Sketching as a Support Mechanism for the Design and Development of Shape-Changing Interfaces

Miriam Sturdee

Highwire Doctoral Training Centre
Lancaster University

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I would like to dedicate this thesis to Paul Whaley, and all of the friends and family who have supported my never-ending journey as a student.

Declaration

I hereby declare that except where specific reference is made to the work of others, the contents of this thesis are original and have not been submitted in whole or in part for consideration for any other degree or qualification in this, or any other university. This thesis is my own work and contains nothing which is the outcome of work done in collaboration with others, except as specified in the text and Acknowledgements. This thesis contains fewer than 59,000 words including appendices, footnotes, tables and equations, and has fewer than 103 figures.

Miriam Sturdee
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Abstract

Shape-changing interfaces are a novel computational technology which incorporate physical, tangible, and dynamic surfaces to create a true 3-Dimensional experience. As is often the case with other novel hardware, the current research focus is on iterative hardware design, with devices taking many years to reach potential markets. Whilst the drive to develop novel hardware is vital, this usually occurs without consultation of end-users.

Due to the prototypical nature of shape-change, there is no specific current practice of User-Centred Design (UCD). If this is not addressed, the resulting field may consist of undirected, research-focused hardware with little real world value to users. Therefore, the goal of this thesis is to develop an approach to inform the direction of shape-change research, which uses simple, accessible tools and techniques to connect researcher and user. I propose the development of an anticipatory, pre-UCD methodology to frame the field.

Sketching is an established methodology. It is also accessible, universal, and provides us with a low-fidelity tool-kit. I therefore propose an exploration of how sketching can support the design and development of shape-changing interfaces.

The challenge is approached over five stages: 1) Analysing and categorising shape-changing prototypes to provide the first comprehensive overview of the field; 2) Conducting a systematic review of sketching and HCI research to validate merging sketching, and its associated UCD techniques with highly technological computing research; 3) Using these techniques to explore if non-expert, potential end-users can ideate applications for shape-change; 4) Investigating how researchers can utilise subjective sketching for shape-change; 5) Building on ideation and subjective sketching to gather detailed, sketched data from non-expert users with which to generate requirements and models for shape-change. To conclude, I discuss the dialogue between researcher and user, and show how sketching can bring these groups together to inform and elucidate research in this area.

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Chapter 1

Introduction

The study of shape-changing interfaces, displays, and objects is an emerging area of research. Shape-change allows objects to physically re-configure their external geometry to convey information [4], enhance output by exploiting the users' rich tactile sense [31], influence social behaviours [91], exploit perceived affordances in physical form [155], and re-appropriate objects through dynamic affordances [67]. Ishii et al. succinctly define these mechanisms as "embodying digital information in physical space" [123]. Shape-changing interfaces have the potential to transform how we perceive and use computers, against the "one size fits all" approach adopted by personal computing [218].

Shape-changing interfaces are part of the wider field of *tangible* user interfaces. Ishii and Ullmer saw their vision of *tangible bits* as "bridging the gap" between digital and physical – essentially suggesting that the world around us has the potential to become our interface [126]. Later, there became the potential for this new style of interface to become physically dynamic, and shape-changing interfaces became a new area of study under the umbrella of graspable interactions with TUIs (tangible user interfaces) [121]. The key characteristics of a TUI (according to Ullmer and Ishii [320]) are that "physical representations are computationally coupled to underlying digital information", and that these representations "embody mechanisms for interactive control". The difference between shape-changing interfaces (as they are described within this thesis) and TUIs lies within the addition of movement and change in form, creating a more complex model of computation.

The output of shape-changing interfaces relies not only on form, but also temporality, in trinity with the interaction gestalt [325], and it must also incorporate existing constructs of computational devices such as the screen and haptic response which are now universally expected. The temporal movement in combination with form presents new possibilities: Parkes et al. suggest that when something is perceived as moving organically, it appears to be alive [228] — yet there is a divide between shape-change and robotics or AI where the goal is to produce validly human outputs: shape-change remains a computational interface.

An additional complication arises when we consider merging screen based design with temporal, 3D form. The standards of Interaction Design cannot currently plan for the extra dimension of shape and animation, as 2D outputs overlaid onto 3D surfaces without adaptation can quickly create distorted viewpoints. By adding dynamic, physical, movement we then further complicate the users' perception of data and imagery. When user interaction with that surface is added as well, then the current guidelines fall short as theory currently cannot be applied to the demands of the device. Therefore, there is a significant gap between the hardware-driven research that is currently in progress, and the eventual adoption of these technologies in the domestic or industrial setting.

Currently, shape-change research is driven by technology explorations or prototypes with a specific application focus — diverse user-led or applications-driven research has not yet occurred. Instead, we see a trend in the literature of documenting (for example): *cartography* [4, 234], *wearable technology* [16, 202], or *mobile phone notifications* [48, 83, 109] amongst others. This trend advances the practical hardware and obvious use cases for shape-change, but we need to also consider *who* will be using these devices, *why* and what *impact* they will have [185] – these questions remain unanswered. To explore the full-potential and range of shape-change, and to focus technical development work, we therefore need to better understand potential use-cases and applications [242] that drive future design (and therefore, adoption), as well as examining the practical requirements for this exciting technology.

To address the needs of the research, it is therefore essential to develop practices that enable the exploration of this novel technology *before it is commercially viable*, meaning that traditional (meaning established practice for 2D UIs) User Centred Design (UCD) methods and its relations to the current practice of Interaction Design cannot adequately support the field in its current state — UCD works well within the bounds of well established interactions (e.g. touch, mouse clicking), but falls down when the underlying technology is not familiar to the designers or users.

In essence, User-Centred Design is a collection of procedures, techniques and steps to ensure that new designs for user interfaces, or new programs to run on them, the main focus being that the *user* must be consulted during the design and testing process. Due to the broad nature of user-centred design, there exist many definitions and suggestions for best practice, e.g. the International Standard [223] which provides "requirements and recommendations". Abras et al. [1] see UCD as " a broad term to describe design processes in which end-users influence how a design takes shape", whereas Chamberlain [28] suggests that UCD is an "approach which aims to involve the users in a meaningful and appropriate way throughout a system's development". Rogers et al. can be seen to simplify further, by stating that interfaces that are enjoyable and easy to use have been "designed primarily with the user in mind" [249]. For the purposes of this thesis, I assume the stance that UCD can be a *broad* term, and is therefore open to interpretation, and development — with the caveat that the user is key to the procedures of design and development for shape-changing interfaces.

User studies for functional shape-changing prototypes exist only as proof of concept for a device or iteration of technology that is almost never going to be taken to a commercially viable state [159]. We cannot directly utilise these existing methodologies due to the lack of currently working hardware, but we can adapt or borrow. By approaching shape-change from an alternative perspective — hybridising UCD with other methodologies — we can complement the hardware and theory driven development by developing an alternative, future-focused mixed-methods approach, providing an end-user perspective on shape-changing interfaces, and also providing current researchers with additional tools to explore and create these devices.

1.1 Research Agenda

If we approach shape-change from a user-centred perspective we must answer the following questions: What is shape-change good for? Further, in what situations might we *need* or *want* this technology? How do we start building the hardware and developing interaction design for technology that works on multiple, often multi-sensory, dimensions?

These questions cannot be answered purely by iterative academic research, where work is often not directly relatable to practical real-world applications. Conversely, this question can also not be answered by the end-user, as shape-changing technology is not available commercially, nor is it possible to present the current state-of-the-art to those not situated within academic research laboratories. The answer to this challenge is to develop an easily utilised methodology or technique to bring these two groups together, in order to explore and design the next generation of shape-changing interfaces.

By taking an *offline*, low fidelity approach to examining shape-change, we can improve communications between researcher and user: overcoming the issues inherent in the availability of prototypical, or even commercial technologies. Within UCD, visual techniques are often used to inform users as to the potential design and interaction with a device or software implementation [23, 89, 311], for example methods such as ideation, creating personas, low-fidelity prototyping and scenarios generation. Such methods can be digitised to a certain extent (e.g. outlines of websites/interfaces [167]), but often rely on the ability of the researcher, or a hired artist, to *sketch* these outputs. We propose to identify how sketching is currently used in UCD (and HCI as a whole), and to subsequently adapt it in order to apply it to the investigation of shape-changing interfaces.

Sketching is a universal construct bound to human development, in similar ways to language [35]. According to Buxton [23], a sketch can explore, question, propose and provoke and more. Sketching is a tool long used by designers in multiple domains [51], to suggest, edit and present ideas to different groups of people. Some sketches are private ruminations, others, the start of a seminal work (e.g. Starck's *Juicy Salif* lemon squeezer [3]). Sketching is a valuable part of the UCD process in HCI and beyond (e.g. software design and engineering [23, 167]) and has a firm place in the exploration and communication of user-interface design, making it ideal to adapt for the purposes of exploring shape-changing technology.

Within HCI in particular, Fleury et al. examined user-generated storyboards to examine this practice, and discovered that drawings break down perceived boundaries between researcher and user, then get swiftly to the heart of the problem or product, in comparison to focus groups and written information [64]. Truong et al. [315] also champion the use of storyboarding technique in HCI and subsequently formed five guidelines with which to guide novice designers or others wishing to make use of this technique. Indeed, Reeder [245] stated that storyboards help users to "better understand the complexity of a product's use, and visualise areas for improvement". This is mirrored by Scott McCloud's demonstration as to how comics can be used to communicate technical concepts with his visualisation of how to use *Google Chrome* [199]. That sketching can enable end users to understand highly technical information speaks volumes for its use in computing. Sketching has also been linked to how designers might approach shape-change, so there is existing support for the technique alongside its technical focus [243].

The appeal of visual imagery broaches all areas of HCI as an interdisciplinary practice [134], from being used as an input technique [133], a desirable output (as with digital drawing on tablet devices), a design method [59], or simply a thought process recorded within archived conference pictorial proceedings [76]. Given its widespread acceptance and usage, ability to communicate complex conceptual information, and availability — it is the perfect candidate to bridge the perceived distance between researcher, shape-change, and end user. The work of this thesis is therefore to examine whether sketching can be a support mechanism for the design and development of shape-changing interfaces, and connect researchers with end users in a cyclical process to enable more informed research.

1.2 Research Objectives

Based on the research gap and proposed solution identified in the section above, this work addresses the following research objectives:

1. To understand the current state-of-the art in shape-changing interface research

Shape-change is a relatively new field within HCI, but has already amassed a substantial body of work in the past fifteen years. Prototypes are rarely similar, and there are a range of materials and interaction styles currently under investigation. In order to begin to design new processes for the field, a comprehensive understanding of functioning shape-changing interfaces prototypes is essential.
Success Criteria: *Conducting a comprehensive review of the field, and identifying all functioning prototypes available during the timeline of this thesis. Investigation, classification and discussion of overlapping themes and hardware types to identify similarities and make recommendations for research directions.*

2. To understand how sketching is currently used as a methodology in HCI research, and therefore how it can be applied to shape-changing interfaces

Sketching is a universally accessible methodology, and can be applied across all disciplines as part of the research process. Therefore, it is likely that sketching can also be applied to the design and development of shape-changing interfaces, despite their advanced technology and complex outputs. As sketching is such a broadly used term, a structured approach must be undertaken to identify the ways in which sketching is currently used in HCI research practice.
Success Criteria: *Using systematic review techniques and identifiable search strategies in order to produce an overview of sketching practice in the context of HCI research. Identification and classification of research into process and application oriented roles for sketching.*

3. To use selected methods to discover how sketching can form part of a "Pre-UCD" process for shape-change research

User Centred Design works well within in familiar settings, or for familiar products, but cannot be applied where technology is not known to designers or users. User Centred Design therefore cannot yet be applied to shape-change, as the hardware for these devices is not yet developed, or commercially available. An accessible, offline, *pre-UCD* methodology using sketching to connect researcher and user will be used, in order to help develop formal design and development practices for shape-change.

Success Criteria: *Identification of sketching methods and techniques for eliciting output already used in HCI for design processes, and application of these methods to the design and running of user studies and subjective research practice.*

4. To use sketching to form a bridge between researchers and potential end-users in order to create dialogue, directions and guidelines to advance research in shape-change

As part of the process to show how sketching can be a viable methodology for the design and development for shape-change sketching will be used to form a bridging methodology between users and researchers. Sketching is used in many different ways in HCI already, but must be focused for the purpose of this thesis, and at present potential end-users also have no prior knowledge of shape-change and are difficult to engage in user studies.
Success Criteria: *The sketching techniques utilised create engagement opportunities for both researchers and potential end-users — users are able to understand and sketch ideas for shape-changing applications, and elaborate upon these to create detailed diagrams and scenarios; Researchers are able to utilise user-generated sketching to elaborate on application ideas, and conduct thematic analysis, to subsequently generate requirements for shape-change.*

5. To use sketching in the design and development of shape-changing interfaces to produce tangible outputs for the field (e.g. requirements, models for development)

Sketching for shape-change research can be used as a bridging methodology between researcher and user, and produce detailed visual outputs. In order to produce useful results for the field, the sketching dialogue, and subsequent elaboration via user studies and researcher-led sketching practice should lead to tangible outputs.
Success Criteria: *The resulting sketched output can be thematically coded to identify requirements for a variety of shape-changing hardware and applications. Coded items can be classifed in order to produce both application level data, but also functional requirements and models for the design and development of shape-change.*

1.3 Chapter Outlines, Methodologies & Contributions

This thesis is divided into 5 chapters, each addressing an aspect of the research questions. Each chapter also contains its own discrete methodology and discussion, but together they provide a detailed exploration of sketching in application to the design and development of shape-changing interfaces, between researcher and user. Each chapter has its own approach, and is subsequently self-contained in respect to methodology and discussion. The final chapter takes the form of a *meta-discussion*, pulling together the themes from each chapter, and consolidating the work contained within this thesis.The following provides summaries, methodologies, and contribution — an overview of the work can be seen in Figure 1.1.

What is Shape-Change?

Chapter 2 contains a detailed review of the field of shape-changing interfaces, examining both existing prototypes and previous papers outlining the major themes and goals in this area and consolidating existing research into themes and subsequently categorizing prototypes by shared materiality and interaction. This categorisation allows us to not only place existing work, but also gives a focus for prospective prototypes and ideas.
Methodology: Here, I conduct a literature review and classification of shape-changing interface prototypes and outline associated theory to set the scene and provide background for the novice reader.
Contributions: The first comprehensive overview, analysis and classification of shape-changing prototypes.

How has sketching historically been used in HCI research?

Chapter 3 is a systematic review of sketching in HCI over the past 60 years, validating its use in this technology-centred field of study, and considers its value as a medium moving forward into the future. The review proposes 8 categories of sketching currently seen in HCI, and explores their contexts and themes in relation to UCD and other methodologies.
Methodology: Due to the large number of sketching-related papers in HCI (in comparison to shape-change), a systematic review technique is employed across HCI related works, year by year, using keyword searches across the two most comprehensive research databases for HCI (*ACM, IEEE*) and one academic search engine (*Google Scholar*).
Contributions: The first systematic overview and history of sketching in HCI, including generation of categories for sketching.

How can we use sketching with potential end users to inform the design and development of shape-changing interfaces?

Chapter 4 outlines a study which introduces non-expert users to the concept of shape-changing interfaces, utilising visual methods and annotation for the ideation of possible — and useful — applications for this technology. The ideas contained within this chapter form a body of work for generating dialogue between researcher and potential end user.

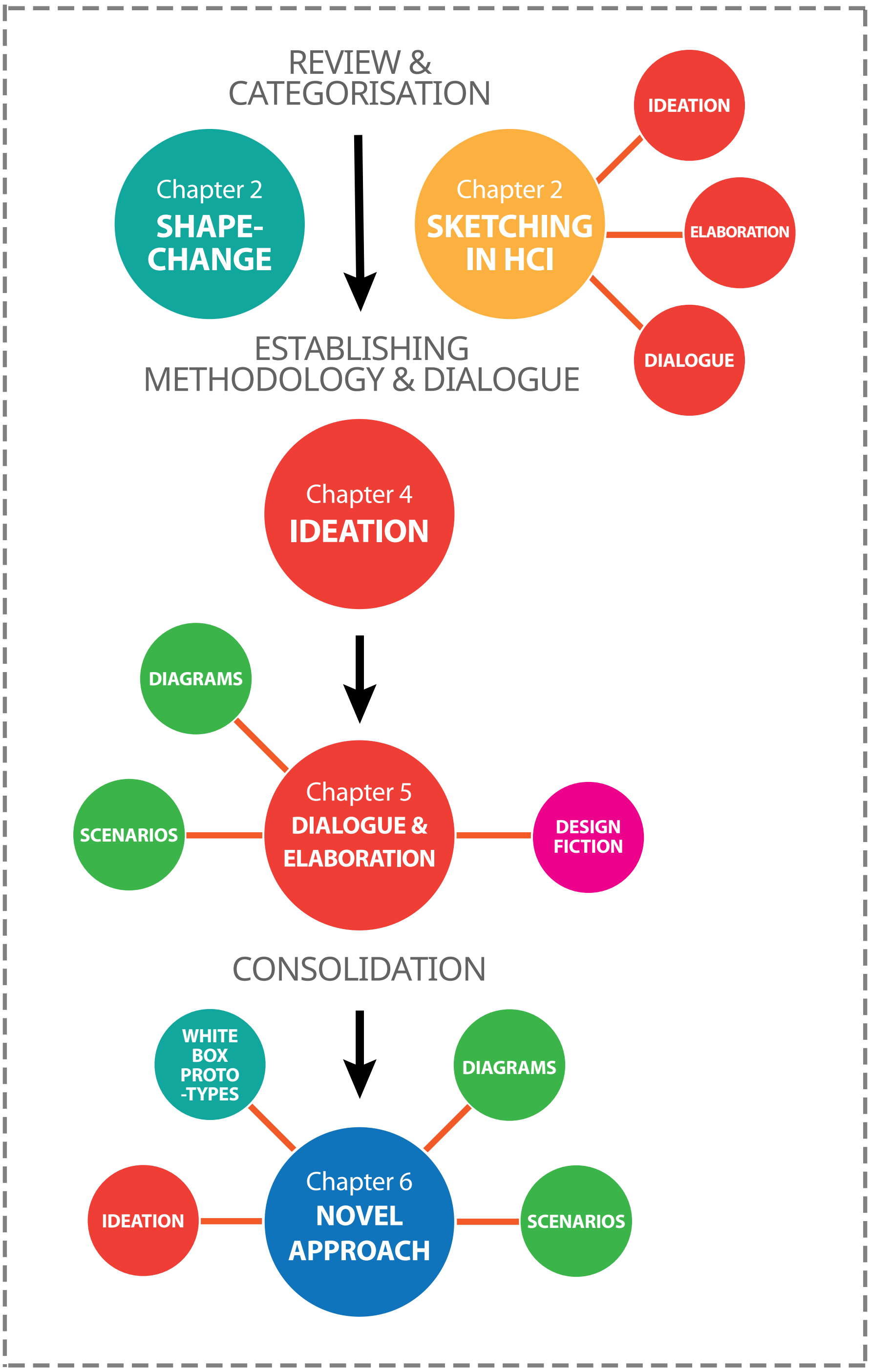


Fig. 1.1 Thesis Roadmap

Methodology: In order to communicate the complex nature of shape-change to non-expert participants, a boundary object (bridging method) is created using a portable, modular shape-changing interface which demonstrates actuation. In addition to this, posters which show other potential parameters of shape-change are shown to participants, to communicate the further opportunities for actuation. I then ask participants to use unstructured brainstorming to create sketched application ideas for shape-change. The qualitative nature of these outputs means that thematic analysis of ideas is necessary, so a grounded theory approach is used. The coding subsequently generates application categories for shape-change so an overview of potential uses can be created.
Contributions: An unstructured brainstorming methodology involving non-expert potential end-users; Categorisation of applications for shape-change; A database of the generated ideas available online at www.shape-change.org/brainstorm/

How can we use the information gathered from potential end-users to inform researcher-led inquiry in sketching and shape-change? How does this inquiry fit in with existing research in shape-change?

Chapter 5 is a subjective exploration of sketching as a tool for addressing the design of shape-changing interfaces from a researcher perspective, in both the ideation and design process (with reference to the body of work from Chapter 4), and also in exploring possible scenarios in storyboard form, based on existing publications. Finally, the theme of gaming in shape-change is elaborated upon in the form of a mixed sketched/text design fiction game manual.
Methodology: This chapter is comprised of three main sections which form a progression through methods of user dialogue, and subjective, researcher-led sketching. The three-part process allows us to see the potential outputs that are feasible for different levels of sketching practice, and therefore ensure that further work bases itself in the most viable methodology to create tangible research outputs.

The initial section is a dialogue between user and researcher. In addition to the application categorisation in the previous chapter, there is the potential for the user-generated ideation sketches to be further used to elaborate upon specific application ideas. These are either linked to current research directions, or are frequently occurring, and therefore likely to be prospects for future commercialisation. The elaboration takes the form of sketching as a thinking and critiquing process, grounding this process in a suggested under-explored area from shape-change research (ethics, security and safety) followed by generation of requirements from that process.

The second section identifies future work prospects relating to the application ideas in the first section, using existing published material as a resource. The elaboration via sketching is then taken further to create detailed scenarios (a common UCD process) which are then used to form a new dialogue with non-expert users and other HCI researchers. This dialogue produces themes and implications for shape-change that reinforce the findings from the first section, and also within the previous chapters. This provides justification for the earlier methodologies, and suggests that more detailed elaboration methods may generate further insights.

The third section merges sketching as an investigative technique with design fiction, which is commonly used to explore unknown future scenarios and prospective technologies, and therefore is a good match for shape-change research. This work produces a design artefact which allows for the subjective generation of complex requirements for both hardware and interaction.

Contributions: A dialogue and elaboration based sketching methodology for communication between user and researcher; A methodology for generating requirements from researcher-sketched imagery; Using case studies to demonstrate the potential of sketching and analysis in order to identify applications or implications for shape-change; Thematic evaluation of sketched user-scenarios for existing shape-changing interfaces from information generated by HCI practitioners and non-expert participants; Demonstration of subjective sketching and design fiction as a further method for elaboration and requirements generation.

How can we use the insights gathered from subjective sketching to generate more detailed responses from potential end-users? Can we use this information to generate requirements for shape-change?

Chapter 6 expands on the success of the previous work by utilising the combined ideas from chapters 2–5 to provide a study which not only provides a comprehensive overview of the field to non-expert users, but elicits diagrams and scenarios from which we are able to generate requirements and a stack model of development for shape-change.

Methodology: In order to connect the subjective practice from the previous chapter with user-based research, the methodologies from the ideation study and the subjective practice study are combined. Potential, non-expert end-users are asked to ideate, elaborate on one idea, and produce a scenario for that idea, set in the future where shape-change is commercialised. The produced outputs are thematically coded by in order to produce applications, requirements and implications for shape-change. These outputs are further coded and consolidated to produce a stack model for shape-change.

Contributions: A combined “videos, boxes, and sketches” hybrid UCD approach that aims to address the challenges of involving users in the requirements generation stage of shape-changing interfaces; A 50 participant study that aims to demonstrate the validity of this approach to generate requirements for this novel technology; A thematic analysis of the generated user requirements; A shape-changing requirements stack model

What does this body of work mean for the field of shape-change?

The discussion contained in **Chapter 7** provides justification for the use of sketching within both groups, for the eventual propagation and elucidation of this research area, and suggests steps for future work which encompass developing these techniques, and also application to novel research areas.

1.4 Contributing Publications & Outputs

The following works contain published material from this thesis. Contributions from co-authors are stated in line with the reference. Further works published during this thesis can be found in Appendix 1.

- **Sturdee**, M., & Alexander, A., 2018. Analysis and Classification of Shape-Changing Interfaces for Design and Application-based Research. In *ACM Computing Surveys (CSUR)*. Vol. 51, Issue 1. ACM. *All work by M. Sturdee with the exception of editing and commentary by J. Alexander*

- **Sturdee**, M., Coulton, P. and Alexander, J., 2017. Using Design Fiction to Inform Shape-Changing Interface Design and Use. *The Design Journal*, 20 (sup1), pp.S4146-S4157. *All work by M. Sturdee, with the exception of minor editing and commentary by J. Alexander, P. Coulton included in supervisory capacity*

- **Sturdee**, M., 2017, June. Drawing Design Futures for Shape-Changing Interfaces. In *Proceedings of the 2016 ACM Conference Companion Publication on Designing Interactive Systems* (pp. 399-401). ACM. *All work by M. Sturdee*

- **Sturdee**, M., Hardy, J., Dunn, N. and Alexander, J., 2015, November. A public ideation of shape-changing applications. In *Proceedings of the 2015 International Conference on Interactive Tabletops & Surfaces* (pp. 219-228). ACM. *All work by M. Sturdee, with the exception of joint thematic analysis and coding, and some editing and commentary by J. Hardy and J. Alexander, N. Dunn included in supervisory capacity.*

Chapter 2

Analysis & Classification of Shape-Changing Interfaces

2.1 Chapter Summary

Shape-changing interfaces are tangible, physically dynamic and often multi-modal devices, surfaces or spaces that allow users to experience real physical 3D computing. The complexity of the materials and the design of these devices is not standardised, and each example covers new ground, and often new hardware and programming.

Here, I examine the current state-of-the-art for shape-changing interfaces in a systematic manner in order to provide an overview of the field from which I can base my investigation. Over the last fifteen years, research in shape-change has produced functional prototypes over many use-applications, and reviews have identified themes and possible future directions — but have not yet looked at possible design or application based research. This literature review suggests that there are underlying themes in materiality and approach which can be capitalised upon for future design and application.

By conducting a meta-review of existing theory papers, I have been able to synthesise research into an overarching view of shape-change which is broken down into *Physical*, *Interactive*, *Temporal* and *Hardware* themes. A further analysis of 84 functional prototypes in relation to this overview produced distinct material and interactive properties, which then allowed me to categorise shape-changing interfaces for use in design and application based research. Eight categories of prototype are identified, followed by discussion and ideas for subsequent work.

This comprehensive review of shape-changing interfaces also made it possible to identify gaps in the theory and design processes for these novel technologies. Most prototypes are built with a single use case in mind and do not follow formal methodologies or use common materials. Although this variety is encouraging, it also means that there is no clear goal for the field. The foundations laid by this chapter allow us to ground the work that follows, and utilise the theory and categories to create dialogue with potential end users.

2.2 The Value of Reviews in HCI

Science and medicine have a long history of meta-analysis and systematic review, with computer science valuing reviews in the publication of high impact journals such as *ACM Computing Surveys* amongst others. HCI is no exception, and through reviewing existing reviews we can gather requirements for a successful and thorough analysis. Reviews in HCI appear to fall into one of two categories: either providing a critical overview or analysis without outlining the process of gathering papers for review [205, 44, 246]; or, providing an overview via conducting quantitative analysis and resulting categorisation or discussion around a subject area [141, 153]. The latter may, or may not include a visible search strategy, though those that do allow for provenance of data and replication of the work, which is often overlooked in HCI [116]. Despite an often rigorous process, there are still limits to many reviews in HCI, such as limited corpus ("we survey some influential textbooks and handbooks" [115]), only using top-ranking journals [152], or reviewing limited venues [141, 49].

The reasons for conducting reviews vary, for example, Hornbaek et al. [115] suggest that if no other reviews exist of an area then a review fulfils a role in expanding knowledge. Kjeldskov et al. compare and contrast two reviews to form opinion on mobile HCI [153] – the purpose being to produce an "empirically grounded characterization of state-of-the-art and current practices", whereas Kamppuri et al [141] regards the benefit of review process as allowing others to see the emergence of a field, categorise existing work, see emerging trends, as well as pinpointing pitfalls and promising directions. Finally, DiSalvo proposes reviews as allowing for a subject (e.g. sustainability) to position itself as a research field within HCI [49]. By conducting comprehensive reviews in this context, I firmly establish the groundwork and theory for the work contained within this thesis.

2.3 Introduction to Shape-Change

Shape-changing interfaces are physically geometric dynamic computational systems which also support an additional range of inputs (such as touch and shape-deformation) and outputs (such as light or sound). Prototypes of this nature are becoming more common within HCI, as advances are made in Shape Changing Materials/Alloys (SCM/SMAs), flexible displays and actuation techniques, thus supporting increasingly more detailed and interactive user experiences. It is feasible to imagine that within the next 50 years, such devices will augment or replace the pervasive 2D screens with which we currently navigate digital space.

Now that the field is maturing quickly, with highly interactive, dynamic and usable prototypes in abundance, we must think beyond the initial test-phase and toward designing meaningful applications (alongside the already identified interactions) for tangible future input and output. Although several research teams have begun to explore and discuss this exciting future, e.g. Roudaut [250] and Jansen [128], at present many applications are either pre-existing program types (such as music players or book readers) [164] or designed for one specific iteration of a device as a demonstration of its capabilities [173]. However, it is because of these explicit investigations, that we have a solid starting point for the evolution of these interfaces. The difficulty lies in creating content for such diverse and multi-dimensional devices.

Poupyrev [236] suggested in 2007 that future research might systematically investigate applications of actuated devices for various uses, outlining how our notion of pixels might further develop as dimensionality is added to graphical information (See Figure 2.1). Additionally, whilst researchers have started to try and make sense of the design space of shape-changing interfaces, where multiple dimensions must be considered at the same time [34, 161, 323] thus far it appears that there has been little consideration for designing generic applications for shape-changing devices, as we might do for standard 2D UIs. Speculative work relating to solving current hardware problems, or the qualities of future materials [123], leaves a space in between the prototypical present, and the near future of marketable shape-changing products.

The basis for this work is the significant body of research on gestures and interactions with shape-changing displays [83, 313] (for example), but the results of these studies have not yet been channelled into a consolidated, cross-paper set of guidelines for designers. There are even prototypes designed specifically for the act of prototyping itself [102, 111] to help designers make the first step, but there appears to be no united front on where that first step falls.

In order to assist researchers and designers in continuing to examine the current state of the field and the potential applications, this review collates some of the existing theoretical work on designing for shape-change — taken from several reviews [34, 161, 217, 242], interaction studies [111, 215], prototyping tools for shape-change [102] and general prototype papers — to create a comprehensive overview of dimensionality within shape-changing interfaces. The resulting amalgam from these detailed reviews (looking at such features as spatiality, temporality, interaction, and hardware) is then applied directly to existing work on these prototypes, so that categories of device are formed. These categories are discussed in relation to the design space, existing research, and limitations. The discussion looks at supporting application design, hybridisation, limitation in design, future use cases, emotionality and user experience, future use cases, perception theory, the notion of temporal design and ethics, whilst considering how speculation might inform future work.

Tangible User Interfaces (TUIs) are swiftly making inroads into retail reality (witness Nokia's *Kinetic Device* [149]), merging with shape-changing displays to create shape-changing user Interfaces. Holman and Vertegaal [112] comment on the complexity of designing for this new generation of shape-changing interface/display, stating that all physics acting upon displays, including their shape, will be used to manipulate information. So we must look not only to the manipulation of physical form to design our applications, but also to the other senses and beyond. The following work is the first consolidated review of shape-changing interface theory, and also the first to provide a comprehensive analysis and categorisation of existing prototypes. The latter is necessary in order to begin to formalise design for the field and should be used to inform detailed application design for current shape-changing interfaces in the research context.

This chapter contributes a contemporary meta-analysis of shape-changing design theory, a detailed database of shape-changing prototypes, and a categorisation of types of shape-changing interface (*Enhanced 2D, Bendable, Paper & Cloth, Elastic & Inflatable, Actuated, Liquid, Malleable and Hybrid*). The aim of the chapter is to assist researchers interested in contributing novel prototypes and their applications to the field, and designers who wish to gain knowledge of current hardware to begin to create meaningful deformable applications for real world iterations of these devices. The main goal of this review is to set the stage for application design for shape-changing interfaces by providing a reference guide for each interface type and their associated interactions, with which we can inspire real use cases for existing prototypes and look beyond this, to the commercial future of shape-changing interfaces.

2.4 Previous Reviews & Analysis

There is a well-cited and succinct body of work that outlines the current design and mechanical aspirations of the shape-changing interface field. These are outlined in this section, and relate to the consolidated dimensions in Figure 2.1. The contribution of this chapter in relation to previous work is in its thorough review of the available literature, combined analysis of leading papers in the field, novelty of the consolidation of attributes and subsequent categorisation of prototypes within this context. This is the first time the field of shape-change has been looked at in as much breadth and depth, and builds upon the valuable contributions made by the researchers discussed below.

Rasmussen's review of shape-changing interfaces [242] suggests that there is a great deal of research into hardware, but that the design possibility of this space is an underexplored direction. If, as Vallgårda [323] states, a "new expectation of the computer is already being formed" we therefore need to rise to the challenge of meeting this expectation with tangible shape-changing interfaces that will appeal to the next generation of users. Vallgårda creates a baseline for the new type of interaction design necessary for shape-changing interfaces, where temporality meets the physical and the interactive possibilities of such devices. This "trinity" should form the cornerstone for any designer wishing to make a start in this area.

Kwak [161], held boot-camps for industrial designers to create platforms for prototyping design for shape-change, meaning that future designers can explore basic transitions and actions which then form the basis for the nascent application of shape-changing interfaces and displays. Six prototyping tools were identified from an initial selection of ten which cover a range of deformations and actions (*Piega, Gato, Yeti, Fantom, Squeezy & Bulge*). These prototyping devices mirror the most common deformation styles found in shape-changing interfaces (bar those that make use of 2D flexible computers), and thus provide a neat overview of deformation styles, which can be aptly applied to the overview of shape-changing interfaces.

From a point of view based on the theory of *Non-Uniform Rational B-Splines*, Roudaut et al. propose a framework for shape-resolution – aimed at assisting engineers in creating high resolution displays [250]. This framework is only as good as the technology allows though, and its advanced features will need to be applied gradually. It also only applies to those mechanisms which can be thought of as having nodes/loci of control (as seen in a mesh overlay), and thus only applies in part to shape-changing materials, which also require thinking in other dimensions which may not be so constrained.

Coelho et al's review [34] focuses on all possible realities for shape-change in a speculative manner, and further provides an overview of the field as it was in 2011. By combining the multiple dimensionality of shape-changing interfaces, they attempt to begin construction of a "soft" mechanical alphabet for HCI (after 18th century engineer Polhem) with which designers can orientate themselves for this conceptually complex research area. This notion supports this review in regards to the need for a modular design theory for those wishing to engage in application design for shape-changing interfaces [102].

From the side of programming interactions, there has been a start on creating a specific languages for designing shape-changing interactions (based on existing *Shader* languages

[342]), but any advances in programming will still need to be relatable to designers. At present, researchers must have a firm grounding in programming, electronics, and mechanical engineering to engage with shape-changing interfaces, although this might change in the wake of the recent surge in interest toward interdisciplinary study.

2.5 Consolidation of Shape-Change Themes

A meta-analysis of papers from Coelho [34], Roudaut [250], Taher [299], Rasmussen [242] and Kwak [161] was conducted, alongside complimentary information from Nørgaard [217], Schmid [263] and Hardy [102] in order to create a comprehensive overview of the state of shape-change as it stands at present. These papers were chosen as they covered the breadth of the area in terms of interfaces, although SCM papers were consulted alongside to ensure that all dimensions of change were covered. The categorisations provided by each researcher are mapped alongside one another in Figure 2.1. Following analysis of these papers, it was also found that the types of change which one needs to consider when thinking around the topic of design followed closely to Vallgårda's [323] "Trinity of Forms". A separate area for back-end, hardware considerations was created, in order to relate back to the hardware and mechanism of shape-changing interfaces, rather than the pure theory.

To summarise the sections in Figure 2.1, the *Spatial* section relates to topology, expansion, height and spread of the interface display area; *Orientation/Path* toward folding and turning abilities of devices; *Resolution* toward textural and pixel quality (which may go hand-in-hand according to Nørgaard [217] – a high enough shape resolution means that the generation of texture is a given); *Materiality* concerns the pliability and strength of the surface; and *Divisibility*, the separation of component parts or ability of a material to let through matter.

The interactive qualities of a shape-changing interface are not expanded in this diagram, as interaction is a multi-faceted aspect of a shape-changing interface and requires a more detailed overview (see [242]). Rasmussen et al. suggest three types of interaction in shape-change: direct, indirect and remote. These types are used in applying classification to the existing prototypes in Tables 2.1–2.8, as well as including types of input/output. These are discussed in the next section.

Temporality is a relatively new concept in design for TUIs (though not in interaction design), but known to those working on shape-change and therefore is vital to any theorist hoping to create content for these devices. Finally, the mechanistic aspects, or hardware in a device are held separate, but nonetheless accountable to the interface itself, for these component parts hold the key to the outer and inner limits of what is possible now, and in the future.

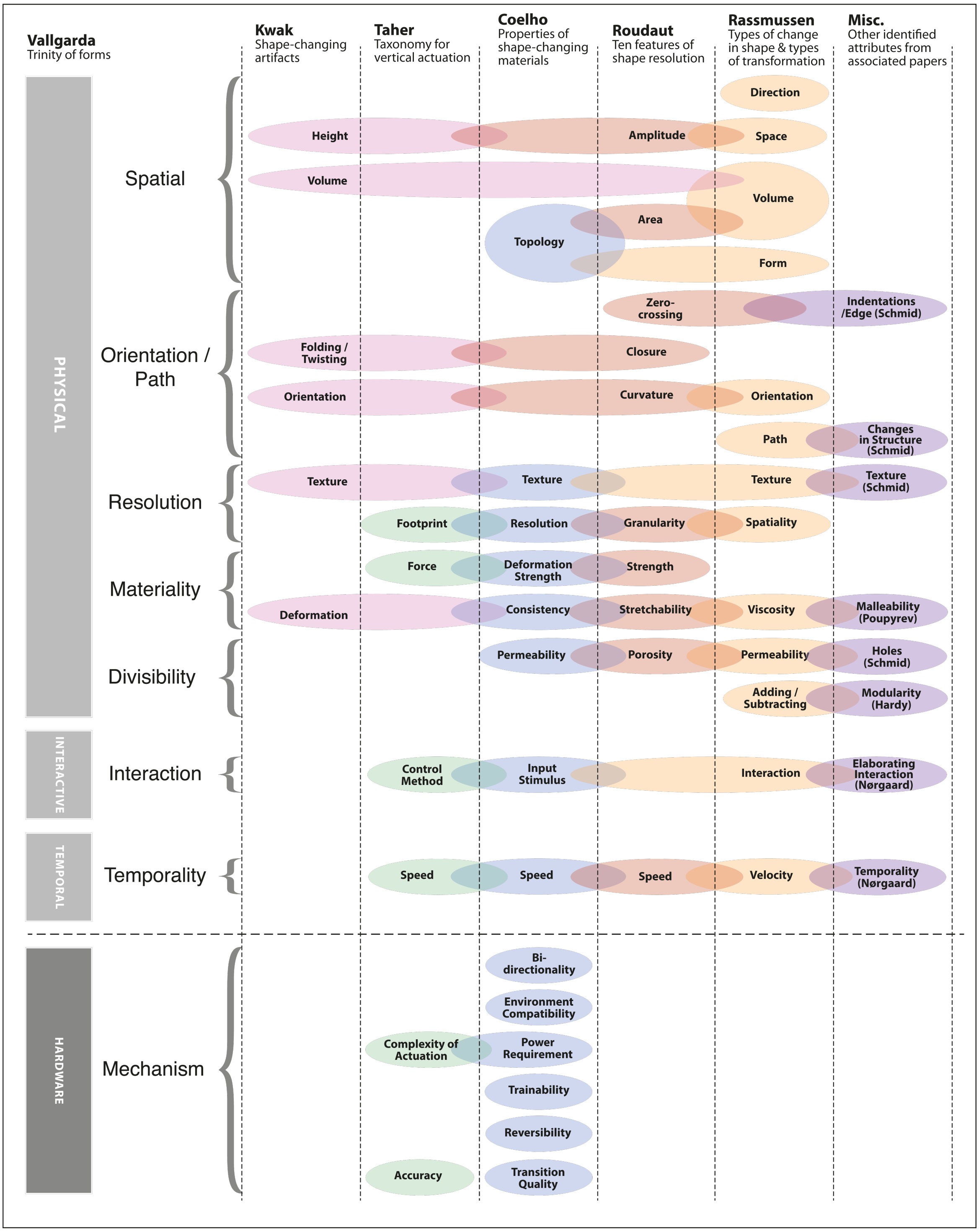


Fig. 2.1 Meta-analysis of shape-change review papers, taxonomies and categorisations

By examining the ways in which these dimensions map alongside each other and interact, we have ensured that we have an easily accessible summary from which we can begin to formalise the nature of this area — all these categories are discussed in more detail in section 2.7. The information in Tables 2.1–2.8 is based on this summary, and the nature of existing devices in relation to the wider theory-based dimensions is discussed later in the chapter.

2.6 Application to Existing Prototypes

Having condensed current theory into a meaningful summary (Figure 2.1), the next stage was to apply this method of analysis to existing prototypes in order to gain an overview of the current state of the art with regards to design and applications. The category descriptions in the previous section are changed to reflect existing deformation types (rather than future possibilities), and the interactive aspect constructed during analyses of the literature. It also proved of further use to add fields to the following tables which give additional information (such as 2D/2.5D/3D).

Tables 2.1–2.8 provide a comprehensive overview of 84 existing shape-changing prototype interfaces from the past 16 years, as they were at time of writing. This builds upon Rasmussen's review of 44 papers on shape-changing interfaces [242], but with a more refined criteria for inclusion and an tabulated analysis which compares the field. Figure 2.2 provides a graphical overview of this categorisation in order to compare between groups at a glance. Further to this, a summary table (Table 2.9) outlines the main features of the display categories.

2.6.1 Inclusion Criteria

The inclusion criteria are that: each prototype must be interactive (have at least one human user), have at least one type of input and output occurring *on the same surface*; and that each included prototype must be composed of a malleable material or deformable mechanism. These criteria mean that *ShapePhone* [66] and *Behind-the-Tablet Jamming* [66] are exempt (because *ShapePhone* is an input only deformable phone prototype with no display mechanism, and *Behind-the-Tablet Jamming* separates deformation area and display) but that *Tunable Clay* is included as the image is projected directly onto the malleable surface [66]. The same reasoning applies to Tangible User Interface (TUI) input-only devices such as *BendID* [215] and *AR-Jig* [8]. Additionally, although Asif Khan's *Megafaces* [148] is an exemplar of an hydraulic actuated display — reflects user input (digital photography and 3D image extrapolation) — it does not behave as a true interface (as described above) in its current iteration. The user in this case is passive, and unable to dictate or influence the output.

Another type of shape-changing prototype that is excluded is Guo et al's *Garden Agua* [94] — despite being described as shape-changing display in the literature — as it deals only with moveable solid objects and not surface deformation. The same premise also applies to *Ariel Tunes* [5] due to the modular and limited nature of its current form-based output. Despite the pixel-like nature of the floating balls in *Ariel Tunes*, the display supports only one type of interaction and one type of output. This is not to say that future iterations of such mechanisms may not fulfil the criteria outlined here. Finally, where there is more than one iteration of the same prototype, the most recent is included, unless a significant change to the usage has been implemented — such as *FuSA 2* [207].

The reasoning behind setting strict inclusion criteria is that tangible input devices require design only for existing 2D output, which is a well established field, hence the same surface must be utilised in order to establish something novel. The same also applies to non-deformable surfaces — there is no need to establish a new framework of analysis or design. It is also worth noting that definitions of "interface" within shape-change differ between researchers, the criterion here are not intended to exclude without reason, merely to draw a line around what a shape-changing interface is for the purpose of analysis. Future work may expand on this analysis to look at the wider field of tangible TUIs and shape-displays within the overview provided here.

2.6.2 Dimensions of Shape-Change

In applying existing prototypes to category headers, I further condensed the dimensions from within Figure 1, and also identified types of prototype hardware currently used in the literature. The resulting fields of classification are discussed below in order to clarify their use.

2.6.3 Hardware

The mechanism, or hardware, of each device is directly linked to its shape-changing properties (see Figure 2.1). As advances are made in the field of shape-change, it is anticipated that the list of hardware types will grow. As of now, 24 basic hardware composites exist from current prototypes, which can be combined to create amalgams of shape and display. Each table outlines a primary and/or secondary mechanism where this is integral to the interaction of the prototype. Incidental structural materials, such as latex or wood, are omitted from this list.

Some of the dimensions of shape-changing interfaces were identified at the consolidation stage, but either do not apply to existing prototypes in a quantifiable manner (i.e. power requirement is something to be considered at the commercialisation phase) or would require additional levels of detail and discussion for each individual prototype which are not possible within the scope of this chapter.

Bi-Directionality

Whereas Coelho stated that bi-directionality is specifically important for designers [34] it is not an exclusive construct within shape-changing prototypes, and thus has not been applied to the list. Bi-directionality refers to the properties of a material/device to physically change shape in the same way when deformed by a user, and when self-actuating. This is important during the design process as it has an effect on other material properties of the interaction surface, and the interactions a user will have with the interface (i.e. Non-bi-directionality might be seen in the case of clay-based interfaces where the user can deform the surface, but the surface itself is passive, in which case it must be manually "re-set").

Most examples have varying inputs and outputs but they are not always linked, for example, form-input is not always directly related to form-output by the mechanism, such as with *Paddle* [238] which utilises purely user-controlled deformation. For *Paddle* to exhibit bi-directionality, it would have to be able to deform itself in response to some other form of input, such as a telephone call activating a form-state.

Some examples do exhibit bi-directionality in limited ways however: *ShapeClip* [102] is bi-directional in respect to the input/output of tangible form and light, but can only react to image-based light input, not produce it (this limitation is addressed by *ShapeCanvas* [58] however, which uses the same base mechanism). The same applies to *LightCloth* [105] which accepts/projects light as input/output, but deformation is an input only (the user can manipulate the cloths' form, but the cloth cannot manipulate itself programmatically). Therefore it can be considered that bi-directionality is not a given, and as such not essential in the design of shape-changing applications as meaningful interactions can be had across modalities.

Environmental compatibility/power requirement

Environmental compatibility (the suitability of a device for its environment [34]) and power requirement are important considerations for the future of shape-changing devices, but at present are not included due to the prototypical nature of the examples — due to the

Fig. 2.2 Overview of shape-changing prototype categories

immaturity of the field, these are future considerations. The application of shape-change in real world scenarios must come before situational problem-solving at this stage.

Reversibility, transition quality & accuracy

Of the remaining aspects of the hardware, reversibility is a given for shape-change in this case, as otherwise there would be no form-based interaction past the initial deformation. Transition quality and accuracy are difficult to assume from the literature alone: without analysis of these aspects in particular for each prototype, I cannot begin to attribute these qualities to the mechanics of each device. The remaining dimensions (accuracy, trainability and complexity of actuation) are rooted firmly in the material/actuation type, and can be related directly back to the primary hardware categories.

2.6.4 Interactive

The interactive aspects of shape-change are expanded from Figure 2.1 as these are the most important aspect of shape-changing interfaces: without the user, a prototype is passive or remote [242]. Interaction is primarily defined by Rasmussen's initial review of shape-change and can be defined as *direct*, *indirect* and *remote*, this is discussed below. Interactive shape-changing art installations are included if they fulfil the earlier criteria (such as *AegisHyposurface* [87] or *Protrude, Flow* [156]).

The proximal considerations for the user are based on Rasmussen's classification of interaction (see previous paragraph), omitting only "none" as a type of interaction, for the reason given above. *Direct* proximity infers that the user can touch the surface of, or interact with the prototype directly (as with *ClaytricSurface* [259]), without the need for an additional item such as a ring or wand (as is the case with *Linetic* [157]). *Indirect* proximity requires an additional construct for the user to interact (such as a connected laptop as with *Flexkit* [111]) or the user can use mid-air gestures as a form of input – but this can exist in tandem with *Direct* proximity. This is also the case for *Remote* operation, which suggests that the interface can be controlled via infrared, wireless or Bluetooth technology, and therefore, in the case of wireless internet communication, from almost any distance.

Almost any kind of input or output could be designed for shape-changing interfaces, but the tables record only current iterations. Smell, for example, has been used in *clayodor* [142] as an output, but this prototype is not included due to the separate nature of the input/output components. Future types of input might include those that are non-visible, such as radiation or air quality. Of the research surveyed, it can be seen that there is currently a greater variety of input than output. Inputs thus include: program (a program is used to control some aspect of the interface, such as the bend of the SMA [83], or visual imagery [221]); gesture [102] [157]; touch/haptic [216, 317]; light [284]; sound [87]; and deform (separate from simple touch sensitivity, this implies some force or movement is applied to change the shape of the available surface, whether it is bending [305], pushing [67] or more advanced deformation [259]).

Output is currently limited to: form (as discussed in relation to bi-directionality) e.g. [251, 334]; sound (deliberately generated, as opposed to an incidental sound generated by the mechanism) [158]; light (often as an artefact of projection [174], or internally generated [235]); and text/image [4, 193].

Number of users was also found to be relevant to interactions with prototypes — because it changes the way designers think about their interface — although it was not always explicitly written how many each device was designed for. *Xpaaand* [147] is a mobile device prototype based around one user perspective, but the discussion highlighted the possibility that a large change in width supports multiple user interaction. In comparison, *inFORM/TRANSFORM*'s *physical telepresence* [173] is specifically designed to support remote interaction between two users. *Aegis Hyposurface* [87] is a large public installation, and therefore can support multiple users, hence it is listed as supporting all three user bases. Where number of users is not explicit, then the prototype user base is estimated based upon size: mobile phone devices are attributed to one user, tablet size devices to two users, and anything of tabletop size and above is seen to support multiple users.

2.6.5 Temporal

The notion of temporality in design is in its infancy, but is inextricably linked to both the physical and interactive dimensions of interaction for shape-changing interfaces [323] (see Figure 2.1). Understanding the limitations of time and speed for each prototype is essential for implementing successful design strategies. Whilst categorizing existing work for Tables 2.1–2.8, the origin of control for speed was found to be important as it affects how interaction occurs and how the user experiences the prototype. Interfaces were found to support three types of control: *program defined* — the speed of change is defined by programming, as in *Aegis Hyposurface* [87] which can move up to 100km an hour; *material defined* — limitations are placed on the speed with which a change can take place due to material constraints, such as with SMAs [250] or actuators [216]; and *user defined* — the user controls the speed of deformation via direct deformation at a chosen speed (but within the limits of the device) [157]; or all three [102].

Designing for temporality is at its most difficult when the potential exists on all three dimensions. The desire for speed from the user may not always match the intentions of the application — i.e. an educational application might move with deliberate sluggishness so the child cannot skip parts, or by increasing the speed of a transformation, essential information might be lost. The opposite is also true — when browsing a shape-library, you may need to skip ahead or traverse options swiftly. These aspects and more must be designed for, or against: the application must be able to control the pace that is most conducive for its purpose.

2.6.6 Physical

The physical characteristics of shape-change emerge as quite distinct from the consolidated dimensions seen in Figure 2.1. Application of these dimensions to existing interface examples allows specific deformations to be noted and discussed. The physical changes of a surface range from the basic (*height/width/bend*) to the complex (*closure/divide*).

Height is the most commonly found change in actuated and material based deformations. It implies that the prototype experiences a change in height of the surface relative to its baseline (non-deformed starting point). This is always limited by the hardware making up the device. Height is also applied as a change to those prototypes which make use of one axis, in one direction [87] as the same idea applies despite the change in orientation.

Width, on the other hand, requires a two-way expansion across a plane, regardless of direction. This can be due to a stretch in the shape-changing material from jamming for

	HARDWARE		INTERACTIVE																	TEMPORAL			PHYSICAL													
	MECHANISM		*PROXIMITY*			*INPUT*						*OUTPUT*				*USERS*			*CONTROL*			*SPATIAL*		*ORIENTATION & PATH*				*MATERIALITY*	*DIVISIBILITY*	*SHAPE RESOLUTION*		*DIMENSIONS*		
ENHANCED 2D PROTOTYPES	**Primary**	**Secondary**	**Direct**	**Indirect**	**Remote**	**Program**	**Gesture**	**Touch/Haptic**	**Light**	**Sound**	**Deform**	**Form**	**Sound**	**Light**	**Text/Image**	**1**	**2**	**3+**	**Program Defined**	**Material Defined**	**Touch Defined**	**Height**	**Width**	**Bend**	**Closure**	**Fold**	**Roll**	**Stretch**	**Divide**	**High**	**Low**	**2D**	**2.5D**	**3D**
Display Stacks [78]	OLED		x	x		x	x	x			x			x	x		x				x	x		x					x		x	x		
FoldMe [146]	Projection		x		x	x		x			x		x	x	x	x					x		x		x	x					x	x		
Paddle [238]	Projection		x					x			x	x	x		x	x					x	x	x		x	x					x	x		
PaperFold [85]	Electrophoretic		x	x	x	x		x							x		x				x	x	x	x	x	x			x		x	x		
Shape Shifting Wall [301]	Roomba Create	Projection	x	x		x	x	x			x	x			x			x	x		x		x			x			x		x	x		
Transform Table [300]	Projection		x	x		x		x				x		x	x			x	x				x			x					x	x		
Xpaaand [147]	OLED		x					x			x						x				x		x				x				x	x		

Table 2.1 Enhanced 2D prototypes comparison table based on dimensions from Figure 2.1

instance [224], or due to a device having the capability to be unfolded, such as with *Paddle* [238].

