Mold-It: Understanding how Physical Shapes affect Interaction with Handheld Freeform Devices

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ABSTRACT

Advanced technologies are increasingly enabling the creation of interactive devices with non-rectangular form-factors but it is currently unclear what alternative form-factors are desirable for end-users. We contribute an understanding of the interplay between the rationale for the form factors of such devices and their interactive content through think-aloud design sessions in which participants could mold devices as they wished using clay. We analysed their qualitative reflections on how the shapes affected interaction. Using thematic analysis, we identified shape features desirable on handheld freeform devices and discuss the particularity of three themes central to the choice of form factors: freeform dexterity, shape features discoverability and shape adaptability (to the task and context). In a second study following the same experimental set-up, we focused on the trade off between dexterity and discoverability and the relation to the concept of affordance. Our work reveals the shape features that impact the most the choice of grasps on freeform devices from which we derive design guidelines for the design of such devices.

CCS CONCEPTS

• **Human-centered computing → Mobile devices**; **Ubiquitous and mobile computing design and evaluation methods**.

KEYWORDS

Freeform interfaces, handheld devices, device form factor

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1 INTRODUCTION

The pervasive rectangular touchscreen, which has dominated the display industry for decades is slowly giving room to a future in which devices may have any arbitrary shape. For example, it is now possible to manufacture displays having any shape [13, 52], and circular displays are already available on many smartwatches. Additionally more research is being conducted to create new materials allowing new form factors such as [61] or [21] allowing to spray displays on complex surfaces geometries. Devices with such non-traditional displays are commonly referred to as Freeform devices [50, 51], as they can assume any non-planar and non-rectilinear shape. Freeform devices take their roots in Shape-Changing (SCI) [1] and Organic User (OUI) Interfaces [22] but constitute a specific subcategory defined by their rigid, non-planar and non-rectilinear nature.

With this fundamental shift in device and display form factors, the looming question that arises for interaction designers includes how to integrate and take advantage of the non-rectilinearity of such interactive devices that may soon become common. Furthermore, opening the space of possible topologies for displays creates a tremendous need for understanding the interplay between shapes, interactions, applications and contexts. To date, characteristics of freeform devices and their supersets, including SCIs or OUIs, have been primarily defined by taxonomies driven by technological innovations [44, 55]. Previous explorations of the design space of such devices heavily focus on shape transformation, for example how a change in shape may relate to a user's emotions [54], input gestures [27] or interaction metaphors [43]. In contrast, little is known on the rationale for selecting rigid shape features, particularly when these are handheld. This knowledge gap was further highlighted in the recent roadmap for SCI research by Alexander et al. in 2018 [1], as being a critical factor in the evolution of this field.

We address this gap by specifically examining rigid freeform devices and the interplay between the rationale for the form factors of such devices and their interactive content. In this way, this work takes an opposite approach to recent developments in freeform device research where investigations were made to understand how traditional rectangular content could adapt to different device form factors. [50, 51, 53]. Here we look at how the shape of such devices can be molded to fit usage and user's experience. In contrast to past literature on SCIs, our work also moves away from looking at the transformation of the devices and rather investigates the state of the device at a given time, i.e. rigid freeform displays. In particular, we know little about the rationale behind the choice of rigid shape features.

We conducted two studies consisting in design sessions using modeling clay props to explore how users may interact with handheld freeform devices. We chose participants with no experience of freeform devices as we wanted to have application examples closer to what everyday people would imagine. In both cases, we designed activities to have participants be involved in ideation. We used interviews, think-aloud processes, and thematic analysis, which are all well-known methodologies to gather and analyse the data and deepen our understandings of how freeform displays can better support and enrich interaction. Our studies both look at complementary aspects of our research question:

- In our first study, we asked participants to mold their own handheld display and think aloud about their rationale and perspective behind the various shape features they selected for such device. Through multiple design sessions involving 24 participants working in pairs, we encouraged and recorded how they built freeform handheld device prototypes, by first sketching and actually shaping these using clay. We identified and discussed three main design goals that are facilitated by freeform interactive devices: Freeform dexterity, Shape features discoverability, and Shape adaptability. We also observed two minor design themes, Shape-content consistency and Tangibility. Our analysis highlights how such themes emerge in relation to shape features of freeform devices and we highlight how these can be used to inform the design of such devices to support novel applications.
- We then conducted a second study to further understand the trade-off between dexterity and discoverability and their relation to the concept of affordance. We asked 12 participants to mold a freeform object for no specific task that unmistakably exhibited some affordances. Through thematic analysis of the produced shapes, we extracted a number of themes related to how rigid shapes features are used to produce affordances such as: indentations, size of contact area, orientation, past experience, or prevention of grasps. We further investigated how indentations alter the choice of grasps in a small follow up study.

This paper is an exploration of the potential impact that freeform devices can have on our everyday digital interactions. To explore this topic we faced the challenges involved with the nascent and emerging nature of such technologies. We adopted a Research through Design[1] (RtD) approach [14, 25, 62], where the act of designing is in itself a confrontation of various forms of knowledge, both formalized and experiential, which brings about new knowledge. This knowledge can for instance be generated by designing an artifact, by the artifact itself, and by evaluations of use, and later be generalized as design recommendations, theories or frameworks. Our twofold contributions consist of: 1) an exploration of the rationale behind the shape features of freeform handheld devices through 2 studies eliciting participants to mold their own artefacts; and 2) a discussion on the implications for the design of upcoming freeform devices.

[1]https://www.interaction-design.org/literature/book/the-encyclopedia-of-human-computer-interaction-2nd-ed/research-through-design

2 RELATED WORK

Related work sits a the intersection of Organic User Interfaces (OUIs), Shape-Changing Interfaces, (SCIs) and studies relevant to understanding how to design such interfaces.

2.1 Freeform, Shape-Changing and Organic User Interfaces

The term "Freeform device" was used by Serrano et al. [50, 51] to refer to devices having a non-rectangular display. By extension, in this paper we consider freeform devices as any device not having a rectangular shape, in contrast to current laptops or smartphones for instance. Freeform devices take their roots in Organic User (OUIs) and Shape-Changing (SCI) Interfaces. Organic User interfaces (OUIs), which originated with the desire to let computational devices adopt natural forms to make a better fit with human ecology [22], are defined by three design principles: "input equals output", "function equals form" and "form follows flow." Alexander et al. [1], define Shape-Changing interfaces to use the physical change of shape or materiality, be interactive, be self- or user-actuated and convey information/meaning/affect. Freeform devices constitute a specific subcategory defined by their static but non-planar and non-rectilinear nature. Research on Freeform devices has also its specific agenda, focusing on the design of non-rectangular content according to static shape features [50, 51, 53]. There are numerous prototypes of organic and reconfigurable devices, from shape-changing phones or tangibles [19, 23, 37, 45, 46] to shape-changing walls, and several papers offer extensive reviews of these areas [24, 44, 55]. More particularly, Roudaut et al. [24, 44] define the shape resolution as a tuple of features mathematically describing shape-changes. Similarly, Sturdee et al. [55] classified existing prototypes into a subset of categories.

