also showed alternatives, such as the degree of openness as signaling more or less. Consequently, research needs to be carried out on the use of metaphors in shape-changing interfaces, systematically exploring metaphors as physically dynamic constructs, as well as deal with how to adopt conventions from 2D or static interfaces and how to ensure that conventions are not formed haphazardly once the first mass-produced shape-changing interfaces are developed. As Norman put it, "*they are slow to be adopted and, once adopted, slow to go away"* (p. [36]).

Strengths and Limitations of the Use of Sketches

The sketches used in the study were completed in a very limited time and consequently do not represent fully elaborated and coherent ideas and might not survive scrutiny in a further design process. Furthermore, using sketches as materials for the study is challenged by the fact that sketches are, by nature, ambiguous [45]. While such ambiguity may be a positive quality in the *design process*, it is far from positive when using sketches as *sources of information* to be analyzed and categorized. A further challenge is that shape-changing interfaces are dynamic, whereas sketching on paper is static. Thus, movement and interaction are difficult to describe precisely.

However, the sketches illustrate a diverse range of strategies for communicating dynamicity. The question remains whether appropriate tools can or should be developed to support such communication. A further advantage of the rapid nature of sketching is that it may be used to elicit information about existing or emerging design conventions: the sketches have a prevalence of design choices that could tacitly and perhaps detrimentally become conventions (up-is-more; corner bending). Sketches from more designers could serve to uncover such trends and make them explicit, forcing the community to reassess emerging conventions before they become standard.

CONCLUSION

The 42 answers to the design tasks have served as a valuable material in discussing the design of shape-changing interfaces, pointing out insufficiencies in current vocabularies and in charting potential benefits for design, using principled approaches to the use of metaphors and affordances. Thus, we have illustrated the strength of bridging exploration of shape-changing interfaces using design with a principled analysis in the spirit of research through design and we invite others to further the advances sketched out in this paper.

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