Bend, is most common with flexible displays such as *Morphees* [250] where the thickness of the OLED display or constraints of the SMA wires means that only a slight deformation of an otherwise 2D item is permissible.

Fold is closely related to closure — but the distinction lies between surface merely creasing and the surface folding entirely in on itself. Reabsorption happens in the cases where a ferrofluid is used (*pBlob* [334]) or edges meeting with a static surface (*PaperFold* [85]).

Roll also often goes hand in hand with highly flexible static surfaces — the best example being *Xpaaand* which is encased in rolls at either end [147].

Stretch is distinct from *width*, as it implies an area expansion from baseline based on materiality rather than simply displaying more of the same substrate. Stretchable materials are usually incidental hardware (like latex) and used over actuators [104] or in jamming [259].

Divide suggests either a modularity in actuators or components as seen in *Hairlytop* [216], *PaperFold* [85] and *ShapeClip* [102] or where a solution can be split into parts and reunited as in *pBlob* [334]. *Shutters* [33] is an interesting hybrid, using folds and splitting simultaneously to allow for a divided (or permeable) surface.

Resolution refers to shape-resolution as coined by Roudaut et al. [250] and incorporates the textural element as discussed earlier in section 2.5 [217]. A high shape resolution is the same as a high pixel resolution in that a 2 dimensional representation of a sphere on a low resolution screen would show “squaring off” or *aliasing* around the edges, whereas a low shape resolution sphere would have angular blocks making up its surface. Liquid interfaces have high shape resolution due to fact they do not rely on set sized nodes as actuators do.

Dimension falls between 2D and 3D, referring to 2.5D as either a limited 3D display (i.e. one plane of deformation only with projection as a separate construct) or as one where there is sufficient deformation possibility that the design-surface would need to allow for form if the display was to have an application design for it. 2D shape-changing interfaces in this case are typically changing their area (width) but the design space is resolutely flat.

2.7 Categorisation and Analysis of Prototypes

Following application of the previous consolidated dimensions to 84 existing prototypes, 8 distinct categories of prototypical device emerged based on the properties of the hardware and mechanism of the collected technologies. Physicality (hardware or primary mechanism) was

		HARDWARE		INTERACTIVE																TEMPORAL			PHYSICAL												
		MECHANISM		*PROXIMITY*			*INPUT*						*OUTPUT*				*USERS*			*CONTROL*			*SPATIAL*		*ORIENTATION & PATH*				*MATERIALITY*	*DIVISIBILITY*	*SHAPE RESOLUTION*		*DIMENSIONS*		
		Primary	**Secondary**	**Direct**	**Indirect**	**Remote**	**Program**	**Gesture**	**Touch/Haptic**	**Light**	**Sound**	**Deform**	**Form**	**Sound**	**Light**	**Text/Image**	**1**	**2**	**3+**	**Program Defined**	**Material Defined**	**Touch Defined**	**Height**	**Width**	**Bend**	**Closure**	**Fold**	**Roll**	**Stretch**	**Divide**	**High**	**Low**	**2D**	**2.5D**	**3D**
BENDABLE PROTOTYPES	*Bendy [189]*	Projection		x								x			x	x	x					x	x	x	x							x	x		
	Bookisheet [339]	Projection		x					x			x			x	x	x					x	x	x	x	x						x	x		
	Cobra [354]	Projection		x	x		x		x			x	x		x	x	x					x	x	x	x							x	x		
	Device Bend Gesture [2]	OLED		x		x	x		x			x		x	x	x	x					x	x	x	x							x	x		
	Flexkit [111]	Electrophoretic		x	x		x		x			x				x		x				x	x	x	x							x	x		
	Flexible Input Device [74]	Projection		x	x		x	x	x	x		x			x	x	x					x	x	x	x	x	x	x				x	x		
	Nokia Kinetic [149]	OLED		x			x		x		x	x	x	x	x	x	x			x		x	x	x	x							x	x		
	ReFlex [289]	FOLED	Haptic Actuator	x		x	x		x			x		x	x	x	x				x	x	x	x	x							x	x		
	Snaplet [304]	Electrophoretic		x	x	x	x		x			x	x	x	x	x	x			x		x	x	x	x							x	x		
	WhammyPhone [84]	FOLED		x			x		x		x	x		x	x	x	x					x	x	x	x							x	x		

Table 2.2 Bendable prototypes comparison table based on dimensions from Figure 2.1

the vital factor in assigning these categories as it had the most influence on user-interaction and shape-input/output. For example, a user interacts with an elastic interface in a very different way to an actuated interface (i.e. it is impossible to stretch a solid-state pneumatic pin).

The 8 categories are: *Enhanced 2D* (Table 2.1), *Bendables* (Table 2.2), *Cloths & Papers* (Table 2.3), *Elastics & Inflatables* (Table 2.4), *Actuated* (Table 2.5), *Liquids* (Table 2.6), *Malleables* (Table 2.7) and *Hybrids* (Table 2.8). These categories are clear groupings which stand out from a combined analysis, as they often share common themes not only within their hardware, but across the interactive, temporal and physical dimensions. A comparison between these categories can be seen in Tables 2.9 and 2.10. Each category is discussed in detail below.

Enhanced 2D

Prototypes make use of multiple incidences of 2D screens which flex along either axis (see Table 2.1). Prototypes must have one or more screen or extra surface available which operates independently from its primary interface surface (see Table 2.1). The primary method of shape-change is touch defined (with the exception of *TransformTable* [300]). Shape resolution is low.

These types of devices account for nearly 10% of the surveyed literature (7/84). Design for *Enhanced 2D* interfaces should exploit multi-screen interactions or applications and either exploit or avoid the ensuing perceptual angles allowed by such prototypes (such as when a geometric shape such as a boat is constructed [83]). With regards to this, designers should also be a focus on user perception over more than 2 screens, as well as number of users and how they communicate about differing screen-states during multiple use interactions. Single user scenarios fit more commonly into existing device designs and therefore there are existing precedents (e.g. *Nintendo DS*™).

Bendables

These devices have one display and interaction surface, but that surface has movement in terms of bend or flex at the corners, middle and edges (including twist) (Table 2.2). The image is essentially planar, and the shape-resolution low in comparison to the visual display, but the added emphasis on user interaction and programmed movement is how these prototypes differ from their *Enhanced 2D* counterparts. Design for *Bendable* interfaces is 2D single screen, with additional movement as its key feature — creating multiple modes of interaction.

	HARDWARE		INTERACTIVE																TEMPORAL			PHYSICAL												
	MECHANISM		*PROXIMITY*			*INPUT*						*OUTPUT*				*USERS*			*CONTROL*			*SPATIAL*		*ORIENTATION & PATH*				*MATERIALITY*	*DIVISIBILITY*	*SHAPE RESOLUTION*		*DIMENSIONS*		
PAPER & CLOTH PROTOTYPES	**Primary**	**Secondary**	**Direct**	**Indirect**	**Remote**	**Program**	**Gesture**	**Touch/Haptic**	**Light**	**Sound**	**Deform**	**Form**	**Sound**	**Light**	**Text/Image**	**1**	**2**	**3+**	**Program Defined**	**Material Defined**	**Touch Defined**	**Height**	**Width**	**Bend**	**Closure**	**Fold**	**Roll**	**Stretch**	**Divide**	**High**	**Low**	**2D**	**2.5D**	**3D**
Cloth Displays [177]	Projection		x	x			x	x			x			x	x	x				x	x	x	x	x	x	x	x	x		x				x
Flexpad [284]	Projection		x	x		x			x		x				x	x					x			x	x	x	x				x		x	
FluxPaper [220]	Electromagnetic		x	x		x		x			x	x				x			x	x	x	x	x	x	x	x	x		x		x		x	
FuSA 2 [208]	Optical Fibre	Projection	x					x	x		x			x	x		x			x	x	x		x					x		x		x	
IllumiPaper [154]	Electrochromism	Electroluminescence	x	x				x						x	x	x					x			x	x	x	x		x		x	x		
jamSheets [224]	Jamming	Projection	x			x		x			x	x		x	x		x		x		x	x	x	x	x	x	x	x	x	x				x
LightCloth [105]	Optical Fibre		x	x					x		x	x		x			x				x	x		x	x	x	x			x		x		
Metamorphic Light [193]	Projection		x	x			x	x			x			x	x	x					x			x	x	x	x				x	x		
Murmur [254]	CPU Fans			x						x		x						x	x	x	x	x		x		x					x		x	
PaperPhone [164]	OLED	Electrophoretic	x			x		x			x	x		x	x	x					x			x							x	x		
PaperTab [305]	Electrophoretic		x			x	x	x			x				x			x			x			x							x	x		
PaperWindows [113]	Projection		x	x			x	x			x			x	x			x			x		x	x	x		x		x		x	x		
PrintScreen [221]	OLED	TEFL	x	x		x		x			x			x	x			x			x			x	x		x				x		x	
Projectagami [302]	Projection		x					x			x				x	x					x	x	x	x	x	x	x				x	x		

Table 2.3 Cloth & Paper prototypes comparison table based on dimensions from Figure 2.1

Bendables account for just over 10% of the surveyed prototypes (10/84), largely focusing on either input and interaction [339] or physical, unobtrusive notifications [189]. Physical changes in shape to inform users of application states has links to the *emotionality* in shape-change, which has been explored in part by Rasmussen et al. [242, 239]. The prospect of anthropomorphising our user-interfaces adds a curious and exciting aspect to creating applications for shape-changing interfaces. Design for a *Bendable* also largely needs to focus on mapping interactions and outputs to the range of supported flexes for any given prototype (*MorePhone* supports 17 interactions [83]).

Papers & Cloths

Table 2.3 shows prototypes which fulfil the criteria of *Papers & Cloths*. These prototypes have one interaction surface, but are highly adaptive in terms of orientation and path, mimicking the characteristics of their non-interactive base-materials. Deformation is primarily user-controlled. These prototypes can borrow from web-design (in that re-flowable content to fit the visually available area is used) or be re-purposed into novel interface designs (wearables/furniture).

Around 16% of the prototypes in this summary are *Papers & Cloths* (14/84). Devices of this nature would be beneficial in situations where they need to be portable, and condensed into small spaces for transport or covert use. For this reason they might be well-suited to multimedia applications where viewing size is important across a range of scenarios.

Elastics & Inflatables

Elastics & Inflatables are deformable interfaces that are made up of materials with built in stretch such as *Elascreen* [358]. Control here is shared between the actor (user) and the material (which has a high-speed return-to-baseline). These interfaces have an organic appeal (such as *EmoBalloon* [207]) but usually have limited shape resolution (with the exception of jamming interfaces [66]). Like *Bendables*, they can also exhibit *emotional* characteristics.

Just over 10% of shape-changing prototypes exhibit criteria which assign them to this category (9/84). Large scale elastic screens [313] suggest use cases such as exploration of data or gaming, whereas the organic nature of such interfaces makes them suitable for communication or tangible interaction with other users. A combination approach between jamming and larger elastic surfaces would yield more complex interaction styles and application opportunities. These pliable materials also have the potential to change their interaction area drastically, which would assist when multiple users need to collaborate on demand.

		HARDWARE		INTERACTIVE																TEMPORAL			PHYSICAL												
		MECHANISM		*PROXIMITY*			*INPUT*						*OUTPUT*				*USERS*			*CONTROL*			*SPATIAL*		*ORIENTATION & PATH*				*MATERIALITY*	*DIVISIBILITY*	*SHAPE RESOLUTION*		*DIMENSIONS*		
		Primary	**Secondary**	**Direct**	**Indirect**	**Remote**	**Program**	**Gesture**	**Touch/Haptic**	**Light**	**Sound**	**Deform**	**Form**	**Sound**	**Light**	**Text/Image**	**1**	**2**	**3+**	**Program Defined**	**Material Defined**	**Touch Defined**	**Height**	**Width**	**Bend**	**Closure**	**Fold**	**Roll**	**Stretch**	**Divide**	**High**	**Low**	**2D**	**2.5D**	**3D**
ELASTIC & INFLATABLE PROTOTYPES	*Deformable Workspace [340]*	Projection		x	x		x		x			x			x	x	x				x	x	x						x			x	x		
	DepthTouch [232]	Projection		x					x			x			x	x	x				x	x	x		x		x		x			x	x		
	ElaScreen [358]	Projection		x								x			x	x	x				x	x	x						x			x	x		
	Emoballoon [207]	Pressure Sensor		x					x			x			x		x				x	x	x	x					x			x			x
	Flexiwall [70]	Projection		x					x			x			x	x			x		x	x	x				x		x			x	x		
	ForceForm [317]	Electromagnetic		x			x		x			x	x				x			x	x	x	x						x			x	x		
	Inflatable Hemispherical Multi-touch Display [287]	Projection		x			x		x	x		x	x	x	x	x		x		x	x	x	x						x			x		x	
	Mudpad [131]	Projection		x			x		x			x			x	x		x				x	x						x			x	x		
	Volflex [127]	Projection		x					x			x			x	x	x					x	x	x	x		x		x		x				x

Table 2.4 Elastic/Inflatable prototypes comparison table based on dimensions from Fig. 2.2

Actuated

Whilst the mechanics of each prototype are different, shape-change for these devices relies on separate mechanisms controlling each shape-pixel. *Actuated* interfaces are sometimes covered with a material substrate to create an undulating surface [87]. Some *actuated* prototypes have visual displays built-in. These prototypes usually have one repeated movement (bi-directional) and a limited height from baseline (flattened plane).

Actuated interfaces make up the largest proportion of shape-changing interface prototypes at just over a third of all those surveyed (29/84). This is likely because of the large variety of actuator types, outputs and ease with which each shape-pixel can be programmed to respond. As the largest grouping, *Actuated* interfaces are also the most diverse — supporting current applications which range from calm, environmental computing [30], to communicative architecture [33]. Researchers have already begun to think around the problem of shape-pixels for actuated interfaces by adapting an existing 3D programming language to allow for interaction and shape-change ([342]). This is a vital step in giving other researchers and application designers the tools they need to build meaningful interactions for such devices.

Liquids

Liquid prototypes are complex and span between highly organic 3D shapes and viscose 2D shapes. Interaction is mainly indirect, although some substrates allow the user to touch the surface of the interface. Despite apparent limitless parameters, the current prototypes support only selected output (namely shapes, or sounds). To keep a liquid in a rigid state, one must exert continuous control, either via an indirect control device (such as a magnetic ring [157]) or via the programming of the control mechanism (usually electromagnetic).

Liquids account for the smallest number of single category prototypes in this area (5/84) — this is possibly due to the complexity of programming interactions and exerting control over such substrates. Despite this complexity, the potential in this area is unbounded. Potential focus might be on increasing direct interaction possibilities — such as through hybridisation with *jamming* [66].

Malleables

Malleables are clay-like or jamming substrates that afford the user a pliable, deformable surface with which to create high shape-resolution forms. Jamming does not take centre-stage here, as other materials are used to create the same rigidity and control (e.g. *Tunable Clay* [66]). These prototypes have multi-dimensional input/output, but rely mainly on projection to supply equally high resolution graphics.

		HARDWARE		INTERACTIVE																TEMPORAL			PHYSICAL												
		MECHANISM		*PROXIMITY*			*INPUT*						*OUTPUT*				*USERS*			*CONTROL*			*SPATIAL*		*ORIENTATION & PATH*				*MATERIALITY*	*DIVISIBILITY*	*SHAPE RESOLUTION*		*DIMENSIONS*		
		Primary	**Secondary**	**Direct**	**Indirect**	**Remote**	**Program**	**Gesture**	**Touch/Haptic**	**Light**	**Sound**	**Deform**	**Form**	**Sound**	**Light**	**Text/Image**	**1**	**2**	**3+**	**Program Defined**	**Material Defined**	**Touch Defined**	**Height**	**Width**	**Bend**	**Closure**	**Fold**	**Roll**	**Stretch**	**Divide**	**High**	**Low**	**2D**	**2.5D**	**3D**
ACTUATED PROTOTYPES	*3D Form Display [210]*	SMA		x	x		x		x			x	x		x		x			x	x	x	x									x		x	
	Aegis Hyposurface [87]	Pneumatic		x	x	x	x	x	x	x	x	x	x		x	x			x	x			x								x			x	
	BubbleWrap [14]	Electromagnetic		x	x		x		x			x	x	x			x			x		x	x						x			x		x	
	ChainFORM [206]	Servo Motor		x		x	x		x			x	x		x	x	x			x		x	x	x	x	x	x	x		x		x		x	
	Changibles [251]	Servo Motor		x	x	x	x		x				x						x	x	x		x	x						x		x			x
	EMERGE [297]	DC Motor	Projection	x	x		x		x			x	x		x	x			x	x		x	x									x		x	
	FEELEX2 [127]	Servo Motor	Projection	x	x	x	x		x			x	x		x	x			x	x		x	x								x			x	
	Hairlytop [216]	SMA		x	x		x		x	x		x	x				x				x	x	x	x	x					x		x		x	
	inFORM [67]	DC Motor	Projection	x	x	x	x	x	x	x		x	x		x	x		x		x		x	x									x		x	
	Kinetic Tiles [150]	Electromagnetic		x		x	x					x	x			x	x			x		x	x						x	x		x		x	
	Lumen [235]	SMA		x	x	x	x		x			x	x		x	x	x			x	x	x	x									x		x	
	Luminescent Tentacles [211]	SMA			x		x	x					x	x	x		x			x			x	x	x					x		x		x	
	Mood Fern [30]	SMA		x	x		x		x				x						x	x	x	x			x			x				x	x		
	Morphees 1 [250]	SMA	Projection	x			x		x			x	x			x	x				x				x		x					x	x		
	Morphees 2 [250]	SMA	Electrophoretic	x			x		x			x	x			x	x				x				x							x	x		
	Morephone [83]	SMA	Electrophoretic	x		x	x		x			x	x			x	x				x	x			x							x	x		
	PolySurface [57]	Stepper Motor	Projection	x	x	x	x		x	x			x		x	x			x	x	x	x	x		x		x			x		x		x	
	Pneuxel [353]	Pneumatic	Optical Fibre	x	x			x	x				x	x	x		x			x			x						x			x		x	
	Relief [175]	DC Motor	Projection	x	x		x	x	x			x	x		x		x			x		x	x									x		x	
	ShapeCanvas [58]	Stepper Motor		x	x	x	x	x	x	x		x	x		x	x	x			x	x	x	x									x		x	
	Shape-Changing Tablet [183]	Servo Motor	Projection	x			x		x			x	x	x	x	x	x			x			x				x					x		x	
	ShapeClip [102]	Stepper Motor	Projection	x	x	x	x	x	x	x			x		x				x	x	x	x	x							x		x		x	
	Shutters [33]	SMA			x		x			x			x			x			x	x	x				x		x			x		x		x	
	SoundFORMS [36]	DC Motor	Projection	x	x	x	x	x	x	x	x	x	x	x		x			x	x		x	x									x		x	
	Sprout IO [32]	SMA		x	x	x	x		x			x	x					x		x	x	x	x	x	x	x	x					x		x	
	Sublimate [174]	DC Motor	Projection	x	x	x	x	x	x			x	x		x	x			x	x			x									x		x	
	Taxel [162]	Piezo-electric	Projection	x	x		x		x			x	x		x	x	x			x		x	x								x			x	
	Tilt Displays [4]	Servo Motor	OLED	x	x		x		x				x		x	x		x		x		x	x							x		x		x	
	TRANSFORM [173]	DC Motor	Projection	x	x	x	x	x	x	x		x	x		x	x		x		x		x	x									x		x	

Table 2.5 Actuated prototypes comparison table based on dimensions from Figure 2.1

Malleable interfaces also represent only a small number of the surveyed technologies at under 10% (7/78). Despite having high shape-resolution, the reliance on projection for visualising complex graphics means that these devices are not, as of yet, portable. In their current state, they are best suited to permanent installations or interactive multiple-user scenarios.

Hybrids

Hybrid interfaces are relatively new in the field, and combine two (with the potential for more) of the former categories to create the interaction surface. This suggests that this category has more of an overarching nature, and could be addressed as such, however, given the limited data I have on these they are shown as a final, complex category. Both *TableHop* [255], *Obake* [41] and the second iteration of *Mephistophone* [110] combine an *actuated* base with an *elastic* surface to create additional methods for user interaction. This layering up of mechanisms is reminiscent of Seah et al's [268] space-suit glove prototype which enables those in sealed suits to experience physical textures – however, much attention has been given in the three hybrid prototypes to the complexity of interaction *between* layers and in combination. Table 2.8 shows an overview the current Hybrid interfaces.

Although some other of the included prototypes already make use of some materials from other categories (e.g. *Projection* is used across the board), these prototypes do not fully support the features of both categories at present, whereas the *hybrid* examples given here enable users to make use of both types of interaction on the same surface. Hybrids are relatively rare in the study of shape-changing interfaces (3/84) but are likely to form part of the next stages of research. The implications for application design for hybrids are that the interaction possibilities become extremely complex, cross different modalities, temporalities, and can support multiple users in each — potentially at the same time. The potential for mismatch, both interactive and perceptual, is such that the possibilities also become a limiting factor.

2.7.1 Categorisation Summary

The current state-of-the-art is largely represented by this categorisation of shape-changing interfaces (Tables 2.1–2.8). The field as a whole however, is constantly evolving — and there may be additions or whole new categories within a relatively short space of time. Each interface category has its strengths and weaknesses, and these are continually evolving, making designing for such structures an iterative process. Many research papers suggest

		HARDWARE		INTERACTIVE																TEMPORAL			PHYSICAL												
		MECHANISM		*PROXIMITY*			*INPUT*						*OUTPUT*				*USERS*			*CONTROL*			*SPATIAL*		*ORIENTATION & PATH*				*MATERIALITY*	*DIVISIBILITY*	*SHAPE RESOLUTION*		*DIMENSIONS*		
		Primary	**Secondary**	**Direct**	**Indirect**	**Remote**	**Program**	**Gesture**	**Touch/Haptic**	**Light**	**Sound**	**Deform**	**Form**	**Sound**	**Light**	**Text/Image**	**1**	**2**	**3+**	**Program Defined**	**Material Defined**	**Touch Defined**	**Height**	**Width**	**Bend**	**Closure**	**Fold**	**Roll**	**Stretch**	**Divide**	**High**	**Low**	**2D**	**2.5D**	**3D**
LIQUID PROTOTYPES	*Fl.Uis [24]*	Water	Projection	x									x				x				x	x							x	x		x	x		
	Linetic [157]	Electromagnetic	Ferrofluid		x		x	x					x	x			x				x	x	x						x		x			x	
	Liquid Interface [158]	Electromagnetic	Ferrofluid	x			x		x			x	x	x			x			x	x		x								x			x	
	pBlob [334]	Electromagnetic	Ferrofluid		x		x	x					x				x			x	x		x	x		x				x	x			x	
	Protrude/Flow [156]	Electromagnetic	Ferrofluid		x		x	x					x				x			x	x		x	x		x					x				x

Table 2.6 Liquid prototypes comparison table based on dimensions from Figure 2.1

		HARDWARE		**INTERACTIVE**																**TEMPORAL**			**PHYSICAL**												
		MECHANISM		***PROXIMITY***			***INPUT***					***OUTPUT***					***USERS***			***CONTROL***			***SPATIAL***		***ORIENTATION & PATH***				***MATERIALITY***	***DIVISIBILITY***	***SHAPE RESOLUTION***		***DIMENSIONS***		
		Primary	**Secondary**	**Direct**	**Indirect**	**Remote**	**Program**	**Gesture**	**Touch/Haptic**	**Light**	**Sound**	**Deform**	**Form**	**Sound**	**Light**	**Text/Image**	**1**	**2**	**3+**	**Program Defined**	**Material Defined**	**Touch Defined**	**Height**	**Width**	**Bend**	**Closure**	**Fold**	**Roll**	**Stretch**	**Divide**	**High**	**Low**	**2D**	**2.5D**	**3D**
MALLEABLE PROTOTYPES	*ClaytricSurface [259]*	Jamming	Projection	x			x		x	x		x	x		x	x			x	x	x	x	x	x	x	x	x		x		x				x
	deForm [65]	Clay	Projection	x	x				x	x		x	x		x		x				x	x	x						x		x			x	
	Illuminating Clay [234]	Plastiscene	Projection	x	x		x		x	x		x			x	x			x		x	x	x	x			x		x		x				x
	GelTouch [201]	Thermoresponsive Hydrogel	Tablet	x	x	x	x		x			x	x			x	x			x	x	x	x		x		x		x		x			x	
	Malleable Surface Touch Interface [330]	Projection		x					x			x			x		x				x	x	x				x		x			x		x	
	Sandscape [125]	Glass Beads	Projection	x	x				x	x		x			x	x			x			x	x							x	x			x	
	Tunable Clay [66]	Jamming	Projection	x	x					x		x	x		x				x	x	x	x	x	x	x		x		x		x			x	

Table 2.7 Malleable prototypes comparison table based dimensions from Figure 2.1

future design modifications for their existing prototypes, and it is these which enrich and take the field forward.

A summary diagram of the prototype categories can be seen in Figure 2.2, whereas an analysis of feature frequency across all 8 categories can be seen in Table 2.9. Table 2.10 provides an overview of the limitations & current uses for each prototype category. The overall comparison of features between categories (Table 2.9) produces some additional findings which offer another perspective to the analysis contained here. These are discussed below.

		HARDWARE		**INTERACTIVE**																**TEMPORAL**			**PHYSICAL**												
		MECHANISM		***PROXIMITY***			***INPUT***						***OUTPUT***				***USERS***			***CONTROL***			***SPATIAL***		***ORIENTATION & PATH***				***MATERIALITY***	***DIVISIBILITY***	***SHAPE RESOLUTION***		***DIMENSIONS***		
		Primary	**Secondary**	**Direct**	**Indirect**	**Remote**	**Program**	**Gesture**	**Touch/Haptic**	**Light**	**Sound**	**Deform**	**Form**	**Sound**	**Light**	**Text/Image**	**1**	**2**	**3+**	**Program Defined**	**Material Defined**	**Touch Defined**	**Height**	**Width**	**Bend**	**Closure**	**Fold**	**Roll**	**Stretch**	**Divide**	**High**	**Low**	**2D**	**2.5D**	**3D**
HYBRID PROTOTYPES	*Bioacoustic Cognition [110]*	Servo Motor	Projection	x			x	x	x		x	x	x		x	x			x	x	x	x	x		x				x			x		x	
	Obake [41]	Linear	Projection	x	x		x		x		x	x	x		x	x			x		x	x	x	x	x	x	x		x		x			x	
	TableHop [255]	ITO Array	Projection	x	x	x	x	x	x			x	x	x		x			x	x	x	x	x		x				x			x		x	

Table 2.8 Hybrid prototypes comparison table based dimensions from Figure 2.1

The Problem with Projection

Over half of all prototypes included in this dataset rely on one form or another of projection, e.g. backlit as with *TableHop* [255] or, more commonly, top-lit as is the case with *Metamorphic Light* [193]. The overuse of projection to achieve detailed imagery or interaction shows that there is a need to put more resources into embedded displays and shows the immaturity of the field in that respect — or that there is a need for advanced materials that have not yet been developed, or are currently being developed, such as Yokota et al.'s *Ultraflexible organic photonic skin* [357]. Embedding high quality displays into shape-changing devices would create a seamless user-experience that is lacking in current prototypes, enhancing the notion of the *phygital* (combining physical and digital into one): Projection is a useful tool for rapid prototyping, but it presents an interrupted user experience when top-lit (occlusion from hands/objects), and makes prototypes bulky and difficult to transport both when top and bottom-lit — meaning it is more difficult to get these devices out of the laboratory for meaningful testing, and that they will be unlikely to go into commercial development and production in their current form.

Multi-dimensional Change

Hardware and mechanism limitations can also effect the interactive qualities of devices. Poupyrev's notion of *RGBH shape-pixels* [236] reflects the current state of play, but does not leave space for the exploration of multi-dimensional change. As an example, actuated interfaces can always display height, but very rarely does this combine with the type of shape-change in the orientation/path category. To attempt to expand on the interactions available to this subset of interfaces, combining the properties of a paper or cloth interface with the mechanised movement of an actuated interface would give rise to some novel data, e.g. using paper-style creases alongside the fluidity of cloth, with the rigidity and movement of actuated shape-pixels.

Number of Users

User data across the categories shows that just over half of all the prototypes analysed are developed for single users, although there is still a significant number which do support 3 or more users. This is likely in most cases to be a constraint of size, lack of divisibility, or difficulties in enabling multiple users to interact on the same surface. Collaborative usage and shape-changing interaction on these interfaces has not yet been well documented, and relates to the complexities of perception which are discussed later.

Control

With regards to temporality and control, there is a tendency for the user to be the primary locus of control of speed for most prototypes (around 84%), e.g. with *Bendable* or *Enhanced 2D* where the mechanism does not deform without user input (although some of the 84% also support multiply defined methods of control). The reasoning behind this could be that the user exerts primary control over shape-change merely because the materials used in such prototypes are not yet complex (e.g. paper or elastic rather than integrated hybrid forms with progammable actuated components) — however, given the importance of the user in any advancement in interaction design for shape-change, focusing on retaining the user as the primary factor in temporal control should be important to researchers.

2.8 Discussion

The story of shape-change so far is one of prototyping within existing technological constraints. By creating content for that which we have now, we will be able to lay the groundwork for a future shape-changing application design. With Ishii's [123] vision-driven design we look to the future, but this can happen only when we have truly understood the present. Whereas Kwak's framework [161] supports design engagement for shape-change via tangible models, it is not based upon contemporary research prototypes. In contrast, Ishii works around existing technology to speculate as to the future of shape-changing interfaces. It is from/with Kwak's explorations and toward Ishii's speculation into which this chapter places itself.

2.8.1 Supporting Application Design

The categorisations supplied in this chapter break down the current state-of-the-art into clear boundaries. Therefore, a designer making an application for any existing interface will be able to look to the associated attributes and supported features, and sketch an outline for what must be considered during the iterative design process. For an *actuated* interface, for example, one must consider how many shape-pixels are available, the speed with which these are required to move to communicate the application's intent, the level of visual detail supported, and so on.

To elaborate, for those wishing to apply the framework in context of interface design, it is suggested that those using the classification query the intended outcome of the research — for example — What is the desired interaction in mind — and therefore what type of actuation best suits this outcome? A study wishing to analyse latency on moving pins would almost certainly need bi-directional actuators, whereas a study examining calm computing and peripheral shape-change might wish to examine the biological movements of natto cells or SMAs. Alternatively, if there is a platform in mind but not the knowledge of the types of user interaction required to enable user-testing then the researcher might look at number of users and the types of input and output supported.

The taxonomy can be interrogated in varying degrees depending on the nature of the research, although it should also be noted that there is a "trade off" between different types of shape-changing interface, which is another factor that can be easily seen from the available data. To provide an example in context of the latter, if you require an approximation of natural movement then you would almost certainly use natto cells or SMAs in lieu of servo motors. Another example of "trading off" could be choosing between hardware types within one category — i.e. if you require the portability of *ShapeClips* but the advanced material properties of *Transform* (recently examined by [206]) you will need to decide which property is more salient for the research at hand.

Essentially, this chapter is a library of shape-change, and can be queried as such: for any of the currently available shape-changing prototypes, a designer can now pick out the key features and limitations. It is hoped that this could open up multi-disciplinary collaborations, as well as those within the field. Although the question is raised: Is it the applications that will drive the technology or the technology that will drive or limit the design of applications?

2.8.2 Limitation in Design

A successful multi-dimensional application designer must not only design for the capacities of shape-change but against the limitations imposed by the hardware of the device (it must conform or have constraints [123]). These limiters actually reign in the design space, and offer a firm ground from which to work backwards from. A future where devices have unlimited dimensional potential (such as Ishii's *Perfect Red* [123]) must be built up to, working toward a theory of content on the lower fidelity devices first. Limitations are not merely device specific however, they can be built in as the program requires — working as areas of rigidity or non-interaction, like the background of a website around a clickable link. The challenge of programmed rigidity is not only one of hardware, but also of temporality — how quickly a force limiter is made or released can affect the users' experience of an application, not to mention interface safety. An exception to rigidity might be for a free-form sculpting application. Hardware limiters include (but are not exclusive to) the following:

Distance from baseline: Several studies state the total usable height [102] or width of their device [147]. For material based interactions, total distance from baseline must be calculated from the maximum stretch or available slack of the surface at one point at any given time.

Shape-resolution: As discussed in the previous section, deformation limiters are based on the type of device for which the application is being designed for. The lower shape resolution but highly interactive devices have narrow limits in comparison to the high resolution liquid shape displays.

Image resolution: Based on the image resolution of the device — a block-pixel image will afford a narrow design space with which to work with, whereas a projected, high resolution image will interact in multiple ways with areas of height and deformation, and present a challenge for users utilizing multiple viewing angles [236].

Stretch: An important consideration when designing for areas of rigidity: rigid areas may limit the deformation of surrounding interaction zones. Stretch ensures that deformation is still possible between closely spaced rigid objects.

Temporality: Speed of change is sometimes limited by the hardware (such as with motorized actuators), and so will need to be built into design considerations. Maximum and minimum speeds for deformation should be made available to the designer, or tested prior to finalizing applications.

		PROTOTYPE CATEGORY								
		Enhanced 2D	*Bendable*	*Paper/Cloth*	*Elastic/ Inflatable*	*Actuated*	*Liquid*	*Malleable*	*Hybrid*	*TOTAL*
		7	**10**	**14**	**9**	**29**	**5**	**7**	**3**	**84**
MECHANISM	**Clay**							1		**1**
	CPU Fans			1						**1**
	DC Motor					6				**6**
	Electromagnetic			1	1	2	4			**8**
	Electroluminescent			1						**1**
	Electrochromism			1						**1**
	Electrophoretic	1	2	2		2				**7**
	Ferrofluid				1		4			**5**
	FOLED		2							**2**
	Glass Beads							1		**1**
	Haptic Actuator		1							**1**
	ITO Array								1	**1**
	Jamming			1				2		**3**
	Linear Actuator								1	**1**
	OLED	2	2	2		1				**7**
	Optical Fibre			2		1				**3**
	Piezoelectric					1				**1**
	Plasticine							1		**1**
	Pneumatic					2				**2**
	Pressure Sensor				1					**1**
	Projection	4	4	7	6	12	1	6	3	**43**
	Servo Motor					5			1	**6**
	SMA					10				**10**
	Stepper Motor					3				**3**
	Tablet							1		**1**
	TEFL			1						**1**
	Thermoresponsive Hydrogel							1		**1**
	Water						1			**1**
PROXIMITY	**Direct**	7	10	13	9	27	2	7	3	**78**
	Indirect	4	4	9	1	23	3	5	2	**51**
	Remote	2	3			15		1	1	**22**
INPUT	**Program**	5	8	6	4	28	4	3	3	**61**
	Gesture	2	1	4		10	3		2	**22**
	Touch/Haptic	7	9	11	8	26	1	6	3	**71**
	Light		1	3	1	9		5		**19**
	Sound		2	1		2			2	**7**
	Deform	5	10	12	9	21	1	7	3	**68**
OUTPUT	**Form**	3	3	5	2	29	5	4	3	**54**
	Sound	2	5		1	5	2		1	**16**
	Light	3	9	9	8	18		6	2	**55**
	Text/Image	6	10	11	7	19		4	3	**60**
USERS	**1**	2	9	7	6	15	5	3		**47**
	2	3	1	3	2	4				**13**
	3+	2		4	1	10		4	3	**24**
CONTROL	**Program Defined**	2	2	3	2	25	3	3	2	**42**
	Material Defined		1	4	7	13	5	6	3	**39**
	Touch Defined	6	10	14	9	20	2	7	3	**71**
SPATIAL	**Height**	3	10	7	9	24	4	7	3	**67**
	Width	6	10	5	2	5	2	3	1	**34**
ORIENTATION & PATH	**Bend**	2	10	14	2	10		3	3	**44**
	Closure	3	1	10		2	2	1	1	**20**
	Fold	5	1	9	3	6		5	1	**30**
	Roll	1	1	10		2				**14**
MATERIALITY	**Stretch**			2	9	3	2	6	3	**25**
DIVISIBILITY	**Divide**	3		5		9	2	1		**20**
SHAPE RESOLUTION	**High**			3	1	3	4	6	1	**18**
	Low	7	10	11	8	26	1	1	2	**66**
DIMENSIONS	**2D**	7	10	7	6	4	1			**35**
	2.5D			5	1	24	3	5	3	**41**
	3D			2	2	1	1	2		**8**

Table 2.9 Category summary of Prototypical Shape-Changing Interfaces showing totals across the consolidated dimensions

Holman [111] mentions the current limitations of readily available electrophoretic displays (less than 1fps) and how designing for such device displays requires advanced programming knowledge. If this knowledge is lacking, the rapid development of applications will suffer. This supports research in which those in the arts are encouraged to learn to code [276] and vice versa [63]. This new space of shape-changing interaction design requires a new generation of multi-skilled designer-makers — it is possibly not enough to simply be a competent developer or designer when new technology stretches the limits of imagination.

2.8.3 Future Use Cases

Application of shape-changing prototypes is so far mostly limited to improving items we already have in 2D such as phones, tablets and worktops. Those prototypes looking at shape construction begin to imply a new way of using form and interaction, however, user-driven research is needed to identify new types of interactive shape-changing product where need or desire exists. Following Bannon's call for a more "human-centred perspective" on HCI, I carried out a study using a participant pool taken from the general public (Chapter 5) and found that a range of shape-changing products were desired or suggested — not limited to, but including, interfaces, architecture, landscapes and wearables.

As the field develops, we may need to re-imagine the interface as something beyond the tablets and mobile-phones that we use today. Wearables and Internet-of-Things technology bring connectivity to the familiar and often mundane, whereas adaptive architecture (e.g. Schnadelbach's *ExoBuilding* [265]) turns our living space into an opportunity for interaction. Within shape-change, *BubbleWrap* [14] looks toward creating a technology that can be wrapped around anything to create an on-demand interface. This is not the only example of future-use cases being highlighted in papers — others suggest the next iteration of their device as they write up the first, and some, like Ishii [123] employ design fictions to envisage the future. It is because of this that it is likely that *interaction*-driven rather than device-driven application design is likely to take priority in the future, and hence developing user-experience design for this field is an important step.

2.8.4 User-Experience and Emotionality

User-centred design is a mature field and well applied in designing current interfaces and applications, but is only just beginning to take the fore in shape-change literature. Most shape-changing prototypes are highly tangible, and usually support multi-sensory input or output. This means that the user must learn a new set of skills to interact with such technologies, alongside their existing knowledge. The prototypes discussed here also have

Prototype	Primary Feature	Limitation	Current Use Cases
Enhanced 2D	Multi-screen	Inflexible	Phone /Tablet
Bendable	User-Interaction	Low Shape-Resolution	Phone /Tablet
Paper/Cloth	Orientation	User-Defined Temporality	Phone /Tablet/Workspace
Elastic/Inflatable	Stretch/Emotionality	Material-Defined Temporality	Emotional Communication/Workspace
Actuated	Bi-Directionality	Low Shape-Resolution	Physical Telepresence/Wrapped Interfaces
Liquid	High-Malleability	Low User-Control	Artistic Installation
Malleable	High Shape-Resolution	Projection-based Graphics	Workspace
Hybrid	Complex Interaction	No full 3D version	Information Visualisation

Table 2.10 Summary of the features, limitations and current use cases of prototypical shape-changing interfaces

the added factor of *emotionality*, that is, that movement and shape-change can create an affective response. Deployment "in the wild" of shape-changing devices has been studied, (such as in the *Shape-Changing Bench* [239]), and it is Rasmussen who is attempting to bring focus onto user-experience in this field. To successfully create applications for these "magical" devices [239], designer, researcher and user must collaborate in first developing a novel practice of user-experience.

2.8.5 Perception

Few researchers make the connection between actuation, and altered perceptive state. Poupyrev, however [236] mentions that differing viewing angles will alter the experience, suggesting user mobility and/or display adaptation as a solution, touching briefly upon the idea that the display could alter to make perception easier from multiple locations, which also relates back to optical illusions (such as distorted advertising blocks on football pitches which appear square when seen from a remote camera).

The distinction is also made between asynchronous and synchronous states (i.e. graphics/shape mismatch), creating yet another dimension for the viewer to interpret, and the designer to create. This links into design prototyping where there is a distinction between "looks like" and "works like". Fidelity in either one of these areas affects possible interactions and thus the overall look and feel of an application design.

2.8.6 Ethical Considerations

If our computers become tangible, we open up ourselves to the notion of unwanted tangible interaction, perhaps unbidden, in the case of 3D spam [204]. Chat rooms become a step more dangerous for our children, as the unknown quantity of remote touch becomes possible. Control thus becomes more important — if *AegisHyposurface* [87] can move at speeds of 100kph, how can we design to prevent injury? Can closure of a surface cause trapped fingers

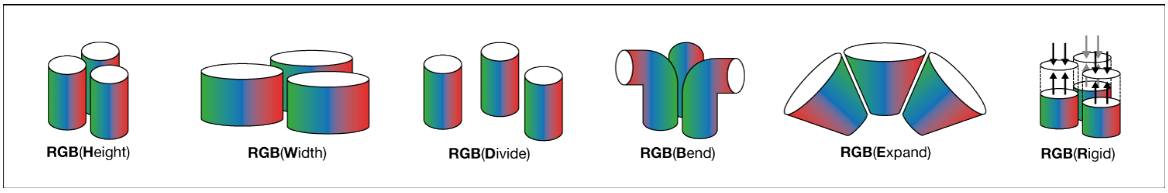


Fig. 2.3 Possible development of Shape-Pixel states based on RGB-H principle [236]

— will there be a safety cut off? This extra concern must be incorporated into design - physical safety adds an extra dimension of concern for designers — something that is not currently needed for 2D displays.

2.8.7 Next Steps

The field of shape-changing interface prototypes as it currently stands is outlined in detail in this chapter. At the time of writing, researchers are already beginning to combine mechanisms and interactions between prototypes to create hybridised interfaces [41, 110, 255]. This suggests that a logical step forward for some researchers would be to combine the characteristics between other current prototypes to create high-fidelity and multiple-interaction supporting shape-changing interfaces.

Hybrids are capable of both sets of interactions, and thus present a more complex design space that must be built from the specifications of the component hardware. Future shape-changing interfaces are likely to incorporate even more aspects of the prototypes seen here, and whereas interaction and applications can be anticipated from the design for their predecessors to some extent, the design space where all interactions are possible registers and even more complex problem to users, researchers and designers. It is hoped that this categorisation of existing prototypes might prompt collaborative work between referenced groups to create such hybrids, and also bring designers on board to test their application potential.

Poupyrev discusses the notion of RGBH graphics, where colour information is as we expect to find in GUIs, but with pixel height as an added numerical component [236]. Although a logical step for actuated displays, for a shape-changing display to be truly malleable, it must not only move on one axis, but several – turning corners, expanding or folding into itself. It would therefore make sense to use the RGB-H space, but replace 'H' with n, where n represents a different dimensional change in shape pixel state (see Figure 2.3 for examples of possible iterations based upon RGB-H). This idea of advanced shape-pixels is far from being realized, but could be expanded on via further reasearch.

The community surrounding these advances is often a highly specialized base of researchers and students, and as such user testing and the resulting inferences might be biased. Bannon [12] mentions that the "human" side of HCI has been lacking in recent years, and Rasmussen [242] calls for more "high quality data" on user experience for shape-change. By eliciting input from non-expert users, we might realize new directions for shape-change, and nurture the design space. Finally, it is anticipated that the categorisation of shape-changing prototypes will be added to as the field moves forward in coming years, and thus there will more complex aspects for designers to consider, alongside the implications for the user.

2.9 Conclusion

This chapter has consolidated multiple reviews for shape-change, mapped existing prototypes onto the resulting framework, and suggested 8 categories for different types of shape-changing interface based on the hardware used and the limitations/opportunities provided by such devices. These categories are further reviewed in relation to application design for shape-changing interfaces, and guidelines are suggested to make the first steps toward a standardised future practice of UCD for shape-change. The analysis and classification of shape-changing interfaces will be a long term ongoing task for researchers as these technologies develop, but this review enables me to make decisions about working toward designing for these devices within this body of work, and carry out relevant user studies which relate back to the field as a whole.

Chapter 3

SketcHCI: A Short History of Sketching in Human Computer Interaction

3.1 Chapter Summary

Sketching has long been a valuable process in design, engineering and science, as well as the arts and humanities — but how does this traditional, often ephemeric practice fit into the futuristic world of HCI? This narrative review and discussion serves to provide a background for the use of sketching within HCI, to support its application in the field of shape-changing interfaces. The breadth and depth of how the sketch has been adopted by HCI over many years is an example of its interdisciplinary potential, and possibilities for use in technical contexts. Themes and categories relating to sketching in HCI are mapped to show how it is used within contemporary practice, and these are discussed alongside examples from the field in order to consider the implications of sketching alongside more advanced methods. The work contained within this chapter complements the systematic review of shape-changing interfaces in *Chapter 2*, so as to gain a comprehensive overview of both fields of interest before investigating application of sketching methodologies in relation to shape-change.

3.2 Introduction to Sketching in HCI

The act of sketching is a rite of passage in human development — we learn to use tools and make marks even before we learn to speak, and this form of *visual* expression is universal to humans. Research suggests that the development of drawing skills follows the same pathways in the brain as does language learning [35]. This kind of visualisation is a human method of thinking, expression, and communication — so how can we reconcile this within

ACM	Title includes: Sketching	972
	Title includes: Sketch	
	Title includes: Sketches	
	Sketching	4036
	Sketch	
	Sketches	
	"Sketching HCI"	761
	Sketching HCI (anywhere)	

IEEE	Title includes: Sketching	883
	Title includes: Sketch	
	Title includes:: Sketches	
	Sketching	4020
	Sketch	
	Sketches	
	"Sketching HCI"	1317
	Sketching HCI (anywhere)	16

Google Scholar	Title includes: Sketching	3870
	Title includes: Sketch	44,700
	Title includes: Sketches	21,700
	Sketching	210,000
	Sketch	2,520,000
	Sketches	1,020,000
	"Sketching HCI"	9,010
	Sketching HCI (anywhere)	2

Table 3.1 Total number of search entries (including citations) per database/search engine (all time – correct at 31/12/2017). Note: IEEE generates linked search for all related "sketch" terms and also includes "sketched", whilst ACM groups search results for the three specific terms. ACM results have been adjusted to remove the *SIGGRAPH Sketches* titled conference format (unless relevant) due to a irregularity in search mechanism.

the construct of Human Computer Interaction (HCI)? The traditional view of the "sketch" is that of a visual representation of an idea, or a short, fast drawing on paper — although it has more meanings depending on the context of use. In HCI, for example, the sketch can take on new roles as diverse as a section of code [15], a collection of actions [355], sounds [194] or even a rapid prototype [38]. The pen and paper exemplar also has a new life within the context of computation, in that the sketch can be recognised as such using algorithms [100], converted from sketch to digital representation in 2D or 3D [117], and even used as an input device [133]. Thus far, HCI has embraced sketching as a method, challenge and tool, but there are limited overviews of sketching in relation to HCI, excepting [134] which examines sketching from the viewpoint of computational support in design, and looks at how hand sketching assisted by technology, but does not provide a narrative review of the full area, or look at how sketching relates to technology in other ways.

I therefore aim address this omission: Firstly, by defining what the term "sketching" means and how it is utilised within HCI; Secondly, by using a keyword-based systematic search strategy with existing research databases and search engines to conduct a narrative review, explore the rise in popularity and identify trends in sketching in HCI year-by-year; Thirdly, using insights gained from the analysis to identify 8 themes for sketching in HCI, which I discuss alongside examples from the field. Finally, I look at major areas of research and events over time and discuss what the future holds for sketching in relation to Human Computer Interaction. It is hoped that this review will serve to inform my work by exploring the breadth of research in this area, and provide a helpful tool for placing sketching into context, as well as outlining prospective and fruitful research directions for sketching in application to shape-changing interfaces.

3.3 On defining the 'Sketch'

Why is it hard to define what a "sketch" is? Sketching is a difficult act to define, as it can have multiple, context dependent meanings, which vary across fields, cohorts and individual practice. The *Oxford English Dictionary* [47] has two definitions of the word *sketch*, with the first being described as "*A rough drawing or delineation of something, giving the outlines or prominent features without the detail, esp. one intended to serve as the basis of a more finished picture, or to be used in its composition; a rough draught or design. Also, in later use, a drawing or painting of a slight or unpretentious nature.*" Other uses suggest artistic or descriptive short forms (i.e. narrative, music, comedy, theatre), however the primary definition is under investigation in this work.

In HCI, sketching commonly takes on three related meanings: first and foremost, it relates to the hand or computer generated image as defined above; second, it relates to *data* or *program* sketches by developers or other researchers who are creating small or partial pieces of code or algorithmic data; third, it simply applies to an short overview of an area, or a technique. There are also sub-categorisations within the former, *physical* sketching for example, that is, creating forms using 3D materials much as you would create a sketch using a pencil and paper, or 3D sketching in digital form. In this chapter, I focus on the sketch as imagery (physical or digital), and although the search parameters automatically include the programmers' "sketch" and related terms as types of sketching in HCI, I have extracted these from the analysis. To fulfil the search criteria in for my purposes, a sketch must be a visual, digital or physical, input or output, and be used within the broader context of Human Computer Interaction, that is, sketching used in relation to computing devices.

3.4 Background

As much as sketching is universal in human culture, it also transcends research disciplines [209]. Art lays the foremost claim, and through this, architecture and engineering emerge as primary users of sketching as a methodology and process. To examine sketching in relation to the computer is not new, however, rarely has it been given a systematic evaluation to the extent that I present here. The following section examines both works that give comprehensive overviews of specific areas, but also those that focus on innovations for, and with, sketching in HCI. To draw with the computer has been of interest since the early 1960s, with the earliest iterations using code to make lines [294], or proposing to involve direct "pencil" to paper interaction [350]. The sophistication of devices such as the *Cintiq Companion* [333] and

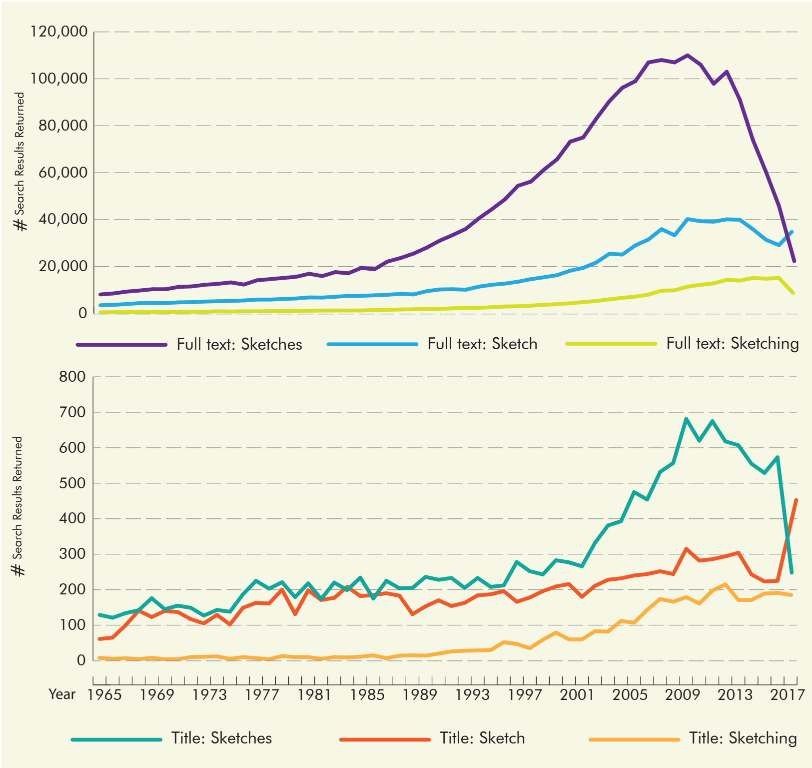


Fig. 3.1 An overview of search results for sketching terms from *Google Scholar* showing the trend between the use of *"Sketch", "Sketches"* and *"Sketching"* for full text (top) and title searches (bottom) from 1957-2017.

Apple Pencil [10] bears testimony to these early ideas, with the ideal being coupling the intimacy and freedom of the sketched image with the power and possibility of the computer.