These frameworks are generative and descriptive but do not answer the question "what should the shape features of our devices be? " and "how such shapes are influenced by specific applications" , which is the goal of our work.

2.2 Designing Shape-Changing and Organic-User Devices

Beyond taxonomical approaches, researchers have produced a consequent number of explorations on the design space of shape-changing interfaces or organic user interfaces. The common element among these explorations is their focus on the shape transformation [42]. These studies have explored, for instance, the level of control offered to the user over the shape change [41], which gestures are employed to bend flexible mobile devices [27], how to convey emotions with shape transformations [54], and what affordances shape-changing buttons provide [59]. Researchers have also investigated the best design approaches for ideating shape-changing devices. Rasmussen et al. [26, 43] investigated the use of sketches, Fuchs et al. [15] employed origami paper prototypes, Everitt et al. [11] conducted a deployment of a prototype in a public environment, while Sturdee et al. [57] first employed brainstorm sessions within a public engagement study, and later proposed an approach combining low-fidelity prototypes, high fidelity video footage, with end-user diagrams and scenario sketching [56].

These papers focused on the design of shape transformations. In contrast, our goal is to explore the design aspects of static and non-rectilinear shape features. As such, we address the challenge presented in a recent roadmap for the field of shape-changing interfaces [1] that highlights the lack of understanding on the design of the shapes themselves.

2.3 Non-Rectangular Interfaces

Researchers have developed novel non-rectangular interfaces for different contexts, ranging from tabletop and projected UIs [7, 32] to round smartwatches [2]. Serrano et al. [50, 51] studied how to generate generic guidelines for the design of such UIs. Their first study [50] focused on text mappings on non-rectangular shapes in terms of reading performance and perceived aesthetic value. Results uncovered new text presentation rules for non-rectangular interfaces. In a second study [51], they focused on visual layouts for web pages, comparing them in terms of perceived symmetry, clarity and preference. Results led to a set of design guidelines, some of which contradict current conventions. Simon et al. [53] extended these studies by investigating how people search information on non-rectangular displays. They used eye-tracking data to unveil which areas are seen first according to different visual structures and help designers placing relevant content on non-rectangular displays. In summary, beyond these initial scenarios, prior work on non-rectangular interfaces has not explored the design features of freeform devices, and rather focused on the perceptual questions of such interfaces.

2.4 Link to Affordances

Our work is of course closely linked to the notion of affordance, which has been long debated in HCI. Gibson [18] introduced the concept with an ecological approach to its reasoning; suggesting that an animal can directly detect the possible actions that are available on an object just by its appearance. Affordances are formed from an object's own information, independent of a user's past experience and interpretation. Norman [33, 35] builds on Gibson's idea by suggesting that affordances should be distinguishable by past experience and knowledge. In contrast to Gibson, this places more focus on the mental competence of the user, as opposed to just their action capability. He proposed the term "perceived affordance" as a designer would only want to bear in mind the affordance that a user would perceive to be evident through "signifiers", rather than all true possibilities. McGrenere and Ho [30] carried out a critical analysis of both Norman and Gibson's definition. They established that Gibson defined affordances as just the possibility of an action, whereas Norman placed focus onto not only the action capability, but also the method in which this possibility is conveyed. It is important to mention the extension and clarification proposed by Gaver [16] and the idea that more focus should be placed on exploration of objects in order to determine the affordances it contains. Gaver divides the definition of affordance into three core concepts: hidden, false and perceptible affordances. Hidden affordance, is characterised by an object having no useful information that is directly obvious to the user. Therefore, actions have to be discovered through other means. False affordances are when information for an affordance does exist but is deceptive, as a user may erroneously attempt to perform an action that may not be physically possible. Perceptible affordance is the existence of information that is readily available for an accessible affordance.

Understanding the definition of affordances alone does not provide sufficient knowledge for designers to create objects with a clear function for users. It is therefore important to learn how users can discover affordances in objects effectively and how false affordances are avoided. Although the use of past experience and mental capabilities are debated within the definition of affordances, there is one aspect that is undeniably agreed upon. This is the form of an object playing a major role in determining the actions that can be taken upon it. Therefore, it is within the design of the object itself that contains the perceivable information and where the focus of design should lie.

To sum up, in contrast to past literature our work moves away from looking at the transformation of the devices and rather investigates the state of the device at a given time t(s), i.e. rigid freeform displays. Contrary to prior work, we investigate the rationale behind the choice of shape features in freeform devices. Morphees or Rasmussen's frameworks [42, 44] are proposing spaces to describe shapes and their transformations (the 'what') but do not provide insights on the rationale for adopting non-linear shape features (the 'why'), which our work does. In this manner, our work is orthogonal to past explorations of shape transformation and as such enriches and complements existing knowledge.

3 STUDY 1: MOLDING FREEFORM DEVICES IN CONTEXT

The goal of this study is to understand the shape features that end-users would find desirable and how the choice of the application context would drive those choices. This is particularly interesting for the case of handheld devices and which present an interesting design challenge in that they must be held while interacting. Crafting small handheld devices is also easier than large-scale concepts. We thus conducted a study where participants freely molded and built their own devices with clay while being told to design a device for a particular context of use.

3.1 Method

We ran two design sessions with a total of 12 participants spread into 2 groups of 6, each session taking place in a different country (Canada and France) to broaden the cultural diversity of participants. In each group participants worked in pairs. All of the participants were students in HCI, but had no previous experience in the area of FreeForm Devices. The participants (3F/9M) were aged 26.3 years on average. Each design session lasted approximately 80 minutes. Each session started by explaining the goal of the research, i.e. that the participants will be asked to rethink the shape of handheld mobile devices.

We gave participants pencils, paper, play-doh, clay and molding tools (Figure 1). Play-doh was meant to be used as an ideation tool, while we asked participants to mold a version of their final design using rapid clay, which dries and becomes solid in 24 hours. We used only one colour of Play-doh and clay so that participants focused solely on the shape instead of color features. The rationale behind using this clay was to allow participants to test their design (i.e. grasp it, touch it, etc.), and to keep a solid version (after drying) of their probes for future analyses. Besides, while all ideation tools have pros and cons (for instance, people usually find it difficult to sketch if they have no sketching skills), molding clay can be a less apprehensive method [29].