Fallman's [59] critique of design-oriented HCI states that sketching is "habitually neglected, and only rarely discussed" within the field, and although he does touch upon its use for prototyping and creating dialogue, he neglects to explore the huge number of possibilities for the hybridization of sketching and the computer. To date, Johnson et al. [134] have provided the most comprehensive overview of sketching in relation to the computer, albeit from a design perspective, in that the computer is seen as *supporting* the sketch. The limitation however, is that the focus is on the potential in improving the hands-on sketching experience using computers, it does not examine the other ways in which sketching relates to HCI. Nearly 10 years on, we can re-examine the connections between sketching and the computer with a broader focus, and ask ourselves how traditional freehand, or enhanced sketching has fared, and if it is still relevant when the computer allows even the most hesitant of artists to create and explore with the freedom of infinite iterations [81]?

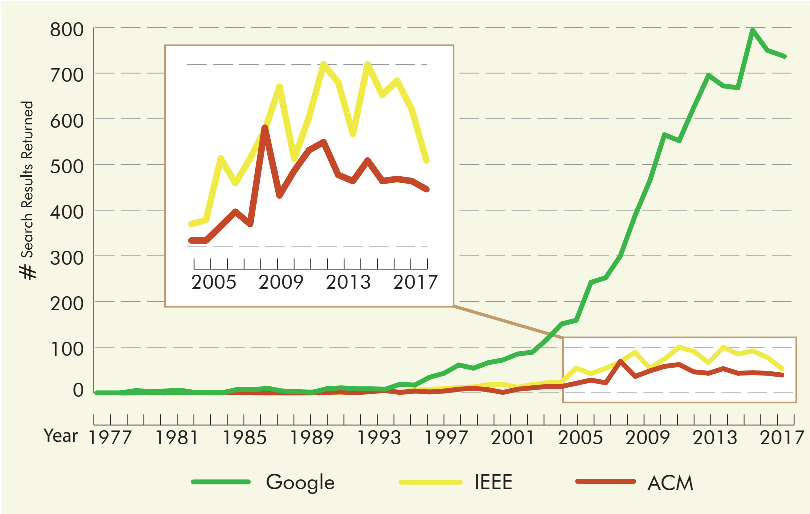


Fig. 3.2 Returned search results for "sketching HCI" from *Google Scholar, IEEE* and *ACM* since HCI first described in texts (1976–2017).

3.5 Search Strategy, Review, & Analysis

In this chapter, I aim to improve the processes utilised by other reviews (see section 2.2), and apply a systematic search methodology to create a narrative review of sketching in HCI. This review differs to the approach taken for shape-changing interfaces, as the number of papers relating to sketching in this context is vast — it is impossible to produce a complete overview of a field containing tens of thousands of outputs, using an unguided literature review search (e.g. related search terms, related work, related topics). In contrast to sketching in HCI, shape-change contains a relatively small body of work, and many papers cite each other, or generate helpful search terms with which to identify unrelated research outputs.

Sketching in HCI has not been reviewed in this manner, yet is widely utilised within HCI — Johnson et al. is the most useful and comprehensive reference to date, although it was conducted nearly 10 years ago [134]. With this review I hope to provide an reference for both this body of work, and for other researchers across the field, enabling the reader to learn about the history, topics of interest, research areas, advancements and future prospects for sketching.

The history of the sketch and human interaction in computing cannot be told purely in academic terms, but I can use available databases to generate an overview of its popularity in research since the birth of the modern computer (the date of which is debatable). HCI is interdisciplinary — hence a singular search database or search engine may not give up all relevant results. I initially used *Google Scholar* for the search as it is a widely used,

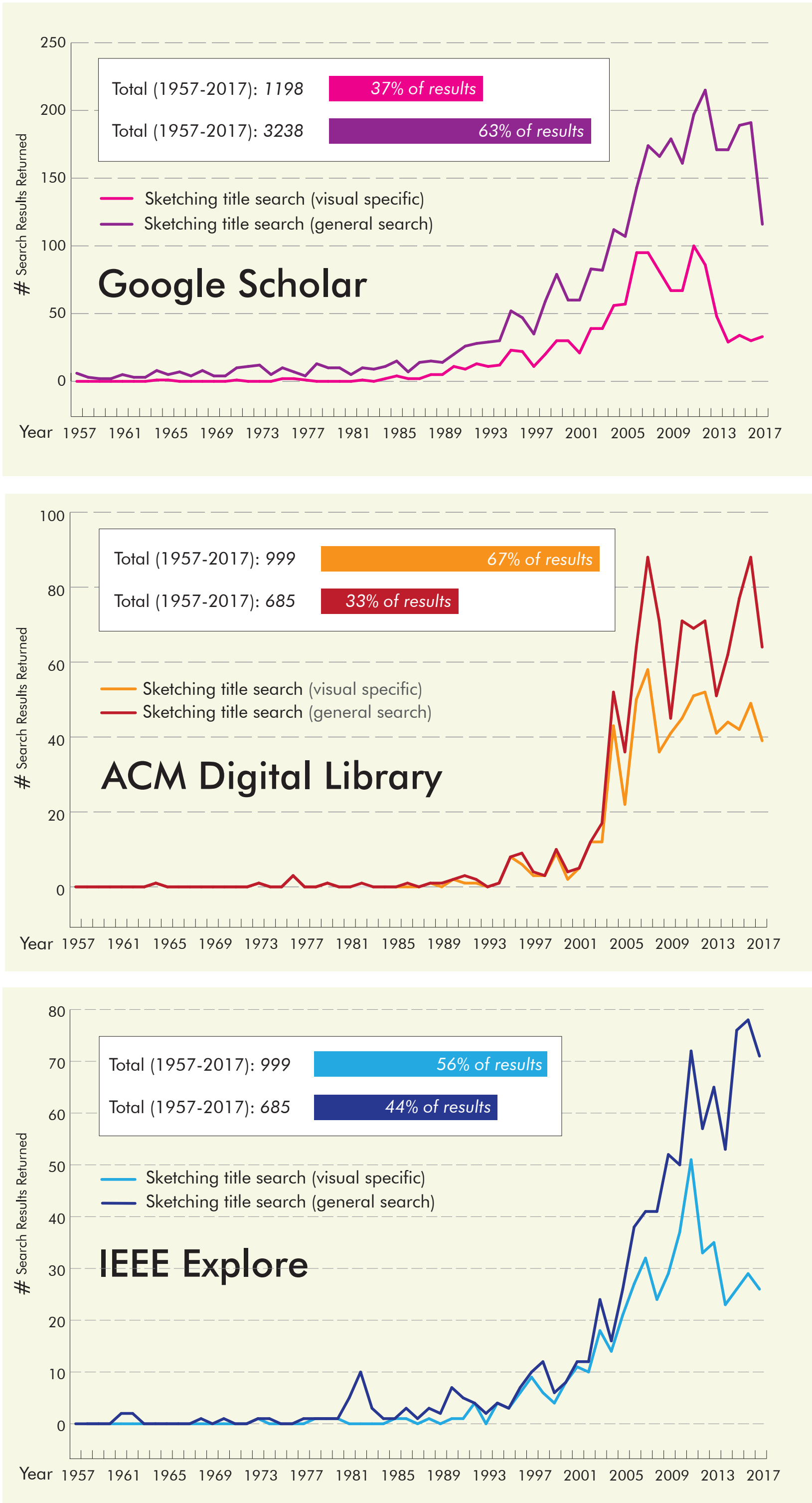


Fig. 3.3 Title search for sketching across *Google Scholar*, *ACM Digital Library* & *IEEE Explore* compared to specific results according to the outlined criteria

generic academic repository which collect and indexes works from a number of sources. To then apply further rigour to the search, I then compared total search numbers for sketching related terms in both the title and full text of papers to two dedicated databases for research in computing: *IEEE* and *ACM*. The complete corpus of “sketching”, “sketches” and “sketch” as search terms is too vast to examine in depth without the aid of additional computational support (Figure 3.1), however, random selection of items returned from each search for “sketches” and “sketch” proved to include a majority of texts using the terms in a non-visual context, whereas “sketching” was more likely to yield results consistent with my purpose. The total search for *sketching* in the title of a text, for “all time” in *Google Scholar*, is around 3710, whereas for 1957-2017 it is around 3320; searching entries prior to 1964 did not produce any results consistent with computational theory or hardware (Note: “Hits” returned by *Google Scholar* can vary [20] so the numbers for the search-by-year pre-analysis can vary slightly). An comparative overview of the number of results for each database, all chosen search terms and outputs can be seen in Table 3.1, before applying any selection criteria. The total number of search results for each term shows how the *Google Scholar* search returns the most results in all but two cases (“sketching HCI” as linked words, and “sketching”).

To further specify the search, I utilised the search term “sketching HCI” (occurring anywhere in text) across each database and search engine and compiled a timeline of that data (Figure 3.2). “Sketching HCI” as a search term (anywhere in a text) generated 9050 results in *Google Scholar* for all time, but is not a reliable indicator of HCI over the period in question, as the phrase “HCI” was only coined in the 1970s, whereas Sutherland’s seminal work relating to pen interfaces was first published in 1964 [294]. However, “sketching” as a generic term generated around 201,000 results — meaning many results were using the term in other ways. Likewise, “sketching computing” generated 48,800 results — and although more focused, did not help with the research objective of providing an overview of HCI specifically, usage in these cases instead appeared to have been used as an expression (see definition in previous section) rather than a description of practice. The differences in the time-lines for “sketching HCI” and generic sketching terms since 1976 suggest that the specific search term (*sketching HCI*) utilised in the analysis does not arbitrarily follow the pattern seen in the generic corpus, although it matches a general upward trend that is to be expected from wider dissemination of research in all subjects since digitisation began.

As not all papers within the field of HCI contain that acronym, it was decided that a generic, yet more focused search would yield more relevant and comprehensive results. Initial examination of data from title searches showed similar trend patterns emerging when compared to Figures 3.1 and 3.2, so a text title search for “sketching” and related terms was conducted for papers and articles from 1957 to 2017. The initial overview of the data I

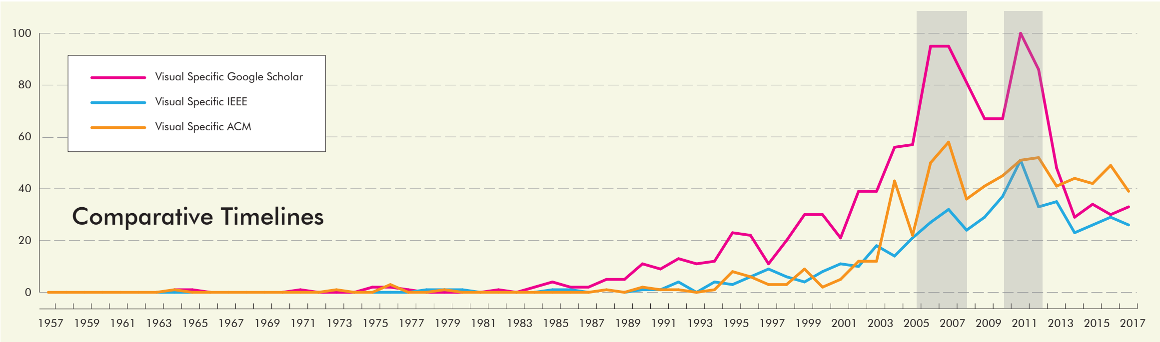


Fig. 3.4 Direct comparison of relevant returned search results by search database/engine.

conducted allowed us to define criteria for inclusion for a more comprehensive search (see below), and these criteria were then applied systematically to my search results by year. To extract relevant entries, I then manually checked (identified paper focus) search data (including citations), checking abstracts, journal types (*ACM, IEEE*), venue (e.g. *SIGGRAPH*), fields, and where necessary (focus of text not apparent preview search entry or abstract), full texts. The criteria used for inclusion in the specific meta-search were:

Criteria 1: Text must relate to visual mark making (non-textual, non-hardware oriented) in sketched form (not final CAD products), either on screen or paper or in 3D, as part of a computational process, system or methodology. Sketching must form part of the work — texts where there is sketched imagery to illustrate a point only are not included.

Criteria 2: Text must be in the field of computing, unless there is significant overlap from another field, e.g. design, engineering or architecture, where a device or system is being developed, tested or used and the focus is on the interaction between human and computer (a paper looking at education in computer assisted drawing (CAD) for engineers would not be included, but a paper looking at a novel system for enabling architects to sketch would).

Criteria 3: Patents and duplicate entries are not included in the detailed analysis. Where a text has multiple entries, only the first incidence of the text is counted. The same applies for editions where author names have been shuffled. Citations, either referring to an unseen text, or without a linked article are also removed from the analysis.

The returned result numbers were mapped onto timeline graphs to show the upward rise in interest in sketching from 1964 onwards, and subsequent peaks and troughs in output: Figure 3.3 shows the resulting breakdown of relevant texts across time for the "sketching" title search, excluding those that did not meet the criteria (also excluding papers in the "sketches" category of *SIGGRAPH* which used the term the title of a type of conference submission) for both databases and search engines, compared to the total search results for each year. Figure 3.4 shows a direct comparison of relevant papers for the three sources, with the peaks in interest marked in grey, and the beginning of a plateau appearing to form in the subsequent years. The generic search, in comparison, shows a discrete continuing upward trend, which suggests that the use of the term “sketching” is becoming more popular in other contexts (e.g. database research, or coding). In terms of search engine accuracy and relevance, the *ACM Digital Library* showed the highest proportion of relevant search results for sketching, closely followed by *IEEE Explore* — this is most likely due to the focused output of both engines when compared to *Google Scholar*, which also sources data from non-computing journals and non-accredited sources. The higher return rate on relevant texts seen from *Google Scholar* suggests however that a wider search is helpful to extract a larger proportion of relevant data pertaining to sketching in HCI.

During the examination of the texts included within this analysis it was possible to identify distinct categories relating to sketching in HCI, which I have elaborated upon using the style suggested by Hornbaek et al. in their comprehensive review of interaction [115] (Table 3.2). Outwith this categorisation, I also identified popular research themes emerging along the timeline, which have been visualised in Figure 3.5, alongside points of interest (e.g. first *SIGCHI* conference).

3.6 A Timeline & History of Sketching in HCI

During the investigation, I was able to identify the start points of prominent research themes within sketching and HCI — Figure 3.6 maps these themes as continuing, as they are by no means exhausted: for example, pen-computer interaction [294], and sketching on tablet computers (the first record of which was the *Sylvania data tablet* [306]), still have not matched the natural affordances allowed by pen and paper [7]. The progress made with digital-paper however is an exciting reminder of how far we have come [113, 305]. Sketch recognition was another early avenue of enquiry (Harrison, 1970 [103]), and recent advances in neural networks now mean that programs can recognise diverse sketches from a number of sources [6], including representations of faces [319]. In combination with sketch input and retrieval (of interest since 1990 [143]), sketch-based interfaces [272] are becoming a user-friendly reality, including collaborative interaction, both co-located (such as Greenberg’s *BoardNoter* 1989 [90]) and remote [341]. Sketching in 3D has transitioned from paper to virtual surfaces, including within Virtual Reality [45], with interfaces even converting simple 2D lines into 3D form directly since 1990 [165, 117]. Similar processes also mean that novice sketchers can have their lines corrected (for beautification/accuracy) to achieve desirable output [144]. Conversely, the line-recognition mechanism can also be used to teach better freehand skills through the gamification of sketching, and this has been applied across all

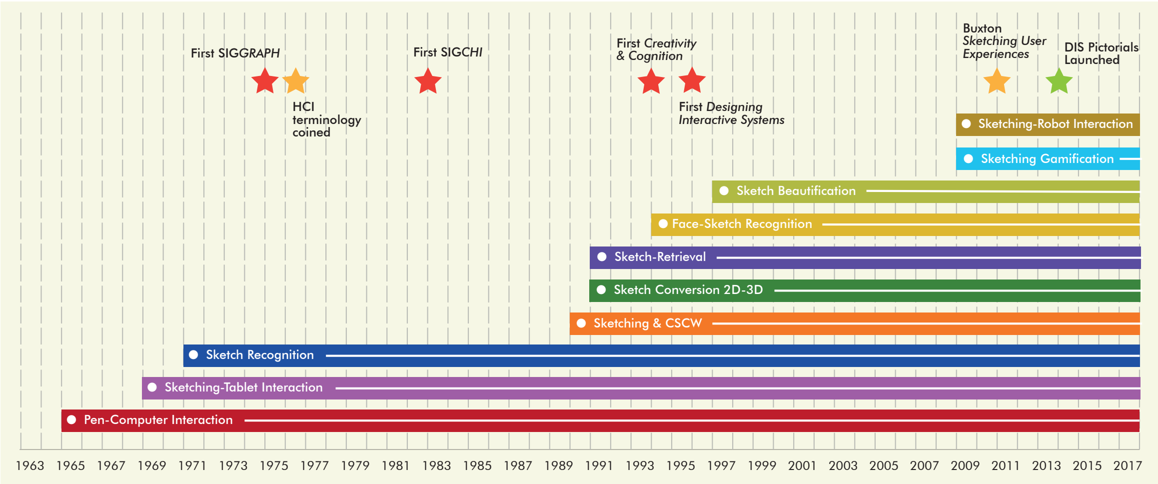


Fig. 3.5 Timeline of research themes within sketching and HCI, alongside relevant events

skill levels [229, 132]. Finally, another recent development sees the birth of *Sketching Robot Interaction* (or vice versa) where *Paul the Robot* creates observational drawings [312] or sketches are used to interact with robots [256].

3.6.1 The Birth of Sketching in HCI (1964–1989)

Although Dix [50] notes that HCI as a discipline appears to have started in 1959 with Shackel's *Ergonomics for a Computer*, the first article to mention the term was from 1976 [27] though it was first popularised in 1983 with the publication of *The Psychology of Human Computer Interaction* [26]. The first mention of sketching in relation to computing can be found in a search of articles from 1964 where Conn et al. [37] discuss curve sketching, and Sutherland's doctoral thesis and latter papers on the *Sketchpad* system [294]. Interestingly, one of only 7 other papers found from that year (*Google Scholar*) is focused on how complex sketching of curves can be done *without* the aid of computers [108]. This suggested mistrust of the automated sketch followed on, as a year later [145] postulated the value of using hand sketching of *Burmester* curves to estimate studies before a computer was used, and to check the data was accurate afterwards. This early research combining the sketch and computing was focused largely on mathematical calculations, though this is not surprising, given that the computer was born out of mathematical curiosity. Before 1964, hand sketching was still seen as preferable to low resolution photographic images (e.g. telescopes) as it had the ability to capture fine detail [307].

Between 1965 and 1971, sketching in computing appears largely absent as a topic, whereas other sketching research focused largely on engineering and even dentistry [318].

Taggart (1975) proposed sketching as a dialogue between designer and computer [296] and this marrying of sketching and computing can be seen in use today as part of user experience design. In terms of the technical elements of sketching-computer dialogue however, Negroponte [212, 213] pioneered sketch recognition and search in the early 70s. With the launch of *SIGGRAPH* in 1974, the computer as an essential part of the production of graphics was born, and by 1975 Taggart et al. [296] were already exploring sketching as an "*informal dialogue between designer and computer*". Then, by 1976, researchers started looking into computer assisted sketching in untrained individuals — the *WHATISFACE SYSTEM* [77], a similar concept to a process *Google* have recently made popular with *Autodraw* [163], amongst others. The first *SIGCHI* conference in 1982 marked a seminal moment for HCI, and offered researchers the opportunity to place their work in a relevant area, although there were few papers relating to sketching until 1984 and Preece's work using sketching and computers for education — with an interactive graph sketching program [237]. Also in this year came Miller's text exploring sketching for page layouts using computers [200], part of the beginning of the evolution of desktop publishing.

3.6.2 The Middle Years (1990–2010)

By 1990 the exploration of sketching had gained in popularity, alongside the Computer Aided Design (CAD) programs which were intended to replace hand drawn schematics for engineering and industrial design, although the two disciplines are frequently examined together, such as Ryan's investigation of technical sketching and computer aided design [253], or more recently, with the suggestion that hand drawn sketching has advantages over CAD [327]. One of the most vocal proponents of hand-sketching is Gabriela Goldschmidt, although her works fall firmly within the design domain, the insights are applicable to HCI in that they provide justification and explanation of the processes, skills and value of sketching [79, 80].

As an indicator of a range of the papers examining *sketching in HCI* during this period, I used the search criteria outlined in the first half of the chapter to generate a top ten list of the most cited research (using the *Google Scholar* algorithm). Additionally, I compared the results with other terms relating to sketching, such as "drawing" in order to return the most relevant results. This list does not however include general design sketching papers, even if seminal (e.g. Goldschmidt [79, 80]) — limited to those directly related to HCI. The top ten most cited papers on sketching in HCI are:

1) *Sketching user experiences: getting the design right and the right design* by Buxton (2010) [23] with 1699 citations. Seminal text outlining the full gamut of sketching in relation to user experience design, and followed up by the practical workbook [89].

2) *Teddy: a sketching interface for 3D freeform design* by Igarashi et al. [117] (2007) with 1637 citations. Interface utilising 2D sketch input to generate 3D forms with which to design meaningful objects.

3) *SKETCH: An interface for sketching 3D scenes* by Zeleznik et al. [359] (2007) with 1070 citations. Uses simplified line drawings to create elements within a 3D conceptual world.

4) *Sketching interfaces: Toward more human interface design* by Landay & Myers [168] (2001) with 602 citations. Exploring how interactive sketches can support the design and application of user interfaces.

5) *Interactive sketching for the early stages of user interface design* by Landay & Myers [166] (1995) with 562 citations. As above, prior text exploring the sketched-interface concept.

6) *Visual image retrieval by elastic matching of user sketches* by Del Bimbo & Pala [46] (1997) with 518 citations. Sketch-based retrieval program which enables the search and return of non-textual items.

7) *Amplifying the mind's eye: sketching and visual cognition* by Fish & Scrivener [62] (1990) with 356 citations. Exploration of the contrast between freehand sketching in early ideation and digital, structured design.

8) *Sketching and creative discovery* by Verstijnen et al. [328] (1998) with 302 citations. An investigation of sketching behaviour to inform better tool design.

9) *Motion doodles: an interface for sketching character motion* by Thorne et al. [308] (2007) with 285 citations. Allows users to directly draw lines which map onto animated character movements.

10) *ILoveSketch: as-natural-as-possible sketching system for creating 3d curve models* by Bae et al. [11] (2008) with 257 citations. Combining freehand sketching input with an interface to draw accurate 3D curve concept models.

This middle-period contains all of the most highly cited texts, and coincides with the upward trend and peak in interest in sketching in HCI for this, although subsequent work has not had as much time to gather interest, the latest work in the list (Buxton [23]) has the most citations, which does suggest that there has been a decline in interest or advancement. At the same time however, advances in other areas of computing have expanded exponentially (e.g. AI, robotics) so it is not clear whether the decline is due to research competition, or that there are no more avenues of discovery available in this area. It cannot be disputed that the advances made in sketch interfaces, and the subsequent commercialisation of tablet and mobile sketching is a direct result of the innovation from this period. 1990-2010 also saw the start of a number of research areas (Figure 3.5) such as sketch-retrieval and sketching in

Concept	View of Sketching	Key Phenomena & Constructs	Successful Sketching	Example of use / support
Ideation	Way to generate ideas	Loose style, quickly generated	Ability to communicate idea with minimal effort	Developing UIs, teaching, design process,
Input	Method of interaction	Drawn image, copied onto or input directly into device	Program is able to recognise key components for purpose	Rapid protoyping of products, converting 2D to 3D imagery
Ouput	Finished product or result of interaction	Drawn image (final) Printed or screen based imagery	Communicates visual research or shows program output	User generated output, computer generated artwork
Tool	Intermediary device	Transient, means to an end	Easy to use, has set purpose	Methodology, communication, used for input
Iteration	Refinement of ideas	Detailed, multiple versions	Shows progression and adaptation	Design process, developing tangible UI
Evidence	Document of process	Collection of images, notation, relates to findings	Can be related directly to research output	Pictorial, dataset, annotated literature reviews
Elaboration	Annotation	Addition to existing data or text	Enhances understanding of information	Annotated portfolio, diagram
Dialogue	Method of communication	Drawn image replaces language	Non-verbal communication of ideas/directions	Multi-language teams, inclusive practice

Table 3.2 Overview of some key concepts of sketching in HCI literature: key concepts of sketching, key traits, what successful examples should provide, and use-cases/examples, based on Hornbaek et al. review of interaction [115]

Computer Supported Cooperative Work, alongside 2D-3D conversion of images — and a surge of interest at each.

3.6.3 The Future? (2011–present)

The apparent plateau in the last 8 years for sketching in HCI does not correlate with a lack of exciting research, merely with the quantity of output, as sketching may have become more incremental in its advancements — but is inexorably moving forward. One explanation may be that the idea of what a sketch is has changed — although Goldschmidt states that the sketch (traditional view) is still relevant [81]. If one takes into account the evolution of the sketch into physical or data or even hybridised, multi-modal formats, then the trend in the time-line tells a different story, one of continual rise. There has also been a rise in sketching courses in computing, and renewed interest in its application in HCI via workshops and tutorials at high profile venues [195, 180].

Novel areas for research include not only education, but also sketching inside virtual reality [261], design fiction [291], and even teaching robots to play *Pictionary* (a popular guess-the-drawing game) [258]. Sketching has been integrated into physical interfaces so that the blind can sketch with haptics [140], and into drawn sculptural images by combining 3D printing with drawing (3D-Doodler [21]). Whilst advances in physical, freehand sketching have been made, the notion of *Magic Paper*, — seamless computational sketching — "magic paper" [7] is still a way off realization, although the emphCintiq Companion 2 comes close to paper texture with its matte surface [333], and flexible OLED (Organic Light Emitting Diodes) and other forms of tangible interface are becoming more sophisticated (see Chapter

2), and more versions of sketching technology are becoming commercially available. Johnson argues that the "sketch" in computing is a niche area, but I disagree, it is more than that, it encompasses many domains, fields and the computerisation of sketching and its adoption by HCI will only expand its reach. Have we reached "peak" sketch in HCI? Or are we about to embark on a renaissance, embracing hybrid forms and interdisciplinary collaborations?

3.7 A Categorisation of Sketching in HCI

The search analysis allowed us to identify 8 forms of sketching within the field of HCI. These can be compared in Table 3.2, and are visualised in sketch-format within Figure 3.6. In order to produce the categorisation, a 5% sample of texts from within the search criteria were subjected to the following rubric examining how sketching was used: 1) Is sketching the a) the focus of the paper, b) utilised in the methodology, or c) a result of the methodology?; 2) How is the sketch used in relation to computer technology? 3) What kind of role did sketching play (direct/indirect)? 4) Does the text contain images of sketching, or is the result computational?; 5) What were the findings/discussion points in relation to sketching (tangible/intangible)? The full texts were also parsed to understand the motivations of the work, and where they were placed within research themes and specific technological applications, as this consolidated the categorisation.

The formation of categories for sketching in HCI allows for us to view works in relation to new criteria (i.e. other than specific domain, such as sketch-recognition) and place them into new contexts of use. For example, *sketching-as-dialogue* has implications outside of the research it relates to (e.g. prototyping collaborative sketch-interfaces). We can also sort research into one or more category to see where it might overlap conceptually with seemingly unrelated papers which utilise sketching, or identify areas of sketching research that are currently under-represented and improve on them. Current research can be judged against the "successful" use of the sketching theme to validate or question a concept, and comparisons can also be made between sketching practice and research within other domains. This is because some concepts are shared with design or artistic practice, but others are unique to HCI (e.g. the sketch as input). On a reflective level, the range of applications for visual sketching shows the potential for further investigation within and across themes, and question the base motivation for this kind of research. Finally, categorisation is not new to sketching research [270], but the way in which it is used within HCI differs in that the scope and application is vastly expanded (e.g. annotation in digital format with interactive properties) and thus sketching transcends the tool/process context of design and evolves. The following sections expand upon the categorisations in Table 3.2, alongside current examplars from the field.

3.7.1 Ideation

Ideation is one of the universal constants in sketching in relation to research, and forms part of almost every (if not all) disciplines. Ideation in this context relates to the quick generation and brainstorming of many different visual ideas and is utilised at the beginning of a project phase, although it can also be used as part of a user-centred process. Examples from the field include: sketching used to increase divergent thinking via an iterative process [73]; digitisation via the creation of an electronic "back-of-the-napkin" to encourage creativity [92]; used as a ideation method to generate ideas for future interfaces by participants in user studies (see Chapter 6); or to examine how novice designers utilise differing ideation methodologies with their basic sketches [191].

3.7.2 Input

Direct input is a use of sketching that is novel to HCI and computing, in contrast to traditional, freehand sketching where the resulting image is a visual output only. The sketch-as-input relies upon complex computational processes to recognise lines, shapes, distances and stroke-widths — as well as intended meaning. The *sketch-as-input* is an essential part of sketch-based interfaces [6] and is made possible by software allowing for *sketch recognition*. In this context, sketches can be input in several ways — directly by stylus, from a scanned or photographed image of a freehand sketch, from a pre-existing digital source, or by gesture inside programs. Examples from the literature include direct freehand input of maths symbols and diagrams (*MathPad2* [169]); network sketches or UML (*Tahuti* system [100]); using 2D sketches to convert into 3D representations (*Teddy* [117]); and there are even sketch recognition languages (*Ladder* sketch recognition language [99]).

3.7.3 Output

The visual output of freehand sketching is an easy concept to grasp, but the way in which sketching output can be generated within HCI is enhanced in comparison to art and design processes. The sketch as output can relate not only to an image on paper or screen, but sketches can now generated by Neural Networks or other programs utilising a variety of imagery, and rendered as if they were a freehand representation for both generic scenes [348] and portraits of people from photographic input [29]. The output can also be coupled with direct sketch input to create refined versions of freehand sketches as part of the beautification process via line correction (*PortraitSketch* [352]), or used as a workable interface design (*SILK* [167]).

3.7.4 Tool

Tool-based sketching is an intermediary concept, where sketching is utilised as a means to an end. This relates to the sketch as having a purpose beyond simple input or output — rather, it provides a *service* in a specific context. In this category, sketching can be used in education research, where the sketch has been gamified and made into a way of improving draughtsmanship [347]. The sketch can also be a tool for increasing interactivity in paper prototyping [95], to direct movement in animation (*Motion Doodles* [308]), or control enhanced [170] or sketched visualisations [22]. The *sketch-as-tool* is also part of sketch-based image search/retrieval [52].

3.7.5 Iteration

Sketching is perfectly suited to the iterative design process, where a product or image has been decided upon, but requires refinement or further ideation. Iterative sketches in HCI relate to the incremental development of visual ideas, much as they would in design disciplines, but are used in relation to the prototyping process, on paper or on screen. Similar to ideation, the iterative sketching process is a visual record of ideas [13], but also the development of those ideas [271]. In HCI research iteration has been used to examine ways of exploring and analysing ideas from researchers in tangible interfaces [243], or as a way of providing an animated record of sketched iterations that can be played back to examine evolution [267].

3.7.6 Evidence

Sketched visuals, including iterations can be a form of record for processes and findings in a highly accessible manner. This kind of usage relates to the published findings and documentation relating to research projects in HCI, and can be purely process related, or show the results from computational output (for example). Though not universally utilised at present, *Pictorials* containing sketches are becoming more popular for documenting processes within HCI [88], and at conferences or other live events, sketch-noting and scribing are being embraced as adding value to both attendance and the legacy of events [335, 195]. Sketches are also used as a (private) documentary of meetings and collaboration, both in research and industry [337, 336], and in public as a form of expression on social media (*UbiSketch* [40]).

3.7.7 Elaboration

Sketching can be conducted on existing items to add value and to aid understanding via a process of annotation. Annotative processes within HCI take on new meaning out-with making notes or doodles on a text when they become interactive, transferable or can be transmitted across the world in real-time. Elaboration in this context has been examined from both the interface development side [9] and in a practical manner to assist medical professionals in tracking illness and making decisions about surgery [135]. Interactive whiteboards allow exploration of visuals [171], whereas in collaborative work, sketched annotation can aid decision-making [55]. Finally, in tangible interfaces, sketched visuals can add meaning to non-planar surfaces [197].

3.7.8 Dialogue

Given the universal nature of the visual sketch, it is therefore a logical extension of the concept that it be used as a form of dialogue. Sketching on interactive tables enhances the collaborative experience [98, 119], and can also be used as a way of communicating concepts remotely via digital pen/paper capture, where textual language cannot adequately demonstrate meaning (*PaperSketch* [341]). *Sketching user experiences* [23] has long been used as a visual method to open a dialogue between researcher and user, and put ideas into believable contexts, and this has been extended into co-creating comic-strips in cyber-security [179] or creating complex visual icon libraries to allow novices to engage in sketching dialogue [178].

3.7.9 Process vs Application Based Sketching

The 8 categories of sketching outlined here can be further broken down into *process* and *application* oriented roles. *Process* meaning they are employed during the design and build process (e.g. product development), and therefore *ideation*, *iteration*, *dialogue*, *elaboration* and *evidence* fit into this role. *Application* orientated sketching, on the other hand, applies to the sketch as *input* or *output* — meaning these aspects of sketching relate to an existing system but do not contribute to the initial design process. In this context, sketching as a *tool* is an outlier that can work in both roles.

In relation to the proposed work in this thesis, the concern is with developing formal UCD processes for shape-changing interfaces, so the *process* oriented sketching categories are of most interest. Specifically, those categories that relate to the initial stages of the design and development process are most important, as the latter — iterative sketching for specific designs, presentation of evidence, or sketching as a formalised tool — relate to established/completed processes or explicit research outputs. By utilising sketching methods from the early stages of UCD, or design processes from other disciplines (e.g. *ideation, dialogue* and *elaboration*), the logic follows that those methods would be specifically helpful in the context of developing related processes for shape-change.

3.7.10 Other forms of sketching in HCI

Although this analysis focuses purely on visual mark making, sketching in HCI has far outgrown these humble beginnings, and the idea of the "sketch" has a life far beyond its original visual mark-making definition. The below examples are a selection of ways in which the notion of sketching has been adopted, though these diverse forms can still be applied to the above themes: *Game-sketching* — making mini-versions of games to test playability and entertainment value [275, 277]; *Sound-sketching* — using voice, music or other aural input to create small vignettes which represent the larger sound-scape [53, 194]; *Code-sketching* — a partial implementation by a programmer [278, 279]; *Body-sketching* — using tangible, embodied forms which are captured in film or animation [196, 260]; *Data-sketching* — small sections of a complete dataset that give an understandable overview [118, 176]; *Physical-sketching* — sketching with paper, electronics, conductive ink or other types of tangible hardware items to create a quick physical prototype or idea [68, 114]. These novel uses of the sketch-concept can also be combined within themselves, e.g. voice with gesture [248] or with the freehand sketch [344].

3.8 Discussion

Outside of fine arts, the perpetual contributors to sketching research output are design, engineering and architecture. Though given the interdisciplinary nature of HCI, and the myriad of applications for sketching that have subsequently arisen through computational support, sketching can be seen as a binding force between HCI and diverse subjects such as medicine [135], education [229] and robotics [188], as well as the former disciplines. In consideration of this, I conclude this review, by examining the methodology, findings, and range of data uncovered, and speculate as to the next areas of focus for the field (such as education and robotics), with the potential for advancement for sketching within HCI and beyond.

3.8.1 Methodological Reflection

This chapter did not initially expect to provide so comprehensive a search, but early forays into various databases soon showed how much could be missed, or lost down the search chain from an over reliance on simple search or a singular database. The work here provides the opportunity to consider employing further rigour in HCI reviews — many appear to review the most prominent, or those of interest, but do not allow for systematic search strategy. This work allows the researcher to gain insight of a complex and wide-ranging field within a relatively small space, much as Myers' review of HCI allowed [205], or Kamppuri's analysis of cultural references in HCI [141]. Johnson et al. [134] elaborate on several of the themes here in their excellent text on computational support for sketching from a design perspective (as outlined in the *Background*, section 2.4) and examine around 200 texts over 81 pages, but do not provide a complete comprehensive overview of sketching in HCI itself. We hope that this work can enhance and elaborate upon the previous work in this area.

It is also worth considering a possible limitation of the narrative review process, in that if you examine records from early work (e.g. before the adoption of word-processing or digitisation of documents) there may be many research outputs that never made it through the process, and still languish within the print archives of academic or commercial institutions. Those that were scanned or transcribed may only represent the popular thought of the time, and therefore could bias the count of papers from the earlier years (circa 1953-1980). Another limitation is that searches within *Google Scholar* often do not flag duplicates, and include citations for papers that either *do* exist in the database (and must be cross-referenced) or *do not*, in which case the citation must be counted if it refers to an *offline* paper — the issue is then further compounded if the signposted articles cannot then be found in other databases (e.g. *OneSearch, IEEE*). The issue with specific databases however is that they only return results from within their own corpus, which is why this work looked at results from searches from multiple sources to ensure important works were not missed. Additionally, there may be issues with using *quantity* as a measure of popularity or research interest, as previously mentioned: the plateau may not be a reflection of lack of solid research, merely smaller increments or slow beginnings of new areas of investigation. This question cannot be resolved until we witness the next period of research in this area however, so we must wait.

3.8.2 Reflection on Categorisation

In developing the categories, it became apparent that there was not an even distribution of papers across each, which may relate to popularity, or more complex factors such as technological advancement leading to a surge in breakthroughs. At first glance, there appears to be a deficit in HCI papers which provide documentary evidence of sketching as part of the HCI research and development process — this may be due to punitive restrictions on publishing page counts, or lack of value for the drawn image in what is essentially a science. The broadest category appears to be that of sketch recognition and the *sketch-as-input*. This could be bound up in the novelty of this form of sketching — it is distinct and exists only within the context of the computer. Researchers in computer-vision and AI interpretation may see sketching as a particularly exciting challenge, due to the rough, personal nature of freehand sketches, and because the meaning behind human-generated images is easy to lose when only the formation of lines and relational distance or corresponding imagery can be used for analysis. *Paul the Robot* [312] may be able to produce observational imagery, but until it can form its own personal style, its output will be without hidden meaning or humanity.

3.8.3 Sketching Education in HCI

Manual sketching *is* still relevant despite advances in drawing tools and CAD [81]. Jonson suggested back in 2002 that traditional sketching might be under threat from computer aided drawing [136] – but this is not the case: more than ever before are practitioners taking up pen or stylus to record visual ideas, course and workshops in sketching are a regular occurrence in conferences and other events. This is also only one part of of the sketching HCI revolution, the sketch is taking on new life in the hybrid forms discussed above, and as an intermediary in interfaces and work-flows. Defining and documenting the sketch in HCI is an interesting focus, but the real challenge comes in the teaching of freehand sketching and drawing as part of the university curriculum, or even sooner, in our schools, where the arts frequently face cutbacks in funding. Students are often reluctant to learn to draw unless they are “a natural”, or put off trying by those around them who appear to have more talent for it [35]. Sketching is commonplace within teaching practice for architecture, design, and engineering, but is not as widely adopted in computing, although there are examples [219]. With the advent of beautification programs and sketch-assisting software, as well as gamified line drawing programs, HCI can take centre-stage in sketching education, and this could be one of the next areas of focus.

3.9 Next Steps

From the preceding analysis and discussion, it is clear that there exists the potential for novel avenues of research for sketching within HCI. The wide-ranging historical uses of sketching suggest that it can be readily applied to the design process of research across disciplines, and as the most promising direction for sketching in HCI appears to focus on novel interfaces (alongside artificial intelligence), I can justify using sketching in the context of the design and development of shape-changing interfaces. More precisely, having identified the processes contained in referenced works within the categorisation framework, I have identified which categories of sketching will best benefit the goals of this thesis.

As discussed in section 3.7.9, and given the precocity of shape-change, initially using sketching as part of *ideation* for shape-change will allow us to explore realistic goals for this research. *Ideation* is also the first stage in all design processes — without an idea, there can be no progression. Chapter 2 already demonstrates the range of ideas generated by researchers in HCI — as well as the gaps in the field of shape-change — so to gain perspective I must identify ideas, and therefore research directions, from other groups. Subsequently, as this work aims to contribute toward the foundations of a practice of *User*-Centred Design for shape-change, choosing non-expert potential end users will supply this perspective.

As the purpose of UCD is to work directly for — and with — the user, I will use the output from the *ideation* stage to form part of a *dialogue* between my research-focus, and the needs or desires of potential end-users. By using the sketch as *elaboration*, I can investigate these outputs further in subjective practice. The *dialogue* process can then be reversed as insights gathered during the subjective research phase can be fed back into the next stage of the work as a refined process with more focused goals.

3.10 Conclusion

Sketching in HCI has played an understated role in the field since its inception. In order to expose its use and popularity, I have provided a comprehensive overview and history of sketching in HCI spanning its inception, parsing over 5000 papers, from which I have visualised its rise in popularity, created a timeline of research themes and events, and developed distinct themes for sketching as research within the field of HCI. These categories provide an accessible overview and resource for not only this work, but also other researchers.

Chapter 4

A Public Ideation of Shape-Changing Applications

4.1 Chapter Summary

The previous chapter outlines how sketching has been — and is currently used — in HCI, and identifies sketching methodologies for early-stage design processes. It also explains how these categories of sketching can potentially be used for the design of *new* processes for shape-change prior to the development of formal, specific UCD for this technology. This chapter builds on the use of sketching for *ideation* in relation to shape-changing interfaces, from a potential end-user perspective. By using a portable, shape-changing prototype made from *ShapeClips* [102] to demonstrate shape-change, alongside some posters showing the parameters possible for shape-change (e.g. height/width change) I was able to communicate the complex attributes of shape-changing interfaces to a non-expert, public participant base. Participants were encouraged to sketch their ideas for shape-changing applications. Over half of participants (54%) chose to draw their designs and *elaborated* upon them with notation about how the device worked, who it was for, and which parts changed shape. The evidence points toward non-expert potential end-users being able to both grasp the concept of shape-change, but produce meaningful application ideas via a combination of sketching and annotation.

As noted in Chapter 2, research both within and outside of HCI continues to develop a diverse range of technological solutions and materials to enable shape-change. However, as an early-stage enabling technology, the community has yet to identify important applications and use-cases to fully exploit its value. To expose and document a range of applications for shape-change, I employed an unstructured ideation and sketching task in the context of a public engagement study. A 74-participant brainstorming exercise with members of the public produced 336 individual ideas that were coded into 11 major themes: entertainment, augmented living, medical, tools & utensils, research, architecture, infrastructure, industry, wearables, and education & training. This chapter documents the methodology in detail, and the resultant application ideas, along with reflections on the approach for gathering application ideas to enable shape-changing interactive surfaces and objects.

4.2 Introduction

This chapter proposes a novel way to address the knowledge gap in shape-change between researcher and end-user via the analysis of 336 ideas generated by 74 members of the general public during a creative thinking experiment. We hypothesise that large public groups can ideate and sketch novel research directions which indicate requirements for shape-change that are situated a diverse range of individual needs and demographics. The findings include themes that expand and diversify the academic design space, and characteristics that help researchers reflect on producing appropriate solutions for the needs of a public user base. The aim is to generate novel processes and research directions for shape-changing technology, and subsequently this chapter contributes: 1) An unstructured brainstorming methodology involving non-expert individuals, carried out over *seven days* with *74 participants* generating a total of *336 unique ideas*; 2) Analysis of the generated ideas using a Grounded Theory approach, identification of common theme categories, characteristics, and descriptive statistics; 3) Discussion around associated emergent themes, ideation output, and ideas relating to existing research 4) Reflection on the methodological approach discussing generalisability, limitations, and considerations for future practitioners and; 5) A database of the generated ideas made available online at www.shape-change.org/brainstorm/.

4.3 Related Work

4.3.1 Existing Shape-changing Prototypes

As seen in Chapter 2, shape-changing prototypes encompass a diverse range of materials, hardware, and usage scenarios. Many of these prototypes focus on a single application output (such as physically dynamic bar charts [297]) or interaction (displays that emulate reading a book [339]); and on material-based technological advancement of the field (Shape Memory Alloys [216] or particle jamming [259]) — although there are cases where subsequent

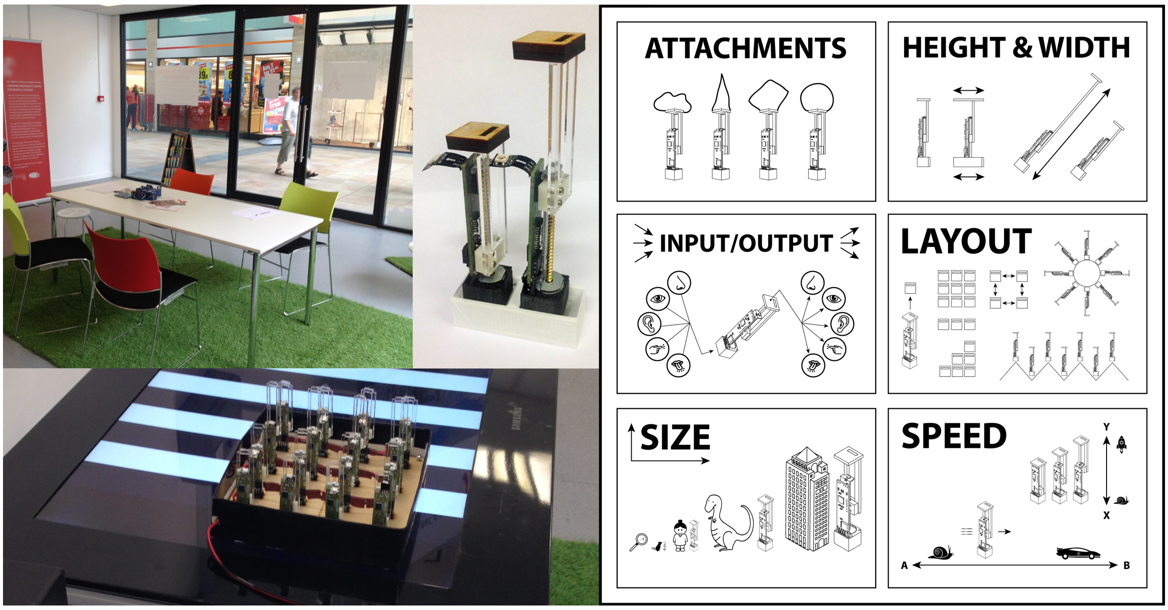


Fig. 4.1 (Top left) The study location; (Middle) Two Shape-Clip display components (at minimum and maximum heights) demonstrated to members of the public. (Bottom Left) Demonstration consisting of 16 Shape-Clips [102]. (Right) Parameter posters displayed during the study

iterations of the same prototype have explored new application directions (e.g. *inForm* [67], *deForm* [65] and *TRANSFORM* [173]).

A large body of research in this area also looks at developing shape-changing versions of pre-existing technologies such as mobile phones [83, 109], tablets [284, 266] and desktops [300], although there are also more novel approaches considering artistic output [156] or emotive social-touch surfaces [207]. Another way in which research into these technologies progresses is to build upon previous prototypes incrementally, or to re-purpose components or ideas from existing work for development in other contexts. By following the citations within any given paper, justification for the prototype could be seen to come from the research community at large, rather than via specific ideation, or by engaging with potential end-users.

4.3.2 User-studies & Prototype Evaluation

Taking a user-centered approach for evaluation of a prototype is commonly seen in a commercial context although the details surrounding this methodology are not always given [149]. In academic research institutions it is common to ask colleagues/student participants to evaluate prototypes, or for studies to use low numbers of participants. Methodologies utilise observational studies either from product placement [91], or artistic installation [207]. Other issues surrounding participant selection due to local availability can stem from gender bias or incentivisation [343], and research familiarity [227]. This is not to say that researchers employing such methods of participant selection are not making valid contributions to the field, but that there is space for an expanded viewpoint around such studies. I aim to address this omission within this chapter.

4.3.3 Brainstorming and Ideation

Brainstorming is a methodology commonly employed within groups for freely generating ideas to solve a particular problem or to generally come up with new ideas — it also is used to generate visual outputs such as idea sketches [3]. As a non-experimental method, it is uncommon to see this kind of free associative thinking in scientific research. In contrast to the norm, Hardy et al's [102] experimental set-up utilised brainstorming to generate new research directions using designers and expanded upon these with rapid prototyping of viable ideas for shape-change. Notably, Jung et al. [139] also held sessions within their process (albeit with fewer participants). Utilising the general public in evaluation is unusual within the sphere of shape-changing interface research, although as previously mentioned both Gronvall et al. [91] and Nakajima et al. [208] successfully integrate a prototype within a public space. This allows both observation of diverse public interaction with shape-changing artefacts, and user testing in a non-pressurised setting. Follmer et al. hosted an open-house during which *deFORM* was showcased [65] but little information is provided as to demographic and experimental organisation. What is missing from research methodology in this area is purposeful and transparent recruitment of a participant pool from the general public. This chapter hopes to elaborate upon participant selection and the use of non-institutional spaces in shape-changing research, following the success of such public-focused studies in co-design scenarios [257] and using brainstorming techniques such as De Bono's system outlined in *Serious Creativity* [43].

4.3.4 Methodology

The study goal was to use sketching to generate shape-changing application ideas from a non-expert public group during an unstructured brain-storming session. These ideas were captured following demonstration of, and interaction with, an existing shape-changing display prototype. Analysis of the ideas isolated themes and characteristics of interest. By sampling a "general public" user-base I hoped to: (1) obtain application ideas that go beyond those currently documented; (2) examine the effectiveness of public involvement; (3) compare and contrast ideas onto existing research literature.

4.3.5 Experimental Setup and Location

The study took place in a vacant retail unit with high footfall in a UK town-centre (Figure 4.1, top left). Banners invited the public to "Take part in a creative thinking experiment". No financial incentive/reward was offered. Participants self-selected, with minors required to be accompanied by an adult. Due to the random nature of such participation, data was collected individually, and without using published ideation techniques. This was to ensure consistency as no group facilitation or other structure could be planned for. The study ran over seven consecutive days including one weekend during school holidays. Alongside writing/sketching space, the unit contained a demonstration of *ShapeClip* prototyping units [102] and posters that facilitated the brainstorming/creative thinking task by communicating the theme of shape-change as a technology to the participants [69, 283]. These are detailed below and in Figure 4.1.

Shape-changing Display: Shape-changing Display: In the study space was an example of a z-actuating shape-changing display using *ShapeClip* units [102] (Figure 4.1, middle). *ShapeClips* are modular prototyping tools containing individually programmable Arduino units. The grid demonstrated how vertical movement can be combined with visual output in a magic-lens style configuration [17]. Participants manipulated the *ShapeClip* lens by moving it across a Samsung SUR40 touch table over a variety of graphical outputs: checkerboard, stripes, sunburst gradient (Figure 4.1, bottom left). Each individual shape-pixel actuated vertically between black/darkest output (0% actuation) to white/lightest output (100% actuation) over a travel range of 60mm.

Parameter Posters: Six posters depicted possible shape-change parameters to consider: different attachments, height & width changes, different input/outputs, layouts, sizes, & speeds. The posters served to broaden the range of divergent thinking by suggesting how the prototype might be altered (i.e. room-scale transformation) without overtly implying specific ideas, and regulated the explanation of such parameters as part of the experimental design (Figure 4.1, right).

4.3.6 Process

The experimental process consisted of four stages: (1) *Introduction & Consent*: The aims of the study were explained and appropriate consent forms completed. (2) *Demonstration & Interaction*: The prototype was demonstrated, participants were encouraged to interact with the technology, and were shown parameter posters. (3) *Ideation*: Participants were asked —without time constraints— to generate as many uses for shape-changing technology

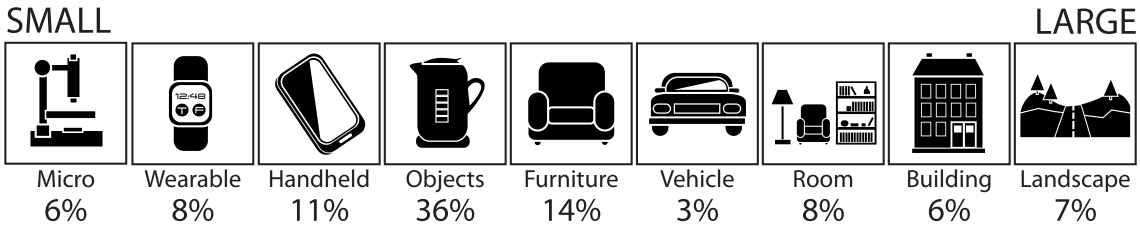


Fig. 4.2 Ideas classified by approximate level of scale and type (Note: there is potential overlap between wearables/objects/hand-held but these were felt to be better represented as distinct entities for the purpose of scaling).

as possible (previously generated ideas were not made available). Responses were paper-based rather than verbal, so as to capture ideas, provide participants with a familiar medium with which they could express themselves without interference, and encourage sketching. Participants indicated when they had run out of ideas. (4) *Exit Questionnaire*: Participants were asked to provide demographic and other relevant written data as pertaining to the study. Questionnaires can be found in Appendix 2.

4.3.7 Data Analysis

The demographic responses and raw ideas were collated and cross-referenced. All of the ideas were then coded according to the basic principles of Grounded Theory in three iterations [288]. This resulted in clusters of idea themes, sub-themes, and characteristics (i.e. three independent 'idea feasibility' estimates, and a 3-point measure of elaboration. Ideas were also annotated with (approximate) scale, interactivity, and use of parameter posters. Our choice was informed by Rasmussen et al's classifications [242]. The data set was then queried by aspects of the questionnaire to identify any interactions between demography and participant output levels, i.e. age, gender, technological comfort, and also discover further variables that might improve the methodology.

4.4 Dataset Analysis

4.4.1 Participant Demographic

Table 4.1 presents descriptive characteristics of the 74 sampled participants, ranging in age from 5-71 years (μ : 30.07, σ : 14.10). The majority held a university qualification (67%). On 5-point Likert responses, people typically agreed with the statement that they were 'creative' (μ : 3.75) and 'comfortable with technology' (μ : 3.82). The majority were

	Characteristic	Value
1	Gender	Male (58%), Female (42%)
2	Age (years)	$\mu : 30.07$, $\sigma : 14.10$, $range : 5-71$
3	Education	School (12%), GCSE (3%), A-Level/Vocational (17%), Undergraduate (34%), Postgraduate (31%), Ph.D (3%)
4	Sector	SciTech (31%), Management & Law (10%), Healthcare & Medicine (4%), Arts & Social Sciences (27%), Unspecified (28%)
5	Creativity (1-5)	$\mu : 3.75$, $\sigma : 0.87$
6	Tech Comfort (1-5)	$\mu : 3.82$, $\sigma : 1.06$
7	Ownership	Smartphone (85%), Tablet (64%), Laptop (84%), Desktop (55%), Wearables (9%), Games Console (62%)
8	Ideas Produced	$\mu : 4.51$, $\sigma : 3.34$, $range : 1-21$, $q1 : 2$, $q3 : 6$

Table 4.1 Descriptive characteristics of sampled participants

technology consumers (line 7). Participants typically generated ($\mu : 4.51$, $\sigma : 3.34$) ideas. Systematic $\tilde{\chi}^2$ and correlation tests found no significant relationship between any of the demography characteristics and the number of ideas produced.

4.4.2 Gender Differences

An independent samples t-test was applied to the data to determine if there were significant gender differences between number of ideas generated. There was no significant difference in the number of ideas for men (M=4.767, SD=2.843) and women (M=4.226, SD=3.955); t(0.686)=72, p = 0.495 (there were no participants who identified with other gender identities). However, plotting the thematic data by gender does suggest that there may be evidence of bias toward particular themes (see Figure 4.3). A larger sample would be required to assert if this generalizes, but it does indicate the importance of mixed groups.

4.4.3 Idea Themes

A total of 336 ideas were generated. These ideas were presented using sketches (6%), writing (46%), and a mixture of both (48%). Grounded coding sessions produced 11 major themes. The themes identified for using shape-change were (with examples for each) *Entertainment* (physical 3D television, drawings which come to life); *Augmented Living* (responsive fake plants, furniture that responds to the body); *Medical* (beds to reduce pressure on injuries, responsive prosthetic limbs); *Utensils and Tools* (re-sizable joinery tools, reactive camera tripod); *Research* (responsive sculpting materials, “Holodeck”); *Architecture*

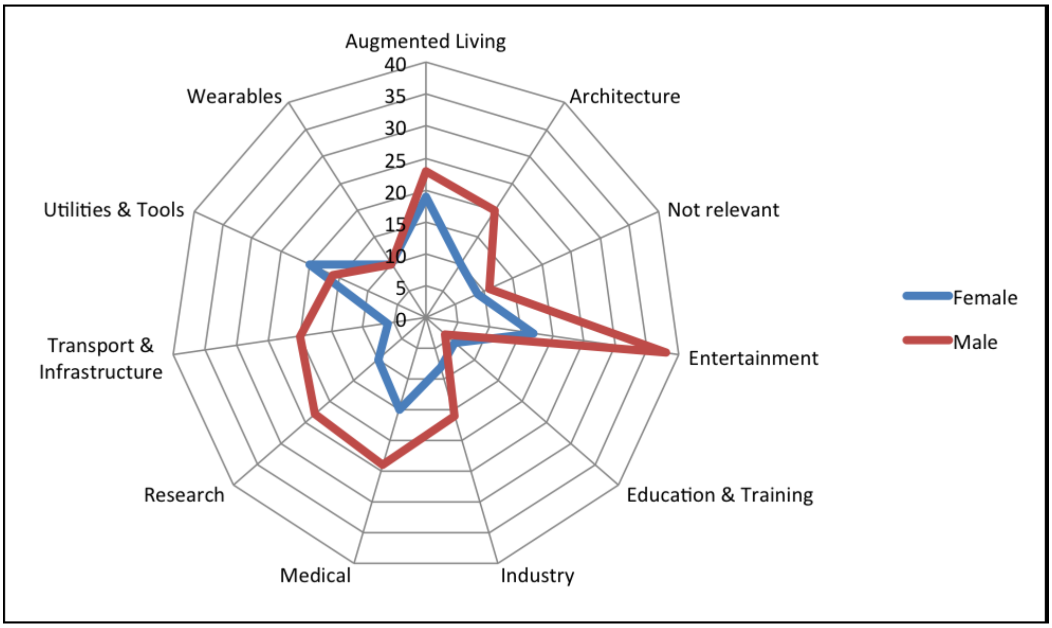


Fig. 4.3 Categories mapped by gender

(earthquake responsive building foundations, reconfigurable rooms); *Infrastructure* (flood-resistant bridges, roads which respond to accidents); *Industry* (remote engineering in space, moulds for slip-casting); *Wearables* (re-sizable bags, anti-mugging wallet); and Education & Training (3D white-boards, shape-changing museum exhibits), with 6.2% of ideas counting as 'not relevant' (headphones that play music when they sense your ear, voice controlled ovens).

Each theme also contained associated sub-categories and cross-over: i.e. a medical bed for coma patients might have a primary theme of *Medical* but a secondary theme of *Augmented Living* with a minor catergory of *Furniture*. The ideas with associated major, minor and secondary themes can be seen at http://www.shape-change.org/brainstorm/.

Table 4.2 summarises the total idea database, the associated categories, and lists these according to most frequent to least frequent. The most ideas were generated in the *Entertainment* category, with *Education & Training* the least populated idea category. A category for ideas that did not map onto the theme of shape-change, or were insufficiently explained was included here as this category comprises a portion of the data set on a par with *Industry*, or *Wearables*. It is not clear whether participants generating unrelated ideas were simply carried away by the brainstorming task, or misunderstood the parameters of the study. The themes are described in more detail in the discussion, alongside the sample ideas in the table. Table 4.2 also presents small graphs that indicate idea feasibility and elaboration within each theme, as well as showing idea frequency per theme.

Feasibility: Each idea was coded according to how viable it was to produce this item using current levels of technology, with a high value (5) indicating that it could be built almost immediately, and a low value (1) indicating only a slight probability that the item could be built, even in long time-frame. Average idea feasibility across the entire data set, on a 5-point scale, was ($\mu : 2.72$, $\sigma : 0.77$). (scored from unfeasible at the lower end, to very feasible at the higher end). Coding was carried out independently by three researchers in the shape-change field using the same method, after which an average feasibility level was generated. Feasibility by theme can be seen in column 4 (Table 4.2), darker blue indicates higher feasibility, e.g. ideas within the *Augmented Living* and *Entertainment* themes appear to be more feasible given current technological advances than *Infrastructure* or *Architecture* – possibly because shape-change in the home/office is already in place, albeit at a lower level of technology (adjustable office chairs), but also at the research stage (shape-changing bench [91], or computer game controller [354]).

In comparison, architectural and landscape/infrastructure level shape-change would require not only a large amount of resource/space, but also significant changes in highly regulated building practices. Although there are real life examples (automatically raising road barriers, meeting room dividers) in daily use, these are at a much smaller scale of what would be necessary to realise the generated ideas in these themes. Comparatively, the Wearables category shows a lower feasibility, possibly because the ideas generated rely on microscopic shape-change (high shape-resolution) that is not currently in evidence in day to day living or cutting edge research. The overall feasibility for all themes (excluding those not relevant) is high, showing that participants were able to generate ideas within the realms of practicality, whilst also thinking speculatively.

Elaboration: Participant responses ranged from single words (e.g. games) to long essays or highly detailed images with accompanying texts. Text responses made use of bullet points, as well as descriptive prose, and whilst the variety of explanation is interesting, there do not appear to be any indicators for type of response in comparison to demographic data. Elaboration was coded in the same way as feasibility, on a three point scale indicating how much information about each idea was available, after initial analysis indicated the range of such information. Highly elaborate (and relevant) ideas suggest a greater understanding of the prototypical technology on display, as well as an analytic mindset.

4.4.4 Idea Properties

Beginning with the poster parameters, 23% of ideas involved attachments to the actuators (such as soft coverings or building foundations), 14% required different heights / widths, 72% used inputs/outputs that integrated the shape-change with other systems or senses

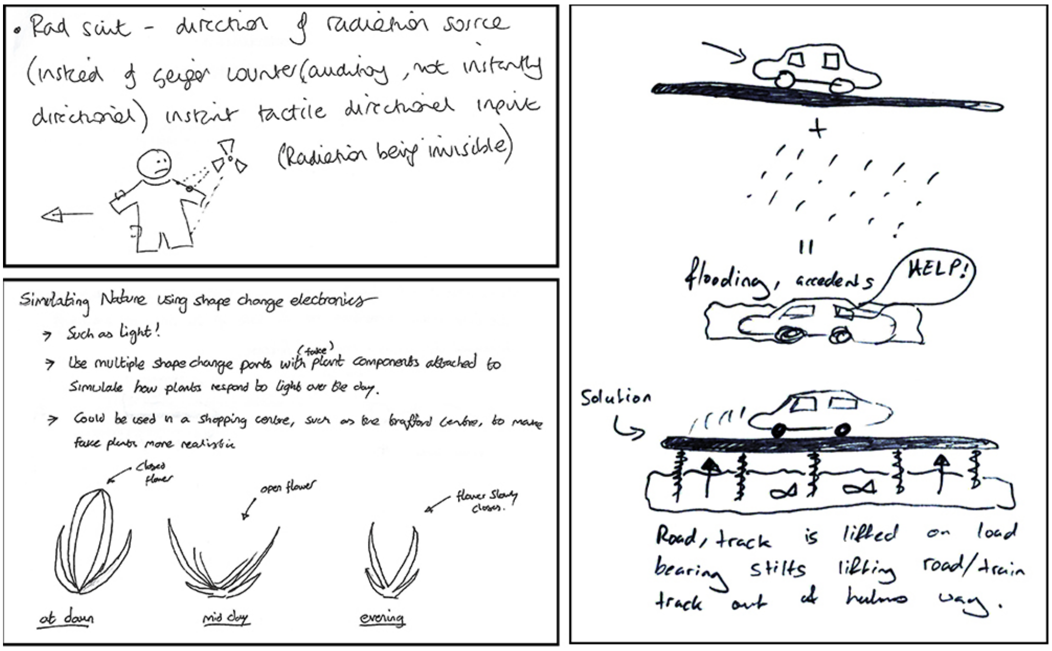


Fig. 4.4 (Top) Mapping ideas onto existing research – reactive clothing; (Bottom) The influence of nature – shape-changing plants; (Right) The use of narrative imagery to describe stages of shape-change.

i.e. light, sound, 21% required non-rectangular or grid layouts of multiple actuators, 92% differed in size from the prototype shown, and 19% required significantly different actuation speeds. These differences are worth noting as the chosen prototype has comparable technical specifications to works in recent literature (closed length: 80mm, fully actuated length: 120mm, maximum actuation speed: 80 mm/s), particularly in terms of size and actuation travel. This makes the resulting ideas even more interesting (1) because participants were able to generalise beyond the object I showed them; and (2) because the literature might be missing categories of actuation/ideas.

To explore the differences in scale and use between the idea set and the literature, ideas were classified according to dominant scale; ranging from microscopic to landscapes. The percentage of the total ideas for each scale are shown in Figure 4.2. The largest number of responses at any one scale was ‘object’ (36%), followed by furniture (15%) and hand-held (11%). This indicates people are willing to see shape-changing devices as “human sized”. The number of furniture based shape-change ideas indicates the integration of re-purposability/customization into what surrounds us rather than stand-alone monolithic devices will be an important design consideration in the future.

To analyse interactivity, ideas were mapped onto Rasmussen’s modes of interaction [242]. The majority of the generated ideas reacted automatically to conditions or input (indirect, 44%) or were hypothesised as needing to have direct input to produce actuation (direct, 37%). No human interaction (16%) and remote interaction (3%) made up the remainder. After the interpretation and categorisation of the ideas, it was surprising to see the number of ideas that suggest operation without human interaction.

4.5 Discussion

In addition to statistical and descriptive analysis, other themes and comparisons emerged from the data and are discussed below. These range from dimensionality, display/device comparison, validation of existing research from a public perspective, sustainable design, gaming, technology vs simplicity, and interdisciplinary thoughts around narrative imagery and temporality.

Most ideas do not exceed a single dimension of shape-change: Despite diverse applications and actuation scales within the idea-set, most ideas actuated to achieve a single purpose (e.g. unlocking a door) or transformation (e.g. moving 3D Braille paper) as opposed to multi-purpose shape-change. From my procedure it is difficult to know if there is no desire for 'generic objects', or if people could not ideate beyond simple actuation.

A dichotomy exists between displays and devices: The majority of ideas were devices (78%) rather than displays (22%). This differs from the focus of much technical research that looks at communication through dynamic visual display affordances. This indicates that initial shape-change applications may be welcome in day-to-day mundane scenarios. The main types of displays suggested were 3D televisions used for entertainment, or tangible browsers for online shopping.

Sense-making in shape-changing ideas: Participants were found to generate data that maps onto existing categories of shape-change and also makes sense to the world around them, such as realistic product predictions or feasible items. They tended not to ideate about things that could be enabled as the wider technological ecosystem evolves (for example, ideas which do not already link to existing items or structures). Ideas appear to be largely driven by desire (e.g. entertainment applications) or actual need (e.g. wheelchair adaptations) rather than technological speculation.

Familiar, mundane, self-actuated shape-change (e.g. convertible cars, automatic doors) did not play a major role in the idea-set. However, several ideas can be mapped onto existing prototypes, e.g. shape-changing vacuum cleaner head [332], shape-changing coffee mugs [139], data visualisation [297], responsive plants [30] or air-quality reactive clothing [151].

Theme	Description	Freq.	Feasib.	Elab.
Entertainment	Relating to devices, toys, games and other recreational activities such as sports or events. *E.g. Skate park ramps; 3D chess; Sensory feedback for video-games; Physical 3D TV.*	16.36%	μ3.24 σ0.86	μ0.74 σ0.75
Augmented Living	Improving general life via home improvements and/or smaller aspects of interior architecture. *E.g. Form sensing furniture; Ventilation controls; Reactive aesthetics.*	12.79%	μ3.33 σ0.89	μ0.79 σ0.74
Medical	Based within the medical or inclusive living field, for the benefit of both staff and patients. *E.g. Wheelchair ramps; Surgical staff training; Braille displays/announcements.*	11.60%	μ3.21 σ0.65	μ0.74 σ0.63
Utensils & Tools	Activity or task orientated hand-held, tabletop or other movable objects which fulfill a set purpose, i.e. a tray for carrying drinks, or a shape-changing microscope. *E.g. Multi-use screwdriver head; Intuitive weapons; Reactive pizza pan.*	10.71%	μ2.94 σ0.82	μ0.88 σ0.66
Research	Loose themes or research based projects with no immediate product value, or that require significant development and further iterations to become practical. *E.g. Shape changing alloys; Environmentally reactive fabrics.*	9.82%	μ2.76 σ0.96	μ0.48 σ0.56
Architecture	Large scale building forms and major interior alterations. *E.g. Seismic-reactive buildings; Architectural visualization tools; Re-configurable rooms.*	8.92%	μ2.63 σ0.89	μ0.70 σ0.59
Infrastructure	Concerned with roads and pathways, vehicles, or town/city level adaptations. *E.g. Dynamic speed-bumps; Weather-responsive vehicles; Intuitive livestock fencing.*	7.73%	μ2.08 σ0.68	μ1.07 σ0.48
Industry	Based primarily in manufacturing, farming or at a business level. *E.g. Remote manipulation for engineering in a vacuum; Slip-casting mould; Bomb disposal tool.*	6.84%	μ2.76 σ1.02	μ0.65 σ0.48
Wearables	Technology carried, worn on the body, or incorporated into fabrics. *E.g. Reactive radiation suit; Clothes that adjust to body shape; Traction-adjusting shoes.*	5.95%	μ2.35, σ0.48	μ0.75, σ0.71
Education & Training	Educational context, specific training tools, and imagery. *E.g. Physically interactive white boards; Data communication in museums; 3D instructions.*	2.97%	μ3.10, σ0.73	μ1.00, σ0.81
Not Relevant	Did not fit into shape changing parameters, possibly due to misunderstanding the concept, or generated as adjunct to shape-change.	6.25%	μ1.48, σ0.81	μ0.52, σ0.60

Table 4.2 Idea themes, descriptions, and examples. Theme frequency and breakdowns of feasibility and elaboration are shown for each theme. *Feasibility (5-point, red=unfeasible, blue=very feasible). Elaboration (3-point, red=minimal, blue=specific).*

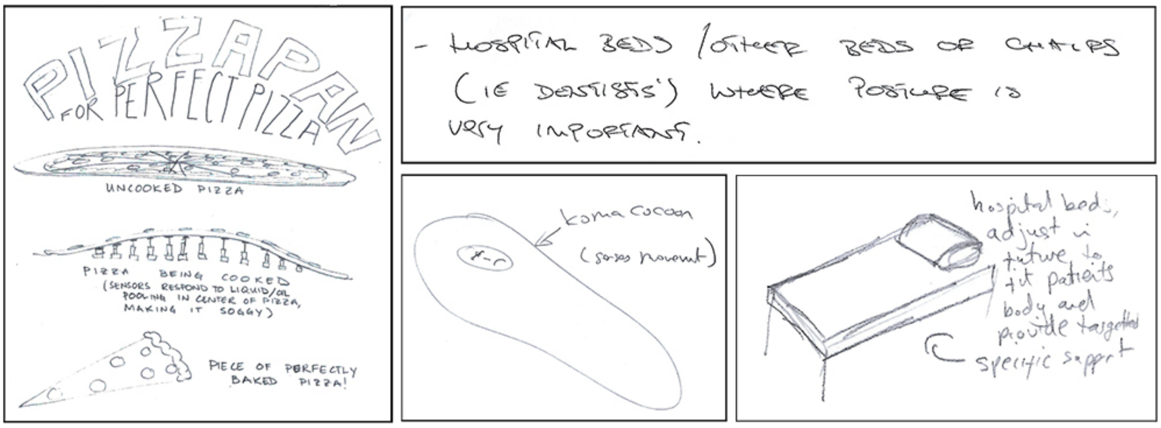


Fig. 4.5 (Left) Novelty in idea generation – heat responsive pizza pan to enable even cooking; (Right) Duplication in idea generation – pressure sensitive hospital beds

This serves as validation for this method of consultation in two ways: (1) Current research projects are validated from a user-led perspective; and (2) Other ideas generated from the public data are thus likely to be viable directions for shape-changing application research.

The influence of nature: Rasmussen's review describes shape-change being rooted in nature (the behaviour of the Southern White-faced Owl) [242]. This link was seen during the study duration whereupon participants either foresaw shape-changing technology as attempting to purely emulate nature (*responsive fake plants*), using examples from nature to describe the movements they wished to outline (*millipede walking platform*) or create animal/technology forms with which to interact (*interactive worm*).

Use of narrative imagery to elucidate shape-change: As well as individual sketches of application ideas, participants also made use of narrative imagery to convey their thoughts (this is common to the use of *scenarios* in UCD, which I explore in the next chapter). The transitional nature of shape-changing technology lends itself to highly descriptive methods such as lengthy explanations or movements drawn in stages. This parallels comic strips in which advancement of time is shown over several drawings. Many participants chose to explore their ideas using this methodology (see Figure 4.4), although there was a greater tendency for participants to draw one image and use text to explain the intricacies of their idea. This usage of narrative imagery is already finding a place in shape-change, be it in describing Ishii's futuristic *Perfect Red* [123] or Poupyrev et al's *Lumen* prototype [235]. Using narrative imagery to explore the nature of shape-change is yet to be examined in research, yet appears to be vital in communicating complex iterations of these novel prototypes in research papers.

"Phygital" gaming: Entertainment was one of the most populated categories of idea, with gaming as a minor theme. Participants either suggested the notion of *gaming* in general, or leaned toward imagining highly specific versions of existing software such as *Minecraft* in

3D. Physical, non-console based gaming was also suggested — ideas in this sub-category ranged from chess pieces that reacted to illegal moves or cheating behaviours, to drawn imagery that fed into 3D playmats onto which toy cars could be placed, to *Legos* that maintained only a transient physical presence. This duality of ideas supports the *phygital* (physical/digital) presence of tangible user interfaces — occupying a space somewhere between the traditional table-top board game and richly detailed visual simulations or displays.

Overly technical solutions to simple problems: One potential issue in looking for applications for a novel technology, is that we may end up generating ideas that do not require actuated technology or a shape-changing display. This does not negate the ideas that were generated to specifically satisfy a *desire* rather than a *need* however (e.g. entertainment).

Such examples could be: a chair that adjusts to the shape of the bottom – already evident in memory foam; skinny jeans that adjust to the leg – achieved by stretchy materials such as lycra; or automatic ventilation systems – in use as air-conditioners. Despite the existence of these products that do not relying on shape-changing gadgetry, this does not prevent novel technologies from eventually replacing their low-tech forerunners, such as micro-level shape-changing materials in clothing, which may then not only fit the form of the wearer, but also offer customisation opportunities.

Novelty of ideas between subjects: Despite the individual nature of the brainstorming methodology, in some cases, unrelated participants were seen to generate similar ideas over several categories. This duplication of ideas could be seen to indicate a collective desire for these technologies, or simply that these ideas are more obvious given the prompting of the prototype, posters and/or study environment. However, novelty within the dataset in some cases could also indicate ideas that are less feasible, or do not meet a practical need. To elaborate, Figure 4.5 shows some examples of duplication and novelty that were uncovered during analysis.

Examples of duplicated ideas: window blinds, re-sizable rooms, adjustable beds, prosthetic limbs, object detection for blind people, braille displays, real 3D TV, aerodynamic vehicle bodywork, re-sizable bags, flooding reactive bridges.

Examples of novel ideas: sun-shelters which grow when there is a high UV index, extendable target-sensing swords, shape-changing electric guitar, the perfect pizza-pan, Elizabethan suffocation collar, 3D police identi-fit, reactive shoe grips, interactive animal enclosures.

Shape-change for sustainability: Themes surrounding sustainability are largely evident within the idea set, with several participants mentioning the housing crisis, or multiple/variable use objects (resizeable pots, kettles (Figure 4.6), houses and aeroplanes). Successful commercialisation and implementation of shape-changing technology at levels

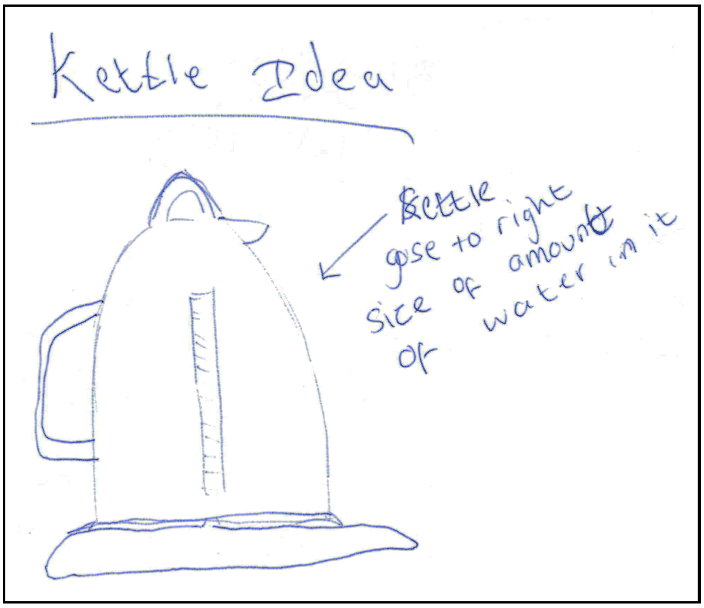


Fig. 4.6 Adjustable kettle which boils water in smaller space to save energy

from the micro to the macro could reduce drain on resources, overpopulation and lower waste production. Current prototypes which embrace both shape-change and sustainability largely focus on design for behaviour change [310] rather than reducing the need for consumption in the first instance. An interdisciplinary approach working with designers in this field, might enable a valuable step forward in making these products a tangible reality.

The discussion above picks out the most interesting observations from the collected data but is by no means exhaustive. There may also be even more of interest from both the ideas themselves, and the qualitative data gathered post-ideation. What can also be taken away from this is that there is a wealth of information that can be gleaned from public engagement with sketching that is not only relevant to existing research, but can further inform shape-change, and other research.

4.6 Methodological Reflection

The experiment method was successful in collecting data on a volunteer basis from a general population without incentivising participation. The diversity of shape-changing applications generated is impressive, and, as I hoped, grounded in the needs and backgrounds of the sampled public. Having analysed the individual ideas, I am left with the impression that not only is there a demand for shape-changing technologies in mundane, day-to-day settings, but also that these technologies will be actively embraced.

4.6.1 Interpersonal factors

For the researcher(s) running the experiment, interpersonal factors were an important component of the delivery. Therefore any public-facing researcher must be able to engage on multiple levels, whilst delivering consistent communication and design in order to reduce the risk of bias. We specifically did not pressure any participants to engage (or require them to sketch if they preferred to write), and felt this helped create a fruitful result. In some instances individuals entered the shop unit and asked to see the technology, but felt that they were not able to take part. This non-participatory interaction nevertheless suggests that there is a interest amongst the general public for engagement in new technologies.

4.6.2 Prototype effects

In terms of experimental limitations, the large number of object-level ideas is arguably linked to the object-level prototype. Although I took steps to expand this with the parameter posters, I suspect that if the study had been conducted with a material-level or room-sized prototype the results would have been different (although it is also possible that the ideas generated may have been more or less diverse) — I explore this idea in Chapter 6. Shape-change is a very broad domain, and I hope that the characteristics of this idea-set will provide this work, and other researchers with interesting reflections.

4.6.3 Using public spaces for research

Research using neutral non-laboratory spaces fulfils boundary principles [69] when used to run public facing studies, offers a possible solution to the skew that may be found when using an academia-specific participant pool/setting [2], and can produce a viable data set. Further work might investigate location-based differences as an adjunct. Outside of the laboratory setting however, controlling all variables can present a difficulty. Despite this, the study is designed to be repeatable, and it can be seen that the specificity of the prototype used does not hinder the final data-set as participants were easily able to think outside of the study setting, and across themes/properties. Further work might focus on not only on varying location however, but also the study population, as identified subsets (such as *designers* or *engineers*) in the demographic could be isolated and then examined in more detail.

4.6.4 Qualitative data

Feedback questionnaires recorded demographic data and responses to the study design — though demographic data did not contain any predictors relating to idea variation however.

Comments relating to the prototype focused on seeing shape-change occur at a micro (i.e. material level), and wishing to experience variable actuation output in order to facilitate ideation. Other types of qualitative data were also gathered which related to personal experience but did not offer an analytic viewpoint at this stage. Investigation of these types of responses may be beneficial however, as it could serve to enhance the human factor that can occasionally be missed from HCI research [12].

Some qualitative responses detailed the positive experience gained from being part of the research project, i.e. P34 *"It is good to know that the public have had the opportunity to contribute ideas"*, P46 *"Thanks for including me"* and P40 *"Interested to see where this tech goes"*. The overall response from the participant pool was overwhelmingly positive, supporting the possibility of applying this type of user study to other HCI research areas (e.g. wearables or mobile phones).

4.6.5 Related methodologies

Although this study is novel in its approach, it does bear some small similarity to Jung's *SKIN* methodology [139], in that brainstorming sessions were used, although Jung et al. used only 2 participants with art/design backgrounds to explore and draw concepts, whereas over half of participants here chose to sketch their work. What can be taken from this structure however, is the process with which ideas were developed and prototyped *after* the initial ideation process (see also [102]) — in the next chapter I examine possible next stages as part of a user-researcher *dialogue* in sketching, using participant outputs to *elaborate* upon application ideas and identify technical requirements. The only other study (to my knowledge) in which there is a parallel to the public-participant model is Follmer et al's *deFORM* [65]) whose *open-house* style session invited a mixture of adults and children into the research setting to interact with the prototype, and informal feedback was given. In this case, however, no detail as to the background of the participants is given, and the focus of the *open-house* is not specific (i.e. were other prototypes on display?). This makes it difficult for other researchers to repeat the process.

The *ShapeClip* brainstorming experiment [102] utilised the same base demonstration prototype as this study, but chose participants with a design-based background to generate ideas, did not require sketched output, and focused on developing these ideas in-situ as part of a rapid prototyping experiment. There were also less ideas generated (86 compared to 336), via fewer participants, and across fewer themes, although more ideas were generated per participant. There were similarities within the themes however, such as *Augumented Living* and *Wearables*, although ideas mapped specifically onto the *ShapeClip* prototype, rather than shape-change in general. The difference in format (full day workshop as opposed to drop in session of self-selecting length) might have led to pressure to generate more ideas in a short space of time than the public study. Additionally, by using experienced designers, there is a tendency for individuals to have familiarity with ideation and prototyping processes. With regards to these preceding research scenarios however, this ideation study can be seen as not only responding to Banon's call [12], but also building on existing shape-change research, whilst employing sketching as a methodology.

4.6.6 Reflection Summary

This work shows that institutional public relations can be enhanced, a larger participant pool accessed, and useful product and theory-level ideas gathered for which there is a user-demand by utilising accessible public spaces in shape-change research. It also evidences that sketching as an ideation output can be gathered from non-expert, potential end users which has relevant contexts for shape-change. This builds upon previous studies in shape-change evaluation, and offers a viable alternative for research participant selection.

4.7 Next Steps

Following the success of eliciting ideas in a non-research environment, I can further develop the methodology used here in an extended and revised fashion (see Chapter 6). Avenues of development might investigate whether using more structured ideation techniques such as co-design might generate more cohesive results — although co-design requires a specific situation or output to design for, and here we are interested in developing a "pre-UCD" process which then leads to additional guidelines and suggestions for shape-change. Additionally, given that there are also differences for demographic factors (although non-significant at the current sample size), running specialised sessions for under 16s or, for example, those with a background in the arts, might produce even more varied data. There is also the possibility of using different shape-changing prototypes in the ideation sessions to explore differences in boundary objects/technology (I explore this in Chapter 6).

Work on the existing data set could also be taken a step further by developing several of the feasible ideas into working prototypes (as in Hardy 2015 [102]), or focusing existing research into areas that are desirable in a commercial setting [149]. Given that several of the ideas generated are already part of research projects, it stands to reason that other ideas within the data set would produce meaningful results in the research setting and beyond. However, these projects may be beyond the scope of this thesis, as I am concerned with putting processes in place to *support* the development of shape-changing interfaces.

4.8 Conclusion

In summary, 74 non expert, potential end-users generated 336 ideas via sketching and notation that, after coding, split into 11 themes. These themes define directions for shape-change and insights into how and where people see it being used to solve problems in their day-to-day life. The responses of the public to the experiment were positive, and sufficient data was gathered to perform analysis and generate feasible ideas for future research directions in shape-change.

The relative ease in which data was gathered suggests that an over-reliance on readily available participant pools is unnecessary, as an enthusiastic and diverse public can be surveyed if given the opportunity. Thus, the methodology implies that the current range of users for shape-changing prototypes may be unnecessarily reliant on university-based data, which may produce bias. That is not to say that this data should be disregarded, but that it should be used comparatively with data collected from a wider pool.

Using an appropriate qualitative methodological approach involving sketching, it is possible to create a space in which a public participant pool can ideate around the theme of shape-change. The resulting data suggests that the public are not only able to utilise sketching, annotation and writing, to generate ideas directly relating to current shape-changing research prototypes, but additionally, novel problem/desire-based directions for research. This reinforces previous calls for a more human-focused HCI [12] and for user-focus on shape-changing applications from a research perspective [242].

Although the study did not explicitly require a sketched output, over half of participants chose this methodology with which to explain their ideas. Additionally, the sketches produce more detailed outputs than the written-only scenario (with the exception of one participant, who was a writer by employment). The time which was given to the study by the participants was also beyond that which was expected, and many became excited by their ideas, and began to imagine them in a future context where shape-change is as readily available as the modern tablet or laptop computer.

Some participant ideas addressed similar themes by chance (e.g. security and safety), and some ideas also map onto existing research, suggesting that there is a demand and interest in these areas. The duplicated themes and research-linked ideas relate to: security and safety; physical telepresence (*Augmented Living*); games (*Entertainment*); wearables, and devices for the blind (*Wearables, Medical & Inclusive Living*). This overlap between user ideas and current research is a direct source of *dialogue* for shape-change. In the next chapter I explore how we can use this form of dialogue to *elaborate* upon user ideas, and explore whether subjective researcher-led sketching can produce meaningful insights and requirements for shape-changing interfaces.

Chapter 5

Sketching as Dialogue, Sketching as Elaboration

5.1 Chapter Summary

The following chapter focuses on subjective sketching as a form of design probe in order to generate further dialogue about shape-change. A probe is an approach which invites people to “reflect on and express their experiences, feelings and attitudes in forms and formats that provide inspiration for designers” [75]. Further to the needs of this thesis, it has also been suggested that a probe can create dialogue with future users [198].

Three styles of subjective *sketching* probe are used: 1) Expansion and revision of user-generated sketches; 2) Expansion of researcher proposals from future work sections in shape-change papers in the form of scenarios; 3) Expansion of a popular shape-change application concept (gaming) in sketched and annotated form.

Following the success of the ideation study in the previous chapter, idea sketches most closely matched to current research — and most duplicated between participants — were identifed (taken from the *Augmented Living, Entertainment, Medical & Inclusive*, and *Wearables* categories). Specific ideas taken from this selection are then used as a sketched *dialogue* between user and researcher. The aims of the chapter are to show how this dialogue can be capitalised upon, via a process of *elaboration*. Additionally, it shows how by applying this elaboration to both user-data and open research questions, sketching can be a reflective tool for researchers to generate complex requirements for shape-change, and identify potential issues or implications in the design and build process for shape-changing interfaces. This is important as there is currently no provision for generating requirements for shape-change from end-user — or researcher generated — data, and implications for adoption have not been addressed in current literature. Finally, the three-stage probe process employed here examines levels of elaboration in relation to the quality of tangible research outputs (e.g. requirements) in order to develop the most viable methodology to take forward into the final user study (Chapter 6), and also for researchers wishing to conduct their own reflective practice. To achieve these aims, the following chapter consists of three subjective sketching probes:

5.2) *Demonstration of user-output as a dialogue and inspiration for elaborative sketching work, to elicit requirements and applicable research themes*: This involves a researcher-led visual exploration of selected ideas and sketches generated by potential end-users (Chapter 4), placed into the context of safety, security and ethics (with associated requirements). From generating diagrams and concept sketches, I show how subjective sketching utilising user-output as a base can lead to technical insights and implications for shape-change.

5.3) *Exploration of the potential of sketched researcher-led output in the form of scenarios, generated from examining current research questions, and creating dialogue between a diverse non-expert and research audience*: In order to achieve this I build on themes from published research, using detailed sketched scenarios from which I collect user and researcher feedback, creating further dialogue. This shows the ability of users and researchers to consider higher level themes and implications for shape-change from future scenarios, and the usefulness of scenarios as a communication tool between diverse groups. The high-level themes can be used to consider more detailed practical, technical and ethical issues concerning the adoption of shape-change, adding to and expanding on the work in section 5.2.

5.4) *Combining sketched research for future shape-change scenarios with textual elaboration using design fiction methodology, to examine whether further elaboration on previous themes using sketching and text can generate more detailed requirements and outputs for shape-change*: I conduct a researcher-led exploration of a single shape-change application concept, with textual elaboration on the sketching process to create a detailed artefact (diagetic prototype), and generate requirements for shape-change. This demonstrates that as levels of elaboration increase, so does the detail of of tangible research outputs.

By using sketching as a probe, I provide justification for the use of researcher-led sketching and elaboration activities, and further justification for the ideation methodology in Chapter 4. This work then informs the development of user-led activities using similar methodologies to generate meaningful outputs for analysis in the next chapter.

5.2 Dialogue & Elaboration with User-Generated Sketches

Creating visual imagery helps us to situate ourselves within unknown worlds and processes, make connections and explore solutions. With this in mind, I curate a collection of images from Chapter 4 to inform the potential for shape-change via researcher-led sketching. The possibilities generated by the ideation study are explored via a process of subjective, elaborative sketching, and grounded in relation to the under-explored themes in shape-change of security, ethics and safety.

The potential for shape-change to enhance our lives can be seen in the previous chapter, but thus far there has been no investigation into the very current problems of cyber-security, physical safety, or the ethics of building shape-changing technologies (as noted in Chapter 2.8.6). If I look at linking sketching to security research, sketching and storyboarding is a more established paradigm than it is for shape-change, for example, Zhang-Kennedy et al. [360] use comic strips to inform and persuade users about security issues. Lewis & Coles-Kemp [179] also employ a visual narrative structure to their output, but utilised participants' sketches and notes to form their final imagery. This elaboration on sketches and notes shows how user-generated sketched data can be valuable in producing meaningful approaches to security. Additionally, using sketched participant data as an active part of the design process has been shown to reduce the perceived "distance" between user-experience designer and participant [181]. These studies suggest that the same processes could be used for shape-change.

We therefore situate this investigation within these contexts in order to bridge the distance between potential end-users and researchers, and derive maximum value by covering new ground in our study of shape-changing interfaces. By exploring ideas for new products, I can also use the opportunity to examine the implications of their place in the world in a visual and accessible manner. Therefore I present participant sketches alongside existing research, with which I then elaborate upon to explore shape-change, the ethical, security, and safety-related design implications, and requirements for shape-changing interfaces.

The chosen participant sketches map onto current research themes within shape-change (*Augmented Living; Entertainment; Medical & Inclusive*, and *Wearables*), and cover sub-themes of *physical telepresence*, *security & safety*, *wearables* and *gaming*. Specifically, the participant sketches chosen for elaboration were: 1) Physical-chat over wifi (Figure 5.1); 2) Shape-changing keys (Figure 5.3); 3) Touch-suit for the blind (Figure 5.5); and, 4) Screen-based shape-gaming (Figure 5.7). Each sketch is then further examined from an ethical, security, or safety perspective in order to provide focus for the discussion, increase knowledge of this area for shape-change, and to ground the product ideas in real-world situations.

In summary, the following subsection utilises the ideas generated by the public participant base from Chapter 5 and re-imagines them as prototypical product sketches, along with consideration of potential pitfalls and implications that come from adoption of such technology — and additionally, requirements generated via that process. The imaginative sketches can be seen as borrowing from design fiction (see Section 5.4), but also taking practical elements into account.

5.2.1 Bridging the Gap between Idea and Prototype

The four specific themes represented by the chosen participant sketches are used in the next four sections to develop product ideas or scenarios in more detail via a series of researcher-generated annotated sketches (sketching as *elaboration*). Knowledge of the technologies currently available in the field of shape-change from Chapter 2 allows for analysis of the practical implications and challenges inherent in developing these devices. The act of creation also forces the researcher to attempt to "solve" problems during the design process, identify potential application interactions, and generate requirements for the development of each product [338]. This process takes the form of a reflective feedback loop from each stage of the sketch into satellite images or amendments to the original idea. As each stage, processes, requirements, issues and further possible iterations emerge (see the requirements at the end of each subsection). These requirements, issues, and iterations are not intended to be exhaustive lists, but are a starting point to demonstrate how sketching can be used to generate these items. The images here are a snapshot of the final potential for each product, but are designed to create discussion and generate input, as well as developing awareness of the implications for adoption. Lindley et al. [185] suggest that the process of creating fictional products can be an essential part of examining the potential of products beyond prototypical implementation.

5.2.2 Physical Telepresence

One theme generated by several participants was that of *physical telepresence* — the ability to be physically with the person you are talking to resonates with those who often find themselves living and working away from their families (Figure 5.1). In current work, Leithinger et al. demonstrate the potential of the idea, also including object manipulation, collaborative 3D workspaces and remote assistance [173]. Leithinger makes use of a 2.5D tabletop physical display in order to create remote presence between two people. The ideas in the original sketches however, imagine the scenario as akin to current internet video-conferencing and chat. Depending on the type of interface, it may be possible to have "grasping" pixels (i.e. true 3D) or even textural interaction. Additionally, there is the potential

Fig. 5.1 (Top)Internet telephone call using tangible screens to create solid-state representation of caller in remote location; (Bottom) Remote jewellery sculpting tool and real-time physical output

for mixed interaction: where one individual has the physical interface and the other uses a projection to translate their actions to the other screen (mapped interaction).

A popular usage for many internet based services is soliciting company from others. The addition of physical interaction to the chat model has many implications: on the positive side, it enables more intimate encounters; on the negative, it may force physical presence on those not able to deal with such scenarios – e.g. minors talking to strangers. Further, physical shapes may take the form of "sharp" objects which could cause actual physical harm. The benefits are equally as obvious however – divided families can hold hands, touch and even hug (if the displays are big and deep enough). The image shown assumes mainly that the interface will be rooted in a screen, but some interfaces are being developed which make use of ferrofluids and other substrates that have the potential for detachable parts. The question

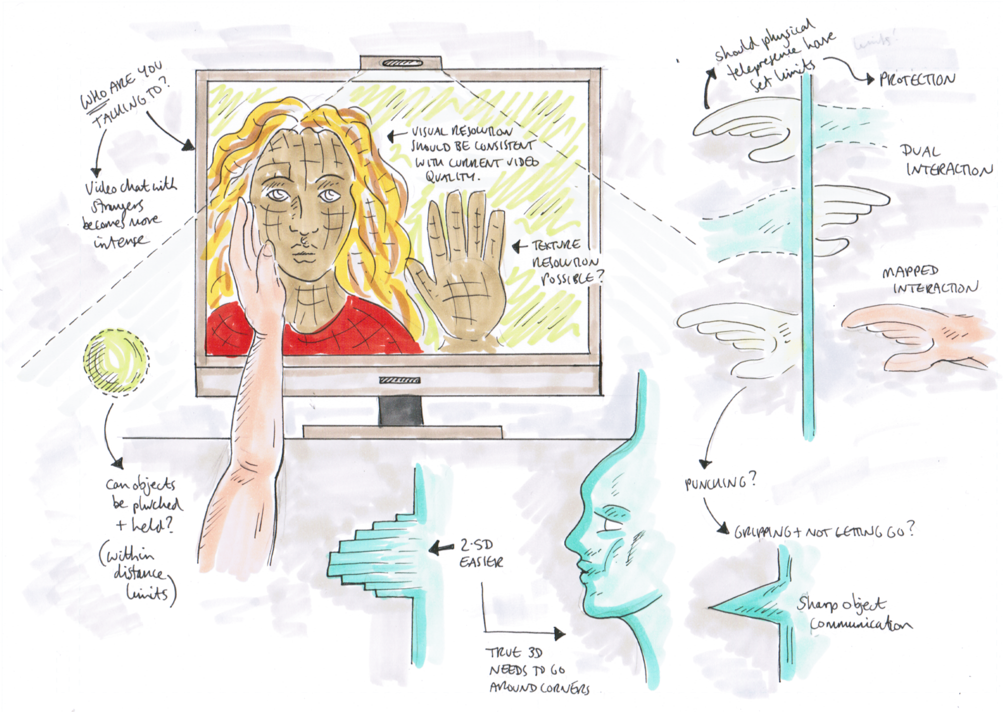


Fig. 5.2 Annotated sketch and ideation around the theme of physical telepresence

is, how long will such physical images last? How far from the monitor can they be moved? The potentials are fascinating, if not potentially dangerous.

In its current form, Leithinger's interface cannot entirely fulfil the ideal outlined in the sketch. By utilising the sketching as an exploratory process with reflective feedback however (see 1.2.1), we can predict certain requirements. These are by no means exhaustive, but offer a suggestion of the types of judgement that can be made via the process:

- *Surface must emulate organic movement (i.e. smooth, non-jerky actuation)*
- *Device/application must have set limits (distance from baseline) for component parts*
- *Surface must have safety limits (speed of actuation, shape)*
- *Device must have low latency, and match real-time interaction*
- *Device must feel life-like*

These subjectively generated requirements suggest that the main feature of physical telepresence that must be utilised is that of providing a realistic representation of the corresponding users. Non-lifelike mechanical interaction would not enhance our interactions beyond the current flat screen-based communication we currently enjoy.

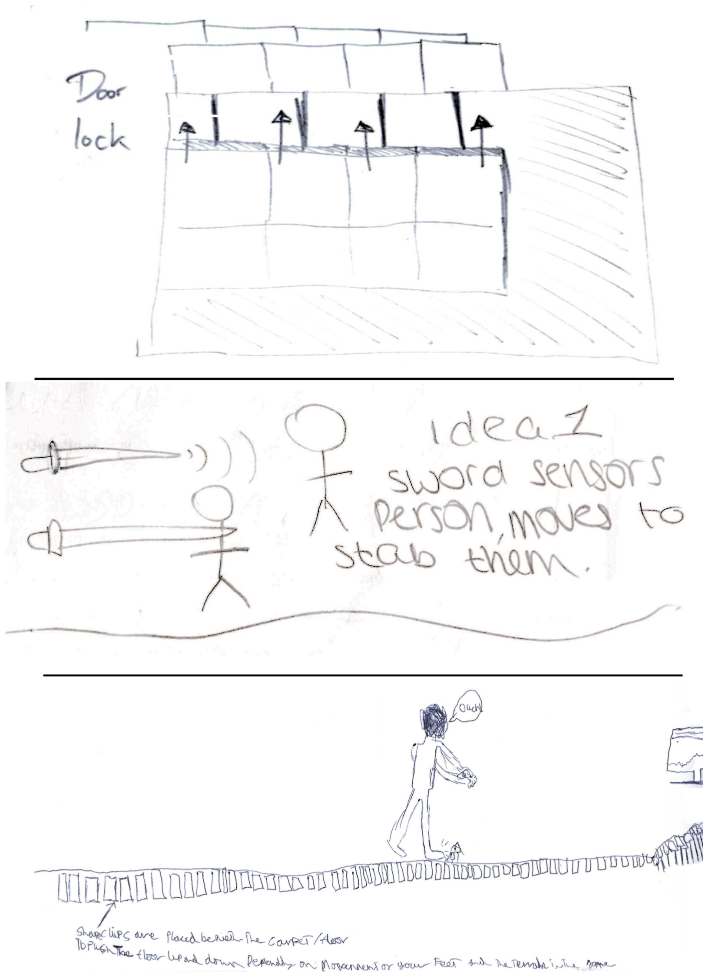


Fig. 5.3 User-sketches relating to security and safety (*Augmented Living*): (Top) Lock that emits light to trigger correct key shape; (Middle) Weaponised shape-change for self defence; (Bottom) Security carpet;

5.2.3 Shape-Keys

Shape-change has not currently been investigated in terms of its potential for security and safety, Figure 5.3 suggests that there is a desire/proposed need for applications which utilise such technologies for protection. This is one of the few themes of research that was not seen in existing prototypes during the analysis in Chapter 2, however, entrance security is linked intrinsically to the buildings (*Augmented Living*) which is a major theme in shape-change. As space becomes a premium (already happening in large cities throughout the world) people will look for new ways to extend and utilise maximum space within their homes. Shape-changing walls in architecture are not new, albeit usually on a low fidelity scale, such as in

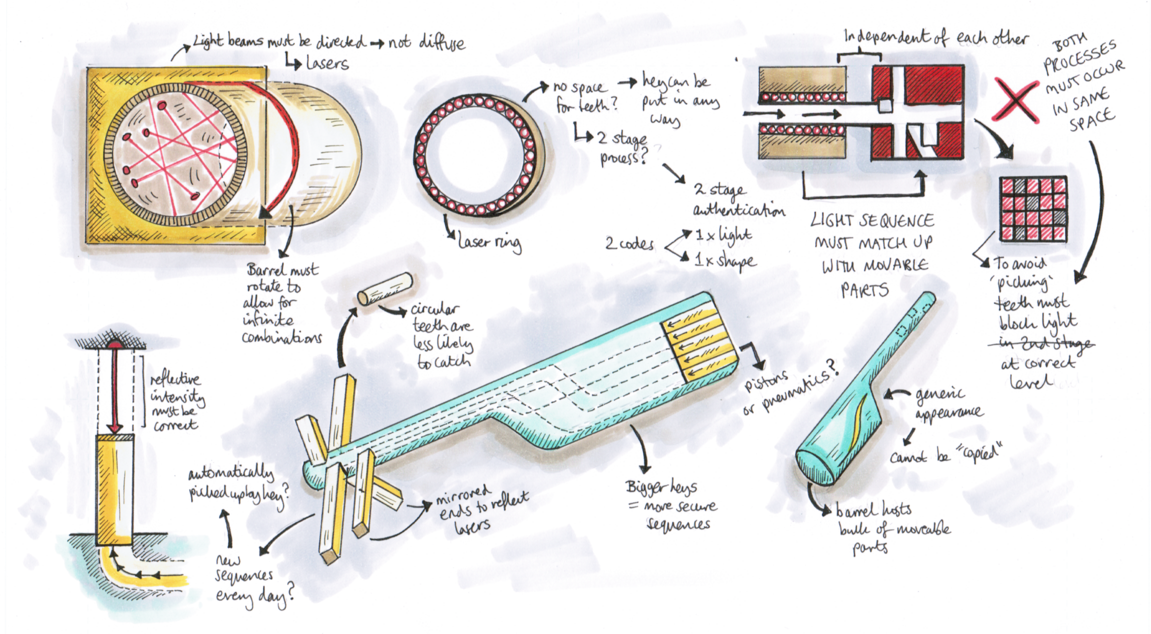


Fig. 5.4 Annotated sketch and ideation around the theme of shape-changing keys

meeting-room dividers, and research is already taking place into shape-changing furniture [91] and utilities such as blinds [33].

The *shape-key* (Figure 5.3) utilises similar properties to the *ShapeClip* [102] in that the actuated components react to light. The barrel of the key contains the actuators (piezo-electric would be appropriate as this means it could be battery powered) and is necessarily bulkier than traditional keys as the teeth of the key must be withdrawn and stored when the key is not in use. Shape-key lock mechanisms would require precise, directed light (e.g. lasers) which would measure the distance of each tooth from a set group of coordinates (the key could be put in any way as the barrel would recognise the sequence in relative terms). The end of each tooth would have a reflective panel which would allow the distance from tooth to point of laser origin to be measured. The actuated mechanism would need to have pre-set lengths to reduce complexity. One benefit would be that the lock could not be picked as it would have a smooth inner, even with mirrors, due to the infinite possibilities. On the opposite plane however, the potential for power failure, and subsequently being locked out of whichever building it was necessary to gain entry to could have multiple negative consequences.

The shape-changing key was chosen as it is a plausible application area for development. The process of sketching again suggested several ideas as to the efficacy of the device and generated a series of requirements:

- *Device must not be overly bulky or heavy as needs to be convenient to carry around*

• *Device needs long battery life, or be charged via the lock, so as not to render the key useless at inopportune times*
• *Actuators must fit into a narrow stem, and so that barrel does not have an aperture that is too large and thus presents its own security risk*
• *Lock needs to be connected to mains power source*
• *Cost of devices must not be prohibitive to adoption*
• *Device should be able to be used in multiple locks to reduce number of keys needed*

The overarching requirement for shape-keys appears to be that of portability — at present shape-change is only seen in portable devices such as mobile phones, but this could readily be expanded to include other devices for augmented living.

5.2.4 Wearables for the Blind

As Shape Material Alloys (SMAs) and other techniques become more advanced, we can begin to explore the possibilities of clothing that has movement, defensive strategy, and even a personality of its own. Catwalk fashion clothing is most often static, save the model wearing it: shape-change opens up a new way of thinking about what we wear, and how we choose to wear it. Figure 5.5 shows participant examples of wearable utilisations of shape-change.