Figure 1: Participants using clay to prototype and test their design. Design sessions involved combined sketching and molding.

Participants were grouped in pairs as we thought this would enable more discussing and elicit natural think aloud between them. Pairs were given two specific scenarios in which a task was defined through two different contexts. They were asked to create one prototype for the task in each context (i.e. four prototypes in total). They had 20 minutes for each prototype. We suggested participants employ 5-10 minutes to sketch or mold different versions, and then employ 20 minutes to mold the final production. They could create more designs but eventually had to choose their preferred one to present to the other participants. At the end of the 20 minutes, we asked them to take some pictures of the prototype along with their imagined way of holding it by placing their hands on the device. They also had to produce one sentence explaining the rationale for the choice of shapes for each prototype. We chose to let the participants design in pairs to elicit discussions around the choice of topology.

Once all pairs had finished creating their productions, participants were then gathered as a group. All the clay productions were placed on a table and each group was given the opportunity to discuss their designs and explain the chosen shapes. Participants were otherwise invited to comment on each other's productions. The experimenter made sure the discussions focused on better understanding the choice of shape. Each pair of participants had 10 min each to present their productions and discuss them with the group.

3.2 Scenario Choices

To define the tasks and contexts to study, we first looked to define the level of abstraction needed. One approach was to look at very low-level abstraction tasks such as the generic sets proposed by Ruiz et al. [47] (e.g. pressing "previous" or "next"). However low-level abstraction tasks can be found in any type of mobile application and do not encompass the richness and differences in manipulation between those applications.

The other approach is to look at a high-level abstraction task, which we chose to ensure the tasks would have high ecological validity. We looked at the most downloaded mobile applications using reports from Apple and Android. For both Android and Apple, we considered game as a a category on its own. Apart from games, this list included 17 Android and 10 Apple apps (with 6 common apps between these lists). Note that those applications do not include common usage of smartphones such as calling or taking pictures, which are independent from any applications. We grouped these apps into 7 categories: Call communication (e.g. phone functions, Skype); Text messaging (e.g. Facebook or Google messenger); Map navigation (e.g. maps,game maps); Capturing (e.g. taking photos, videos); Linear reading (e.g. feed, newspaper, web searches); Gaming (e.g. swipe accelerometer or video games); Video watching (e.g. Netflix, YouTube).

From this list, we generated scenarios for the participants. We chose not to embed watching videos because it is a relatively passive task where few inputs from the user are required compared to the other tasks, which involve complex manipulation of the device. From the six other tasks, we then generated six scenarios encompassing two different user contexts each. This ensured we could not only study the effect of task on form factors but also the effect of context. We chose the contexts in order to generate the maximum variability in the generated shape (e.g. one hand vs. two hands).

3.3 Data Collection

We video recorded design sessions for each pair of participants to collect their actions and discussions using GoPro cameras attached to their tables (for an overview of the setup, see Figure 1) and Jabra omni-directional microphones connected to a laptop (for better sound sound capture). We also video and audio recorded the actions and discussions during the general briefing using the same setup. We collected all 24 drawings and 24 molded prototypes (Figure 2). Drawings and clay models were used to generate prototype concept sketches (see following figures).

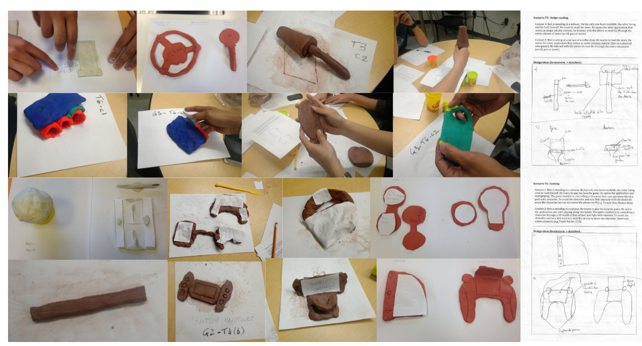

Figure 2: Example of collected data, beyond the discussion transcripts: participant sketches, clay prototypes and pictures illustrating how to grasp the devices. To better illustrate the original intentions of the participants, we created illustrations which showed at the same time the device and the intended usage.

3.4 Analysis

Using the video and audio recordings, we first transcribed all the think-aloud discussions within each pair of participants during the design sessions. We used thematic analysis [5] to analyze these transcripts and better understand the rationale behind the design choices. This followed a process of developing from lower level codes to five higher level themes. A first coder proceeded to create initial codes that were refined with one other coder. The entire transcription was then coded and an additional coder was brought in to refine the codes and to proceed to the grouping by themes. We particularly focus the analysis by looking at the rationale behind the choice of shapes and present them below, from the most frequently mentioned to the least. We start by looking at the overall results before discussing the themes that emerged. We exemplify the themes with excerpts from the participants' discussions, by identifying the pair that made a given comment (e.g. [pair1]).

4 STUDY 1 RESULTS

As said earlier, we developed from lower level codes to five higher level themes, which we divided into three major themes (Freeform dexterity, Shape features discoverability, and Shape adaptability) and two minor themes (Shape-Content consistency and Tangibility), which we present below.

4.1 Theme 1: Freeform Dexterity

One of the most recurrent themes relates to the dexterity of the overall freeform device. By dexterity we mean the ability to hold the device securely while enabling the interaction [8–10]. Four subtopics emerged frequently: firstly, participants clearly identified that there is a tradeoff between holding the device and interacting with it; secondly, they discussed about how certain shapes are better than others at either holding or interacting; thirdly, they proposed solutions involving a contraption such as a hole or a ring to help achieve both actions (holding and interacting) seamlessly; finally, they discussed the tradeoff between occlusion (of the screen) and interaction. We look at these in more detail.

4.1.1 Tradeoff Between Holding and Interacting. The first sub-category concerns the tradeoff between holding the device and interacting with it [8]. Participants reasoned that the problem with this kind of devices is that all fingers hold the device and only one is free to interact (Figure 3 - left): *"So let's have a design that lets you hold and have two fingers to interact" [pair 5]* (Figure 3 - right). Participants deliberated about solutions to improve interaction while holding the device, such as *"tapping the back of the device."* [pair 1] These examples clearly express that the ways of holding the phone was an obstacle (or a benefit) to the action of performing certain gestures or touching parts of the device. Interestingly the effector of those gestures was mainly the thumb: *"The first challenge is how to hold the mobile [...] in a way that your thumb is relaxed."* [pair 6] This could be simply due to the importance of thumb interaction on current smartphones [4], which seemed to inspire some of the proposed interactions: *"When you hold it in the hand you can scroll with the thumb."* [pair 3] This could also be an indication of the lesser importance of using other fingers for input, i.e. they would just serve to hold the device.