The applications for wearable technology span far beyond those currently in use (i.e. fitness bands and pacemakers). The potential to enhance the lives of those with medical conditions is one of the most useful applications of shape-changing technology. This sketch maps out requirements for an object-to-touch suit for the blind and visually impaired. The idea being that those who cannot benefit from a guide dog can move freely outside of the house without a cane. The suit responds to near objects with increasing urgency and pressure depending on the speed of approach and distance. This can be used for not only static, but moving objects such as projectiles and animate items.

The *object-to-touch suit*'s (Figure 5.5) purpose is to create a safe passage for the visually impaired so that they can navigate public spaces without the need for guides or sticks. The life-enhancing qualities include personal independence, ability to move swiftly out of danger in an emergency and experiencing visual objects through embodied interaction. Although the primary purpose here is safety, there are also inherent dangers: Multiple inputs occurring simultaneously could cause indecision as to the direction of movement and result in injury; the potential for technical fault becomes more life-threatening – a motor burning out might leave a blind spot; a programming malfunction may cause a repeated interaction where no obstacle is present, and so on. One of the main concerns in wearable technology is that

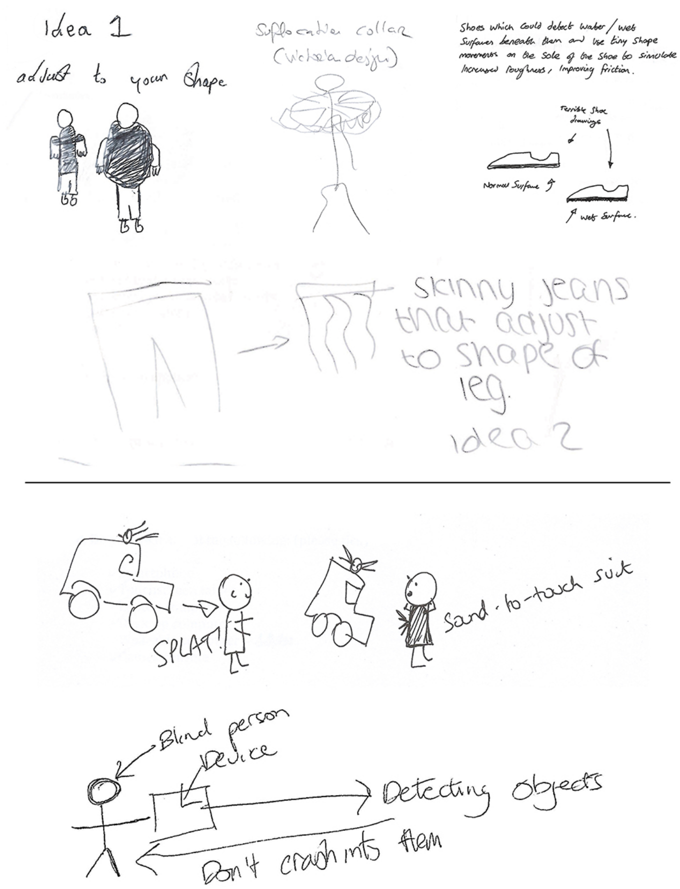


Fig. 5.5 User-sketches relating to wearable shape-change (*Wearables, Medical & Inclusive Living*): (Top left & middle) Automatically fitting clothing using shape-changing cloth; (Top middle) Wearable torture device; (Top right) Shape-changing shoe soles to enhance grip; (Bottom) Clothing for the blind which uses touch to inform the wearer of incoming obstacles

as it becomes more intrinsically linked to our physical presence, the more disastrous the consequences are if such technology is hacked.

As of yet the damage caused by hacking wearables is limited to little more than data theft (e.g. taking account details), although recent articles talk about *FitBits* being targeted [138] which suggests the potential for further trouble. As wearables become more ingrained in our lives – as with pacemakers – or even cyborg-style implants – we open ourselves up to physical damage from hacking as well as financial damage. Current shape-changing wearables include *Awakened Apparel* [231], *Scarfy* [331] and *bioLogic*, a new shape-changing material formed from natto cells [353].

The design and build process for any assistive technology must be thorough, so as to offer the best possible experience for differently-abled consumers. Possible requirements for

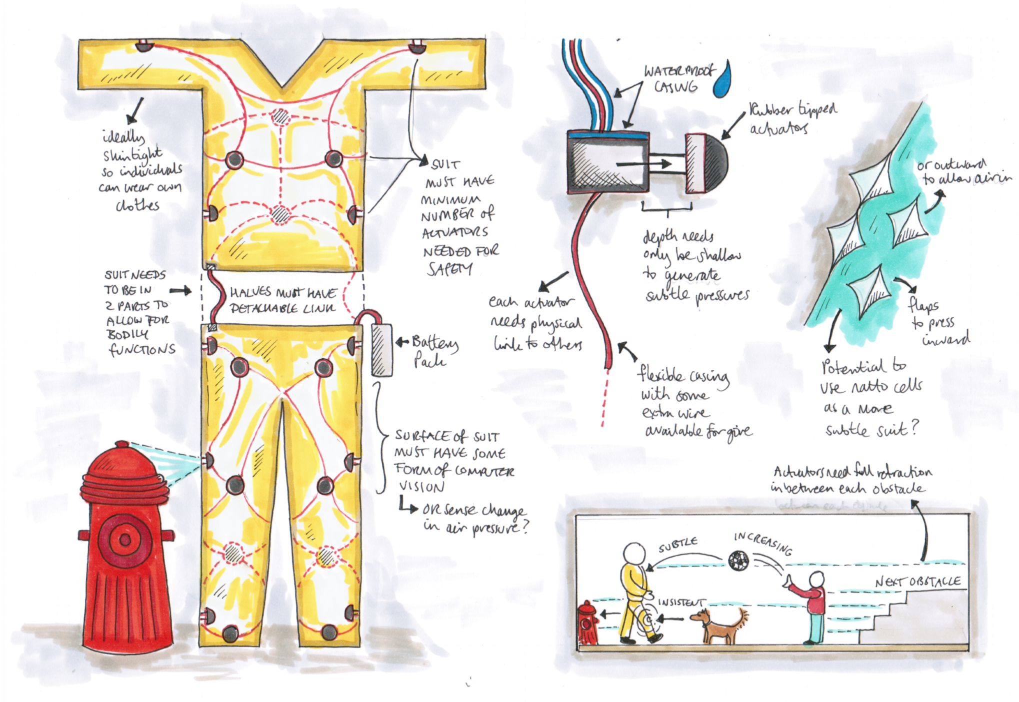


Fig. 5.6 Annotated sketch and ideation around theme of wearable safety suits for the blind

this wearable might be:

• *Actuators must not be bulky (wearables should not be punitively heavy or uncomfortable) or visible from the outer layer of the suit (wearables should not be undesirable)*

• *Suit must have a long battery life, or have the means of self-charging via kinetic energy to prevent accidents*

• *Suit must have training mode so wearers can practice their reactive interactions*

• *Suit must have protective casing around actuators to avoid accidental damage*

The main goal of all assisted living, inclusive technologies is that they serve to enhance the life of the user, and, if this is not done, the reason for that technology to exist becomes moot. In the case of these requirements, if wearing the suit becomes more trouble than the benefits it supplies (i.e. uncomfortable, prone to faults) then the technology is not feasible.

5.2.5 Shape-Gaming

Entertainment, and especially games, proved the most popular topic for possible shape-changing applications. Suggestions from the ideation study ranged from the benevolent, to extreme physical interaction such as fighting. Off-line gaming was also proposed, with ideas such as fun changeable cookie cutters or play-mats that turned drawings into physical

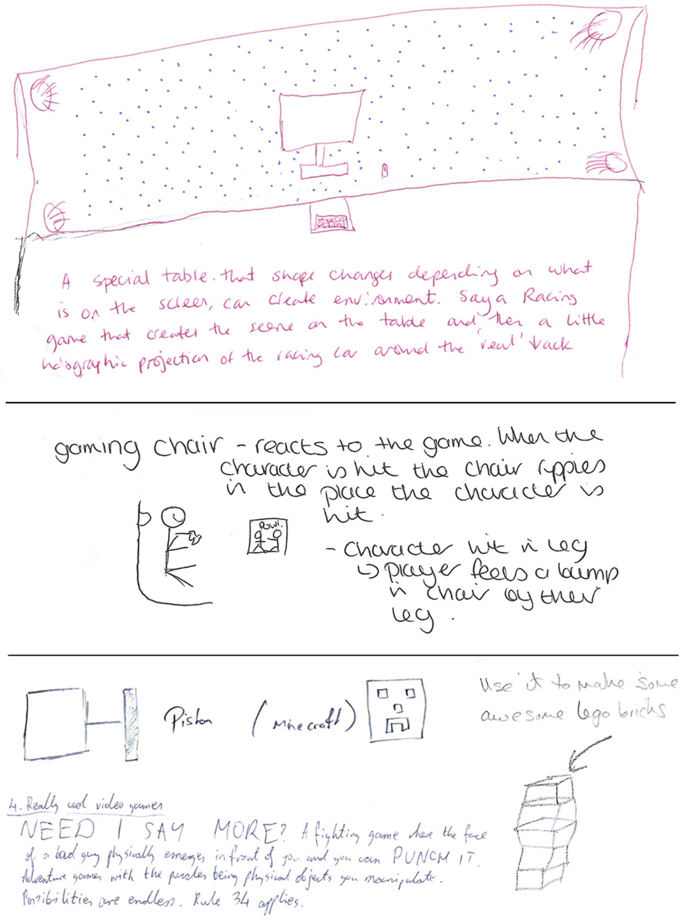


Fig. 5.7 User-sketches relating to shape-change gaming (*Entertainment*): (Top) Multi-application computer-table shape-changing environment with potential for mixed reality components; (Middle) Reactive shape-changing chair reflecting physical harm from the game environment; (Bottom left) Physical *Minecraft*, notes on gameplay where you can physically harm game characters during play; (Bottom right) Combining shape-change with existing brick toy.

objects within a set environment. Computer games and entertainment are big business, and shape-changing games are one of many applications proposed for prototype platforms. These tangible interfaces allow a greater connection with the game environment, such as with *Cobra* [354], but also can co-exist with current technology and offline objects [183]. Non-computational shape-changing toys are already being explored, such as Topobo [228] and gaming iterations of *ChainFORM* [206].

Shape-change and gaming is one of the most varied potential applications for the technology, although the variety of game types makes it difficult to design a console that works for all styles. The physical telepresence interaction style shown in the first sketch would be ideal for role-playing games with limited combat, but of little use for the first person shooter.

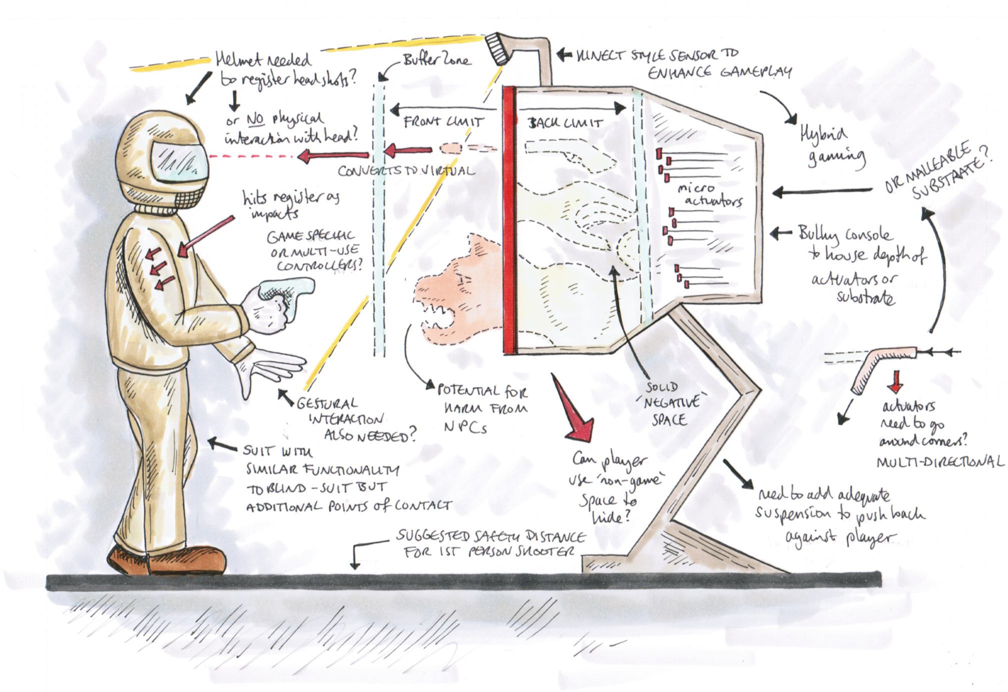


Fig. 5.8 Annotated sketch and ideation around the theme of physical gaming

The need for complex actuated interaction might also necessitate a return to the bulky size of cathode ray televisions, as matter must be hosted somewhere, and cannot be created out of nothing (though inflatable interfaces might have potential applications here). Physical gaming can be linked to hybrid gaming, i.e. making use of both physicality and virtual or gestural aspects.

Realistic physical, yet virtual, interaction has long been the dream of science fiction, and shape-changing technology is the first step toward achieving this — but also comes with potential dangers — maintaining some form of distance and detachment means retaining an aspect of safety. The sketch in this section suggests a hybrid platform – enabling the enemy to “fire” on the player, but with the console having a limited distance in which it can maintain physical presence. The main danger in physical, tangible gaming is that of monitoring both the manufacture of devices and the developers of third party applications. Badly designed software or glitching safety constraints can cause more than just frustration, they can cause actual bodily harm. This suggests the need for a governing body developed for physical software, and strict testing on every application to reach the market.

Physical gaming could take many forms, but for the idea outlined I can imagine several possible requirements (including constraints) in order to offer the best possible (and safest experience):

• *Players must not be able to come to physical harm from in-game objects or during Player Vs Player (PVP) interactions (similar to the requirements for physical telepresence)*
• *Console and programs must have low latency matching at least human reaction times to ensure seamless experience*
• *Console must also support multi-modal interaction (e.g. gestural, voice, gaze)*
• *Actuators must be multi-directional (3D not 2.5D)*

This is a short list given the huge number of application ideas, and therefore gaming platforms that were generated by participants. These requirements are top-level (that is, they should apply to most shape-gaming experiences), but specific games and platforms may have detailed requirements that do not apply broadly. As gaming was the most popular application idea, I explore this theme further in Sections 5.3 and 5.4.

5.2.6 Section Discussion

Having both reviewed existing participant sketches, and created more detailed renderings of the ideas, I can begin to get an idea of the requirements needed for these shape-changing devices, and the associated regulations and usage guidelines that must be put in place to protect the user from harm, be it due to system failure — or, more seriously — dangerous physical engagement from other users or poorly made application programs. Novel technologies are vulnerable to the same dangers that our current infrastructures are, so we can build security and safety limits into shape-change before it becomes problematic. Creating formal UCD processes for shape-change will mean supporting the safe and inclusive production of this technology.

Subjective Generation of Requirements

The requirements generated here are based on subjective analysis of the sketching process and ideation resulting from that process. The issue with this kind of requirements generation is that it may not cover the full gamut of possible requirements, and therefore cannot be directly applicable to an end-user base – although it is a helpful place to start. The sketching-requirements technique here is a proof of concept: the act of sketching forces the individual to think through any potential problems or solutions, and further examination of the visualisations can assist with decision making. Exploring these ideas in relation to a single subject also can focus the design process. Using elaborative sketching to generate requirements is further examined in section 5.3, and in more depth in Chapter 6.

Security in IOT

Shape-change has links to the current spread of *Internet of Things* technology — that is, the idea that everyday items can be linked to the internet and to each other [351]. There have already been reported “attacks” on the accounts of fitness band users [138] and electricity smart meters [54]. Current harm is limited to financial or administrative inconvenience, but physical computing allows for the harm to reach beyond those constraints – to touch our very selves. This means all shape-changing devices will need to have enhanced security to prevent the connection by malware or malicious users.

Potential for Safety: Potential for Harm

The very mechanisms that create the benefits of shape-change are also the very mechanisms that can cause harm. Physical telepresence is a benefit to remote individuals — but for parents already traversing the management of their children online — to have to deal with the potential that strangers can reach into their homes is a frightening prospect. This is in addition to physical harm from impact, trapped fingers and hands, and glitching applications. This danger also applies to wearables, hacking a shape-changing scarf could enable strangulation, changing a game’s programming could overrule in-game rules. These dangers mean that limitation in design is essential (2.8.2), such as restricting the size of gaps in the shape-change surface or imposing strict temporal guidelines that cannot be overridden.

Mechanical Constraints

Shape-change is a complex technology, and whilst it can replace existing items (such as keys) we may embrace overly complex solutions to situations that can be solved with low-fidelity solutions. All mechanisms with moving parts have the potential for failure. There is also the requirement that shape-change requires access to power (with the exception of Natto cells [206]). By placing reliance upon mechanisms, we remove agency, and if these devices are complex, we can only get assistance from trained individuals with access to specific tools and programming knowledge. Static items cannot be hacked, short-out, or fail due to computer error. There is a tendency for researchers to focus on the positive aspects of their work, and ignore the possibility that it may not be useful, or could cause harm. There needs to be more reflection in shape-change research to best place the technology where it is needed most.

Emotional Implications

A final thought is that if we already place so much of our agency into our laptops and mobile devices, if we then had the potential for physical interaction as well as audio and video, would we become less connected to the real physical world? This, and many other questions must be addressed for the safe and ethical advent of shape-change — but these cannot be answered without further exploration.

5.2.7 Section Summary

The sketches here are not meant as a polished design schematic for a new prototype, or even a simple image of an idea, they are placed to stimulate discussion in shape-changing interfaces, and consider how we might begin to generate requirements which can contribute toward designing or adapting specific UCD processes for shape-change. This section demonstrates how we can use participant generated idea sketches as a form of *dialogue* and subsequently *elaborate* upon these sketches to create more detailed investigations of these ideas. These investigations can force the researcher to critically examine prototype ideas before inception, and place them into context for end-users. Each sketch in this section directly elaborates upon the initial participant suggestion, but the results only supply one perspective (that of the researcher). To continue the dialogue, the next section examines shape-changing interfaces using scenarios as a method of further elaborating upon both user and research based ideas.

5.3 Dialogue & Elaboration with Scenarios

The development of shape-changing interfaces can lead researchers to speculate further iterations, use-cases, or technological advances which might feasibly allow adoption. It is common in HCI to create sketched narratives (scenarios) as part of User-Centred Design — but this is thus far limited in its application to shape-changing interfaces. In this section, I examine expectations for shape-changing technology from recent research, and develop ideas from three prototypes in a sketched exploration of future user-scenarios as *elaboration* on the previous section. These stories focus on plausible everyday activities, and are evaluated in terms of the insights that are elicited through the act of making, but also the themes and implications generated by the process of reading. Potential applications and issues surrounding the public adoption of shape-change are examined in relation to existing research, design fiction, creativity and sketching practice, to suggest new themes and methods of discovery in this area. This section provides a demonstration of the subjective value of sketching within an HCI researchers' research interests, and should be viewed as an exemplar of the application of sketching in the development of novel technologies. These scenarios link research back to user-ideas, as part of the continuing dialogue of sketching, and offer a more detailed output than the images in the previous section.

Despite a variety of information from each user-study in shape-change, there has been limited analysis of the field from specific approaches from User-Centred Design, making use of techniques such as low-fidelity prototyping, persona creation and specifically, developing illustrated user-scenarios. The use of sketching to understand and develop products and application ideas is used already in interaction design, and its importance is highlighted in HCI through workshops [195], papers [282], and specifically, shape-changing interfaces [243]. However, it has not yet been widely used in generating plausible and coherent user-scenarios for shape-changing technologies.

Shape-change is a new and extremely diverse field, whereas sketching and illustrating scenarios is well established in UCD. Although some attempts have been made to utilize sketching in shape-change, I take this link further by analyzing how sketching can be used to influence, direct, and represent shape-change research. Therefore, this section aims to explore the concept of utilising sketched user-scenarios to engage in dialogue with potential end-users. The benefits of this practice are (i) Being able to explore design iterations in a rich and meaningful manner, and (ii) Communicating research to a non-specialized audiences for the purposes of user-testing or stakeholder engagement. Generating sketched user scenarios has already been proven in numerous academic and commercial settings [23] as part of the wider application of UCD, and the belief is that it will be of benefit to those creating and developing shape-changing interfaces, and ultimately, the end-users themselves when these technologies reach fruition.

To demonstrate these benefits, I explore three shape-changing prototypes and present illustrated future user-scenarios for each. These narratives describe future use-scenarios based on each researcher's existing discussions around shape-changing prototypes, and each scenario links to potential products based on possible trajectories for this technology, and previous ideation research. The narratives also form an accessible bridge between current research and adoption prospects. The intended audience for these scenarios is HCI practitioners already working in, or interested in developing shape-changing devices, and designers wishing to get involved in application design for these novel technologies, as well as the general public as part of research dissemination — the end user. The intent is to open dialogue within and between these groups.

The contributions offered by this section are: (1) Using case studies to demonstrate the potential of sketching and analysis in order to identify applications or implications for shape-change; (2) Thematic evaluation of sketched user-scenarios for existing shape-changing interfaces from information generated by HCI practitioners and non-expert participants; (3) Reflective discussion on the process, alongside a proposal to actively engage researchers in shape-change with sketching practice. In essence, these scenarios are a talking point, a development of existing ideas, and an easily accessible way of generating discussion around shape-change between researchers and a wider audience, building and expanding upon existing work in the field.

5.3.1 Sketching User-Scenarios for Shape-Change

User-centered design in HCI is not a new concept, but has been approached in a fragmented fashion in its application to shape-change (such as isolating formalised user testing [91, 297] or use of focus groups [102]). Analysis of existing research on design processes in shape-change suggests that there is a space in the literature for this work. Specifically, user-scenarios are becoming popular in other areas of HCI, along with the narrative form and written research portrait [82]. A user-scenario is a narrative that tells us how a person might use a future object or system, and is part of the process of user-experience design. User-scenarios can range from sketched images, to high fidelity renderings as the design process progresses. Pedersen et al. [230] conducted a large scale study on hand-held mobile devices using realistically rendered videos of a device user scenario, finding that over three quarters of the participants preferred this style of animation to a hybrid or sketched version. In this case, the aim was to generate very specific comments as to the interactions, rather than the exploration and generation of interest that comes from a sketched story [23]. The use of narratives and scenarios in HCI is a long-standing methodology, however, they can also be seen as lacking "felt life" [19]. Blythe and Wright argue that combining such scenarios with fictions encompassing human experience can create valuable resources for design (see Section 5.4).

Ishii was the first to showcase future shape-changing technology via sketching in his collaborative storyboard outlining *Perfect Red* [123]. Although this product requires a substantial leap from the current level of technology available — and falls within the realms of design fiction rather than a user-scenario for a product in development — it also outlines the potential of the drawn image to spark creativity and communicate complex ideas. Speculation around technology was also used in Chapter 4 (the public ideation of shape-changing applications). Narrative structure can also be seen in Rasmussen et al.'s paper investigating designers' sketching of shape-changing interfaces [243]. Here, 21 designers were asked to produce sketches exploring design elements for either a shape-changing mobile phone or radio. These drawings were then analyzed in the context of developing a vocabulary for shape-changing interfaces, and make a further case for the validity of the drawn image in this field of research. Nørgaard et al. also used sketching as part of a complete design process to design and build shape-changing toys [217]. They show how the complete process can spawn from sketch to completed product, and suggest that the drawn image has a well defined place in design for shape-change — “aimed at exploring and raising questions, rather than testing solutions”.

The following exploration falls between Rasmussen and Norgaard’s design-sketching, the ideation study, and Ishii’s approach. These narratives build upon the notion of initial design sketches [282], but then focus instead on existing prototypes and base themselves around the user-experience of each particular study. This *formalization* of turning sketches into sketched narrative allows the designer or researcher to more coherently communicate the story and interaction between the user and the interface [51], whilst still leaving the way open for questions and discussion. Finally, creating sketched user-scenarios in this context draws upon not only existing research on the design of shape-changing interfaces, but upon drawing practice and scenario generation in the wider context of HCI.

5.3.2 Method

This study aims to apply the production and analysis of narrative, illustrated user-scenarios to the design-space of shape-changing interfaces, and show how this kind of exploration can be a valuable reflection on the field. To explore the use of such imagery for shape-change within the scope of design possibility, future prototyping, and concept communication, I selected three prototypes to create scenarios for. Using a variation on the *Marvel Method* (also called *plot script*, where the artist works only with a basic synopsis, or story idea), I developed basic story-lines for each, and worked these into sketched scenarios. The finished works were then sent to two groups for feedback (*dialogue*), e.g. on the quality of the method to communicate the novel concepts, impressions of the technology, likelihood of adoption, ease of understanding, and visceral response to the proposed devices. These groups were divided between those with experience working in HCI, and those from a non-computing background. I then used thematic analysis to pinpoint emerging topics and potential issues with the proposed technology, and identify the prospects of using this method to assist in the design of shape-changing interfaces.

Prototype Selection

The publications relating to the 84 shape-changing prototypes from Chapter 2 were examined to find out which would have the potential to run multiple applications (as single use devices would not require an application design methodology), and have variable input and output (as these offered more scope for creating rich narratives). These were further classified according to age of research of less than 5 years — e.g. Nakatani et al.’s *3D Form Display* [210], proposed the notion of *physical telepresence* in 2005, and this has actually been

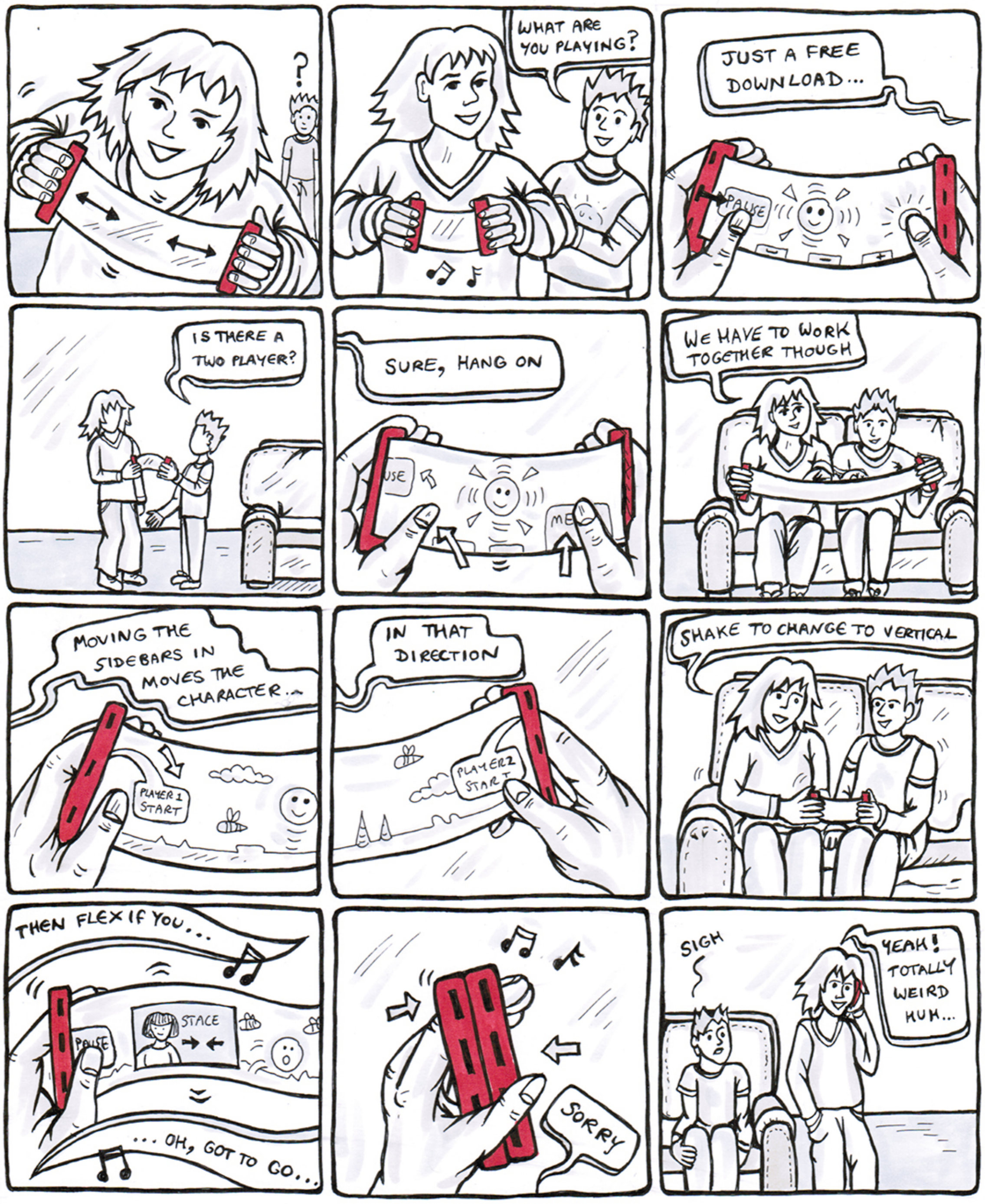


Fig. 5.9 Scenario 1: *Xpaaand*, an expandable mobile device and phone

well-documented recently by Leithinger et al. [173]. Having a recent timescale for selecting research means that the generated scenarios will be up to date in terms of the current state of hardware for shape-change. A final criterion was applied that the chosen papers must mention future iterations or possible future use cases (in order to keep the sketched scenario in line with the research proposed), and not be already in public use (i.e. *Protrude/Flow* has already been presented in a public space in its final form as an artistic installation [156]). Of the initial 84 papers, this left 18 for selection. Three of these 18 were chosen for development as they specifically mention future use contexts and allowed for meaningful translation into the drawn medium. It was also deemed of interest to select varying types of device (i.e. not to select 3 mobile-phone styled devices) so as to generate different kinds of story, and to try to think *beyond* devices as we know them now, to a world where these shape-changing interfaces are part of our everyday environment [293]. The prototypes chosen for sketched user-scenarios were *Xpaaand* [147]; *JamSheets* [224] and *Hairlytop* [216], these are discussed individually below.

5.3.3 Scenario 1: Xpaaand

Interaction Techniques for Rollable Displays

Xpaaand is a mobile device with an extendable screen that rolls up into two slim end pieces, giving the user the option to extend or contract the usable space [147]. It was chosen as it can change its surface area, and also has the potential to support haptic input and bend gestures. Khalilbeigi et al. show that *Xpaaand* can support a number of contemporary mobile application interactions, and suggest that the device could also support multi-user viewing and interaction, as well as being used to control games. Of the other papers under consideration, *Flexpad* [284], *Cobra* [354] and *Bendy* [189] have similar gaming scenario possibilities, but *Xpaaand* is the only prototype which can also increase or decrease its surface area of reviewed hand-held devices. Finally, *Xpaaand*'s authors also embraced the use of sketching to outline the potential of their device, and show how the final product might appear, lacking the bulkiness of the working prototype. The scenario in this section (Figure 5.9) focuses on the gaming theme, as this is a recurrent theme across similar devices.

5.3.4 Scenario 2: JamSheets

Thin Interfaces with Tunable Stiffness Enabled by Layer Jamming

jamSheets are thin sheets of variable stiffness made using pneumatic actuation, and capable of being formed into multiple products [224]. *jamSheets* were chosen over *Cloth Displays*

[105] and *LightCloth* [177] due to the way they can change state from malleable to solid, as well as having the potential for advanced visual content. Ou et al.[224] make a case for multiple usage scenarios, from simple viewing screen to dynamic footwear, and discuss future interactions in some depth - such as “saving" and “replaying" a shape. The future *jamSheets* are seen to be able to cross the divide between device, environment, wearable and furniture, and thus this scenario looks at both wearable technology and display-based interfaces. The *jamSheets* scenario (Figure 5.10) also incorporates ideas from recent artwork *Caress of the Gaze* by artist Bahnaz Farahi [60] in which garments can respond to the visual attention.

5.3.5 Scenario 3: Hairlytop Interface

An Interactive Surface Display Comprised of Hair-like Soft Actuators

Hairlytop differs from other actuated interfaces as it makes use of a sideways-bend movement and Shape Material Alloys (SMAs) to achieve actuation, whereas other actuated devices (e.g. *Emerge* [297]) work only vertically. It also is designed to have a soft, tactile user-surface. *Hairlytop* is a good choice for a user-scenario as the paper suggests that future usage may be as a fur interface on a robot animal. In this respect, it is a unique prospect, blending artificial intelligence and robotics with shape-change. Nojima et al. also make the case for the communication of emotional content, which is, as previously discussed, a major theme across user-testing in shape-change. The scenario here (Figure 5.11) looks at the prospect of animal-as-interface, as the idea of devices becoming part of our environment is gathering increasing support.

5.3.6 Plausible Futures

By basing the proposed scenarios in existing research, I already begin to examine the notion of *plausibility*. The imagined future uses of each technology fulfil the qualities of diagetic prototypes — that is, they exist as fully functional objects in the worlds they are presented in. Bruce Sterling’s *NEXT* keynote speech suggests that “It means you’re thinking very seriously about potential objects and services and try to get people to concentrate on those”. By using individual prototypes as functional products — rather than a general notion of shape-changing technology — I focus the thought process of the user on the specifics of that product and its specific range of interactions. Coulton et al. [39] suggest that if we wish to enable individuals to consider future scenarios, we can qualify these in terms of plausibility, i.e. is the scenario *probable* (likely to happen), *plausible* (could happen), *possible* (might

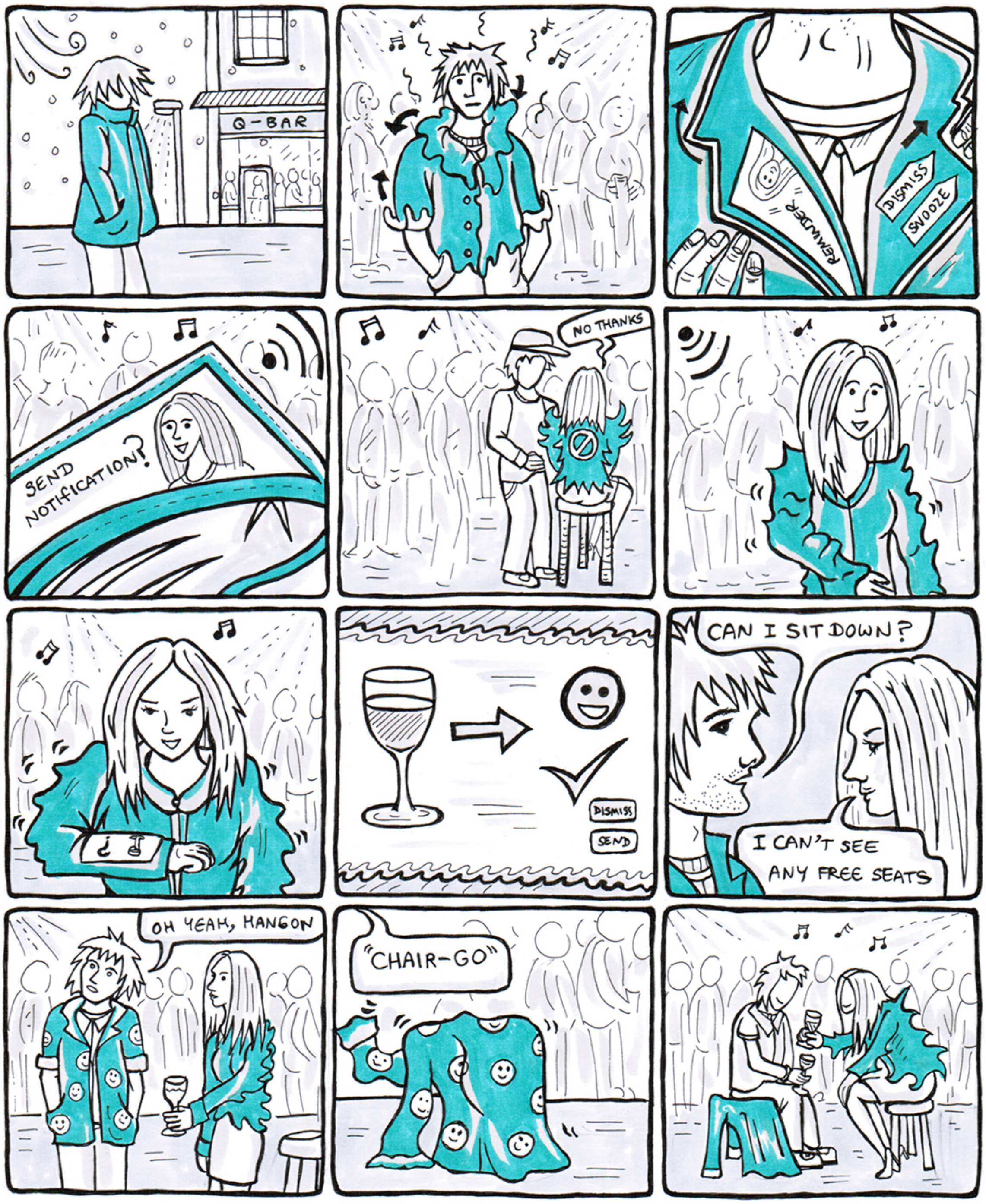


Fig. 5.10 Scenario 2: *jamSheets*, responsive wearables and communication devices

happen). For the purposes of this section, the final category of *impossible* is omitted as we wish to explore technological applications, rather than fantasy. The final scenarios therefore fit into one of each these categories: *Xpaaand* as probable, *jamSheets* as plausible, and *Hairlytop* as possible.

5.3.7 Questionnaires

Upon completion, the scenarios were then sent to 7 HCI practitioners (of varying sub-disciplines) and 7 non-expert individuals who were asked questions relating to plausibility, timescales, clarity and format of scenario, benefits and issues surrounding the adoption of shape-change and other possible usage scenarios (see Appendix 2). The questions focused on qualitative responses rather than a Likert scale in order to facilitate discussion, and are based upon the ideation study questionnaire in Chapter 4, with added questions around the concept of probable/plausible/possible futures [39]. These responses were examined using thematic analysis.

5.3.8 Analysis

A process of dual analysis was employed during the study, first, the researchers identified issues and made design choices during the making process, borne out of working through the stories and graphic representations of each technology; and second, the responses from the participant set, were examined for themes and implications for adoption.

Design Choices During the Sketching Process

Scenario 1 needed to show how the interface handled menu options and game-play, requiring the consideration of hand position and novel interaction styles (e.g. using the sliding side bars to move the main character, or shaking). The device also works in the opposite way to old “clam shell” mobile phones, by closing to take the call. The dual-play option also has implications for the materiality of the device —– it must be flexible enough to enable simultaneous movement from two individuals who may work at odds to each other, but strong enough to retain a degree of rigidity.

Scenario 2 was based around the emotional interaction between two people utilising the wearable technology, looking at utility (e.g placement of screen-based items on the lapel or sleeve for discrete and accessible detailed notifications; or, using the item’s rigidity as a tool) rather than detailed interaction with a specific application. The wearables also change shape and colour to signify the wearer’s emotional state (i.e. signifying having no

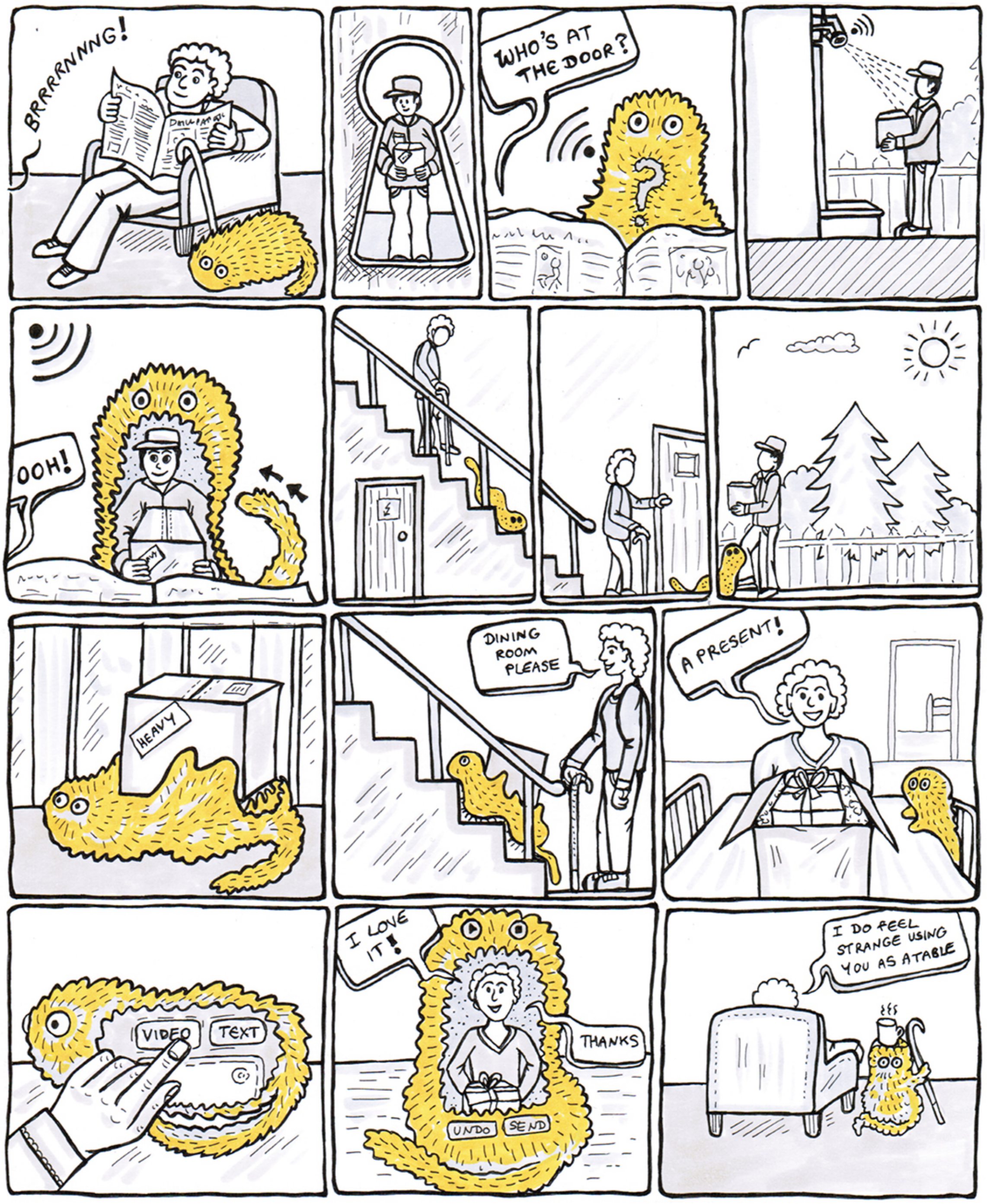


Fig. 5.11 Scenario 3: *Hairlytop*, a shape-changing robotic animal interface

interest in a potential unknown suitor). Voice activation for the state-change was added so the command did not need to be typed onto something that was about to change shape rapidly upon command completion.

Scenario 3 the "robotic shape-changing pet" was the most difficult to imagine and place into context. The final decision was to put the technology into the home of someone who could most benefit from its company and utility, thus demonstrating a range of uses. It was given a tail, so as to be relatable to common household pets such as cats and dogs, and eyes, even though discrete sensors could be employed. This implies anthropomorphisation of the pet. The pet's fur needs to be dense, and each strand must be able to display visual information (as in fibreoptic technology) as part of a whole image. This surface must also be robust so the surface does not get damaged when interacting with objects. Finally, the pet must have a consistent, malleable mass in order to elicit gestural commands and grip objects and move around —– in this respect it is more similar to an invertebrate.

Participant Evaluation of Sketched User-Scenarios

The completed scenarios were assessed by 14 participants via the series of questions outlined in the method section above. The age range was between 22-45 for the HCI group (5 male, 2 female), and 32-71 for the non-expert group (3 male, 4 female). Both groups self-selected by responding to an email invitation for participants, although those working within HCI were sent an invitation which was worded to explain the value of their input against the non-expert group. The HCI group also had no prior knowledge of the research prototypes being explored. Five high level themes were identified from the responses: *Hacking* (implications for physical technologies); *Fear* (of independent physically actuated technology); *Health & Safety* (survival/material contamination/physical harm); *Sustainability* (reducing the need for multiple devices); and, *User-Responsibility* (potential for malicious use). *Hacking, Health & Safety* and *Sustainability* replicate themes from the previous section, as well as Chapter 2 and 4, confirming that these are salient issues for shape-change.

Plausibility, Desirability and Implications

Both groups of participants found the almost limitless applications of the *Hairlytop* difficult to grasp, whereas those working in the field suggested that trying to integrate too many uses into one piece of hardware would cause issues of quality or technical fault. It was also viewed with delight and/or suspicion between groups, either through being unable to understand the underlying technology or because of the security implications. Plausibility and timescale were linked within groups, with answers ranging from "now" to "a thousand years" (the latter extremes being more popular amongst the non-expert group). The possibility of *jamSheets* also had a wide range, though it was seen to be marginally more plausible than *Hairlytop*. Only *Xpaaand* appeared easy to imagine in production within a short timescale, possibly because of its similarity to devices already in use (such as LG's rollable OLED display [182]). *Xpaaand*, although rated the most plausible and easy to understand, was plagued by imagined issues in terms of interaction and material strength, control and durability. Some in the HCI group saw it as a quickly outdated technology, due to advances in the field of mobile devices. It was also seen as the most "physically" dangerous, in terms of trapped fingers or being used as a weapon.

Benefits and Potential Issues

Hairlytop was seen to be a desirable, and useful tool with almost infinite applications by the general user group, although it was also thought that it may inspire laziness – unless use for assisted living, in which case it would be invaluable. Only one HCI respondent found the concept "horrifying", though the fear of decline in between-human interaction was postulated by both groups. Hacking and malicious use was seen to be the biggest potential issue of the *Hairlytop* technology between both groups, as it holds a privileged position within the household and has multiple abilities which are open to abuse. Potential benefits of the *jamSheets* focused on survival and comfort, especially allowing for the changes between clothing and shelter, and a general theme of protection. This was seen as more useful than a blended interface and wearable. Other positive comments from the general users were related to sustainability – the idea that shape-change will reduce waste across multiple products. This is mirrored by findings in Chapter 4. Negatives were largely seen as the responsibility of the user, such as ambiguity or unpleasantness of material communication, or malicious use.

Multiple Applications

Those in the HCI category were more likely to criticise multiple application use over single-use shape-changing devices, whereas the non-expert group were excited by the potential multiple interactions and uses for both *Hairlytop* and *jamSheets*. Those within the HCI group were also more confident of their answers with regards to timescale and plausibility, perhaps due to a working knowledge of some of the supporting hardware. Many of the alternate applications and usage suggestions mirrored categories and applications from Chapter 4, confirming that public ideation via sketching as a dialogue may be a valuable research technique for shape-change. Although the interactions shown were not novel, the theme of shape-change in these applications is. By looking at probable applications rather than hardware requirements alone, researchers can attempt to "future proof" their designs, and build toward something with practical application, rather than a research tool. The purpose here was to engage practitioners in creative practice, discussion and push for novelty in design — and also had the benefit of inspiring dialogue with a non-expert user group.

5.3.9 Section Discussion

The formation and evaluation of the three narratives supports the aims of extending the sketching methodology as dialogue to generate research insights. These scenarios are designed to be useful to researchers in the field of shape-change, but could also be helpful for designers interested in the potential of these devices, and future end-users during or before user-testing. They are not intended to simply communicate an idea to technically minded researchers — more than this — they are intended to be a tool to communicate to a range of audiences, and, importantly, to create discussion between researchers and the public in order to inform prototype development. The act of creating the illustrated stories in itself allowed for insights into the design of future prototype iterations, and this was further enhanced by the input of the participant groups involved in generating the themes and discussion. The creators' viewpoint mirrors the experience of McCloud in creating the *Google Chrome* comic "a very organic adaptation" [199], whilst relating back to Truong et al.'s "five significant attributes of storyboards" in order to build upon existing research in the field.

Encouraging Drawing Methodology in Shape-Change

Drawing practice may be a barrier to some practitioners, due to lack of confidence or perceived difficulty, although it has been shown that everyone has the potential to draw [35], it is a matter of learning. The benefits of exploratory sketching and story-boarding the intended path of prototypical shape-changing interfaces could lead to new insights or the early identification of unforeseen problems. There is a precedent from engineering research to encourage researchers and practitioners to become more familiar with sketching ideas and concepts to enhance their practice and outputs [264] and therefore there is a body of prior research to support this transference to the field of shape-change. We propose that encouraging the sketching of ideas, and drawing user-scenarios is a useful skill to obtain and apply to existing design-practice in this field, and a valuable tool for bridging knowledge gaps and disseminating research to a general audience (Chapter 4). Where there is not the potential for this skill however, creating narratives can be assisted by using external artists, tactile visual libraries [179], or computer-based storyboard generators [167], which support the process without requiring additional skills. Despite the technical focus of developing shape-changing interfaces, the drawn scenario must be validated in a qualitative sense [82] — it cannot be tested with a statistical approach. Practitioners can therefore approach this technique as part of a dual analysis with practical build and user-testing, and see it as an useful extension to the prototyping process and final product design. The human-centred perspective must take a forward role in designing shape-changing interfaces, as Banon [12] suggests it does in HCI as a whole.

Overlap with Existing Research

Chapter 4 produced ideas that complement two of the scenarios outlined in this section: shape-change gaming and wearables. However, the concept of merging AI or anthropomorphic attributes with a shape-changing device was not seen. This may have been due to the demonstration prototype being limited to linear-actuation, or it may be that we do not yet think in terms of merging these disciplines in a meaningful context. This idea was formed during exploration of the possibilities of shape-change with the designer and researchers, and based on Nojima et al.'s comments [216]. It illustrates the value of discovery during the sketching process. The illustrated scenarios also focus on the *personality* and *emotion* inherent within shape-change. This relates well to the comprehensive reviews and explorations made by Kwak [161] and Rasmussen [242] among others. *Emotional* or even *magical* qualities were suggested during the scenario evaluation for both *jamSheets* and *Hairlytop*, and this links directly to Kwak [161] and Rasmussen's work [240]. Part of the appeal of organically shape-changing interfaces is their unknown and unexpected qualities.

User-Scenario or Design Fiction?

This approach looks at probable, plausible and possible future scenarios based on the expected path of prototype and technology in development [39]. By framing these scenarios in *design fiction* as an additional methodology [18], it is possible to also explore alternative futures through stories, artifacts and imagery. Speculation in this chapter could be seen as "simplistic, short term, and focused on utility" [187], which suggests we should think outside of current work and further ahead. However, I suggest that this cannot be done without first examining what we already have, and utilizing the type of user-scenario shown here as a stepping stone to more creative and far-reaching visualizations. Researchers in HCI may also not have the skills to engage at the level required for design fiction, the means — or the desire — to employ skilled individuals with whom to create these visions of a future populated by shape-change. These sketches should be seen as distinct from design fiction in that they fall firmly in the role of *plausible* and *possible* and do not leap far from simple interactions. They are also concerning the artefact alone, whereas design fiction also considers the world in which such artefacts might exist. The scenarios are less about imagined stories, and more about the practical use of shape-changing items based on real research discussions. They could be used internally as part of the UCD process to enable better design, but also to communicate research to, and gather feedback from, users to enhance and support the design process.

Limitations

Pedersen suggests that realistically rendered videos are a more appropriate way of exploring user scenarios for shape-changing mobile devices, and also propose to enhance the resulting feedback by subsequently using hands on exploration using physical prototypes [230]. The drawback of this approach is the time and technology required to create these representations lacks the immediacy of the comics-style scenario, and the resulting form is difficult to edit. Read advocates the use of physical tools in designing OUI (Organic User Interfaces) but still rely on the scenario form to fill in the narrative components [244]. Additionally, it is harder to raise questions about "polished" output — more discussion can be generated where the user feels that the process is not yet complete [282]. Therefore, the argument here is to utilise the drawn scenario as part of a consolidated process, rather than either/or, as is the case with *Perfect Red* [123] which makes use of both the sketched storyboard *and* a realistic video.

Limitations within the study itself are that it could have explored a wider range of devices, and have gathered responses from larger number of participants, perhaps also recording the technological familiarity of each person in the non-expert group. Using scales to record responses would have also given some numerical data to explore, although quantitative methodology may not best represent the type of exploration I was initially interested in — that is, that of using the imagery as a starting point for discussion. With this in mind, it would have also helpful to both create the narratives and conduct the discussion in a co-creation setting to develop ideas further.

Further Research Ideas

Having shown the possibilities in drawing user-scenarios for shape-changing technologies, the next logical step is to utilise this process during the initial design-phase of a new prototype for a shape-changing interface, or shape-changing application. It would also be of benefit to ask other practitioners to reflect upon the usage of such techniques in their own practice, both current and future. Sketching and drawing could also be applied at idea inception across teams, and expanded to encompass other UCD practices such as persona generation

[82] in relation to shape-changing interactions. Buxton suggests that design should be a funnel moving toward the completed product [23], and working directly with researchers in shape-change would be ideal to apply a broader practice of UCD. An extension of this would involve end users in the design process, developing the stories or use-cases as part of a conversation between public, practitioner and designer — a "bottom-up" process (such as used by Read et al. [244], rather than the "top-down" process I have employed here. Rasmussen's paper on designer-led sketching of shape-change is a useful starting point for this [241]. Other extensions of this work might investigate animating sketches, or comparing acted and sketched stories to discern the best form of scenario communication. A deeper practice could also make use of group workshops to encourage discussion, and blend design fiction with user-scenarios to encourage non-linear research directions in shape-change [19]. As the *Tangible Media Group* ask: "what other materials can you imagine?" [122].

5.3.10 Section Summary

I have presented three sketched user-scenarios generated from existing discussions for shape-change, which have elicited complex requirements concerning usage, materiality, emotional content and interaction style in the field. I have then shown that these scenarios have the potential to stimulate discussion and generate implications for the adoption of shape-changing technologies via a thematic analysis. Finally, I have also shown that such practice can enhance and expand upon existing research into shape-changing technology. This section serves both the purposes of sketching as *elaboration*, as it builds on themes in Section 5.2, but also sketching as *dialogue*, as the scenarios were a source of discussion between researchers and potential end-users. The final section looks at taking the process of elaboration further, to investigate whether creating more detailed artefacts and images corresponds to the generation of more complex requirements. To do this, I select the most frequently occuring theme from Chapter 4 (shape-change gaming) and focus on combining sketching with design fiction as an elaborative approach.

5.4 Extending Elaboration with Design Fiction

As an extension of the subjective sketching methodology, there also exists the possibility to expand this work into writing, making and world-building via the use of design fiction (*elaboration*). Whilst research within shape-change often proposes future use-cases for prototypes during discussion, they are seldom in a form that presents them as everyday artefacts. Here, I present and discuss a sketched and written game-play instruction manual for a truly high resolution shape-changing game entitled *First Hand*, which aims to draw parallels between current gaming practices and the tangible nature of shape-changing interfaces. Gaming was chosen for three reasons, i) As a follow on from parts 5.2 and 5.3; ii) As entertainment was the most popular application category within Chapter 4; and, iii) Due to the frequency of gaming as a proposed application in published research.

Current inquiry into shape-change remains far from the high-resolution interfaces we see within science fiction [314], and researchers are left to ponder the implications of their prototypes, should technology eventually allow the blending of surface and material into a seamless, malleable interface [124]. As seen in the previous section, discussion around future application areas is a common theme in shape-change, with suggestions encompassing gaming [147, 354], data physicalization [129, 299], robotic pets [216], and multi-purpose clothing [66].

Combining the current state-of-the-art into meaningful, prospective avenue of enquiry is a difficult proposition, as is considering devices that can operate beyond the current application design. To enable us to take a leap forward, I suggest employing *design fiction* as a further form of *elaboration* to create a plausible product based on the current trajectory of the field, which can then feed back into current research practice: exploring both the viability of this methodological approach (sketching and elaboration for design fiction), and generating plausible requirements for specific shape-changing devices. I therefore propose *First Hand*: a game concept that allows the user to "play god" and either shape planetary life, or the planet itself, as a single player or in a *Massive Multiplayer Online Role Playing Game*, presented in the form of a game-play instruction manual, with further credence given via an article written about the game launch and the corresponding technology required to run the program.

5.4.1 Design Fiction in HCI, Shape-Change & Games

Design fiction is not a new concept, although it has only recently become popular in HCI research [184] [292], and refers to the creation of artefacts with which we can explore and analyse future scenarios. Design fiction tells worlds – not just stories [286], blending narrative, films, comics, and ephemera to immerse the reader in a possible future [39]. Design fiction describes the area, though the artefact discussed within this chapter is classed as a diagetic prototype (i.e. an object existing within a piece of narrative art), exploring the gaming scenario as a use-case for shape-changing technology.

Design Fiction has already been incorporated into several areas within HCI. Tanenbaum [303] makes the case for design fiction in HCI and interaction design, by suggesting that it can be methodology, communication tool, and motivation or inspiration for design – allowing us to explore requirements prior to the build process. Most relevant to this chapter perhaps, are Linehan et al's *Alternate Endings* [187] which looks at contemporary HCI research and a long term view of the technologies they depict – challenging the short-term, utility driven work that is seen the field; and Lindley & Potts [186] work on prototyping using design fiction.

The gap between technologist and designer can be broad, but there are those within the field of shape-change who are already embracing the concepts explored in this section. Ishii et al. [123] proposed a material called *Perfect Red*, which was part of a project exploring a vision-driven design process of shape-changing interfaces, and explores the idea of a clay-like material that also has computational attributes (such as snapping to geometric shapes, or merging distinct pieces).

The future of gaming has also been seen in science fiction films (e.g. *eXistenz, Lawnmower Man*), and is a popular speculative topic, but not often addressed in research. Game designers are quick to adopt new technologies to explore their entertainment potential, e.g. eye-tracking [329] or mixed-reality [274], but do not focus on what is not yet available, as much as they do on improving current technology. Design fiction as a methodology has not yet been applied to the design space of shape-changing games, despite the popularity of gaming as a theme in research.

5.4.2 First Hand

Why gaming?

Gaming as a theme for the diagetic prototype was chosen for several reasons. Primarily, Chapter 4 shows that the most popular category of idea was games and entertainment. Second, several papers concerning shape-change are either based around gaming [354] or suggest gaming as a future direction for research [147, 149, 172, 193]. Others in HCI also suggest that gaming, and game-play, plays a vital part in shaping the future of the interface [120]. Central to the principle of shape-change, is the fact that the interface is physically tangible, dynamic and directly graspable in a way that eludes current game-ready hardware. Thus I focused on building the game concept around the interface novelty, rather than adapting an existing game for the potential interface. Features that are collectively unique to shape-changing interfaces (in this application) include:

- **Physicality** – Tangible surfaces and spaces upon which the user can exert force to change the physical shape.
- **Dynamicity** – The surface of the interface can react physically to stimuli (be it environmental or programmed) and is not passive.
- **Sculpting** – Using hands or tools to manipulate the surface in meaningful ways.

• **Multi-Sensory** – Shape-change can harness a wide variety of inputs and outputs.
• **Option to incorporate hybrid gaming environments** – Shape-change can be combined with existing technology to enhance the player experience and add multiple dimensions to the interface.

Although additional features are possible, for the purposes of the creation of the design fiction I focused on a "wish-list" which would be necessary for a rich user-experience within the game world. These features informed and were expanded on during the design process.

The Making of *First Hand*

First Hand is a 34 page game manual "quick start guide" similar to those used in 1990s console gaming (see Appendix B). In *First Hand* you have the option to "play god" in that you are in the control of either the terraforming of a planet to better suit the lifeforms living on it, or the evolution of the lifeforms to better suit the planet they live on. There is an emphasis on a "hands on" approach, making use of real-life techniques such as sculpting and painting combined with meaningful game-play.

The manual takes the potential player through the first steps of starting a new game in *First Hand*. The player has the option to specify whether they wish to play as the guardian of the planet or the lifeform, and whether they wish to choose a pre-existing world (e.g. earth-type, landlocked, silicate) or lifeform (e.g. earth-type humanoid, silicate-based or aquatic). There is also the option to play a randomly generated world or lifeform, with varying levels of difficulty. For example, starting as an aquatic lifeform on a landlocked planet will be harder than an aquatic lifeform on a water-based planet.

After the initial choice, the player is taken through the basics of editing their lifeform or planet prior to the game beginning. After the first turn, editing is only possible through the earning of *interventions*, which are the game's currency. If your lifeforms thrive, or those that live on your planet, then you will earn extra interventions on top of basic, time-based interventions.

Players have the option to continue to develop their world or lifeform, with no fixed end point (other than success/failure depending on the desires and whims of the player) in single player mode, or to play toward planet-wide population success and eventual colonisation of other planets. It is this stage in the game that also opens up the the collaborative/computer generated universe option. Players may colonise and conquer further planets playing against the AI, or join the online community of *First Hand* where they open up their world to the dangers of existing in a universe where not every species is friendly.

The creation of *First Hand* took place over several stages (see Figure 5.12 for the manual cover). Initially, an exploration of current and past games was made which fit around the

Fig. 5.12 Cover for *First Hand manual*

theme the researchers had envisaged (e.g. *Populus, Civilization, Spore, Elite*), utilizing the knowledge of experienced gamers and bibliographical research conducted online. The initial theme itself was borne out of the idea that shape-change gives us infinite possibilities and sensory experience, and to have that kind of power to manipulate our environment might be akin to being omnipotent (albeit within the confines of the interface).

Novelty was an important factor in the design of the game and its play, thus I combined both the idea of "playing god" and the concept of a second stage involving space exploration and an overarching theme of intergalactic domination to differentiate the game further from its predecessors — not relying simply on the tangible nature of the interface to carry the idea. The multiple-stage game-play allows the shape-changing interface to show off numerous features, whilst maintaining a consistent narrative (e.g. planet formation, species evolution, species saturation, exploration of space and settling new worlds). Sketching even the basics of the game idea threw up questions that required answering before finalizing the diagesis. These are discussed in the following section.

5.4.3 Analysis

Analysis of the Diagetic Prototype

Using design fiction to create an artefact or prototype means that traditional evaluation cannot be employed [18]. HCI user-studies usually involve a working prototype with which the user can perform set tasks and the researcher can gather data as to the efficacy of the device or application in use. In comparison, a design fiction or diagetic prototype might be examined via multiple methods. Here, I view *First Hand* via anticipatory ethnography [186] — a technique designated to "operationalize the practice (of design fiction) in industry contexts" — by looking at the process of creation (e.g. what insights were gained during the making process, how were design decisions made?), and the study of the content itself (what insights can be made by the viewer/reader upon completion?), then document the findings from the content/thematic analysis (the potential for audience interaction is explored within the discussion).

Themes, Ideas and Implications

Creating the *First Hand: Quick Start Guide* produced many points of interest, e.g. the need for tool based interaction. Some points were "solved" during the creative process (i.e. decisions were made by the designer), and others emerged as themes discovered after the game manual was completed (see Figure 5.13 for examples).

Following completion, the manual content was explored via thematic analysis, and three distinct categories emerged: *Interaction, Hardware*, and *Conceptual* (i.e. non-tangible concepts or themes not directly relating to interaction or game-play), containing a total of 19 features. These features were generated by comparing current working prototypes with the proposed hardware capabilities of the novel interface, looking specifically at novel (and currently undeveloped) interaction styles and application design. The features are mapped onto the three categories in the following sections:

INTERACTION

• The *Riffler*: Examining sculpting as an interaction in game-play quickly gave rise to the need for tool-based interaction for fine detail when sculpting creatures and landscapes. This tool became an addition to the interface design, named the *Riffler* (a tool used for shaping fine detail in a number of materials).
• Rotation of suspended items above another layer: Editing the life-form/planet necessitates a 360 degree view, hence items being edited need to be rotated in space and remain in place

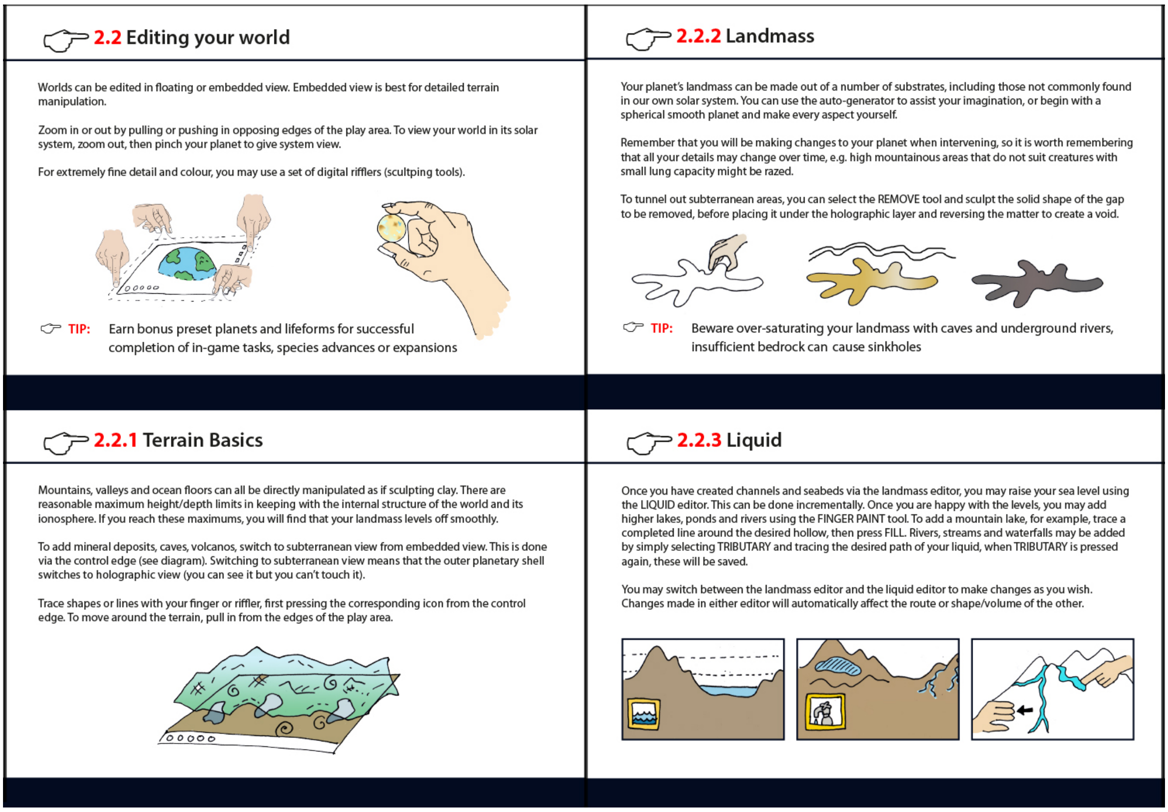


Fig. 5.13 Page examples from the *First Hand* manual

when pressure is applied.
• Painting/drawing on shape-changing surfaces: Mark-making on dynamic 3D surfaces is akin to painting 3D objects, but there must be an algorithm which dictates how that surface is managed during topology changes — i.e. surface area vs perceptual volume.
• Using buttons and menus: Despite the added dimensionality of shape-change and tangibility, it was still deemed necessary to have tool-bars which could be "raised" and interacted with to change between editing modes, layers and screens.
• Animation by recording movements: This feature can be linked to robotics or physiotherapy in terms of manipulating items in the desired manner and "saving" or adjusting them to the most favourable movement.
• Physical "Undo": This works in the same way as it would in an text or image editor — physical changes can be reversed, step by step.
• Adding gestural interaction: Gestural interaction can be used to execute large "area" commands — i.e. close layer, close game.
• Moving solid objects within space: Objects within the game environment must retain a rigid position in space, and be moved only within the limits of the game program.

HARDWARE

• Distance from baseline: Device-based game-play cannot be infinite due to limitations of contained mass in the interface, range, and safety aspects. Therefore I postulate that there must be a limit as to how far matter can be projected or moved from the central processing unit. In game-play, this manifests itself as a smoothing of surfaces when maximum zoom and distance from baseline are reached, or as a maximum distance that spaceships or other objects can be placed from the processing unit.
• Representing liquid and solid concurrently: Variable rigidity must be possible to differentiate between liquids and solids in the interface, e.g. a liquid must be pliable and flow around objects with a greater density.
• Placement of pre-formatted 3D objects: Items can be dragged from tool bars and have a pre-set 3D form, i.e. limbs in creature mode or volcanoes in terrain editor.
• Switching between solid and holographic layers: Game-play requires the function to work between solid (i.e. tangible) and projected (non-tangible) layers, and choose which is solid at a particular point in time.
• Multiple solid-state shape-changing layers: The game requires solid objects to be present at various distances from the baseline at any one time, e.g. spaceships floating above planets.
• Transitions between modes/views: Transitions might need to occur instantaneously (switching between planet and space/creature view) or gradually during interaction (zooming in and

out).
• Exporting physical items for 3D printing: The tangible nature of the sculpting process might give form to works of art that can then be exported in a fixed state.
• Physical "life force" bars: Game dynamics such as health, interventions, technology etc. might be represented by physical objects which varying in size, shape and colour.

CONCEPTUAL

• Ethics and safety: Temporality and physicality give rise to the potential of physical harm, either via hardware malfunction or safety settings, or via a third party acting upon the player.
• Managing Massively Multiplayer Online Role-Playing Games (MMPORG) on a physical level: Levels of attachment to lifeforms or planets may be higher than those on planar screens due to the time taken to create them and the emotional attachment present in physicality, therefore resulting damage caused by third party players may cause additional distress or consequences that might be explored.
• Proficiency at real-world sculpting/painting translating to gameplay: Relating to the previous, proficiency at sculpting creatures and planets can directly translate into artistic practice outside of the game-world.

These features address various aspects inherent in the design of shape-changing interfaces, from an application perspective. Their potential contribution to the field is considered within the discussion.

5.4.4 Section Discussion

The creation of design fiction on the subject of shape-changing interfaces is an novel approach that can add potential value to application and further prototype development. This can be further capitalised upon: via application of the findings to existing research practice; examining the practice as artistic endeavour; considering the limitations and potential improvements of the approach; via discourse around how the work presented here could be further expanded to allow wider audience access; and finally, used with existing user-based studies to create a blended methodology.

Implications for Shape-Change

Via thematic analysis of the diagetic prototype, I identified 19 novel features or ideas across 3 categories – some being recently under consideration in the research context (which supports the findings of this section), although not at the level of detail present in the fictional account.

Interactive qualities in shape-change are currently the most comprehensively explored: examples from *Interaction* include Vallgarda et al's notion of tool use in shape change [324], which has parallels to the *Riffler*; moving solid objects within predefined space e.g data-plotting using ultrasound [222]; adding buttons and menus to interfaces [297] or gestural interaction [102].

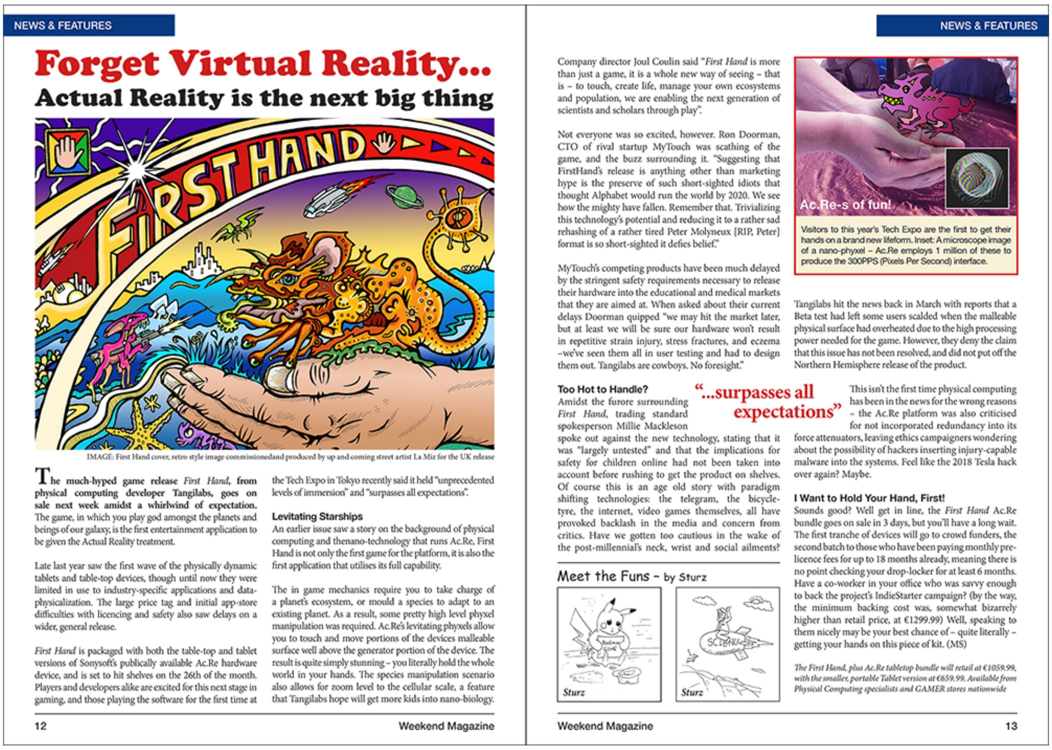
Some features from *Hardware* are largely absent from current research, not because they cannot be explored, but because they have not yet been approached, e.g. smoothing of surfaces at the limits of devices (distance from baseline), or painting and drawing on shape-changing interfaces. Others, like transitions between modes, require an advance in technology that is beyond current practice -– most interfaces employ a single materiality, or the transition is dictated by the hardware (i.e. actuator speed/elasticity in *TableHop* [255]). Other themes here are between the aforementioned states of enquiry, such as how to switch between solid and holographic layers (jamming only works for physically present surfaces [66]), although there is potential to use ultrasound/sonic manipulation in tandem with projections [190]. Also, the advent of 3D scanning means that there is the potential in the near future to scan time-points of an interface and export this data to print. This combination of tangible making and computational intervention/output has also been seen in prototypes such as *ReForm* [342].

The *Conceptual* themes give rise to the potential for philosophical enquiry, encompassing emotionality [161, 239], personal safety and boundaries, and even the long proposed idea that playing computer games has a benefit in developing real-world life skills. The idea that utilising shape-changing interfaces can bridge the gap between the digital and physical world in a meaningful context is perhaps one the most exciting propositions arising from the analysis. The magazine article (Figure 5.14) also approaches some of the more conceptual themes from a societal point of view.

Given the promising identification of features and ideas from the use of the diagetic prototype, it is hoped that the overlap in themes and challenges seen between the design fiction approach and that of traditional technologists can bridge the gap between disciplines, and offer up a new design space for enquiry. This might be achieved by disseminating research and presenting work at large scale events, as well as via collaboration with other researchers at the design stage of shape-changing interfaces (e.g. using the identified features as components in the development of new prototypes).

Diagetic Prototypes as Artistic Endeavour

A design fiction can exist as a standalone artefact within a research area, however, I might explore how it works as a blended methodology to encourage interaction and discussion. In



NEWS & FEATURES

Forget Virtual Reality...

Actual Reality is the next big thing

IMAGE: First Hand cover, retro style image commissionedand produced by up and coming street artist La Miz for the UK release

The much-hyped game release *First Hand*, from physical computing developer Tangilabs, goes on sale next week amidst a whirlwind of expectation. The game, in which you play god amongst the planets and beings of our galaxy, is the first entertainment application to be given the Actual Reality treatment.

Late last year saw the first wave of the physically dynamic tablets and table-top devices, though until now they were limited in use to industry-specific applications and data-physicalization. The large price tag and initial app-store difficulties with licencing and safety also saw delays on a wider, general release.

First Hand is packaged with both the table-top and tablet versions of Sonysoft's publically available Ac.Re hardware device, and is set to hit shelves on the 26th of the month. Players and developers alike are excited for this next stage in gaming, and those playing the software for the first time at the Tech Expo in Tokyo recently said it held "unprecedented levels of immersion" and "surpasses all expectations".

Levitating Starships

An earlier issue saw a story on the background of physical computing and thenano-technology that runs Ac.Re, First Hand is not only the first game for the platform, it is also the first application that utilises its full capability.

The in game mechanics require you to take charge of a planet's ecosystem, or mould a species to adapt to an existing planet. As a result, some pretty high level phyxel manipulation was required. Ac.Re's levitating phyxels allow you to touch and move portions of the devices malleable surface well above the generator portion of the device. The result is quite simply stunning – you literally hold the whole world in your hands. The species manipulation scenario also allows for zoom level to the cellular scale, a feature that Tangilabs hope will get more kids into nano-biology.

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NEWS & FEATURES

Company director Joul Coulin said "*First Hand* is more than just a game, it is a whole new way of seeing – that is – to touch, create life, manage your own ecosystems and population, we are enabling the next generation of scientists and scholars through play".

Not everyone was so excited, however. Ron Doorman, CTO of rival startup MyTouch was scathing of the game, and the buzz surrounding it. "Suggesting that FirstHand's release is anything other than marketing hype is the preserve of such short-sighted idiots that thought Alphabet would run the world by 2020. We see how the mighty have fallen. Remember that. Trivializing this technology's potential and reducing it to a rather sad rehashing of a rather tired Peter Molyneux [RIP, Peter] format is so short-sighted it defies belief."

MyTouch's competing products have been much delayed by the stringent safety requirements necessary to release their hardware into the educational and medical markets that they are aimed at. When asked about their current delays Doorman quipped "we may hit the market later, but at least we will be sure our hardware won't result in repetitive strain injury, stress fractures, and eczema –we've seen them all in user testing and had to design them out. Tangilabs are cowboys. No foresight."

Ac.Re-s of fun!

Visitors to this year's Tech Expo are the first to get their hands on a brand new lifeform. Inset: A microscope image of a nano-phyxel – Ac.Re employs 1 million of these to produce the 300PPS (Pixels Per Second) interface.

Tangilabs hit the news back in March with reports that a Beta test had left some users scalded when the malleable physical surface had overheated due to the high processing power needed for the game. However, they deny the claim that this issue has not been resolved, and did not put off the Northern Hemisphere release of the product.

Too Hot to Handle?

Amidst the furore surrounding *First Hand*, trading standard spokesperson Millie Mackleson spoke out against the new technology, stating that it was "largely untested" and that the implications for safety for children online had not been taken into account before rushing to get the product on shelves. Of course this is an age old story with paradigm shifting technologies: the telegram, the bicycle-tyre, the internet, video games themselves, all have provoked backlash in the media and concern from critics. Have we gotten too cautious in the wake of the post-millennial's neck, wrist and social ailments?

"...surpasses all expectations"

This isn't the first time physical computing has been in the news for the wrong reasons – the Ac.Re platform was also criticised for not incorporated redundancy into its force attenuators, leaving ethics campaigners wondering about the possibility of hackers inserting injury-capable malware into the systems. Feel like the 2018 Tesla hack over again? Maybe.

Meet the Funs – by Sturz

Sturz

Sturz

I Want to Hold Your Hand, First!

Sounds good? Well get in line, the *First Hand* Ac.Re bundle goes on sale in 3 days, but you'll have a long wait. The first tranche of devices will go to crowd funders, the second batch to those who have been paying monthly pre-licence fees for up to 18 months already, meaning there is no point checking your drop-locker for at least 6 months. Have a co-worker in your office who was savvy enough to back the project's IndieStarter campaign? (by the way, the minimum backing cost was, somewhat bizarrely higher than retail price, at €1299.99) Well, speaking to them nicely may be your best chance of – quite literally – getting your hands on this piece of kit. (MS)

The First Hand, plus Ac.Re tabletop bundle will retail at €1059.99, with the smaller, portable Tablet version at €659.99. Available from Physical Computing specialists and GAMER stores nationwide

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Fig. 5.14 Article created to add depth to the game-world

many cases, the making of diagesis is not simply a method of inquiry, it is a creative act that has meaning for the researcher beyond the act of investigation. For some, it affords the opportunity to bring creative practice to their work, for others it adds an interdisciplinary angle. Lindley et al. [186] suggest the importance of the act of creation, and it is this process that adds dimensionality to the research. HCI research has scientific rigour, but the human aspects are sometimes lost [12]. By employing design fiction as artistic practice in addition to research practice, we can appreciate research on a deeper level.

Limitations

Design fictions and diagetic prototypes are often co-created [316], but are also often the product of one practitioner. This leaves the value of the artefact open to bias, be it during the process of creation, or whilst presenting analysis. The easiest way to address this bias would be to require the artefact to be exposed at some level to a non-expert audience: examined, reworked and re-presented for consideration.

There is also the possibility of creating a "bubble" around certain scenarios or artefacts — something that can be addressed via a process of world-building [292] — rather than relying on single objects or individual ideas. These worlds can contain multiple ideas, artefacts, stories and imagery, by many different researchers or participants, thus expanding the view around the initial diagetic prototype in a detailed and meaningful manner. It might be suggested that the initial prototype sets the stage for the associated explorations, thus limiting further creativity, but by building these worlds together we can inspire — rather than limit – each other.

5.4.5 Next Steps

We investigated the potential of using design fiction as a tool to inform the design of shape-changing interfaces via a diagetic prototype, however the next steps require adoption of such methodologies within the field, to supplement and enhance current thinking and prototype design at an early stage. For example, the researcher might better imagine the context and direction of their work, or the user may explore how prospective devices might fulfil their needs. The challenges in this approach lie within adoption in the research setting, and in taking on board the innovations it produces.

First Hand is a comprehensive enquiry into the future potential for shape-changing games, however, this work could be extended further from the initial artefact and article to include further items to support the "world building" proposed by Sturdee et al. [292]. Such items might include physical artefacts such as game cartridges, 3D printed items depicting the game environment (e.g. creatures in various stages of evolution, or world types).

An additional extension would be to create a WOZ (Wizard of Oz) study, where the ideas and implications borne from the workshop and creative process could be tested. WOZ testing involves creating realistic prototypes that participants do not realise are being controlled by a hidden researcher, e.g. Rasmussen et al.'s shape-changing bench [239]. WOZ methodology would create a bridge between existing user-testing on shape-changing interface prototypes and design fiction, and we might also further explore the process of creation, moving a step closer toward realising the kind of interaction design needed for shape-change. Working around the design fiction can also be approached using lo-fidelity methods, such as sketching and creating illustrated user-scenarios. Whereas these lack the realism of WOZ, they can be quickly co-created with researcher and user to analyse and discuss the research. *First Hand* provides a jumping-off point for research in either direction, and a focus of inquiry.

Finally, design fictions of the type explored here may also have benefit in other fields where novel technology is still in development, such as brain-computer interfaces [322] or advanced gestural interactions [93]. Design fiction can also evolve alongside technology, creating ever more complex investigative possibilities, and could enable us to "catch up" with and reflect upon our past fictions to compare speculation with actuality.

5.4.6 Section Summary

First Hand is the first piece of research utilising design fiction to explore shape-changing games, with consequences for the wider field. We show that the creation of design fiction on the subject of shape-changing interfaces is an exciting, inclusive approach that has potential value to the field (e.g. to direct technology development or user studies), as well as for the design and application of other emergent technologies. We envision this approach being used for the creation of shape-changing prototypes and their applications, to create a blended practice of artistic and scientific inquiry. Additionally, I hope to inspire researchers to embrace this alternative practice as a methodology when creating these exciting devices.

5.5 Conclusion

This Chapter links user and researcher via sketching practice through *ideation*, *dialogue* and *elaboration*. By developing the level of detail used for the sketched images during the process, I am also developing more insights, and generating more requirements for shape-change. The benefits of the subjective sketching practice outlined in this chapter are threefold: 1) The technique requires no complex equipment, or study space; 2) Outputs are easy to understand, and relatable to other researchers and users; and, 3) The process allows for complex requirements and implications to be generated for shape-change, which can then be validation via other methods or by continuing the development process. There are, however, limitations with this method — although I based this work in user-generated ideas, the subsequent elaboration and analysis are (as previously mentioned) subjective, and therefore cannot adequately reflect the needs of the end-user. In order to address this, the next chapter merges the subjective practice seen here with the user ideation study in Chapter 4, in order to consolidate a novel practice for shape-changing interface design and development.

Chapter 6

A Novel Approach for Requirements Generation in Shape-Changing Interfaces

6.1 Chapter Summary

The previous chapter looked at subjective sketching to generate requirements propose questions, and consider implications. However, this highly subjective process cannot be seen as *user-centred* despite the sketched dialogue between the participants in Chapter 5 and the researcher. Therefore the further application of the techniques examined in Chapters 4 and 5 to a potential end-user base must therefore be examined.

Chapter 4 showed that non-expert participants were able to grasp the concept of, and generate a range of applications for, shape-changing interfaces — but the discussion theorises that the single actuation type of the boundary objects (bi-directional, actuator-based prototype) may "trap" the user into one type of output. Having identified 8 types of shape-changing prototype in Chapter 2, we therefore needed a way to communicate the range of the field in an accessible, portable manner, in order to engage with further potential end users.

To achieve this, we borrowed the concept of low-fidelity prototyping from User Centred Design, and built *white-box prototypes* which reflected the material properties of shape-changing interfaces. Then, to additionally explain the current state-of-the-art to the participants, we chose videos outlining and explaining functional prototypes. These parts of the process expanded upon, and replaced the posters/*ShapeClip* boundary object concept in Chapter 4.

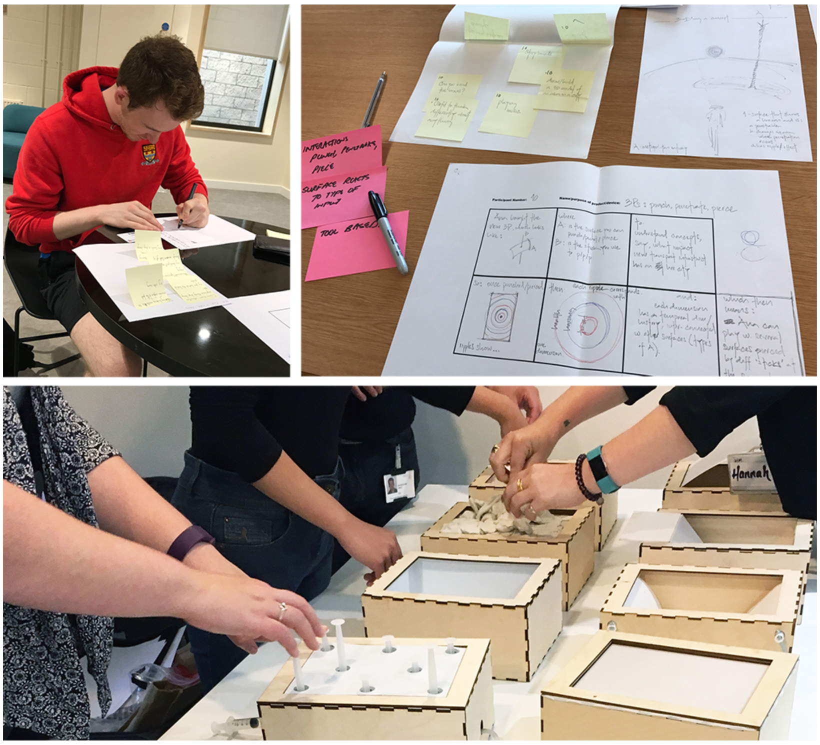

Fig. 6.1 Study overview – Top left: a participant figures out a diagram; Top right: final output and beginning of analysis; Bottom: participants interact with the white box prototypes after the video session

The participant output stage was also expanded, based on the findings in Chapter 5. The ideation stage remained in the same format as that seen in Chapter 4, but participants were then asked to choose one idea and *elaborate* upon it in the manner of the subjective exploration in Chapter 5.2. Following this, participants were then asked to place their application into a meaningful context by creating a sketched scenario – which could either be practical or probable in the near future, or be based in a futuristic fictional world (Chapter 5.3 & 5.4).

The sketched outputs then became a dialogue between user and researcher, and formed the basis for the researcher-led requirements generation stage – thus removing the subjective component of self-directed sketching and ideation. The collected requirements then were used to create a tool for shape-change development in the form of a stack model. The following sections explain the process and result in more detail.

6.2 Introduction

Despite the diverse range of shape-changing prototypes researchers have developed (Chapter 2), there are no formal methods, guidelines, or tool-kits available to assist in shape-changing interface development – with the exception of rapid prototyping, often using modular devices [102]. User-Centred Design is a process that ensures the tasks, needs, and context of end-users drive and reflect upon the development of a new system, but presently cannot be applied to shape-changing interfaces as it is to contemporary devices and technology. This is because, at present, we are not designing shape-changing interfaces to solve a particular problem, or designing specific hardware or interaction (although we are moving toward this approach) — we are purely striving for innovation. In addition to this, potential end users are not aware of shape-change as a technology, what it can do, and the range of available hardware is difficult to demonstrate due to issues of location, portability or safety. In the cases where users are given the opportunity to interact with a shape-changing interface prototype, they may also become "trapped" into thinking about shape-change as being of one particular form (e.g. actuated pins [58]).

Much of the work on shape-change appears to pick directly from different areas of User-Centred Design, but does not seek to employ it as a specific methodology during the research process: for example, building hardware is often the first step in exploring shape-changing interfaces, and is then followed by a short usability study for whichever application best suits the platform [289, 298]; or studies might focus on user-ideation or co-design for non-specific products [57] (see also Chapter 5). The reason behind this may be that a strict view of UCD practice (e.g. following the stages of planning, user research, user evaluation, information architecture [**?**]) may not fit exactly with emergent hardware which does not already have a predefined role within the world. This is not to say that UCD cannot be fluidly interpreted — in fact I rely on this fluidity to allow for this exploratory study.

At this stage, we hope to utilise and adapt UCD techniques, to provide a baseline of requirements for shape-changing interfaces. By focusing on a practical start-point — requirements generation — we believe we can begin to adapt and build specific processes of UCD for this exciting technology from the ground up. Following the generation of requirements, we can model these to form an overview of the field and its possibilities. This chapter therefore contributes: 1) A combined "videos, boxes, and sketches" UCD approach that aims to address the challenges of involving users in the requirements generation stage of shape-changing interfaces; 2) A 50 participant study that aims to demonstrate the validity of this approach to generate requirements for this novel technology; 3) A thematic analysis of the generated user requirements; 4) A shape-changing requirements stack model to support practitioners in requirements-gathering activities for shape-changing interfaces. The stack model is intended to provide a cohesive resource for those building and testing shape-changing interfaces with the view to their eventual adoption.

6.3 Related Work

Generating user-requirements for devices that do not currently exist is a challenging prospect. In order to address this challenge we suggest utilising accessible techniques already used in UCD in order to inform and engage potential end-users about shape-changing interfaces. Understanding current applications and approaches to shape-change — alongside these already validated techniques – can assist us in designing a hybrid process for these novel devices.

6.3.1 User-Centered Design & Future Use-Cases

Usability refers to how easy a system or device is to learn and employ, for the intended end-user, although there are many definitions across the field. It employs various techniques to ensure that the user is involved at the heart of the design process in a meaningful way, for all types of new products, software or applications [1]. The practice of User-Centred Design has been established and standardised (ISO 9241-210:2010 [223]), and is acknowledged as an essential part of the ergonomic design process, but there are not prescriptive methods for each stage of the process [321]. It is also proposed as a *viable alternative to traditional HCI* [106] and as a technique to ensure the design of useful, functional and even pleasurable products and devices [137]. Generally the stages of UCD are seen to include *specifying context*, *generating requirements*, and *generating/evaluating designs* [321], but can be interpreted as to the needs of the system at hand, as I do here.

The stricter view of UCD becomes difficult to follow when anticipating future use-cases or products however, as the context of use cannot be predicted for unknown interfaces. Nelson attempted to address this issue by using idea generation to limit bias which might be linked to existing devices and applications – and to avoid over-reliance on analysis of retrospective use — the resulting ideas were used to create related scenarios to help build a framework of *prospective use analysis* [214]. The limitation of this in application to shape-change however is that it relies on existing technologies, and thus limits the framework to anticipating use-cases for current thinking. Another example is to use narratives and scenarios to collaboratively build low-fidelity prototypes of future products or devices, which are then examined by the user and researcher together to highlight the importance of *narrative* as a technique [281]. These examples suggest that adaptive, creative UCD processes may be the answer to exploring and envisioning user-centred design for futuristic technologies such as shape-change. As a specific context of use cannot be predicted at this stage, investigating requirements generation (the next part in the formal view of the UCD process) would be a logical step.

6.3.2 Requirements for Shape-Change

Requirements are, simply put, the things a system should have in order to function and fulfil the needs of the user [160]. They can be gathered in a systematic (as with software requirements engineering) [280] or informal manner, with a preference for the former. However it is not possible to apply current requirements engineering practice directly to shape-change as there are no existing parameters to work with. Stakeholders (in this case potential users) have no existing schema for shape-change, so first the concept and structures must be communicated. For shape-change, the easiest way is to demonstrate and allow interaction with existing hardware, but this is not practical given constraints such as geographical location and accessing multiple devices from different research labs. The second challenge is how to capture the stakeholder responses as you cannot simply interview the user about their experiences with a product that does not exist, and that they have not used. To overcome these barriers, we might explore the possibility of using creative UCD methods [214] to elicit early stage requirements in three ways: by employing an efficient method of *communication* [356] to describe the state-of-the-art of shape-change; by creating opportunities for *interaction* [233]; and by using an accessible method of information *production* [23]. The appropriated techniques described below are not new in their application to UCD – and the outcomes and evaluation are challenging – but in combination, and given the potential output and relevance to shape-change, they form a novel application and methodology.

6.3.3 Video as a Communication Strategy

High-quality video is often produced alongside published work in order provide quick explanations of a hardware or system concept, without reading the accompanying text. It can also be used throughout the UCD process to inform, communicate or explore concepts [356]. To a large percentage of users, receiving information in this way is a normal, accessible part of smart (and other) device interaction (such as *YouTube* or *Vimeo*) [71]. For actuated prototypes, a realistic rendering style was found to be the optimal way of communicating a concept to users in a study of shape-changing phones [230], whereas Gong et al. [86] suggest that high quality videos depicting novel hardware allow users to "suspend their disbelief" and make judgements about how useful a prospective technology might be. Videos have also been used within studies in combination with low-fidelity prototypes to generate high-level comments [192] which suggests that combining this media with other techniques may yield useful results. In context, video also enables us to present work that we do not have access to, due to geographical, or other, constraints, and is therefore an apt method to communicate of high-level concepts.

6.3.4 Exploring Low Fidelity Prototypes

Low-fidelity prototypes are quick mock-ups of designs or devices allowing concept testing without committing to an expensive or lengthy build, making them ideal in the requirements-gathering stage of the design process [252]. In HCI, concepts such as *paper-prototyping* [269] and *rapid-prototyping* [102] are often used, examined and critiqued for their role in research. For shape-change, the difficulty in creating low-fidelity prototypes is mirrored by the range of technically complex hardware and interactive capabilities of the high-fidelity, working prototypes. By thinking about the *materiality* of shape-change however, we can emphasise its tangible nature in a simple, easy-to-build manner. Schmid et al. suggests and tests a form-first approach using glass objects to generate ideas for tangible interfaces [263]. The reasoning behind using low-fidelity, white box, prototypes to explore shape-change are twofold: 1) Existing prototypes are often bulky, heavy, expensive and situated in laboratories across the globe; 2) White box prototypes allow for the presentation of matter in a consistent way (i.e. all the same size, colour) so that participants are unbiased by incidental details. Examples include: Kwak's *Repertory Grid Study* [161] where a variety of actuated white box prototypes were created to explore the expressive and emotional qualities in shape-change; Petrelli's work on tangible interfaces which looked at the psychological affect inherent with concepts of shape and haptic interaction [233]; and, Winther et al. who generated white box protoypes following an exploration of form language for shape-changing interfaces [349].

6.3.5 Sketching and Storyboards

Sketches are often seen as low-fidelity – they are rough ideas that welcome opinion and modification [62], and also explain concepts that are hard to suggest with words [79]. Sketching has long been part of the user-centred design process, and Buxton's book *Sketching User Experiences* has actively encouraged and enhanced researcher engagement with this format [23]. Sketches are also cheap to produce, and are an inclusive way of generating output as they require only access to a pen and paper. Sketching also has an established place in the design of user interfaces (UI), giving rise to computer-based UI design programs which either utilise, or appear to be sketches and storyboards [97, 168] and can be annotated or embedded

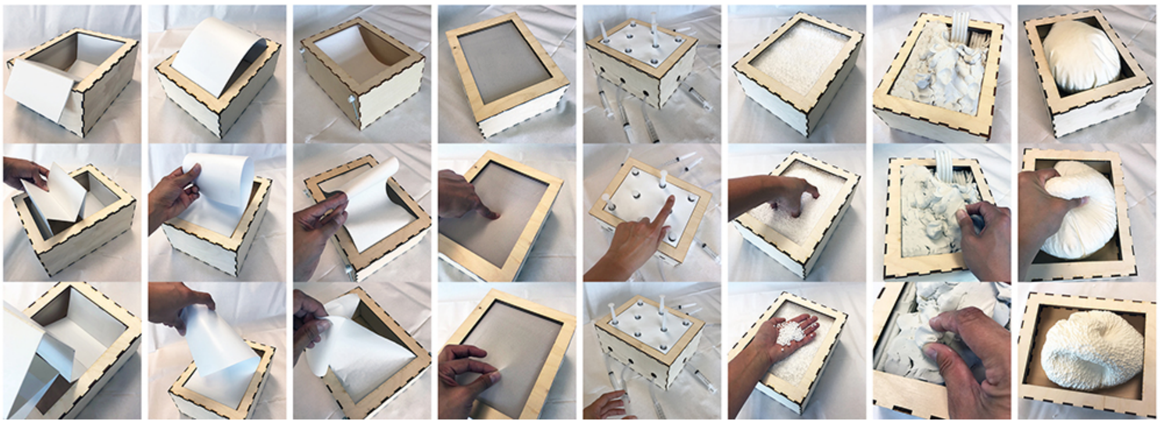

Fig. 6.2 White-box prototypes, from left to right: Foldable; Bendable; Paper/Cloth; Elastic; Actuated; Liquid; Malleable; Jamming. Based on the categories from Chapter 2, with the addition of *Jamming* to demonstrate the ability of shape-change to vary in state/rigidity.

with metadata [96]. Storyboards used in the design process can also lead to more effective design [346] or help communicate research findings [107]. There is already a precedence for using storyboards to generate requirements, whether via sketched, computationally enhanced outputs [96] or the traditional, hand drawn versions [295]. Storyboards and comics are also already used in HCI within areas such as software engineering [346] and cyber-security [179, 360], and can are accessible, quick-to-produce medium for proposing future scenarios. Sketching in direct application to shape-change has already been employed in the ideation process as a method for users record their thoughts (Chapter 6), as a way of exploring the design of interactions for shape-changing devices [243] and even to explore and storyboard a futuristic material [123]. Therefore there is already a precedence for both users and researchers to use sketching as part of the design process.

6.4 The ‘Videos, Boxes & Sketches’ Approach

In order to overcome the difficulties in exploring outcomes for shape-changing interfaces, and begin to develop the beginning of a specific practice of UCD for shape-change — specifically requirements generation — we must start from the beginning. We therefore approach requirements generation for shape-change by utilising and combining the existing methods that we have described to create a hybrid model of requirements generation. We take inspiration from both our review of techniques, and the hybrid approach to exploring organic user interfaces (where comics and material prototyping were used in combination to communicate ideas about materiality and change [244]). For shape-change it makes sense to blend parts of the analytic and design stages where feasible in order to take advantage of the benefits of user-centred techniques. Shape-change is also diverse in its materiality and potential interaction range, so to attempt to represent and explain this technology in a simple, single step would be prohibitive. This is not, however, an exercise in co-design, as we are not attempting to design a final product for a particular community, but we believe that this approach will be valuable in the future when the field is better established. Likewise, it does not fit into the formal idea of what UCD is, but we believe that using this established practice as a starting point in the fluid view of UCD will better inform our process and outcomes.

To begin, we propose using videos to inform and educate, low-fidelity prototypes to enable exploration and basic interaction, and sketched output in the form of diagrams and storyboards to both assist in explanation and later, interpretation (the diagrams play the role of *annotation* or *metadata* for the storyboards [97]). The desired outcome of this process is to "reduce the distance" between the researcher and the end user [203] and create a meaningful collaboration. We propose 4 steps to enable participants to produce meaningful data about shape-change (or other emergent technology) for subsequent coding and analysis. Participants have the option to revisit the stimuli (boxes) during later stages of the process in order to explore their ideas:

Step 1 *Introduction:* High-quality video produced by researchers is shown to users in order to explain current state-of-the-art and show proof of concept;

Step 2 *Interaction:* Interaction with a range of low-fidelity material prototypes is encouraged so that users can experience examples of the materials they have just seen in the videos;

Step 3 *Ideation:* Application of shape-change to the context, scenario, or task at hand to generate simple ideas for devices and/or applications;

Step 4 *Elaboration:* Participants explore, refine and sketch out their ideas in the form of diagrams and storyboards.

The analysis that follows these 4 steps *Coding* can extract requirements from this output in a number of ways: *directly* through specific notations and imagery in both diagram and storyboard; *indirectly* by examining the interactions and use-case shown in the storyboard; and through exploring the *context* of use (proposed aims, results).

6.5 Testing 'Videos, Boxes & Sketches'

In order to understand the appropriateness and viability of our approach, we conducted a large-scale requirements gathering exercise. The study employs the adopted components of UCD processes explained in the previous section, and is based upon the techniques suggested in the related research.

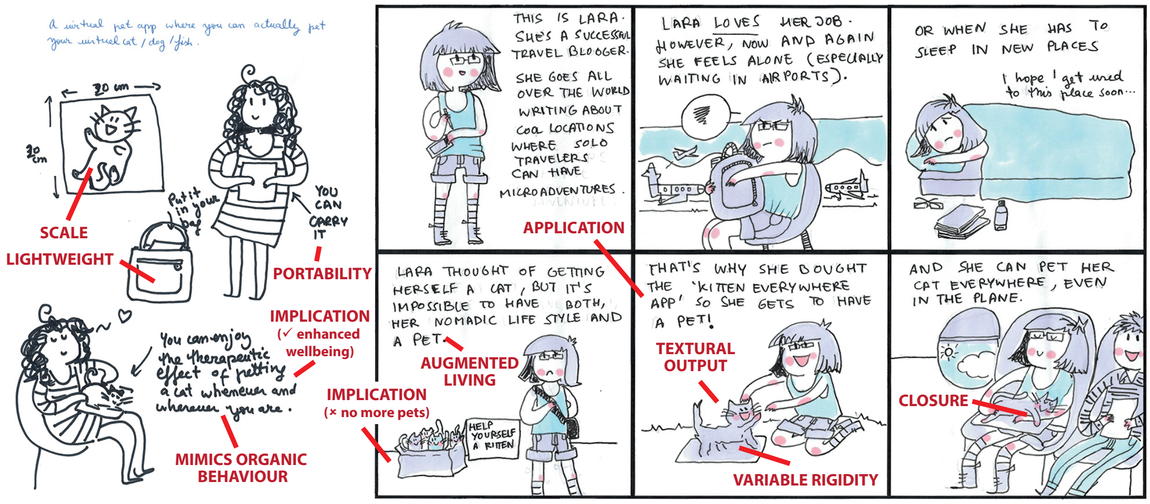

Fig. 6.3 Example data: diagram & scenario for *Kitten Everywhere* app, with annotation to show how requirements are generated from visual data

6.5.1 Study Overview

The study was a five-stage process lasting between 40 minutes to 1 hour, including explanation, questions and feedback: 1) Introduction to shape-change using video material from existing research; 2) Exploration and interaction with white box prototypes; 3) Idea generation; 4) Idea elaboration and diagram creation; 5) Storyboarding and scenario generation. The participant output was collected for coding and analysis. Figure 6.1 provides an overview of the study process and outputs.

6.5.2 Participants

Fifty participants (24 male/26 female) were recruited using social media, email, or from volunteering after observing the study set-up directly in shared social/study spaces. Participants with diverse social and professional backgrounds took part (of the 50, 22 were not involved in academic research or study, and 28 were either students or university staff). The age range of participants was 21-69, (mean 49).

6.5.3 Video Material

Participants were shown 7 videos relating to existing research into shape-changing interfaces, chosen for quality, specific actuation type and related to the material properties of white box prototypes (see below). The videos served to inform those taking part about the state-of-the-art in shape-change research, and introduce the concepts of materiality in prototyping. The chosen works were: *Physical Telepresence* [173] (actuated interface); *Protrude, Flow* [156] (liquid interface); *Lightcloth* [105] (paper/cloth interface); *ReFlex* [289] (bendable interface); *Paddle* [238] (foldable interface); *Claytric Surface* [197] (malleable interface); *Obake* [41] (elastic/inflatable interface).

6.5.4 White Box Prototypes

We created 7 white box prototypes reflecting the materiality of a range of existing shape-changing interfaces representative of current functional prototypes within the field (see previous paragraph), one of which also demonstrated the ability of these interfaces to change state via jamming [66] — see Figure 6.2 for categories and images. By utilising white-box prototypes which span a range of shape-changing materials, we can communicate the intended interaction of shape-changing interfaces in a simple, portable manner.

6.5.5 Ideation, Elaboration and Storyboarding

Participants were asked to explore the white box prototypes through touch and comparison, then write down ideas for applications, hardware, surfaces or spaces that would benefit or enhance their own lives in some way (e.g. in work, hobbies, social contexts). This was similar to the process employed in the public ideation study (Chapter 6) but with a user-specific focus. Following this, they were asked to choose their favourite idea and expand on it via sketching a diagram and writing notes about — for example — how it works, the user base, interaction, and so on. Finally, the chosen idea was put into context within a storyboarded scenario of use (see Figure 6.4).