4.1.2 Less and More Ideal Shapes for Holding and Interacting. The second aspect of the dexterity theme concerns the labeling of certain shapes as being more or less ideal for holding or interacting. Participants discussed shapes being too large or too thin: *"If [the device] is large it won't be practical as you cannot hold it in your hand,".* [pair 1] Participants often mentioned their own devices

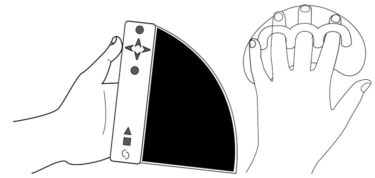

Figure 3: Participants reasoned about the problem that all fingers hold the device and only one is free to interact (left). Among the proposed solutions, a design that leaves two fingers to interact (pinky and thumb fingers on the right).

to exemplify their problems and identified the rectangular (traditional) handheld shape as not adapted: [38]: *"One of the problems here [showing his phone] is that you have difficulties reaching certain areas with the thumb."* [pair 6] In contrast they viewed rounder shapes [39] to be better adapted to both grasp and interaction (Figure 4): *"kind of oval shape, probably easier to grip."* [pair 5] Only one pair of participants mentioned the weight of the device to be a critical aspect for the choice of shape, probably due to the clay used for the prototypes which was relatively light. But the weight of a device may surely have an impact, as the heavier it is, the harder it is to both hold the device and perform interactions.

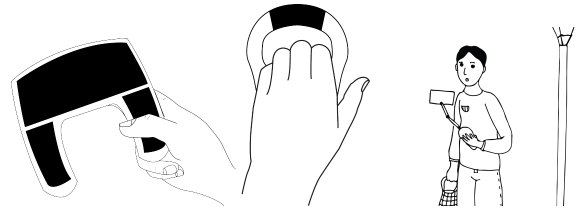

Figure 4: Participants viewed rounder shapes to be better adapted to both grasp and interaction.

4.1.3 Overcoming the Dexterity Tradeoff. The third aspect of the dexterity theme concerns the identification of solutions to overcome dexterity tradeoffs. Some groups thought of fastening the device as an approach to facilitate interaction: *"The problem is holding and doing these actions is hard [...] so what if [...] the device is not going to move."* [pair 5] To this end, many groups thought of using rings (Figure 5 - right): *"Maybe the phone can attach here, like a bracelet, or maybe a ring."* [pair 1] In fact, it is possible to buy a similar contraption online, e.g. rings to glue on the back of a phone to help grip the device more securely. Another interesting solution was to include holes in the device (Figure 5 - left): *"To hold it with one hand [...] I imagine here you have holes and you fit your thumbs into [them]."* [pair 3] Similarly, another group thought of wearing the device *"as a glove, like a small fabric that you put your hand in."* [pair 6] In some ways, it is possible to see those contraptions as a way of introducing hook and scissor grasp types (from Napier [31]). However, it appears that participants considered these contraptions not only for holding the object more securely, but also to ensure the fingers are placed at the right place for interaction.

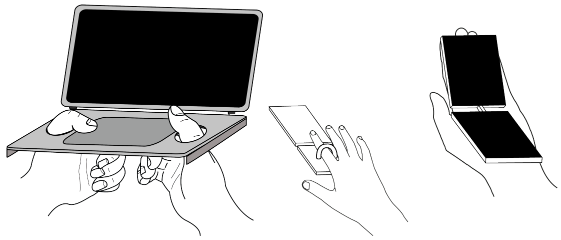

Figure 5: Participants identified various solutions to overcome dexterity tradeoff, such as using holes (left) or rings (right).

4.1.4 Occlusion. The fourth and final sub-category relates to the occlusion between the fingers and the screen [60]. Some participants weighed up the advantages of adding more screen real estate, *"This should be a total display, even though there are parts that can also be touched,"* [pair 4], while others seemed reluctant *"No, [touchscreen everywhere] is annoying because there is occlusion everywhere."* [pair 2] The majority of the pairs of participants was concerned that the hand and the finger would occlude the screen and had to think about solutions to address this, such as the aforementioned handles. Another approach was to reconsider the placement of screens: *"I would have put [the screen] further up because when you play, you look in front of you."* [pair 3] This led to thinking about fragmenting the device: *"We can separate the display part from the keyboard part [...] So I can hold it here and see it here."* [pair 4] The fact that this sub-category was frequently discussed is interesting because it means that designing interactive objects is fundamentally different from designing objects without touchscreens as designers must carefully balance the areas that are touched, grasped, or viewed. Additionally, the feedback suggests that we do not need the entire device to be covered with touch sensors and displays, which clash with some of the visions proposed in the current literature [20, 49].

4.2 Theme 2: Shape Features Discoverability

The second most recurrent theme concerns the discoverability of the overall device. By discoverability we mean the property of shapes to invite users to hold and interact with the device in the correct way without prior instructions [17, 34]. Participants particularly discussed two kinds of solutions for increasing discoverability: using metaphors or using shapes where the hand can dock (as in a jigsaw).

4.2.1 Metaphors. Most of our participants suggested using the shape of common objects (Figure 6) to help people understand how to grasp or interact with the device, such as *"a flip mirror or make-up container in two parts,"* [pair 2] *"a steering wheel shape,"* [pair 3] *"a newspaper, you can hold it with two hands,"* [pair 3] or *"like an umbrella, you can open it, it becomes flat, and then it becomes your smartphone again."* [pair 5] They thus clearly use metaphors or analogies with the real world to increase discoverability [3]. Some participants were inspired by existing devices as *"game controllers,"* [pair 4] or other electronic devices, such as *"a TV remote,"* [pair 3] or *"like VTECH with two hands."* [pair 2] Maybe this is not as surprising as the shape of game controllers has received significant attention from gaming companies and are well adapted to the task they are designed for, i.e. playing. This may clash with the shape of mobile phones which could be seen as universal, or basic so as to accommodate a myriad of tasks. In this light, game controllers may be seen as an ultimate ergonomic standard. However it is unclear if their shape can be really adapted to other tasks.

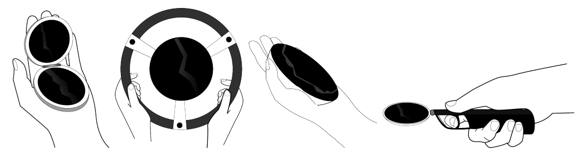

Figure 6: To improve discoverability, many participants suggested using the shape of common objects, such as two-parts mirrors and car wheels (left). Participants also elaborated on how certain shapes could fit the palm of the hand (right).

4.2.2 Docking Hands. Another solution participants used to help people understand how to hold or interact with the device was to use shapes that would invite a person's hand to dock, i.e. like how two pieces of a jigsaw puzzle match together. Participants elaborated particularly on fitting the palm of the hand (Figure 6): *"if I dig this part a bit [...] it takes the shape of the palm, like a bit round."* [pair 1] Fingers were another body part often referred to: *"We could do an ergonomic shape with the print of the finger on the shape."* [pair 3] This solution appears interesting, and perhaps game controllers only are designed as such. After all, docking fingers is a motor skill we have learned since kindergarten (e.g. shape sorters) and grasping could use a similar mental process. In such a case, users may typically place their hands in the part of the shape that looks like their counter-shape.

4.3 Theme 3: Shape Adaptability

This theme focuses on how well a given shape adapts to a usage scenario. Discussions suggest that one shape cannot fit all functionalities a handheld device can offer. This shape dilemma was nicely exemplified by a quote from a pair of participants: *"I mean, do you think it is an optimum shape for the phone? It is good for texting maybe, but not for much else."* [pair 4] This theme thus relates to the ability of the device to adapt to either the task, the user(s), or the context [58]. It is interesting to note that although we did not ask participants to consider shape changes, some participants clearly identified cases where reconfigurability of the device is an advantage. We now look at those aspects in detail.

4.3.1 Adaptability to the Task and Context. By looking at the prototypes we can clearly see that there is no single shape for all the contexts, and that participants really explored diverse form factors to fit the particular needs of their scenarios. Despite the fact that participants were confined to prototype for only one task, they still mentioned adaptation to task and context in several ways. For example they talk about changing the form factor to offer a different functionality, such as *"a device with small screens that can reconfigure."* [pair 3] Increase/decrease the size of the screen (Figure 7-left) was also considered through different means, such as folding: *"We should be able to unfold the screen"* [pair 2] or *"It could be a cylinder that you can unfold [...] like unfolding a map."* [pair 1] We also observed a couple of participants mentioning the ability of the device to adapt to multiple users to ease collaboration [28]: *"The user placed the device in the middle [of the table]. [...] At the beginning it would be square, but you can extend it like clay"* [pair 2] (Figure 7-right). Only one pair of participants mentioned the adaptation to the environment of the user during the task and proposed to morph the screen shape to fit the shape of the road.

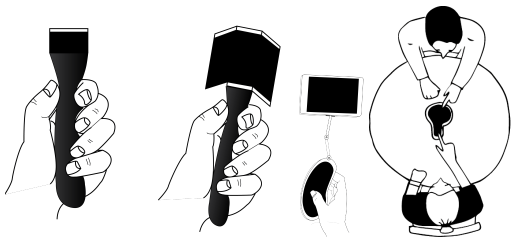

Figure 7: Although our focus was not on shape transformation, some participants suggested shape changes to adapt to tasks, context or collaborative activities.

4.3.2 Practicality. A lot of our participants discussed how to adapt the device shape to increase practicality in diverse cases *"I find it more practical to make the different parts of the device slide. It is divided in several pieces, and when put together it creates the shape."* [pair 1] Participants put a focus on storing the device when not used *"you have it in your pocket and when you take it out you can unfold it,"* [pair 3] Other participants reflected on this once they had already proposed a prototype: *"We were happy with the 'lamp' shape, but then you cannot put it in your pocket"* [pair 5] (Figure 8).

Figure 8: Certain devices were discussed as being impractical, such as this lamp shape that the user can not put in her pocket.

4.4 Minor themes

We also found two other minor but interesting themes: shape-content consistency and tangibility.

4.4.1 Theme 4: Shape-Content Consistency. This theme involves finding shapes or shape elements that suit the content: *"A round screen makes like a tunnel effect, like in the game Temple Run"* [pair 3] and *"We could have an oval screen, so that it has the same shape than a face [for the Skype application]."* [pair 1] It was particularly interesting to see that participants noted that most current digital content is rectangular and that we might need to rethink the content itself for it to be consistent for freeform displays: *"but the photo is rectangular, it is not round so we have a problem".* [pair 2] This particularly corroborates with some work done within the field of freeform interfaces in HCI [50, 51].

4.4.2 Theme 5: Tangibility. This theme includes decisions made to bring haptic features to the shape: *"I don't like a touchscreen; a scroll wheel would be better to bring haptic feedback."* [pair 2] Some considered haptic elements such as physical buttons to be interesting because *"we can put them everywhere."* [pair 2] Others mentioned using these haptic features for eyes-free interaction.

4.5 Summary

Our analysis highlighted three major themes concerning how people envision the shape features of freeform devices, i.e. Freeform dexterity, Shape features Discoverability and Shape adaptability, as summarized in Table 1. These three themes echo previous work in HCI research, which we cited in summarizing our results. However, to our knowledge, these themes have never been linked to freeform devices and present an interesting direction to explore. Other interesting minor findings relate to the shape-content consistency and tangibility of such devices. The Freeform dexterity theme, and the problems surrounding the trade-off between grasping and interaction in freeform devices, seem to be at the core of most design considerations. Hence we decided to further explore this theme in a subsequent study.

5 STUDY 2: TRADE-OFF BETWEEN FREEFORM DEXTERITY AND DISCOVERABILITY

With our first study we found that the three themes surrounding the choice of shape are of course intrinsically related to how the user holds and grasps the freeform device. This depends on a trade-off between the dexterity the user wants to achieve, and the grasp discoverability. Although Napier [1] described how different object sizes play a role in grasping, there is little knowledge into what properties of an object's shape can change a user's grasp choices.

5.1 Task

To investigate what shapes and features would have an impact on the device's grasp dexterity, and its interlink with discoverability, we asked participants to create device shapes, which would range from a high discoverability (a single affordance), to low discoverability (multiple affordances). Then we asked participants to update these devices for different grasp actions, to further investigate the interlink between discoverability and dexterity, as detailed below.

We first asked participants to design three devices according to three different levels of discoverability, through the use of affordances. The first instruction was to form an object that displayed one affordance (i.e. high discoverability); to simplify the comprehension of the term we told them to find an object that only allowed for one grasp possible. The second task still required participants to restrict the number of affordances, but this time it was to three (i.e. medium discoverability). The third instruction was to create an object which had "many affordances" (i.e. low discoverability), this meant that they no longer had to restrict grasp types but, instead prepare for as much grasps as possible.