6.6 Analysis

Fifty participants generated 255 ideas for shape-changing interfaces, applications, surfaces and spaces (mean 5.1). They then selected one idea to elaborate upon (n=50). The majority of chosen ideas were indicative of shape-changing hardware (43/50) rather than specific applications for a generic device, although most would allow for multiple applications. Two of the chosen ideas did not specifically address shape-changing technology so were not used in the analysis.

6.6.1 Requirements Generation

In order to elicit requirements from the data, four HCI researchers (one of whom was independent from the study) coded the data using collaborative card-sorting and thematic analysis. Initially, a data set from one participant was chosen at random and examined by all four researchers using the method outlined in approach description, who then generated post-it notes suggesting requirements, interactive properties, context and possible implications for the technology. The group then split into pairs and worked on a set from the data, and these pairs were rotated so that each researcher worked with one another. Requirements were extracted in several ways (see Figure 4 for an example of participant data): *directly* through notation on the diagrams and storyboards (e.g. device is 20cm by 20cm, device is portable); from examining the *interaction* (device has furry texture, folding and closure must be possible); from the proposed *output* (mimics organic form); and from *context* (device has thearapeutic purpose). The *implications* of the technology then arose from the questions that having access to a lifelike, adaptable non-organic representation of a pet would have – e.g. decline in pet ownership. A guide to the coding process to generate requirements is shown in Figure 6.3.

6.6.2 Coding

Mid-way through the process the coding for requirements was halted to examine emergent themes and categories, and it became clear that there was much more information in the data than simple hardware/software requirements and basic human factors. The post-it notes were then recategorised under specific titles (for example) scale, interaction, portability, multi-sensory, device dependent properties, context of use and so on. The remainder of the initial data analysis was then completed (with further categories emerging organically during the process) before the next stage, where the clear hardware/software requirements and interaction types (based on [242]) the *physical properties* were temporarily separated off, and the complex, *operational properties* were recoded entirely by the group. Finally, all the categorisations and themes were cross-referenced with the original data and recoded where necessary to create multiple categorical levels, then proofed and the entire dataset digitised and checked for errors.

6.6.3 Results Presentation

Analysis of the participant sketches produced 506 items across three categories – *Requirements, Applications* and *Implications* – with multiple sub-categories. This section presents the findings of the approach in three sections: 1) We provide the most frequently occurring requirements for the dataset so as to give an overview of how people appear to think about shape-change; 2) We show a categorisation of the top level themes which enables a stacked requirements model; 3) We analyse individual findings and current works using this model to demonstrate the validity of the stack model.

6.7 Frequently Occurring Requirements

In total, 333 requirements were generated from the coding process, across 5 top level categories (Input, Output, Construction & Assembly, Control Systems, and Interactions & Behaviour). The following text contains the highest frequency sub-categories emerging from the analysis (in order of highest frequency), suggesting specific, perhaps essential, requirements for the design of shape-changing interfaces. Examples of the original data from each category are shown alongside the examples below (Figures 6.4-6.19). These categories also may form part of a larger, overarching grouping, but stood out within those groupings as specific areas of consideration.

Between Device Communication

Between device communication made up 28/333 requirements from the coding process. This finding suggests that our current devices will co-exist with their newer, physically dynamic counterparts. Concepts such as *up-scaling* of film or image from 2D to physical 3D are explored. Shape-change is also expected to communicate *between* devices e.g. Photo album for the blind (Figure 6.4). In this scenario, a flat photograph is sent to a shape-changing device and the technology is able to create a scene in physical 3D for the user to examine and enjoy. Other examples suggest that we build in ports such as USB in order to transfer "flat" data to our shape-changing technology, or we can transfer screen-based bar charts to shape-changing physically interactive maps (Figure 6.5). Between device communication is an essential part of the commercial adoption process, as most new technology is expensive when it first comes out, and not everybody can afford to purchase it, therefore backwards compatibility is essential.

Rigidity

Rigidity formed 12/333 requirements (note that this is different to the *strength* requirement). Varying the material qualities of a device was communicated by the *jamming* box, and was used in conjunction with other material categories to create behaviours in which a device or

Fig. 6.4 Between device communication — Physical photo album

Fig. 6.5 Between device communication — Shape-changing data map

application moves between states depending on context of use. This variation is especially important in generic devices where multiple uses are anticipated e.g. an interface which becomes a playable guitar (Figure 6.5). Fluid rigidity is also important when the device must be adapted and used in human-contact contexts, such as the concept of remote massage (Figure 6.6). The notion of varying rigidity was of great interest to many participants as this is the context of shape-change that appeals to the sense of true physical reconfiguration. The utility of being able to create many items from one item could revolutionise the way we purchase (e.g. a kitchen aide application that becomes many different utensils), and has implications for sustainability as well — reducing the demand on manufacturing and disappearing resources.

Strength

Strength as a specific feature was seen in 10/333 requirements. Shape-change is not only expected to display data, provide comfort or simulate environments, it is expected to be load-bearing in architectural contexts, move boulders with the tap of an application and

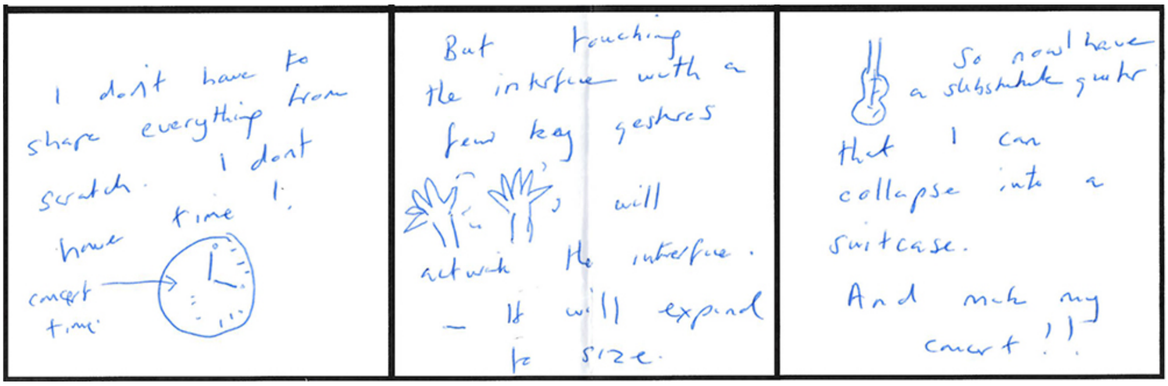

Fig. 6.6 Rigidity — Shape-changing travel guitar

Fig. 6.7 Rigidity — Shape-changing remote massage

support multiple bodies as a sofa, car, or podium. To this end, the materials and construction used to create shape-change must be physically robust (e.g. flooring, Figure 6.6). Strength also has links to the concept of rigidity, but the application of the device might need be also able to allow the user to perform feats of strength through the medium of the shape-changing interface (e.g. boulder moving application, Figure 6.7). The constant reconfiguration of shape-changing devices also means that the technology must endure repeated demands on its mechanism, so strength is an essential part of the development of shape-changing interfaces. To be able combine variable rigidity with strength is a major challenge for shape-change research, and will require advances in material properties that are not yet achievable.

Modularity

Modularity was seen in 9/333 requirements. Modularity not only refers to the ability of identical devices to communicate with each other (different from the between device communication with other devices mentioned above), but for parts of other types of material surface to be removed, used, and reintegrated, or for components of shape-change such as

Fig. 6.8 Strength — Shape-changing floor

Fig. 6.9 Strength — Boulder moving app

actuators to communicate with each other (e.g. toy blocks, Figure 6.10). In the case of the reconfigurable book (Figure 6.11), changing the sequence of the pages creates a new situation for the reader to enjoy, and the connectivity shared by the pages keeps the book as a whole device, no matter which direction they are put together in. Modularity also has implications for sharing parts of devices, in the context of play (as above), but also where individuals are asked to collaborate around one device. In a commercial sense, modularity means that the buyer can buy "add-ons" if they wish to extend their device, or swap out parts that are defunct, or no longer desired.

Portability

Portability made up 7/333 of the generated requirements. A high number of the original participant ideas (pre-coding) were categorised as portable object-scale devices, suggesting the need for novel batteries or charging methodologies such as using body movement (kinetic), solar, or wireless. In the requirements, portability emerged as a distinct theme both for tablet-style devices, but also wearables, where the ability to transport yourself is essential (e.g.

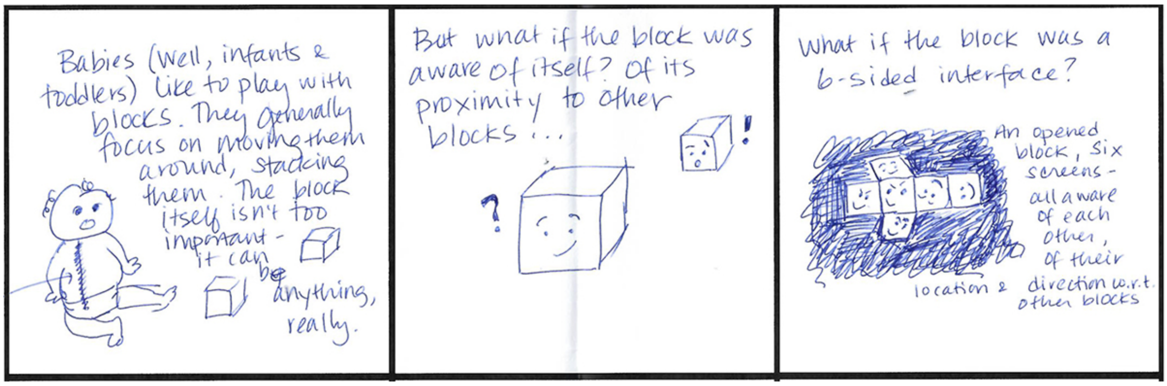

Fig. 6.10 Modularity — block toy

Fig. 6.11 Modularity — Reconfigurable book

armour, Figure 6.12). The latter has crossover with rigidity, as the armour must be lightweight but also strong enough to withstand attack. Portability is especially important in travel, where the user might want home comforts (such as large widescreen cinematic viewing, Figure 6.13) but is unable to currently utilise these things on mobile phones. The difficulty with devices that change in size is that the original mass cannot change, so shape-change must be lightweight, but extendable beyond its baseline state. Where travel abroad is intended, shape-changing devices may also cause security risks, as dangerous items might be hidden within reconfigurable devices.

Multi-sensory Input & Output

Multi-sensory input and output made up 7/333 requirements. Users are expecting interfaces to not only allow for deformation as an interaction technique, but for this technology to also employ the full range other human senses in their application and design, emphasising the organic potential of shape-change (e.g. drinkable computer, Figure 6.14). Multi-sensory applications for shape-change were seen by some participants as full-immersion experiences,

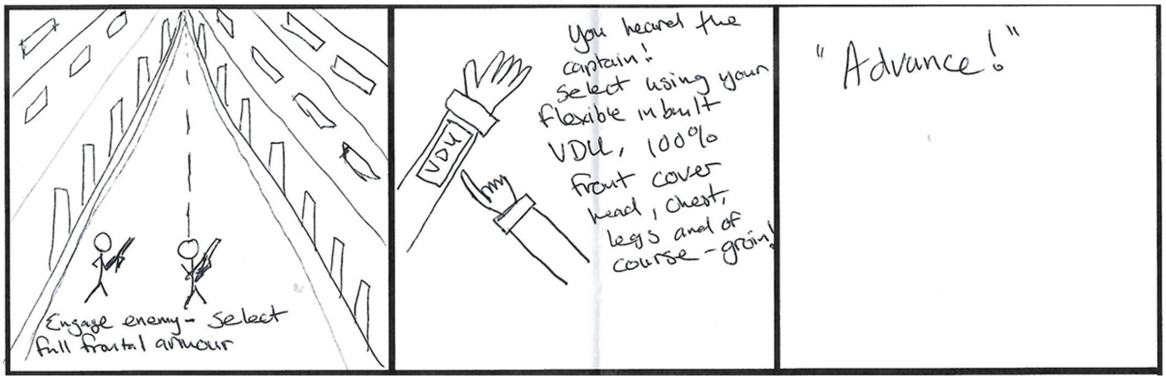

Fig. 6.12 Portability — Shape-changing armour

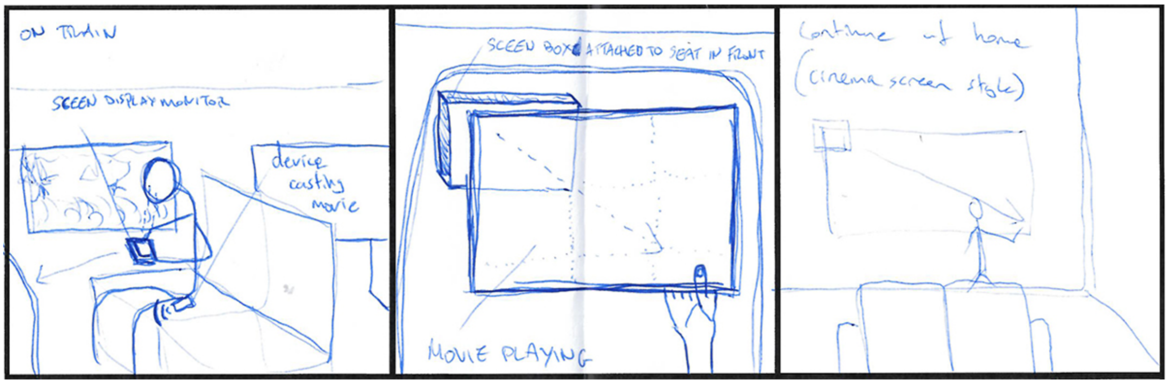

Fig. 6.13 Portability — Shape-changing tablet

where the user can be transported to another world or environment (e.g. terrain simulator, Figure 6.15). The link between the ability of shape-change to emulate organic matter (see next section) may be responsible for the desire for a more multi-sensory experience, as we see reality as a rich, tangible experience. Multi-sensory output already exists in 2D devices, but is usually limited to sight, sound or vibration.

Organic Movement

6/333 By attributing natural and humanistic qualities to the range of movement possible, shape-change crosses over into the territory of Artificial Intelligence, or the mimicking of life. Organic movement in shape-change has links to *comfort* and *sensitivity*, reflecting a positive computational behaviour (e.g. prosthetics, Figure 6.16). Prosthetic applications also link to device personalisation (see next section) where limbs can be manufactured in bulk, then link to the specific person, mimicking their own natural gait and bone structure. The fake "flowers" in Figure 6.17 have all the aesthetic qualities of real flowers, but can protect themselves against vandalism by retracting if threatened. The potential for replacing organic

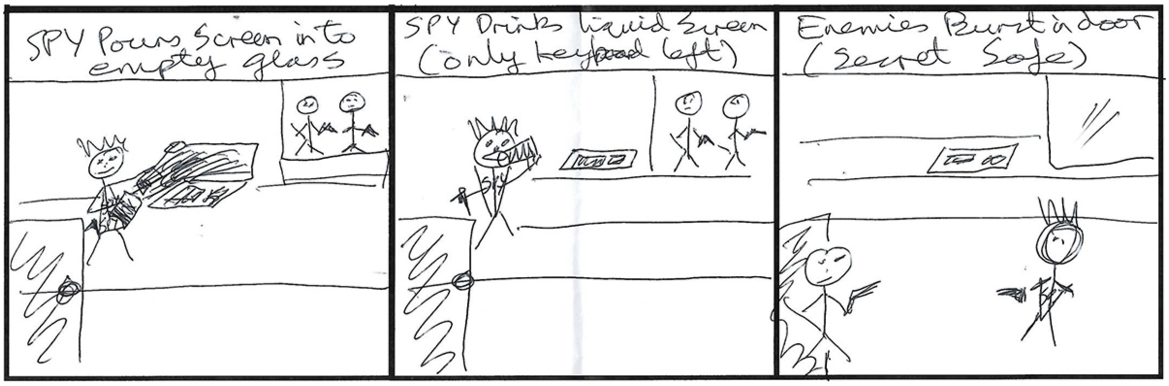

Fig. 6.14 Multi-sensory — Drinkable tablet computer

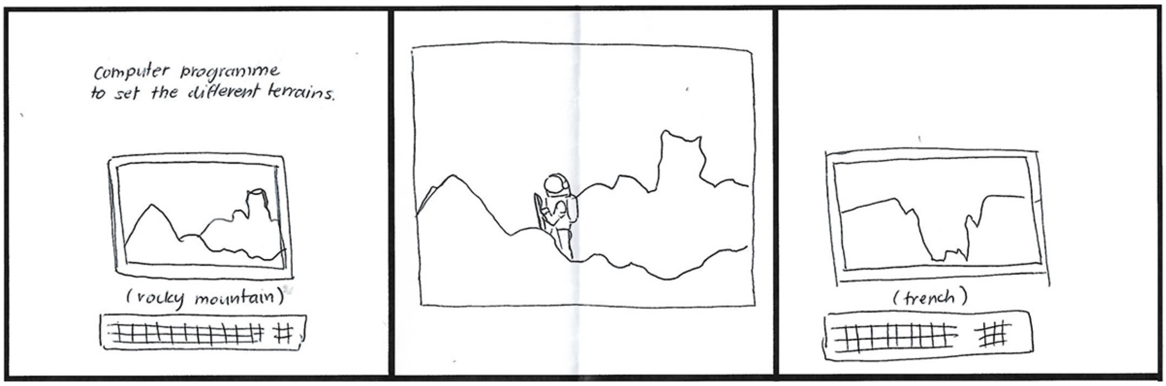

Fig. 6.15 Multi-sensory — Terrain simulator

matter with shape-change has multiple applications, such as using them in inhospitable environments to enhance living areas, or for people who cannot tend to gardens either due to time constraints or illness. However, there is also the potential for artificial life to “replace” life, for those who prefer convenience. Despite the potential negative implications of adding organic movement to computation, the addition of this behaviour will allow for richer, more intuitive experiences.

Device Personalisation

Device personalisation also made up 6/333 requirements. For planar, screen based devices, personalisation usually takes the form of a physical accessory such as a screen protector, or amendments to the display or applications. These amendments can also be attributed to shape-changing devices, but additionally we might control the shape, texture and even how it feels against our bodies (e.g. Shape-changing pillow, Figure 6.18). The shape-changing pillow also allows for temperature control, and variable firmness — suggesting that device personalisation also links in with multi-sensory output and rigidity. Shape-change and

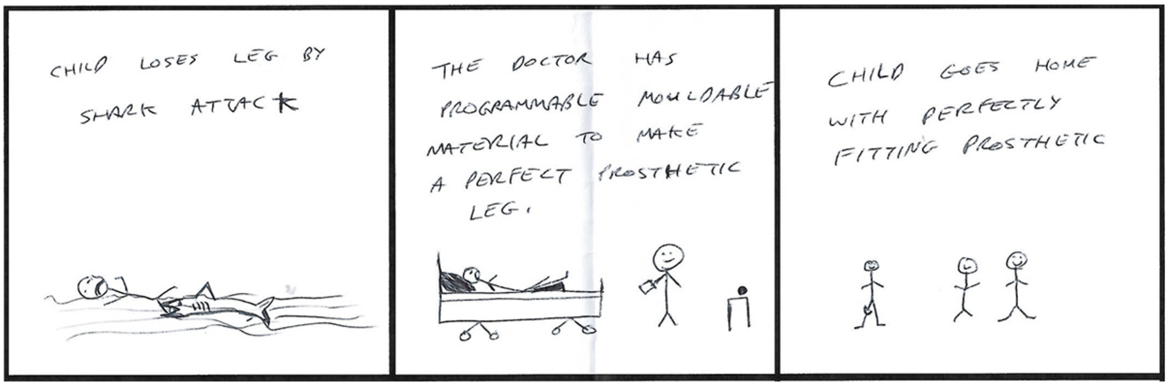

Fig. 6.16 Organic movement — Prosthetics

Fig. 6.17 Organic movement — Fake flowers

device personalisation are inextricably linked as if an item is able to reconfigure its output in multiple ways, it is more likely to suit multiple users, even if the same device is shared. In the case of the shape-changing office cubicle (Figure 6.19) this could relate to hot-desking, where one employee might have privacy preferences, but another might prefer the open plan environment. In a world where the user is the focus of design processes, the ability for a device to adapt is key to engaging with the widest possible audience.

6.8 Toward a Requirements Model

Our synthesis of requirements of shape-changing interfaces revealed five overarching categories, each at a different level of abstraction. Together, they logically fit into a stacked layer model (Figure B.5) describing levels of requirement and implementation in shape-changing interfaces, and differentiating between physical/operational characteristics. Under the top-level categories, we also identified eight sub-categories of requirements. The top-level

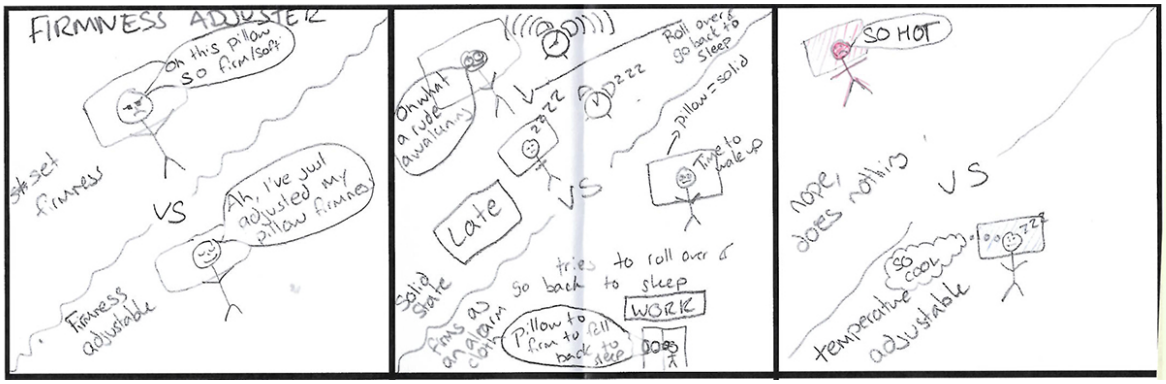

Fig. 6.18 Device personalisation — Pillow

Fig. 6.19 Device personalisation — Office cubicle

categories are outlined below alongside the *Implications* category which was major theme arising from the data but not directly connected to requirements.

6.8.1 Applications & Context

Sub-Themes — ***Entertainment; Augmented Living; Medical; Utensils & Tools; Research; Architecture; Infrastructure; Industry; Wearables; Education & Training; Generic (non-specific applications / multi-use device)***. *Applications* are defined as the specific use envisaged for the device (such as battle armour in Figure 6.4), and also actual “apps” (such as *Kitten Everywhere* in Figure 6.3). *Context* applies to where, when, what and why of using the application (e.g. in the home, during working hours, to provide remote massage, so as to travel less for work). Just over a fifth of the items produced during coding were application and context related (104). Often the context also dictates the application, and this is especially the case for generic, catch-all devices. Poupyrev et al. [236] reviewed potential uses for actuated, tangible interfaces ten years ago and suggested applications and areas based on the literature at that time, creating 5 categories: *Aesthetics; Information Communication;*

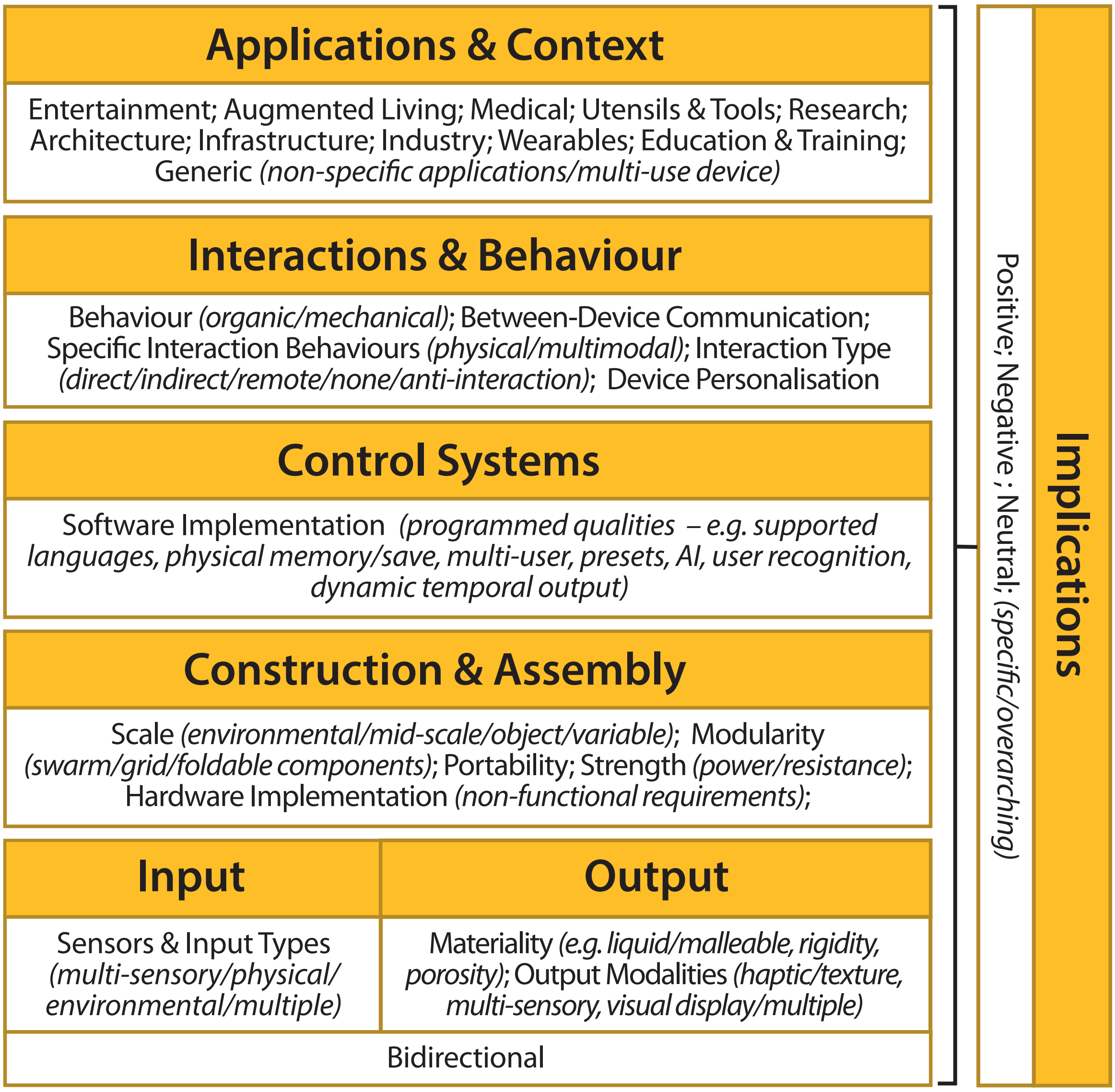

Fig. 6.20 A stacked model of implementation for shape-change

Mechanical Work; Controls — Data Consistency; and, *People to People Communication*. In the intervening 10 years however, the range of devices and applications has grown and the five categories remain relevant, but can be blended into the overarching contextual categories generated from more recent work e.g. the 10 themes found in Chapter 6. The application areas generated in our work can be mapped directly onto those found in the ideation study, (e.g. *Entertainment; Augmented Living; Medical; Utensils and Tools; Research; Architecture; Infrastructure; Industry; Wearables;* and *Education & Training*) with some exact application ideas being repeated such as responsive computational flowers, remote massage, or actuated storybooks for children. However we also propose here a wider *generic* category where the properties of the device or surface are used for multiple use-cases.

6.8.2 Interactions & Behaviour

Sub-Themes — *Behaviour (organic / mechanical); Between-Device Communication; Specific Interaction Behaviours (physical/ multimodal); Interaction Type (direct / indirect / remote / none / anti-interaction; Device Personalisation*. *Interaction* refers to the relationship the user has with the device and includes the type of interaction, e.g. specific behaviours identified during coding (*squash-to-delete*) but also the interaction the device has with other technology (*between device communication*). *Behaviour* encompasses software actions – what the device does (*switches between planar/3D output*). Eighty-four items fall into this category. Interaction for shape-changing interfaces is perhaps best classified by Rasmussen [242] who developed the framework of *Direct*, *Indirect* and *No Interaction*. The requirements for basic interaction in this model also offer other options: *anti-interaction* (the device actively avoids or puts off, interaction), encouraging interaction, and device-to-device communication, covering interaction between shape-changing devices and also between shape-change and current mobile devices and computers. In addition to these high level categories, the behavioural aspects of shape-change are explored with regards to how the device or surface acts or moves to initiate the programmed output, and whether you can personalise your device.

6.8.3 Control Systems

Sub-Themes — *Software Implementation (programmed qualities — e.g. supported languages, physical memory / save, multi-user, presets, AI, user recognition, dynamic temporal output)*. This layer covers the *Software Implementation* for the shape-changing device, outlining *how* the device puts the hardware features into use in terms of programmed, pre-set features and attributes. This is the least dense layer with 20 items, and includes requirements

<table>
<tr><th colspan="2">Applications & Context</th></tr>
<tr><td colspan="2">Artistic installation</td></tr>
<tr><th colspan="2">Interactions & Behaviour</th></tr>
<tr><td colspan="2">Dynamic reaction to changes in magnetic field, trembling/rotating, defying gravity, increase/decrease in size, organic movement, forms spikes along magnetic field lines</td></tr>
<tr><th colspan="2">Control systems</th></tr>
<tr><td colspan="2">Variable magnetic field</td></tr>
<tr><th colspan="2">Construction & Assembly</th></tr>
<tr><td colspan="2">Ferrofluid contained in plate, helical iron tower</td></tr>
<tr><th>Physical Input</th><th>Materiality/Output</th></tr>
<tr><td>Magnetic field, electromagnet</td><td>Liquid, dynamic shape, texture</td></tr>
</table>

Table 6.1 The stack model applied retrospectively to *Morpho-Tower* [156]

such as *physical shape-memory* and *must have user recognition software*. This can be thought of as the operating system for the shape-changing interface.

6.8.4 Construction & Assembly

Sub-Themes — *Scale (environmental / mid-scale / variable); Modularity (swarm / grid); Portability; Strength (power / resistance); Hardware Implementation (non-functional requirements)*. The physical requirements that are unrelated to sensory input and output are contained in this layer, it contains specific information on hardware and appearance of the device (such as size and portability) as well as non-functional requirements (*washable, lightweight*). It also contains the *Hardware Implementation* which includes information such as *integral camera* or *low latency over internet*. This layer contains over a third of the requirements and over a fifth of the total items.

6.8.5 Input & Output

Sub-Themes — *INPUT: Sensors/Input Types (multi-sensory / physical / environmental / multiple); OUTPUT: Materiality (e.g. liquid / malleable, rigidity, porosity); Output types (haptic / texture / multi-sensory / visual display / multiple); BIDIRECTIONAL*. This physical layer describes the input and output sensors utilised in shape-change, incorporating multi-sensory information in addition to visual and shape output, and specific information such as GPS, speed, texture, temperature and air pressure. Despite a tendency toward two-way multi-sensory interaction for generic shape-changing devices, bi-directionality was not seen as an essential quality for application specific shape-change, which contradicts previous work which suggests this is an overarching feature of tangible interfaces [34].

<table>
<tr><th colspan="2">Applications & Context</th></tr>
<tr><td colspan="2">Rapid-prototyping</td></tr>
<tr><th colspan="2">Interactions & Behaviour</th></tr>
<tr><td colspan="2">Variable topology, height changes in response to input, reconfigurable</td></tr>
<tr><th colspan="2">Control systems</th></tr>
<tr><td colspan="2">Javascript API, RGB value sampling,
supports HTML5, WebSocket-to-Serial bridge,
awareness of clip-position</td></tr>
<tr><th colspan="2">Construction & Assembly</th></tr>
<tr><td colspan="2">Stepper motor, LDRs, RGB LED, ATmega328p,
arduino, 3D printed base, circuit board, modular, portable,</td></tr>
<tr><th>Physical Input</th><th>Materiality/Output</th></tr>
<tr><td>Light sensor, gesture, force, data</td><td>Actuated pins, form, colour, light</td></tr>
</table>

Table 6.2 The stack model applied retrospectively to *ShapeClip* [102]

6.8.6 Implications

Sub-Themes — *Positive; Negative; Neutral*. Sixty-nine *implications* were generated from the context and use cases implied by the applications. An implication, in this format is a possible direct result or reaction deriving from the adoption and use of a shape-changing technology. The *Implications* were realised both from the application ideas that were generated, but also from specifics within the scenarios and diagrams that the participants created. They are categorised into: *Positive* (of benefit to the majority of the population, such as faster recovery from debilitating injury, improved well-being, and sustainability); *Neutral* (not clearly mapped onto a specific target group or are cannot be categorised, such as "more money for cinemas" or "consequences of shape-changing AI left to own decisions") and *Negative* (of negative benefit to the majority of the population, such as removing the need for labouring work, or reducing human contact). The possibility of AI taking jobs from people is already a hot topic, and shape-change could enable a far more obsolescence.

6.8.7 Using the Requirements Model

I envision that the requirements stack can be of use to several groups. For UCD researchers interested in shape-change, it can be used to ensure users produce requirements at all levels (this is important because the decisions at one layer effect the layers above and below). It could also help categorise and synthesis many requirements together, and also function as a tool to direct users to think about certain types/areas of requirements during early design phases. Designers could also use it to ensure they have considered input at all levels (as incorrect assumptions at one level can propagate), and technologists can use it to understand the impact of their technology decisions (bottom layers) on the upper layers. Within the existing framework of shape-change, it could also be used to assist researchers to better understand existing prototypes.

6.8.8 Applying the Requirements Model to Our Dataset

The breakdown of the overarching requirements and subcategories from the analysis can be seen in Figure 6.5. The chart shows a distribution across all types of requirements, with a slight bias toward the multi-sensory, bottom layer of the stack (input/output). Software implementation (*Control Systems*) is interestingly the most under-represented layer, perhaps due to the participant sample we used (non-technical background), but this omission could be addressed by asking users to specifically think within the stack system. Looking back at the participant data in relation to the stack model, we can re-analyse the diagrammatical and storyboard data and identify extra requirements that the user may not have explicitly thought about during the elaboration process. In the case of the *drinkable tablet – Figure 6.4* which we know has *variable rigidity* and is *safe to ingest* we might now return to the under-represented *software implementation* and extract the information that if it is a tablet then it also runs apps, and we can see from the sketch that it also supports a 2D planar screen, meaning it should be backward-compatible. The demonstrates that the stack model therefore can support directed thinking for the researchers by identifying specific areas and therefore eliciting further requirements. Observation of the participants during the study suggests that a mixture of top-down and bottom-up approach is used to create the data: either where an application idea was realised via consideration of what hardware would be required to achieve that goal, or beginning with an idea relating to a specific hardware type based on the white box prototypes, and moving up the stack for application and contextual design. For example, the *drinkable tablet* idea came directly from the liquid interface prototype, blended with the idea of variable rigidity (although in context of a science fiction story, the practical information remains relatable). Then the context in which this would be helpful was then realised (concealment of data) and a scenario drawn.

6.8.9 Applying the Requirements Model to Existing Prototypes

We applied a retrospective analysis of the stack model to two existing prototypes to confirm the layers fit with current research, and to get an idea of where build focus is. Kodama's ferrofluid works [156] are born out of the desire to emulate organic movement and create computational artworks, therefore the focus in the stack is on the application, and the interactive/behavioural qualities: a top-down perspective (Table 6.1). Conversely, for *ShapeClip* [102] the focus was on the hardware: building a bidirectional actuation device that was low cost, modular and easy to use (Table 6.2). This suggests a focus on the lower two layers of the stack (bottom-up), with omissions in detailing interaction behaviours. Both papers refer to future hardware improvements, applications or use-cases (e.g. *advertising, sound equaliser*; *third skin*) but do not consider the longer-term implications for their projects (this loosely supports the notion that this research is very technology driven, and not focused on long term adoption [159]). This is helpful as it identifies the requirements focus for different types of shape-change, and where researchers have concentrated their efforts. It also demonstrates the difference between *application* (*Morpho Tower*) and *utility* (*ShapeClip*) focused work.

6.8.10 Limitations and Additions to the Requirements Model

During the coding process, it became clear in that the aesthetic and emotional aspects of shape-change were largely overlooked, relegated to resulting from, or being incidental to the device or application itself. Participants tended to focus on the practical aspects of shape-change, which usually started with an application idea (top of the stack) rather than a hardware type, although some items (e.g. shape-changing, responsive flowers) were built with aesthetics in mind, and the non-functional and functional requirements were built around that notion. The lack of focus on aesthetics may suggest two things: That design for aesthetically pleasing objects is a given; or that the desire and design for aesthetics occurs further down the stack — for example, comfort and beauty may be built into the construction phases of implementation (which makes sense if the purpose of the device is as a furniture provider). In terms of emotional content or outputs, these are more likely be an implication of, or bound up in, the type of application (such as a virtual physical pet to provide company). However, Kwak et al. [161] noted that the *behaviour* of his prototypes was implied by the way in which they were actuated, and gave rise to emotional content e.g. *stubbornness* or feeling *hopeful*. This links to the *Interactions & Behaviour* category within the stack, within which a number of the behavioural themes related to organic movement, meaning emotions would be built in after the software implementation cycle. The stack model could thus be adapted to add a subcategory of *emotional content*, bound up in the design of organic movement (one of the minor themes from the coding process), whereas aesthetics would become a category within *Construction & Assembly*.

6.9 Discussion

The stack model and analysis suggests that the methodology has the potential to expand our understanding of how these devices will work, and applies an organisational structure to the development process; whereas the implications generated can stimulate discussion about future adoption of physically dynamic interfaces. Our adapted UCD methods fulfil their intended purpose: we communicated complex, novel technology to non-expert end-users who were able to generate detailed outputs from which researchers could elicit requirements. The commonly occurring sub-themes also elicited novel requirements for shape-change that (to our knowledge) have not been documented (e.g. portability, between-device communication, backwards compatiblity). Between device communication *within* shape-change is not a new concept, but these requirements also consider integration of shape-changing interfaces into existing technological structure — e.g. having an integrated USB port, or sending planar data to be upscaled. Device personalisation has been addressed in shape-change, but only in attribution of types of actuation to different mobile phone notifications [226], when personalisation could potentially also involve texture, form, complex organic movement and multi-sensory experiences — that shape-change should be multi-sensory is another under-explored facet, especially given that the only essential output is change in form. Finally, although many of the requirements are pre-existing in other technology development processes, the way the stack model addresses these requirements, and how the extra dimensions of movement, organic behaviours (and so on) are integrated makes the result specific to the application of shape-changing technology. The fact that this study has produced similarities with other work also means that we (as researchers) are in a good place to begin formalising process and practice for shape-change — requirements generation needed to be approached in a way that was tailored to shape-change, and I believe the process has been appropriately managed.

6.9.1 Methodological Reflection

At present, this approach cannot be viewed as an exact fit with user-centred design, as shape-changing interfaces cannot be shoehorned into a process that has been created for familiar technologies. Also, due to the large range of possible materials, interaction and applications, I did not apply our approach to a specific scenario or hardware type (e.g. design a shape-changing interface for mobile gaming / design a music application for a malleable device). This may be seen as a limitation, or an over-complication of the process, but given the proof-of-concept nature of our approach, I felt that choosing one application or problem to solve would ask the researcher to arbitrarily define that issue, and bias the process toward one kind of shape-change. By asking users to define their own problem and solution, we explore the nature of the process in way that still provides focus. A further attempt to limit bias was employed during coding. In addition to the researchers that were actively involved in data collection, another member of the project team, and an unrelated practitioner were asked to collaborate in the thematic analysis and requirements generation, and then during the categorisation and re-categorisation process. Multiple-person coding is also of value to question, resolve conflicts, and work collaboratively to analyse data.

The introduction and ideation stage of the process had a mixed evaluation from users. Whilst most found the videos helpful, a couple found it difficult to relate what they had seen to the boxes which did not have a self-actuation component. Others became quite excited by the boxes, choosing to have one next to them while they thought so they could return to a concept, or taking part of the material (malleable) with them to work through interactions. The *jamming* prototype box was seen as the most engaging, as the material concept was novel and the transition between states illustrated how a shape-changing interface might move between material properties, but it also worked because it was in context of the other boxes. Another observation was one of the *hedonic* qualities of material interaction [242], some participants enjoyed simply to touch the materials, and focused upon how the pleasant sensations could be utilised in an application. Upon reflection, removal of either of the two stages would be detrimental to the process, as establishing technological context sets the scene and explains *what*, but providing tangible, low-fidelity examples encourages participants to ask questions and suggest improvements about *how* without focusing on single use-cases.

The sketching and storyboarding process was an ambitious output to ask of non-designers, but allowed the contextualisation of ideas in an easily understandable, visual output. Drawing is something we all do as children, but as we grow older many people stop for various reasons [35]. Several participants expressed anxiety during the task, but were reassured and asked to focus on the idea behind the diagram or story rather than producing high quality artwork. In total, all but two participants produced sketched output, and those that did not draw still produced detailed notes on their device. Asking participants to sketch even had a positive effect, e.g. "*I haven't drawn in years, I had forgotten how much fun it was*", with some participants spending up to an hour producing detailed artwork. Given the success in both informing and engaging with end-users for shape-change, I propose to use and validate the "Videos, Boxes & Sketches" process in the beginning stages of a new research project. The technique here could be directly applied using a single white box prototype, and specific application. There is also scope to explore the next stages of developing shape-changing interfaces in relation to user-centred design practice (functional prototype development / interface design). The value of applying UCD-style processes before full adoption might seem premature, but I argue that consolidating these processes beforehand can future-proof the field, and avoid timely, or possibly costly mistakes in the early stages of adoption. User Centred Design arrived late in the evolution of current technological products, so I am advocating structure, organisation and, most of all, rigour in the adoption of this practise to shape-changing interfaces.

6.9.2 Implications for Adoption?

As well as approaching user-centred design from the standpoint of shape-changing interfaces, I am also attempting to consolidate research in this area, and encourage the organised advancement of specific interfaces. HCI as a field has been accused of an unfocused attitude toward research, rarely developing topics so that they enter the mainstream [159], or criticised for focusing on short-term utility [187], so by offering up a methodology to engage with possible end users and suggest constructive avenues to pursue, I attempt to counteract this view. As an extension to this, some researchers suggest reaching even further into the future to explore not only the adoption of technology, but the implications of that adoption [185] — how might domesticating technology affect people in both positive and negative ways? An unexpected but welcome side effect of the requirements-gathering process was the generation of implications surrounding the adoption of shape-change. This allows researchers to focus on potentially interesting build-concepts but to also ask *should we*?

6.9.3 One Device to Rule Them All

Amongst the ideas generated were a number of single-use shape-changing devices, that is, they did not support other applications (program or use-based). Such ideas are called *information appliances* [218] and in these cases were often integrated into an existing mechanical structure (bicycle/prosthetic limb). The argument put forward by Norman is that, in contrast, if you design generic, multi-use devices then they become ever more complex as they must work for everyone, all the time. This is especially true in this context: a single use shape-changing interface can utilise one materiality, one set of behaviours and be personalised to fulfil a particular purpose — but shape-change in its very nature transcends even the ubiquity of the Personal Computer in that the ideal of it tends towards generic, multi-materiality, multi-purpose applications. If it can *become* anything, it can *do* anything, and how one begins to design for that future could be anybody's guess.

6.10 Conclusion

Shape-changing interfaces are complex, emergent technologies for which it is difficult to apply pre-existing design and build processes — to address this, I proposed and tested a UCD-based approach utilising non-expert users in generating requirements for these devices.

This process produced multiple levels of requirements which form a stack model of shape-changing interfaces and can be applied to current and future work in platform development. The findings demonstrate new ways of approaching the design and development for shape-changing interfaces and support the continuing development of highly organic, variable computational experiences. Finally, this work also considers not only the practicalities of adoption, but the long term implications of shape-change.

Chapter 7

Discussion & Conclusion

7.1 Chapter Summary

Shape-changing interfaces have the potential to transform the way we interact with technology. Over the past four years I have investigated how we can design with, and for, this technology, situated in the use of sketching as a form of *dialogue*, *ideation* and *elaboration* for both researcher and potential end user. This Chapter concludes my thesis by revisiting the aims and objectives laid out in Chapter 1, and confirming the contributions of this work. Finally, I review the discussion points from Chapters 2-6 in context of current and future practice.

7.2 Revisiting Aims & Objectives

The *Introduction* states 5 research objectives for this work. Below, I describe how the work contained within Chapters 2-6 completes these objectives.

1. To understand the current state-of-the art in shape-changing interface research

In Chapter 2, I provided a comprehensive literature review, analysis and classification of shape-changing prototypes from which I placed my work into context within the field. I identified 8 categories of prototype and gaps in formal processes for design and development, as well as a gaps in the literature for themes such as ethics and safety.

2. To understand how sketching is currently used as a methodology in HCI research, and therefore how it can be applied to shape-changing interfaces

In Chapter 3, I used a systematic search strategy in order to detail the history of sketching in HCI, and classify current types of sketching usage into process or application oriented sketching. I identified 8 categories of sketching within these themes, 3 of which were applicable to developing into a sketching practice for shape-change.

3. To use selected methods to discover how sketching can form part of a "Pre-UCD" process for shape-change research

In Chapter 4, I identified which types of sketching practice in HCI were of most use for examining novel technology (specifically shape-change) and developed a user study to test *ideation* in sketching for shape-changing interfaces. These categories of use were *ideation*, *dialogue* and *elaboration* — all can be used in early stage design processes and to bridge the gap between researcher and user. To begin the process, I focused on ideation, and how this could be used to elicit application ideas from a non-expert, public audience.

4. To use sketching to form a bridge between researchers and potential end-users in order to create dialogue, directions and guidelines to advance research in shape-change

User-generated outputs were utilised as a sketched *dialogue* with which I was able to create elaborated sketched diagrams and subsequent requirements in Chapter 5. The themes from the initial stage were developed into user-scenarios which then formed part of a new dialogue between researcher and user, generating high level themes and implications for shape-change. The final stage showed that as the level of *elaboration* increases, so does the quality of the inferences and therefore requirements and tangible research outputs generated.

5. To use sketching in the design and development of shape-changing interfaces to produce tangible outputs for the field (e.g. requirements, models for development)

In Chapter 6, insights gathered from the previous chapters were consolidated to create a novel user study with which to generate detailed and wide-ranging applications, and also requirements for shape-change. These outputs were coded to create a stacked model for shape-change interface research which can be applied retrospectively to published work, but also used moving forward, to situate and inform the design and development of shape-changing interfaces.

Figure 7.1 provides an additional visual overview of the process and themes surrounding this text, and shows the developing dialogue between types of sketching practice and user/researcher.

7.2.1 Applicability of Sketched Research Output to Advancing the Field of Shape-Change

Chapters 3 laid groundwork for utilising sketching methods in shape-change research by addressing not only how sketching is used in HCI as a whole field, but also how it is an accessible methodology for novices in HCI, and outlined existing sketching practice in HCI with experienced researchers. The knowledge in this chapter was subsequently successfully applied to studies with non-expert potential end-users (Chapters 4 and 6), and formed part of a shared practice and continuing dialogue with between researcher and user (Chapter 5). The methodologies contained here show how sketching can be used to elicit and shape information pertaining to applications, requirements, limitations and implications for the future design and development of shape-changing interfaces. Additionally, Chapters 2 and 6 produced meaningful frameworks which researchers can utilise to design and build shape-changing interfaces for specific hardware or application needs (classification & analysis of prototypes; stack model for shape-change). Finally, the discussion contained within this chapter consolidates the findings of the preceding work and outlines the next steps for formalising User-Centred Design for shape-changing interfaces, in order to precipitate the commercialisation and adoption of these devices. The applicable contributions to the first research question are outlined in section 2.3.

7.2.2 Sketching Creates Engagement Opportunities for Researchers and Potential End-Users

Engagement is more difficult to measure by success criteria, as it has no specific tangible output, however Chapter 4 demonstrated how the lack of public facing user studies in HCI is an unnecessary omission. Members of the public were eager to learn more about the research and get involved, and they also generated useful data for analysis. The ideation study was subsequently published and created discussion within the research community at a high-profile conference. User-generated ideation data was subsequently utilised for subjective research practice (Chapter 5), and dialogue was opened with a new participant group made up of researchers and non-expert potential end-users — the meaningful insights produced show the level of engagement with both groups. Chapter 6 again showed that there

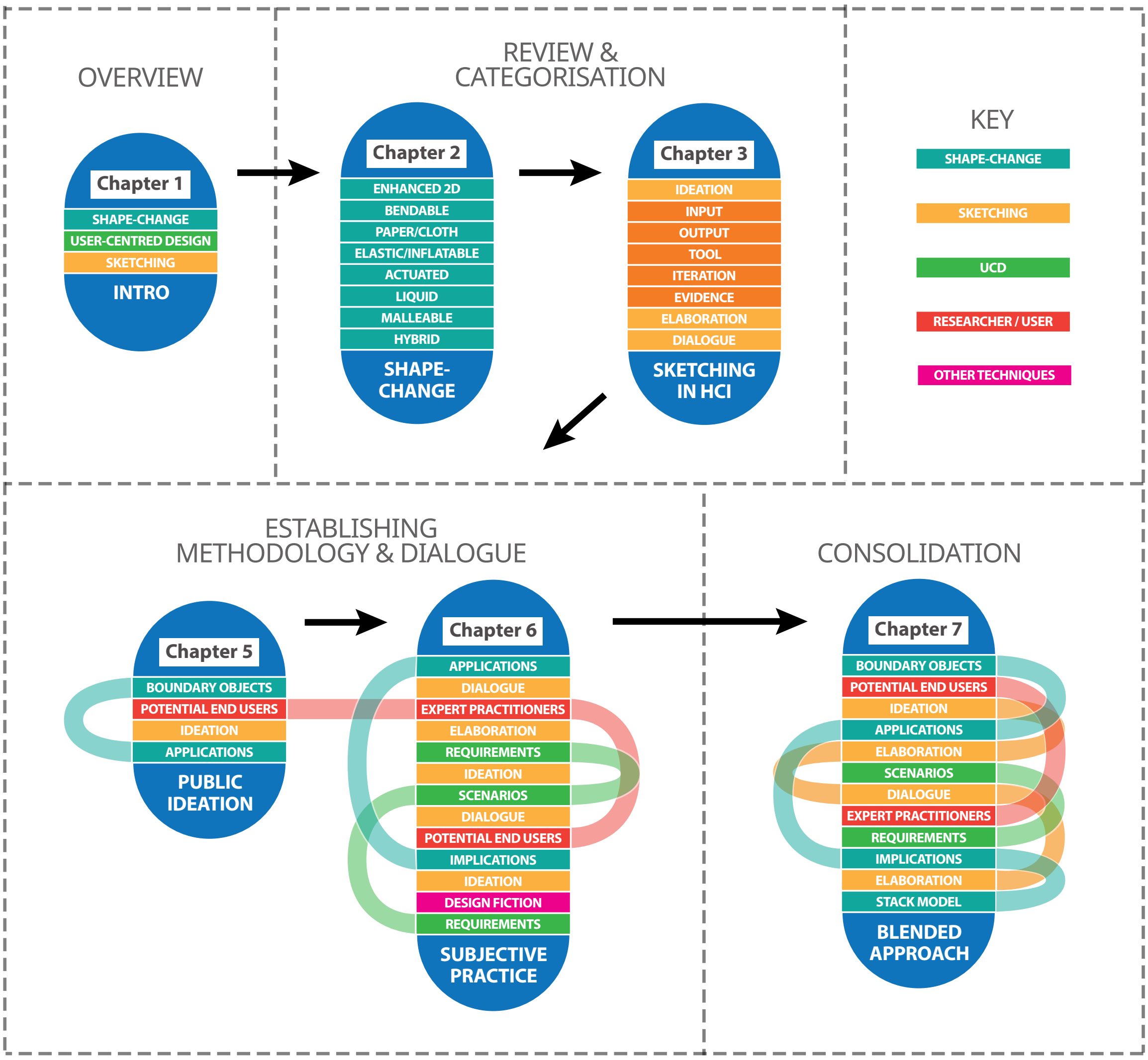

Fig. 7.1 Road-map of the thesis showing connections and dialogue between stages

is a potential engageable user-base out-with the current model (internal staff and students), with participants spending up to 1.5 hours at a time to complete one unpaid study session. The high numbers of participants (n=74 in Chapter 4; n=50 in Chapter 6) also showed that more detailed insights can be gained with larger participant pools, and provide researchers with valuable data for analysis. Finally, unexpected benefits came from engagement via sketching, as participants grew in confidence at producing visuals, and enjoyed the process, having often not sketched since school. The success of all studies in this thesis should encourage the use of sketching as a form of dialogue — and therefore engagement — between researcher and user, and in HCI as a whole.