Themes	Sub-themes	Findings
T1: Freeform dexterity	Tradeoff between holding and interacting	Holding devices is an obstacle to performing gestures
	Less and more ideal shapes for holding and interacting	Shapes too large or thin vs. rounder shapes
	Overcoming the dexterity tradeoff	Fastening or wearing the device
	Occlusion	Reconsidering placement of screens
T2: Shape features discoverability	Metaphors	Grasping and interacting inspirational devices, e.g. umbrella, game controllers
	Docking hands	Shapes that invite a person's hand to dock
T3: Shape adaptability	Adaptability to the Task and Context	Single task vs. fit-all prototype
	Practicality	Storing the device, fitting in the pocket

Minor Themes	Findings
T4: Shape-Content consistency	Shapes that fit the content
T5: Tangibility	Bringing haptic features to the shape

Table 1: Overview of the major and minor themes emerging from the design session analysis.

Figure 9: Participants during the focus group.

Secondly we asked participants to combine their previous ideas to create objects for the actions 'pinching', 'pressing' and 'twisting', to further explore the device dexterity according to its discoverability. Participants were encouraged to make objects themselves and were prompted to discuss their design choices within the group. At the end of the task they were asked to pick their favourite design amongst the group and discuss why this one was better than the others.

5.2 Participants

12 participants took part in the study, of which six were female and six were male. The minimum age was 20 and the maximum was 22, with a mean of 20.8. Participants were split into four groups of three to elicit more qualitative feedback. All participants were HCI students with no previous experience in freeform interfaces. None of them had taken part in the previous studies.

5.3 Method

Prior to the study, participants were presented with information which introduced the concept of affordance, and outlined some of the possible grasp types. This was to illustrate to users that there are many different grasp types, that they may not have previously considered. Each group, consisting of three participants, took part in the study within the same meeting room, in the same set up. The participants were each provided with a pot of modelling clay. Every participant was given only one colour in order to reduce the temptation to make affordances more discoverable through the use of different colours, instead of shape.

5.4 Analysis

Feedback was gathered in the form of a video recording which was later transcribed. We adopted the same thematic analysis process as in the study 1, except that we analyzed both the discussion transcripts and the molded objects and that our thematic analysis specifically focused on coding shape features that we report below.

6 STUDY 2 RESULTS

Figure 10 shows examples of the collected data organised as follows: on the left an example for each affordance (one, three, multiple); on the right objects created for specific actions. Beyond presenting all the shapes, our interest lied within the rationale made by the participants that we present below grouped by themes.

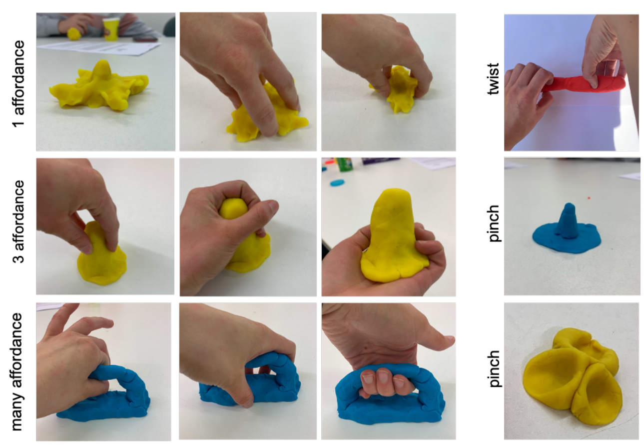

Figure 10: Example of objects created in the study 2.

6.1 Indentations

Grooves and ridges were essential for displaying the intended affordance of an object. Participants mentioned that it made discovering where to grasp 'much clearer' and 'easier'; the majority of the objects possessed some level of indentation for fingers. Participants varied this, with many making holes and others, only very slight impressions into the clay. Albeit, the general consensus among participants was that creating an indent too deep into the object was the least desirable; it produced the possibility of an alternative grasp (the pinching of the protrusion made by a deep indentation).

When dealing with the second task (designing for 3 affordances), many participants removed the majority of indentations for hands and experimented with new features such as knobs or loops. Most groups concluded that the indentations added during the first task were too restrictive, as they made the objects biased to one particular grasp. Many participants scrapped all indentations on the objects, whereas only two out of the four groups initially adopted a different approach to make the indentations into the objects shallower. For the third task, all indentations were removed from the objects as participants did not want to sway users to a specific grasp.

6.2 Orientation of Features

Furthermore, not only the presence of the indentations is important, so is the direction in which they face. One participant moulded a small ball with two deep impressions on either side, intended for a thumb and forefinger. This participant then stated that 'naturally you want to pinch (the object) because they (the indentations) are in the same direction as your fingers'. The group that this participant was part of then debated whether the indentations should point upwards or sideways. They concluded that if they pointed upwards the wrist would have to bend at a 90° angle in order to pinch it, which was uncomfortable; therefore, not the most intuitive.

6.3 Preferred Shapes

The most popular shape made in the first task, made by three out of the four groups, was a solid ball, with indents in the shape of a hand on it. These finger impressions were placed at a hand's resting position, with the thumb dent positioned at a 45° angle away from the index finger. The most favoured shape made during the second task was a simple ball too, similar to that made in the first task, but without any fingerprint impressions. Alongside this two of the four groups made very similar shapes, one described as a 'bugle' and the other described as a 'wizard's hat', were considered to be the best shapes. The most common shapes made by participants in the third task were all variations of loops, some were large and slack, whereas others were more rigid handle like objects. When asked what was it about the shape that made it the best, one group responded that 'it's the two portions, they allow for your hand to go through and are big enough to fit your whole palm'. Another said that 'the hole in the middle means you have a large edge around that you can try lots of grasps with'.

6.4 Size of Contact Area

The size of the object and intended contact area was essential to participants in this study. Many participants claimed that very small objects would reduce the number of affordances possible with it. They explained that the smaller the object was, the fewer places a hand could have contact with the object, therefore reducing the grasp possibilities. Also encompassed into this idea of object size, was the notion that the thickness of an object also alters its affordance capability. A completely thin, almost paper like object, was made and discussed by three out of the four groups within this study. Many participants stated that a 'thinner object needs lots of support'. Therefore, fewer combinations of hand variations exist that retain the much-needed support for the object.

6.5 Shape Features for Preventing Grasps

Persuading people to intuitively choose one specific grasp was found to be easy by participants, yet specifically restricting other grasps was seemingly more difficult. All but one group found that the best way to deter users from certain grasps was to include sharp or spikey edges. These would discourage users to touch certain parts of the objects, thus averting users from discovering the unintended grasps.

6.6 Shape Features for Actions

When considering incorporating actions not just a grasp, impressions become important once again, probably as one grasp per action is required for each object. The direction of the impressions on the objects created by participants became essential for this task. No longer were they just for comfort (which was seen in the previous tasks), but they also had to expose the actions that were available. We noticed that participants would purposely put the impressions far from the resting hand position, to illustrate to the user that there may be a more complicated action required. In the case of the twisting action, the impressions made for the hands were at opposite sides of the object, compelling users to put one wrist angled forwards and the other backwards. Users would then move their hands back to the resting position, thus producing a twisting action. In addition, many indentations (not just those in fingertip and finger form) were put at the angle in which the action was required (slanting left for a left twist).

6.7 Past Experience

One concept that was discussed by all four groups during this task, was the idea that some level of previous knowledge was required in order to make grasping decisions. One participant stated that 'if people experienced different things, they might pick up things differently' and another mentioned that 'you can't account for every person on earth (to grasp the object the same way) because this is learnt behaviour'. This concept was developed throughout the course of this study.

6.8 Summary

This second study revealed the shape features that impact the most the trade off between dexterity and discoverability. This study highlighs that designing for various grasps is a difficult task, as the shape properties chosen for the "one affordance" condition were the least desired for the "many affordance" condition. It also shows that shape features such as indentations are not only important for conveying a particular grasp, but also to suggest possible actions such as twisting. We further discuss the implications of these findings for the design of handheld freeform devices in the Discussion section.

One of the most important results of this study is the addition or removal of indentations, which was not the sole focus of this study. While our participants employed indentations to vary the level of discoverability, it is unclear whether this strategy would actually work. To further investigate this we performed a small follow-up study.

6.9 Follow-up Study on Indentations

We were interested to know if the presence of indentations could persuade users to change their pre-established perception of well-known objects and the grasps they would choose to hold them. We recruited 6 new participants with similar background that our two studies but with a wider age spectrum to enhance the external validity of the results (2 males, age between 22 and 56 with a mean of 45 and a standard deviation of 15.65). Participants were presented with 9 pre-molded objects on Figure 11: a mug, a cylinder, a sphere with 3 indentation level possible (none, finger indentation, full hand indentation). Participants first observed each of the objects without any additional features, then indentations were added in order to see if participants would change their grasp. We encouraged them to discuss their reasoning.

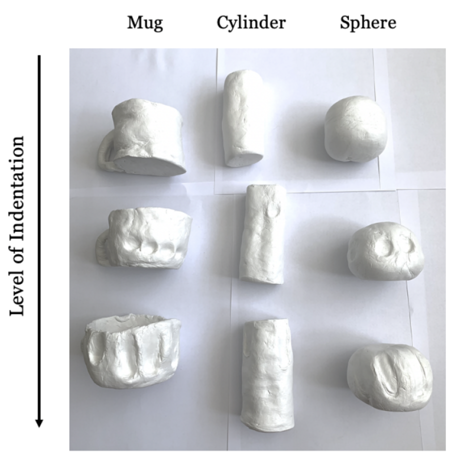

Figure 11: Example of objects created in the study 2.

With no indentation, we saw participants using common grasp (spherical power grasp) for the sphere with variation of the preferred wrist angle when grasping (two had their palm facing downwards, holding the object from the top). For the cylinder, they all decided on a power cylindrical grasp with thumb pointing upwards. The only difference between the grasps that participants used was whether the thumb was straight, or bent at 90 degrees. The mug object had two favoured grasps, these being a hook grasp through the looped handle and the other was a cylindrical power grasp around the side. The number of fingers used in the hook grasp ranged between one and three.

With one finger indentation, over half of the participants chose a spherical power grasp, with fingers placed in the finger indentations. One participant said "it would annoy them to choose a grasp where my fingers didn't line up with the dents" and another stated "It's hard to consider other options now, because I feel I have to use the indentations". However, two participants did not place their fingers into the indentations as they felt as though their fingertips were too large to fit in. Unlike the sphere, the indentations in the cylinder did not persuade any participants to change their grasp. Two participants did not notice the indentations and others excluded them as a potential visual aid for grasp choice. For the mug, the position of the fingertip indentations were set out to persuade users to perform a precision lumbrical grip. Only one participant attempted to put their fingers into the indentations. When asked why that grasp was not considered when previously given the same object with no indentations, the participant said, "I hadn't tried to hold the mug like this before, didn't cross my mind, but I feel it's a lot more stable".

With the full finger indentations, all participant used the same grasp for the sphere, with all fingers placed within the ridges. The position of the indentation can be potentially leading the user to see the hand imprint, thus suggesting a particular affordance. One participant stated that "it feels satisfying, like my fingers are supposed to fit in there'. When asked if there were any other grasps they would consider, one individual responded with "no, because I feel I have to put my fingers there, I would feel like I'm holding it wrong". With the cylinder, half of the participant altered their grasp (adopting a tripod precision grasp). When asked why they attempted this grasp only now, when the full finger indentations were added, one participant said that "these indentations all point to one place, so I know where to place my palm". The other half, who did not change their grasp, retained the cylindrical power grasp. One stated that "I noticed the ridges in the object, but I didn't want to use them". Lastly the indentations on the mug did convince three participants to try the new lumbrical precision grasp. Although similar to the cylinder, the new grasp was considered less comfortable than the previous grasps they had chosen. One individual expressed a concern that the size of their fingers was not compatible with finger indentations, exclaiming that "my finger is too short to rest on this part". The two individuals who did not change their grasp said they had noticed the added dents, but it could not convince them to change their grasp.

To *sum up*, this follow up study confirms that the presence or absence of indentations, as well as their level (partial or full finger) and size, can all alter the grasp choice. However, our study also shows that it highly depends on the shape of the object, as well as the perceived comfort of the new grasp. We can conclude that any addition of indentation on a freeform object needs to be specifically tailored for the object in question.

7 DISCUSSION

In this section we discuss our results in light of our goal which was to investigate the rationale behind shape features of handheld freeform devices. We particularly discuss the differences we found with previous work that were more technologically driven and highlight directions for future work.

7.1 Designing for Dexterity: Stability vs. Interactivity

Of the three themes of our design sessions, dexterity appears more prominently. One reason might be that there is a learnt fear of

Shape features properties	Impact on grasp discoverability and dexterity
Indentations (Grooves, holes and ridges)	Indentations conduct to one particular grasp Deep indentations can introduce alternative grasps Indentations can be restrictive to change grasps
Knobs, Loops	Allows for a variety of grasps
Orientation of features	Features oriented in the same direction than fingers help in discovering grasps Features orientation can bend the hand at uncomfortable angles
Solid ball shape	Ball with fingerprints is the most preferred shape for high grasp discoverability
Size of object and contact area	Small or thin objects reduce the number of grasp possibilities
Sharp or spiky edges	Discourage users to touch certain parts of the objects Deter user from certain grasps
Features to convey actions	Shape features placed far from hand position Shape features at the angle in which the action is required (slanting left for a left twist)

Table 2: Summary of the impact of the different shape features on grasp discoverability and dexterity.

having the device fall, and break, during interaction. Participants particularly point at the need to maximize thumb reachability in all instances, for one- or two-handed operations. In most of the prototypes the other fingers clearly serve the purpose of holding the device securely, either by using a traditional power grip, or a combination of hook or scissor grips. Interestingly, current catalogs of grasp postures [12] have not considered interactivity, i.e. movement of fingers during grasp. While not a concern for studying the fundamentals of grasp, this becomes a prominent concern when it involves input dexterity on freeform devices [48].

Dexterity and grasping have been extensively studied in Robotics but our results suggest that when grasping interactive devices, users must maximise stability and interactivity. This challenge has not be investigated so far as the goal in Robotics is often to hold an object or to use an object for an action external to it. In the case of grasping interactive devices, the action happens directly on the object itself. Thus users will look to maximize: (1) the area that can be reached on the object with any finger (although it is possible that the thumb might be the most prevalent digit for interaction); (2) and the stability of the grasp. We think there is a need to systematically study the dexterity of the novel shape features introduced by freeform devices, such as finger holes, handles, etc.

7.2 Designing for Discoverability: Acquired or Innate

Discoverability, i.e., the affordance of the device, is a well-known theme in object design [17, 34] and there is a well known debate into the question of whether the affordances are innate or acquired. Our results reflect this question as these were essentially the two ways used to suggest how people should use and grasp the devices.

Existing metaphors: these are common in HCI and interactive devices. What is interesting in our exploration is to uncover where these metaphors come from in terms of freeform devices: while some of them come from real world objects, such as umbrellas or pocket mirrors, others are iterations of current interactive devices, such as phones or game controllers. This highlights that freeform devices are a new generation that implicitly builds upon the previous generation of handheld devices.

Hand print features: What our research also uncovers is the use of hand print in form factors to suggest users how to handle it. Using such features is really interesting because it has been used in many other objects (e.g. bottles) but we are not aware of work done for embedding such features in interactive devices. In our follow-up study, we looked at how reliable the hand print needs to be to suggest an appropriate grasp. Results show that the presence or absence of indentations, as well as their level (partial or full finger) and size, can all alter the grasp choice.

7.3 Designing for Adaptability: No Universal Shapes

Our work challenges the fact that there is a universal shape that fits all functions. So far this shape has been rectangular but even when offering the possibility to design for any shapes we found that not only users stayed within relatively simple shapes, but also they mentioned the need for the device to morph from one shape to another in order to better fit the functionality. Our work thus further corroborates the need for shape-changing devices.

That being said, such a perspective means that there is much research to be done into how to adapt the content on any possible shape, even if there is a small amount of shape the devices can morph into. For example, a user interface on a sphere might be very different from a triangular one because of the way visual elements can be placed on it and also the way users will interact with such form factors. We believe this may open a significant research agenda into how to design adaptive user interfaces for multiple form factors.

7.4 Desirable Physical Features

Our second study revealed the shape features that impact the most the trade off between dexterity and discoverability, which are summarized in Table 2. We observed that the shape properties chosen for the "one affordance" were the least desired for the "many affordance" instruction, such as indentations. Indentations were pivotal for "one affordance", but were made shallower and then completely removed for the "many affordances". This removal helped prevent bias towards just one grasp. Other more complex features such as loops and handle were also considered: while they were quickly dismissed by all groups for the "one affordance", they were quickly adopted and deemed the most appropriate shape for an object with an infinite grasp affordance. We also discovered that choosing correct shape properties and features became important when considering a grasp action: the addition of an unclear feature could be misinterpreted, in turn leading to an incorrect action.

Although the trend of diminishing impressions was prominent during this study, one aspect that was not clear was how deep these indentations should be. This attribute was varied by all participants in the different groups. It was mentioned that indentations too deep would leave the elevated parts open to pinch, introducing another grasp. The most desired level was not considered, nor was the question whether the fingertip indentations was sufficient or a whole hand imprint was necessary. We further investigated these questions in our follow-up study, which revealed that while the level of indentations can impact the choice of grasp, this is dependent on the object's shape as well as the foreseen comfort of the grasp.

7.5 Technical feasibility of handheld freeform devices

In this work we tackled the challenge of understanding the shape of free-form devices through the use of clay to let end-users mould devices which of course does not reflect a real device. However this approach is coherent with standard research methodologies using probes or mock-ups for gathering user's insights (e.g. in [6] using Augmented Reality to study shape-changing affordance). We took this approach because there is limited empirical data around such devices because the technologies required to build them are still in their infancy, making the exploration of interaction on them and their manipulation limited. Like others in the area of free-form displays and shape-changing devices we made use of an alternate material to explore such space.

There are many improvements needed in terms of hardware to explore the full spectrum of interaction with shape-changing devices [1] and researchers are now working with material scientists to speed up technological developments [21, 40]. Previous research used thin-film electroluminescence (TFEL) to create freeform and bendable displays [36]. More recently, Hanton et al. [21] are exploring the combination of 3D printing and spray coating to create touch-sensitive displays of arbitrary shapes. As said in the related work, many non-rectangular interfaces have been developed for different context, ranging from tabletop and projected UIs [7, 32] to round smartwatches [2]. We believe these examples only scratch the surface of what free-form displays can enable and we hope this can inspire researchers and designers to extend the form factors of interactive devices.

In the meantime, gathering empirical data in parallel with developing necessary technologies can be valuable for researchers and accelerate the development of appropriate interfaces. Our work provides recommendations in this direction.

8 CONCLUSION

As our interactive devices start adopting new form factors, we need to consider suitable shape features. In this paper we explored this question through a set of design sessions, focused on handheld freeform devices, which uncovered important considerations related to the shape features of such devices. Our first design session revealed the main themes related to grasping such freeform devices: freeform dexterity, shape features discoverability and shape adaptability. We further explored the interlink between shape dexterity, discoverabiliy and freeform shape features in two subsequent design sessions. These revealed that designing for various grasps is a difficult task, as the shape properties chosen for the "one affordance" condition were the least desired for the "many affordance" condition. It also shows that shape features such as indentations are not only important for conveying a particular grasp, but also to suggest possible actions such as twisting. Our work opens up many perspectives on the use of such novel devices and reveals the need to systematically study freeform shape properties, which constitute a roadmap for the upcoming research on freeform devices. In the future, we plan to develop design probes corresponding to the proposed ideas of handheld devices. We will carry both controlled studies on the dexterity and discoverability of such devices, as well as longitudinal studies similar to [11] so that we can investigate the practicality of freeform devices.

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