7.3 Academic Contributions

Each chapter contained within this thesis makes a novel contribution to the field of either shape-changing interfaces or sketching in HCI. **Chapter 2** contains the first published comprehensive review of shape-changing interface prototypes in HCI (and beyond), alongside a unique classification concept, where shape-change is categorised not only by materiality, but analysed for other attributes relating to hardware, interaction and temporality. Specifically, current functional prototypes can be categorised within the following headings: *Enhanced 2D; Bendable; Paper/Cloth; Elastic/Inflatable; Actuated; Liquid; Malleable;* and, *Hybrid*. These headings can be used as part of a top-down (desired application mapped onto most appropriate hardware) or bottom-up (hardware looking for most appropriate applications) process for designing with shape-change. The full text of this chapter has been published (*Issue 51, Article 2; ACM Computing Surveys, 2018*).

Chapter 3 started a new line of enquiry to investigate how sketching is, and has currently been, used in HCI. To achieve this we conducted the first systematic review of sketching in HCI since its inception in 1964 [294]. The trends seen in the papers published suggest that there was a surge in interest for sketch-based research between 2008-2011, but that there has been a reduction in the number of publications relating to sketching since that time. The review process allowed us to discern 8 categories of sketching in HCI: *Ideation; Input; Output; Iteration; Tool; Elaboration; Evidence;* and, *Dialogue*; and also to propose what the next areas of interest for sketching and HCI might be (including for shape-changing interfaces). (*Associated publication currently under review*).

Chapter 5 offers a novel methodology for engaging users with technology, and also presents a categorisation of possible application areas for shape-change: *Entertainment; Augmented Living; Medical; Utensils & Tools; Research; Architecture; Infrastructure; Industry; Wearables;* and, *Education & Training*. We also learned that participants thought about shape-change in a situated manner – that is, the application ideas fit into their pre-existing notions of the world and did not span into unknown futures. The links between application ideas and existing research in shape-change can also be seen as a form of validation for the approach in this work (also seen in Chapter 6), and the ways in which participants used visual narrative to describe their ideas also informed the subjective practice in Chapter 5. The full text of this chapter has been published (*Proceedings of ACM Interactive Tabletop Surfaces (now Interactive Surfaces and Spaces), 2015*).

Chapter 5 entailed an extensive researcher-led investigation following the categories and themes generated by the participants in Chapter 4 – this connection forms the *dialogue* between researcher and user, and this dialogue is continued in the second part of Chapter 5 (see linkages in Figure 7.1). The contributions from the three parts of this chapter are: An sketched and annotated *elaboration* of the ideas and images generated by participants in Chapter 4 based around the theme of security, ethics and safety (also linked to the discussion in Chapter 2); a study of sketched visual narratives in comics format with which to gauge acceptability and implications for specific shape-changing applications based on existing research; and, an elaboration of the gaming in shape-change concept in the form of a sketched and written *design fiction* diagetic prototype. The latter investigation drew parallels with Chapter 4 in that the requirements generated from the diagetic prototype also mapped onto existing research (e.g. tool-based interaction), whereas part 2 also demonstrated the validity of using comics as a form of researcher engagement for technical practice. The overall contribution of this chapter is to demonstrate how sketching relates to critical and investigative thinking, can be used as a dialogue between user and researcher, and how we might generate requirements from such practice at a research level. Part 3 of this chapter has been published in full (*The Design Journal, 2017*).

The final chapter (**Chapter 6**) consolidates the work from chapters 2-5 in a large scale user study intended to generate requirements for shape-changing interfaces. The novel methodology borrows from UCD, but applies the techniques in such a way that complex technical concepts can be communicated to and understood by non-expert potential end users. The first stage of the process repeats the *Ideation* methodology from Chapter 4, but adapts the boundary objects so that the full range of shape-change is accessible (videos, white-box prototypes). The white-box prototypes (based on the categories from Chapter 2) offer a tangible way of thinking about potential applications and scenarios, and the resulting ideation was more insightful and detailed. The contributions of this final study are: a novel methodology for eliciting requirements for shape-changing interfaces; and, a stack model derived from the requirements, behaviours, interactions and implications gathered from coding the participant output. A further item of interest is that the concept of a single, multi-purpose device was proposed, and this links into the theme of sustainability from Chapter 4. (*Associated publication currently under review*).

In summary, the contributions within this thesis span theory, methodology, novel data, applications and suggestions for the future of the field of shape-changing interfaces. The intention being that these contributions can be used by researcher to enhance and elucidate their knowledge of both the hardware and application of this complex technology.

7.4 Other Contributions

Alongside the academic contributions of this thesis, there were unexpected benefits to conducting the research. The public ideation study (Chapter 4) acted as a form of public outreach and raised the profile of the university, as well as giving members of the public the opportunity to feel like they were a valued part of the research process. This value also extended to the promotion of sketching practice within the studies – nearly all participants did not draw regularly, and were happy to have rekindled a relationship with an old skill, and many gained confidence in their draughtsmanship. Many on the non-expert user base were also excited to learn about shape-changing interfaces and where computation is heading, and felt like they gained value from learning about the field. The contribution inherent in these kinds of studies is that it reduces the gap between researcher and user, making it easier to form dialogue of all kinds, and create an atmosphere of shared practice.

On the research side, the promotion of sketching methodologies also had benefit to those already working within HCI from a tutorial I co-taught at *NordiCHI*, with attendees valuing the time they spent learning about mark making, ideation and narrative. A later workshop at *DIS2017* took this shared practice a stage further by engaging with current practitioners who already use sketching in research and strengthening community ties. The community building is also not limited to sketching as a focus, as I attended a workshop on sharing perspectives on shape-changing interfaces [290], and utilised sketching to create a visual record of the event (Figure 7.2).

Finally, the anonymous yet highly visual nature of these studies means that we are able to make participant data available as a data-set online, so that further insights may be gained by researchers interested in both the methodology, and shape-change as a whole.

7.5 Major Insights & Themes

By analysing the discussion points from Chapters 2–6 I was able to identify potential items for inclusion for the formation of a user-centred approach for the design and development of shape-changing interfaces. The main theme that runs alongside the sketching for shape-change focus, is that of the applicable insights for re-imagining user-centred design within the context of these novel interfaces. Additional points of interest include the potential for continued use of sketching in shape-change research; sustainability; security, ethics and safety; and, most importantly — the implications of our work, and the eventual adoption of shape-changing interfaces.

Fig. 7.2 Sketchnote record of discussions at workshop on sharing perspectives on shape-changing interfaces

7.5.1 Toward a Formal Practice of UCD for Shape-Change

I can divide the insights into two parts: 1) *Pre-UCD* — The pre-emptive development of techniques, models and methods for shape-changing hardware and applications in order to "future proof" the field against negative outcomes — for example, avoid a shape-change example of *The Case of the Killer Robot* from happening [56]; and, 2) *Post-UCD* — Hardware has been commercialised and adopted, formal UCD processes are in place for shape-changing interfaces. This thesis is firmly based in the *Pre-UCD* stage, focusing on defining practice in increments utilising the methods we currently have available (there are no shape-changing interfaces to buy and test). We imagine that the *Post-UCD* stage will utilise existing UCD and interface design methods (e.g. personas, usability testing), with additional considerations for the nature of shape-change (safety, emotional content, temporality in the context of form, perceptual considerations). We need to reimagine the interface as not just a tablet or computer (for which there are adequate design processes in place) but as a multi-modal, multi-sensory experience, for which there are no guidelines in place.

Top Down, or Bottom Up?

Chapter 2 asks whether applications will drive the technology, or whether the technology will drive or limit the applications? Currently shape-change sees both sides of this process, in design engagements with low fidelity prototypes or techniques [161, 243], or with the development of functioning hardware prototypes onto which particular applications can be mapped [206, 289]. Rarely is shape-change co-created [57], with continuing dialogue and support of the end-user. If the range of hardware continues to be material dependent however, then the *top-down* or *bottom-up* approach may find favour. This idea can also be seen as platform focused or application focused (see Tables 6.1 & 6.2) and can be linked to the stack model (Figure 6.5) in Chapter 6.

Due to the impracticality of building multiple shape-changing interfaces for usability testing for the top-down method, and given the unlikelihood of the "one device to rule them all" in the near future, we might predict that low-fidelity prototyping will follow the proposal in Chapter 6, with tangible, white box prototypes. These would allow for interactions to be modelled alongside projected visual output, in a low cost manner, meaning mistakes in implementation can be avoided without an overly time consuming build process. This fits in with Jansen et al.'s theory that we must use *proxy technologies* as current technology levels do not allow us to conduct accurate studies. In the future, if multi-hardware, commercially available devices become available, it may be possible to utilise these for evaluation, but modelling for multiple form-outputs is complex and time consuming (see Figure 7.3). Another solution for modelling these complex interactions might be *Wizard of Oz* (Chapter 4), where interactions are simulated instead of programmed. Regardless, users felt that the most important aspect to communicate shape-change using tangible interventions was that of *movement* (e.g. the *jamming* interface in Chapter 6), so whichever method is ultimately chosen, it must perform an detailed approximation of the final interaction.

Perceptual Challenges for Shape-Change

On planar displays the issue of perception is rarely considered, unless the device is not back-lit, or there are accessibility issues (e.g. blindness, colour blindness). This issue comes into context however when collaborative tabletop work is examined – meaning multiple users must view the same information from different viewpoints [101, 345]. Perception in shape-change has only been considered in brief [33], but also relates to temporal factors in addition to the angle of viewing [326]. Usability testing for shape-change must consider these aspects when designing *visual+form* output. In order to do this we might consider borrowing heavily from both graphics research and the psychology of perception. As well as orientation there are considerations for depth (both visual and touch) [247], and the potential mis-match between visual and form output [72, 225]. Light levels and sources of illumination may also affect output [25, 309], and whilst existing research can deal with static, and image movement, when we add form movement and temporal aspects the output becomes increasingly complex. Perception is not the only challenge for developing a UCD practice for shape-change however – there are other multi-modal outputs at play.

Additional Modalities for the Design of Shape-Changing Interfaces

As well as the obvious physical parameters of shape-changing interfaces, my investigations have outlined the importance of emotionality, temporality (visual/tangible), personality (self-actuated objects can be seen as having the qualities of a living thing [228]), and, the limitation or control of all of these things. The most basic idea of current UCD practice examines the relationship between the interaction gestalt and the visual output. For shape-change we might consider UCD as "multi-track" with each type of interaction requiring a separate modelling strategy, gradually building up a realistic prototype as part of a cycle for final, consolidated user evaluation (Figure 7.3). This ideal of computing is a far cry from Norman's *Information Appliances* if customisation works on an emotional, physical and behavioural level.

Another item to consider is that we must design within certain limits, not only to the thresholds of human perception, but also within limits of depth and force [247], as well as physical size [130] – *fat-finger* problem in mobile HCI [273] may become a *fat-hand*

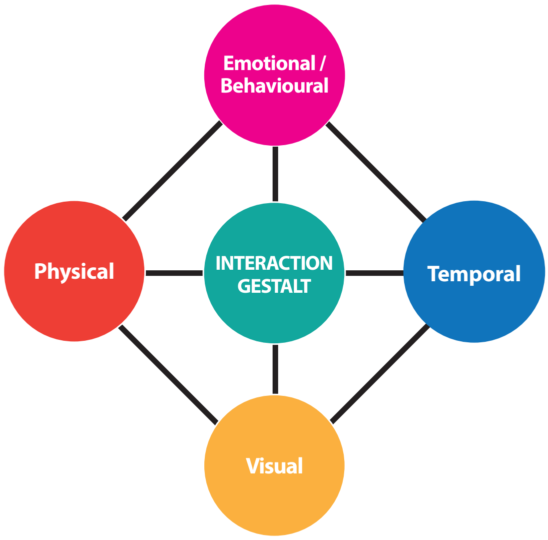

Fig. 7.3 Additional modalites for the cyclical development of shape-changing interfaces within a novel UCD approach

problem. There are also thresholds in human emotion, what might be acceptable for on person, might go completely unnoticed by someone with autistic spectrum disorder, for example. In this case, the adage of designing for the *least able* might ensure usability for all.

7.5.2 Integrating Sketching & Shape-Change

This work considered only three of categories of sketching in HCI (Chapter 3) for inclusion within the methodology, due to their usefulness in process-oriented practice (ideation, elaboration, and dialogue). These three methodologies of sketching worked in a cyclical manner for our purposes, enabling effective communication between researcher and user, and acting as an intervention to link design to shape-change. Now I reach the end of that process however, I can return to those categories that remained unused to see if they might fit into future practice.

Overall, I have used sketching as a *tool* in order to achieve our desired outcomes, and provided the reader with *evidence* of our process by including both researcher and user sketches. I predict that iterative sketching for shape-change will expand from it's current form [243], when hardware becomes open source, or more accessible to adaptation, as this is one of the most popular forms of design sketching [3] — however, sketching as *input* and *output* remains within the domain of computational interaction or artistic practice.

If we change our perspective and consider the potential of computational applications of sketching however, we may find further common ground between practice and the design of shape-changing interfaces. It is not untenable to consider drawing *ON* shape-changing interfaces with finger or tool (Chapter 5) [41, 197], or *with* shape-changing interfaces [61] – shape-change and sketching can be linked in non-procedural ways, e.g. sketched *input*. Existing work on sketching as input may also have connotations for UCD though – if we can sketch 2D items as input for conversion to 3D [117], or build up physical 3D shapes with sketches [262], then we may be able to further integrate sketching with designing for shape-change. The addition input of movement (animation) via sketched input [308] or turning sketches into animated figures themselves [42] in combination with the former means that we may be able to model complex 3D interactions solely via sketching. If creating tangible sketches is feasible, then this method could also be applied to scenarios, adding form or movement, to create a higher fidelity communication experience.

7.5.3 Sustainability, Safety, & Implications for Adoption

Concurrent themes within this thesis revolve around not only the precipitation and propagation of shape-changing technology in research, and ultimately real user-contexts, but with the implications surrounding this kind of ground-breaking interface — good and bad. Chapter 6 outlines a variety of user-gathered perspectives, but major implications emerged during the earlier stages of this work. For example, ethics, safety and security were proposed as items for investigating in Chapter 2, and this was picked up again in Chapter 5.1 — both IoT and organic, tangible user interfaces are open to corruption, and the effects are likely to be much worse than simple data-breaches. Conversely, as sustainability reaches the fore in HCI research, the prospect of a "one device" seems attractive, if it means that multiple devices for different contexts do not have to be purchased — although this kind of development is still open to the corruption of designed, planned obsolescence.

HCI can often be guilty of incremental advances that rarely reach commercialisation and adoption by end-users [159], but considering the *implications* of shape-change has been something that has emerged during each iteration of our process. During the birth of the personal computer, this kind of forward thinking was not realised, such was the desire for technological advancement, but we live in a wiser world, with access to hindsight and an arsenal of novel design techniques such as design fiction [285]. To make sense of something that does not exist, to fit it into the world around us, we can use speculative, creative techniques to help build our vision.

7.6 Next Steps

I do not claim to have solved the design conundrum for shape-change, but I envisage that these findings will enable researchers to address their work with more context and insight. There remain several accessible next steps for this work to take it forward toward a practice of User Centred Design for shape-change: Firstly, by applying the stack model in a design and build process for a novel hardware or application in the early stages of development, as suggested in Chapter 6; Secondly by examining other stages of the UCD process and seeing how these could be adapted for shape-changing interfaces (as mentioned earlier). Utilising WoZ for modelling different stages of the UCD process would enable us to predict how user evaluation might work, for example.

Given the success of using sketching to support the design and development process of shape-changing interfaces, I might also propose that sketching could be used in the same manner for the design and development of other novel technologies, or other disciplines, in ideation, elaboration and dialogue, but also in the creation of design fiction and communication to those outside academic practice. Imagined visuals are already used to suggest how dinosaurs or far-distant planets might look, so it is not so much of a stretch to place sketching into other scientific contexts, especially robotics, given its overlap with shape-change in the context of behaviour and personality. Human-Robot Interaction is a burgeoning field, and exploring these relationships before AI is fully realised may allow us to identify potential issues (or benefits) before they happen — especially since the definition of a "robot" is so broad. However, sketching can only be used to show what is already known, or can be imagined in terms of context, technology and life — there may be limits to what can be sketched — at least using current techniques.

7.7 Conclusion

The aim of this body of work was to examine the validity of using sketching as a support mechanism for the design and development of shape-changing interfaces — blending low-fidelity techniques with highly complex technical outputs. We have shown that sketching has practical outputs in the form of requirements generation and creating models for the design and build process, and also intangible outputs in the form of subjective insights, as well as dialogue and engagement with both users and existing HCI researchers. Not only have I shown the value of sketching in this context, but I have produced and published meaningful advances in the field of shape-changing interfaces which can shape the future development of this exciting research. Finally, I have explored the hitherto unknown implications of this field — we know how we can design and build shape-changing interfaces, but *should we*?

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Appendix A

Publications & Outputs

A.1 Contributing Publications & Outputs

Sturdee, M., & Alexander, A., 2018. Analysis and Classification of Shape-Changing Interfaces for Design and Application-based Research. In *ACM Computing Surveys (CSUR)*. Vol. 51, Issue 1. ACM.

Sturdee, M., Coulton, P. and Alexander, J., 2017. Using Design Fiction to Inform Shape-Changing Interface Design and Use. *The Design Journal*, 20(sup1), pp.S4146-S4157.

Sturdee, M., 2017, June. Drawing Design Futures for Shape-Changing Interfaces. In *Proceedings of the 2016 ACM Conference Companion Publication on Designing Interactive Systems* (pp. 399-401). ACM.

Lewis, M., **Sturdee**, M., Alexander, J., Van Dijk, J., Rasmussen, M.K. and Hoang, T., 2017, June. SketchingDIS: Hand-drawn Sketching in HCI. In *Proceedings of the 2016 ACM Conference Companion Publication on Designing Interactive Systems* (pp. 356-359). ACM.

Sturdee, M., Hardy, J., Dunn, N. and Alexander, J., 2015, November. A public ideation of shape-changing applications. In *Proceedings of the 2015 International Conference on Interactive Tabletops & Surfaces* (pp. 219-228). ACM.

A.2 Additional Publications and Outputs

Coulton, Paul and Lindley, Joseph Galen and **Sturdee**, Miriam and Stead, Michael (2017) Design fiction as world building. In *Proceedings of Research through Design Conference 2017.*

Lewis, M, **Sturdee**, M., and Marquardt, N., 2018, April. Applied Sketching in HCI: Hands-on Course of Sketching Techniques. In *Proceedings of the 2018 CHI Conference Extended Abstracts on Human Factors in Computing Systems*. ACM. (accepted)

Lindley, J., Coulton, P. and **Sturdee**, M., 2017, May. Implications for Adoption. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems* (pp. 265-277). ACM.

Hur, Y., **Sturdee**, M., Alonso, M.B., Markopoulos, P. and Alexander, J., 2017. Fiction and Physicality: a designerly approach towards complexities of emerging technologies. *The Design Journal*, 20(sup1), pp.S3849-S3862.

Sturdee, M., Coulton, P., Lindley, J.G., Stead, M., Ali, H. and Hudson-Smith, A., 2016, May. Design fiction: How to build a Voight-Kampff machine. In *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems* (pp. 375-386). ACM.

A.3 Community Engagement

– Organiser of Sketching Workshop at *ICT4S 2018* (upcoming)
– AC for *Alt.CHI, CHI2018*
– PC for *CHI2018 Workshops*
– Formation and running of *Sketching in HCI* community 2017
– Organising committee for workshop on *Re-Imagination/Redesign through Bodily Movement* at *DesformX 2017*
– Organisation and running of workshop on sketching in HCI for *DIS2017*
– Posters Chair for *Interactive Surfaces & Spaces 2016*
– Committee member on the Lancaster University *SCC Athena Swan Bronze Award*

Appendix B

Supplementary Materials

B.1 Demographic / Basic Data Collection Form

As part of the study we wish to collect some basic demographic data so that we can see if there are any relationships between the study results and basic information such as age or occupation. You are not obliged to answer these questions, although it is helpful to the study if you do. If you wish to withdraw this information after the study, please let us know within 3 weeks of the date of the study. Many thanks, Miriam, Jason and Paul
Participant Number:
Age:
Gender:
Occupation:
Any other comments about the study:

B.2 Exit Questionnaire — Chapter 4

Participant Number:
1. Age:
2. Gender: (delete as applicable) MALE/FEMALE
3. Highest level of education completed: (please tick one)
In school
GCSE
A Level/Vocational Qualifications
University Undergraduate

University Postgraduate Masters
PhD or equivalent
Post Doc
4. Subject area: (if applicable)
5. Occupation: (if still in school, or full time education, please select 'none'
6. On a scale of 1 to 5, please rate how creative you think you are? (Please write number below, 1 being 'Not at all' 5 being 'Extremely')
7. On a scale of 1 to 5, how comfortable are you with new technologies? (Please write number below, 1 being 'Not at all' 5 being 'Extremely')
8. Do you own any of the following: (please tick)
Smartphone
Touchscreen tablet
Laptop computer
Desktop computer
Wearable computer
Games console
none of the above
all of the above

9. Do you ever watch/read science fiction? (Such as Doctor Who, Star Trek, Avatar): Y/N
10. How would you describe the shape change technology?
11. How likely do you think it is that the shape-change technology could be used for actual products in the next 5 -10 years? (Please write number below, 1 being 'Not at all' 5 being 'Extremely')
12. What do you think you would have to change about the shape-change technology to make this happen?
12. Did you find the diagrams helpful in communicating the parameters of the equipment? Y/N
11. If no, how could these have been improved? (Please comment in writing)
12. Which scale (size) of shape changing interface would you be most comfortable with?
Mobile phone screen
Furniture scale
Room scale
Other (please elaborate)
13. Which day to day technologies do you think could be improved by having a shape

changing display?
14. What do you think we could do differently to think of new ideas for shape changing technology?
15. Any other comments/suggestions

B.3 Scenario Questionnaire — Chapter 5

For each attached scenario could you answer the following?
(1) Did you think the scenario was plausible, i.e one that could likely happen in the future?
(2) What timescale could you see these interfaces being introduced within?
(3) Can you describe in three sentences what is happening in each scenario?
(4) Does the format of scenario seem appropriate to communicate these concepts to multiple audiences?
5) What issues could you see if this technology was available tomorrow?
6) What benefits?
7) Can you list some other possible uses for each technology?

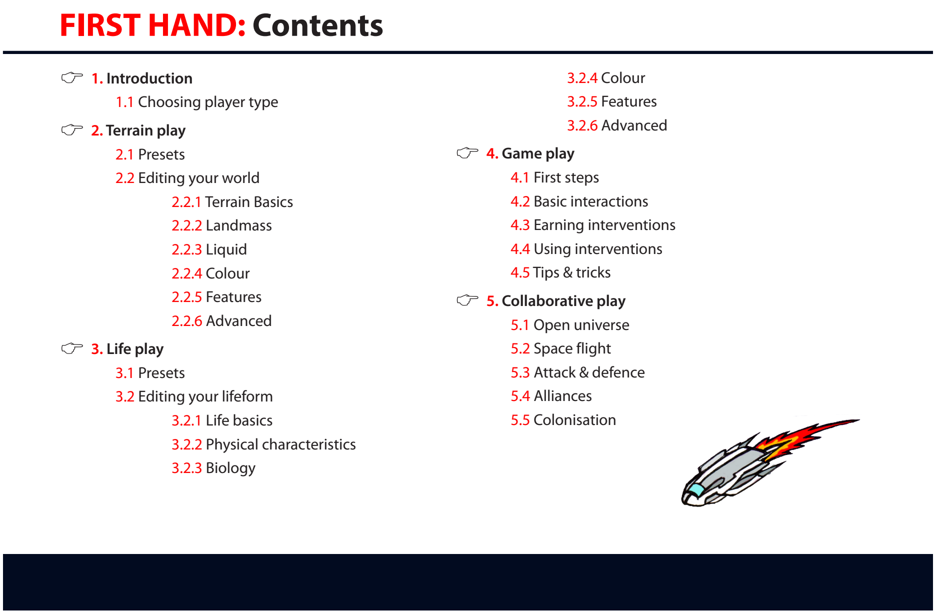
B.4 Design Fiction Manual – First Hand, Quick Start Guide

(See images on next page)

B.5 Examples of participant output from Chapter 6

(Starts on page 229)

Fig. B.1 Cover



FIRST HAND: Contents

Fig. B.2 Contents

1. Introduction

First Hand is a fully integrated touch and gesture based alien-life simulator. It can be played cross-platform either on physical-tablet, tabletop interface, tangible computer or via console link-up to enabled telephysions.

First Hand enables you to be the controlling creator for a new world or lifeform. You decide what form this creation takes, and how it evolves over time. From microbiology to macro characteristics, from gullies to crevasses, your hands will shape existence.

Game-play utilises full touch capabilities, in tandem with holographic visual support, and gesture recognition. Shape resolution of up to 500^3SU (Shape Units) is supported, at a temporality of 1000pps (Pixels Per Second).

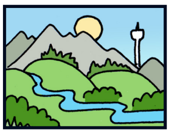
Players may choose to act upon the planet itself, or the lifeform of that planet. If terrain-play is chosen, you will be assigned a lifeform at random, and must use your interventions to shape the world to suit and nuture your species. If life-play is chosen, you will be assigned a planet at random and must evolve your species to suit your planet.

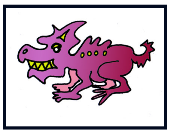
TIP: Creating extreme life-types or world-types may limit your initial growth, but can provide a reduced chance of invasion by competing species

Fig. B.3 Introduction

1.1 Choosing Player Type

Start a new game by pushing in either the raised LIFE icon or the PLANET icon.

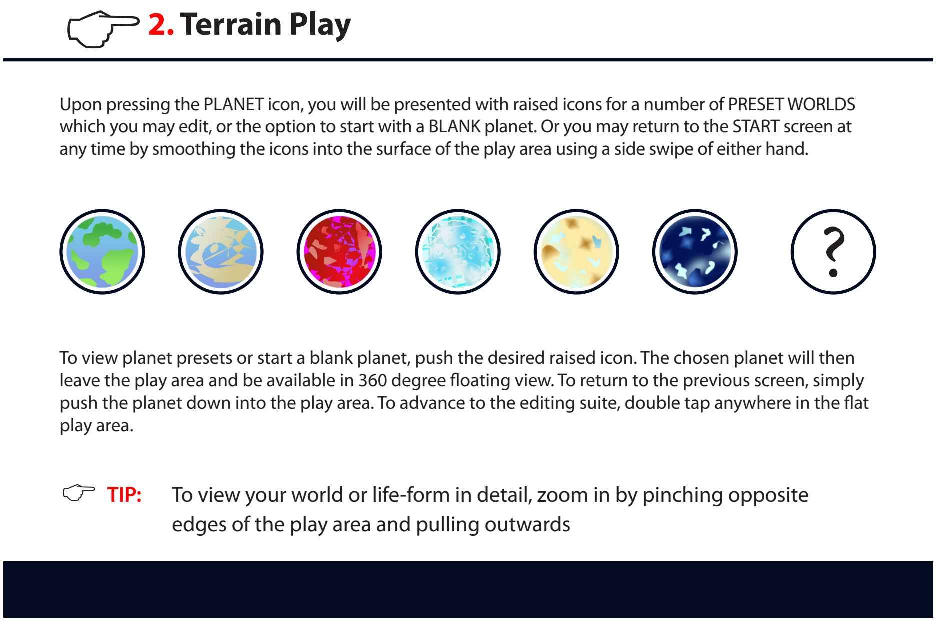




LIFEFORM (Life-play) mode allows you to sculpt a being either from an existing gallery, or from scratch. You will use your hands to shape the outer shell of the lifeform, and use further program features to add biological function, colours, textures and more. If playing as lifeform, you must evolve your species to thrive on their planet by using a series of ***Interventions***. ***Interventions*** vary from the *physical* i.e. adding extra limbs for life on difficult terrain; to addressing mentality or even basic biology.

PLANET (Terrain-play) mode allows you to sculpt an entire planet from either adapting gallery presets, or from a clean sphere. You will use your hands to create topology and water, and use further program features to add atmosphere, spin rate, atomic structure and more. When playing as planet, you are able to adapt the terrain and atmosphere to ensure propagation of your primary species using ***Interventions***. These vary from the physical i.e. removing barriers to fertile land; to changing atmospheric content or weather systems.

Fig. B.4 Choosing player type



2. Terrain Play

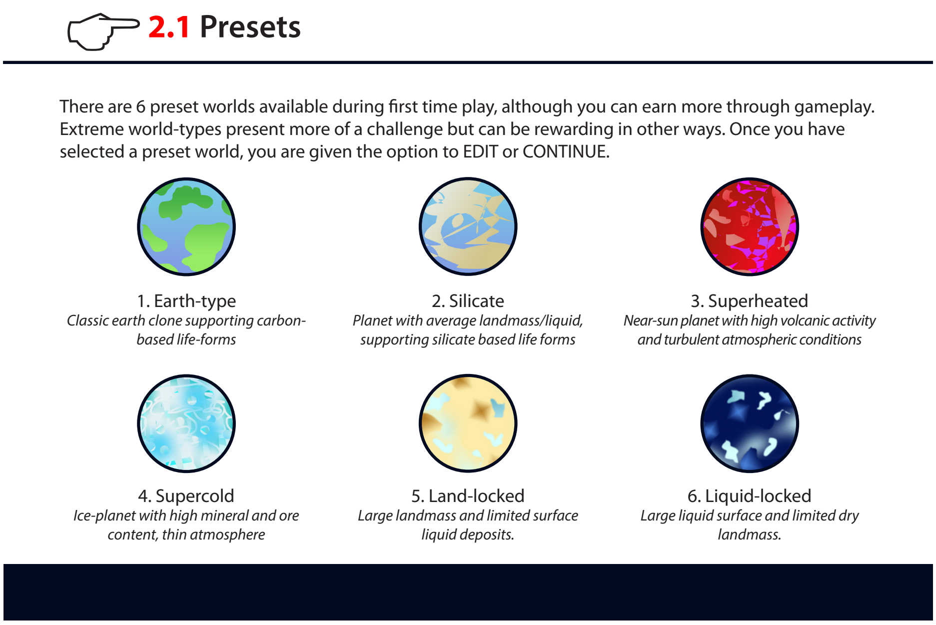
Upon pressing the PLANET icon, you will be presented with raised icons for a number of PRESET WORLDS which you may edit, or the option to start with a BLANK planet. Or you may return to the START screen at any time by smoothing the icons into the surface of the play area using a side swipe of either hand.

?

To view planet presets or start a blank planet, push the desired raised icon. The chosen planet will then leave the play area and be available in 360 degree floating view. To return to the previous screen, simply push the planet down into the play area. To advance to the editing suite, double tap anywhere in the flat play area.

TIP: To view your world or life-form in detail, zoom in by pinching opposite edges of the play area and pulling outwards

Fig. B.5 Terrain play



2.1 Presets

There are 6 preset worlds available during first time play, although you can earn more through gameplay. Extreme world-types present more of a challenge but can be rewarding in other ways. Once you have selected a preset world, you are given the option to EDIT or CONTINUE.

1. Earth-type
Classic earth clone supporting carbon-based life-forms

2. Silicate
Planet with average landmass/liquid, supporting silicate based life forms

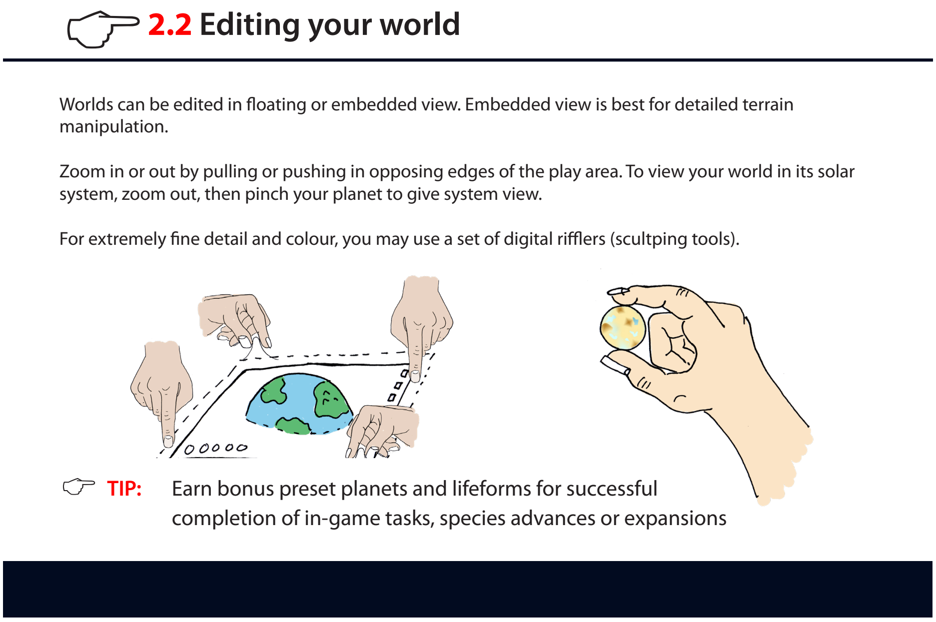
3. Superheated
Near-sun planet with high volcanic activity and turbulent atmospheric conditions

4. Supercold
Ice-planet with high mineral and ore content, thin atmosphere

5. Land-locked
Large landmass and limited surface liquid deposits.

6. Liquid-locked
Large liquid surface and limited dry landmass.

Fig. B.6 Presets



2.2 Editing your world

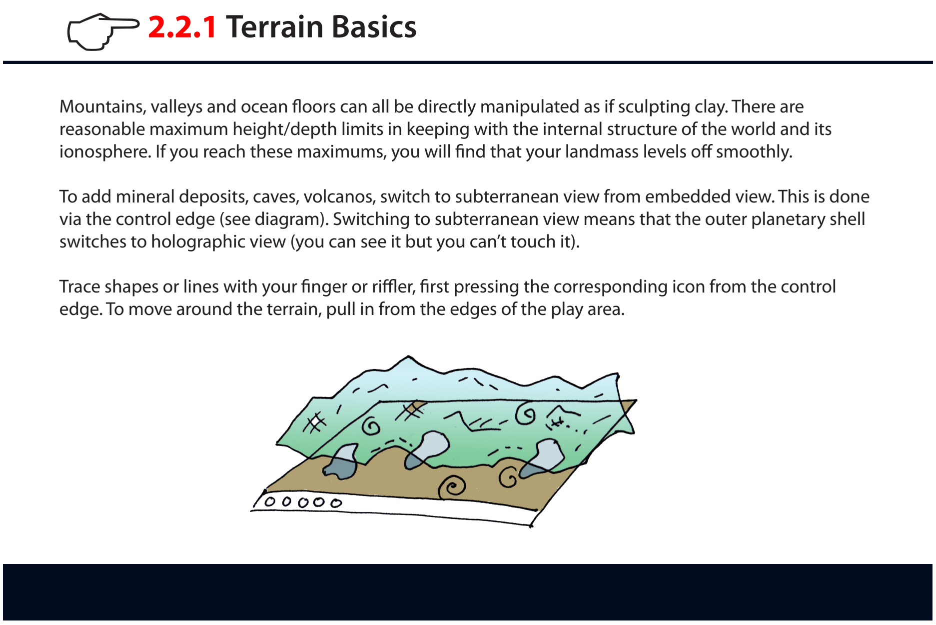
Worlds can be edited in floating or embedded view. Embedded view is best for detailed terrain manipulation.

Zoom in or out by pulling or pushing in opposing edges of the play area. To view your world in its solar system, zoom out, then pinch your planet to give system view.

For extremely fine detail and colour, you may use a set of digital rifflers (sculpting tools).

TIP: Earn bonus preset planets and lifeforms for successful completion of in-game tasks, species advances or expansions

Fig. B.7 Editing your world



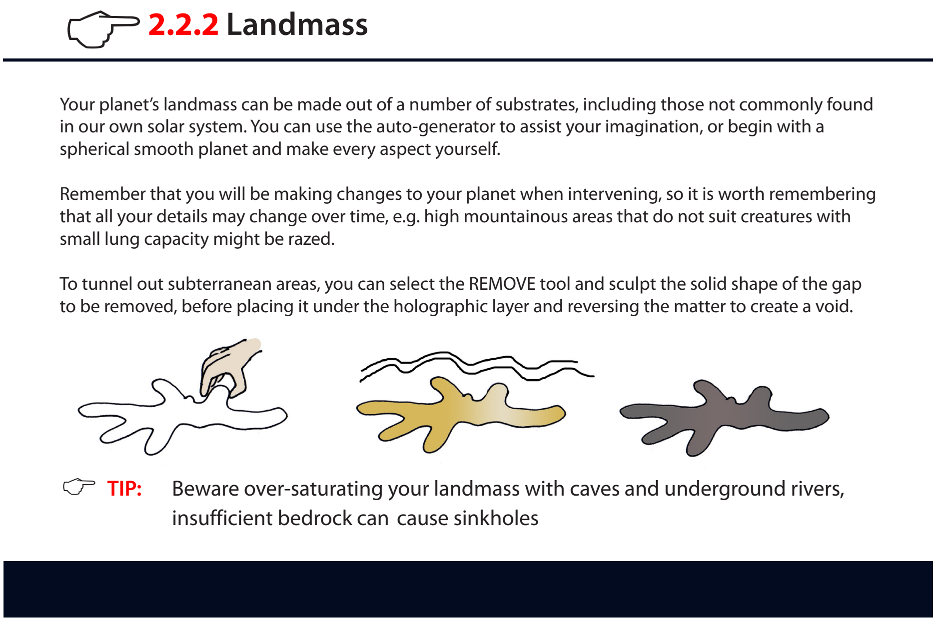
2.2.1 Terrain Basics

Mountains, valleys and ocean floors can all be directly manipulated as if sculpting clay. There are reasonable maximum height/depth limits in keeping with the internal structure of the world and its ionosphere. If you reach these maximums, you will find that your landmass levels off smoothly.

To add mineral deposits, caves, volcanos, switch to subterranean view from embedded view. This is done via the control edge (see diagram). Switching to subterranean view means that the outer planetary shell switches to holographic view (you can see it but you can't touch it).

Trace shapes or lines with your finger or riffler, first pressing the corresponding icon from the control edge. To move around the terrain, pull in from the edges of the play area.

Fig. B.8 Terrain basics



2.2.2 Landmass

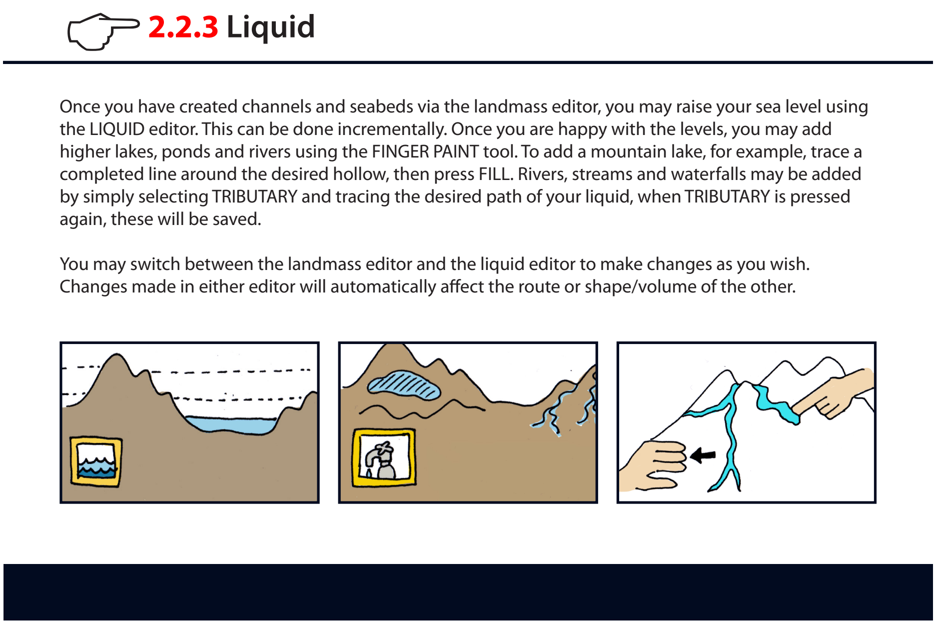
Your planet's landmass can be made out of a number of substrates, including those not commonly found in our own solar system. You can use the auto-generator to assist your imagination, or begin with a spherical smooth planet and make every aspect yourself.

Remember that you will be making changes to your planet when intervening, so it is worth remembering that all your details may change over time, e.g. high mountainous areas that do not suit creatures with small lung capacity might be razed.

To tunnel out subterranean areas, you can select the REMOVE tool and sculpt the solid shape of the gap to be removed, before placing it under the holographic layer and reversing the matter to create a void.

TIP: Beware over-saturating your landmass with caves and underground rivers, insufficient bedrock can cause sinkholes

Fig. B.9 Landmass

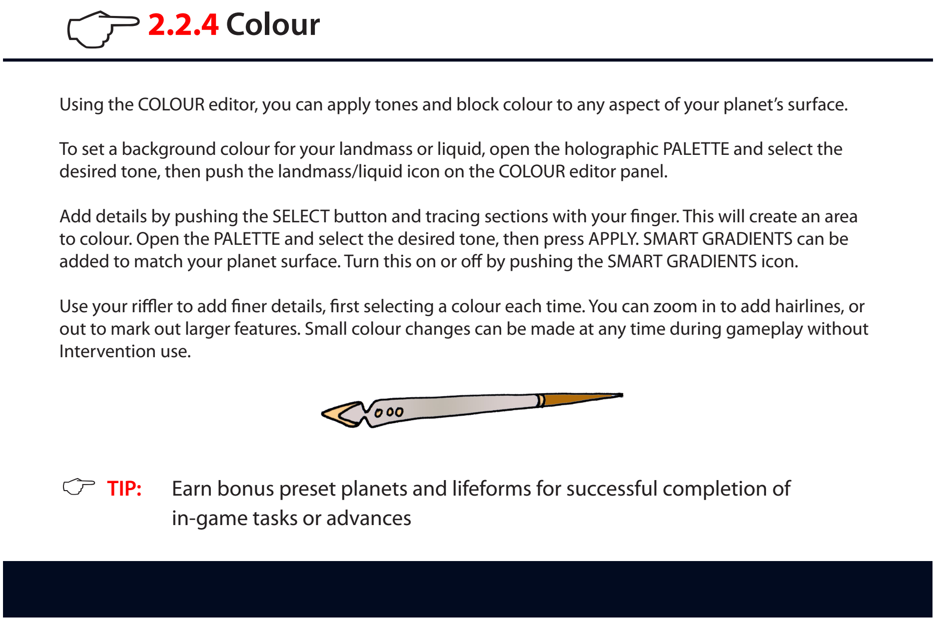


2.2.3 Liquid

Once you have created channels and seabeds via the landmass editor, you may raise your sea level using the LIQUID editor. This can be done incrementally. Once you are happy with the levels, you may add higher lakes, ponds and rivers using the FINGER PAINT tool. To add a mountain lake, for example, trace a completed line around the desired hollow, then press FILL. Rivers, streams and waterfalls may be added by simply selecting TRIBUTARY and tracing the desired path of your liquid, when TRIBUTARY is pressed again, these will be saved.

You may switch between the landmass editor and the liquid editor to make changes as you wish. Changes made in either editor will automatically affect the route or shape/volume of the other.

Fig. B.10 Liquid



2.2.4 Colour

Using the COLOUR editor, you can apply tones and block colour to any aspect of your planet's surface.

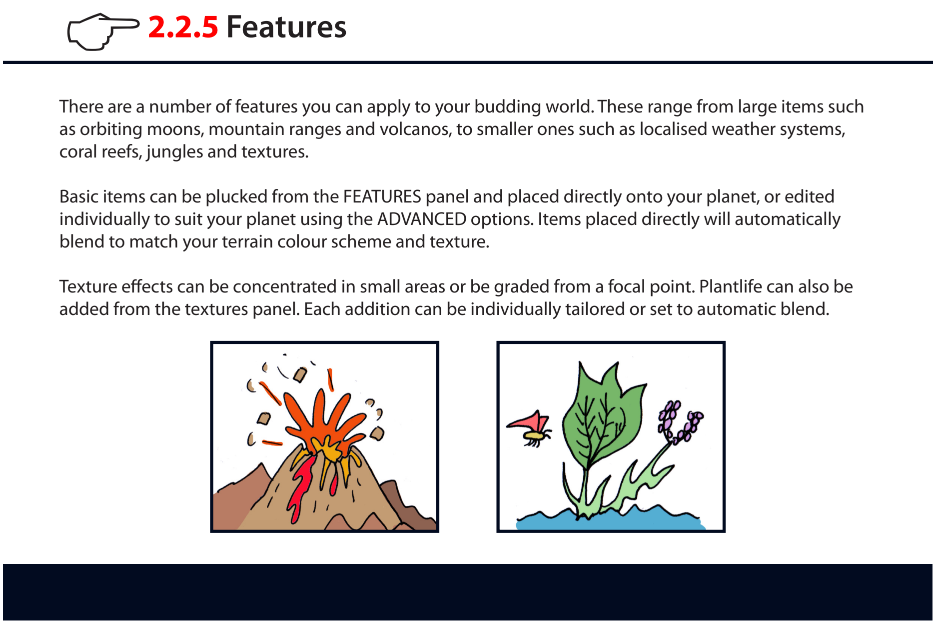
To set a background colour for your landmass or liquid, open the holographic PALETTE and select the desired tone, then push the landmass/liquid icon on the COLOUR editor panel.

Add details by pushing the SELECT button and tracing sections with your finger. This will create an area to colour. Open the PALETTE and select the desired tone, then press APPLY. SMART GRADIENTS can be added to match your planet surface. Turn this on or off by pushing the SMART GRADIENTS icon.

Use your riffler to add finer details, first selecting a colour each time. You can zoom in to add hairlines, or out to mark out larger features. Small colour changes can be made at any time during gameplay without Intervention use.

TIP: Earn bonus preset planets and lifeforms for successful completion of in-game tasks or advances

Fig. B.11 Colour



2.2.5 Features

There are a number of features you can apply to your budding world. These range from large items such as orbiting moons, mountain ranges and volcanos, to smaller ones such as localised weather systems, coral reefs, jungles and textures.

Basic items can be plucked from the FEATURES panel and placed directly onto your planet, or edited individually to suit your planet using the ADVANCED options. Items placed directly will automatically blend to match your terrain colour scheme and texture.

Texture effects can be concentrated in small areas or be graded from a focal point. Plantlife can also be added from the textures panel. Each addition can be individually tailored or set to automatic blend.

Fig. B.12 Features

2.2.6 Advanced

There are advanced options for each editing screen, to access them push the ADVANCED icon on any screen. A full list of ADVANCED options is available in the online manual.

ADVANCED options may normalise themselves to fit in with the ecosystem, but will retain the user-imposed restrictions where the algorithm for the whole system is not compromised.

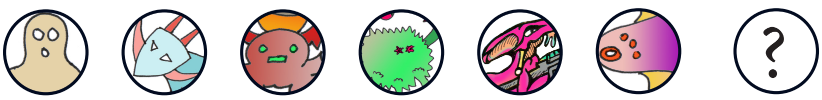
Explore the ADVANCED options and share your discoveries with friends online!

TIP: Import custom textures or items from real world terrain or objects using 3D photoplates and your tangible scanner.

Fig. B.13 Advanced

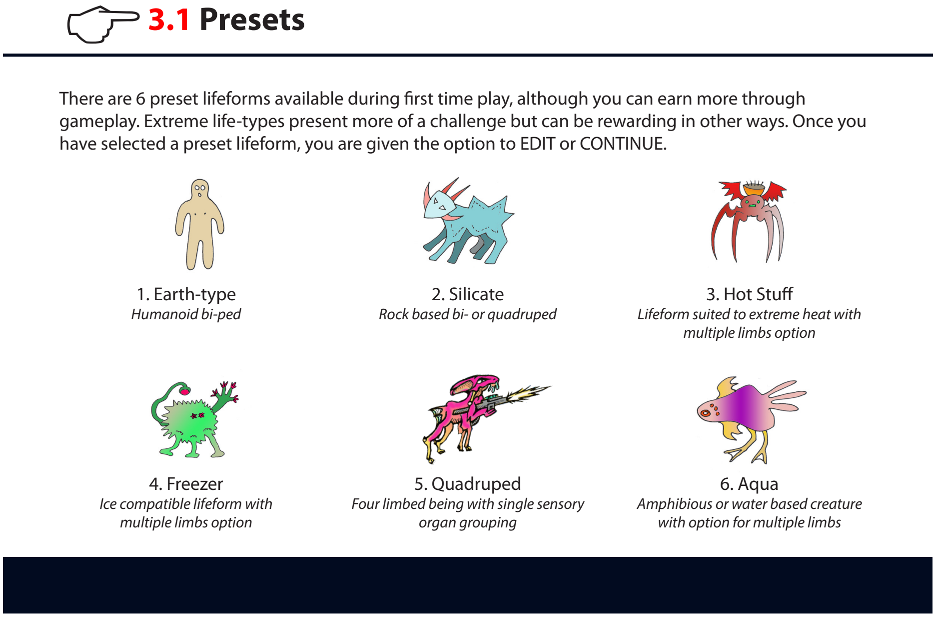
3. Life Play

Upon pressing the LIFEFORM icon, you will be presented with raised icons for a number of PRESET LIFEFORMS which you may edit, or the option to start with a BLANK Lifeform. Or you may return to the START screen at any time by smoothing the icons into the surface of the play area using a side swipe of either hand.



To view lifeform presets or start a blank lifeform, push the desired raised icon. The chosen lifeform will then leave the play area and be available in 360 degree floating view. To return to the previous screen, simply push the lifeform down into the play area. To advance to the editing suite, double tap anywhere in the flat play area.

Fig. B.14 Life play



3.1 Presets

There are 6 preset lifeforms available during first time play, although you can earn more through gameplay. Extreme life-types present more of a challenge but can be rewarding in other ways. Once you have selected a preset lifeform, you are given the option to EDIT or CONTINUE.

1. Earth-type
Humanoid bi-ped

2. Silicate
Rock based bi- or quadruped

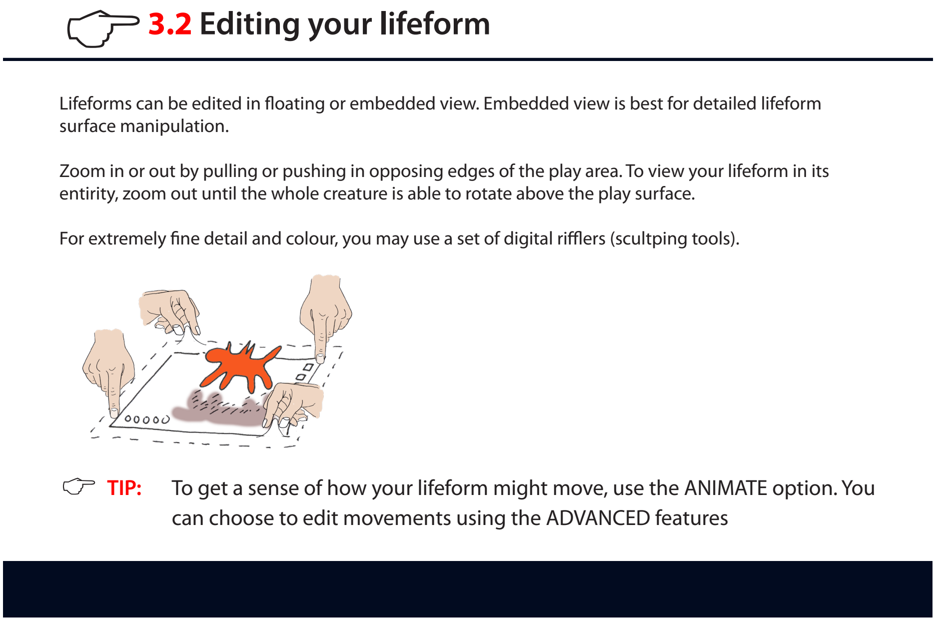
3. Hot Stuff
Lifeform suited to extreme heat with multiple limbs option

4. Freezer
Ice compatible lifeform with multiple limbs option

5. Quadruped
Four limbed being with single sensory organ grouping

6. Aqua
Amphibious or water based creature with option for multiple limbs

Fig. B.15 Presets



3.2 Editing your lifeform

Lifeforms can be edited in floating or embedded view. Embedded view is best for detailed lifeform surface manipulation.

Zoom in or out by pulling or pushing in opposing edges of the play area. To view your lifeform in its entirity, zoom out until the whole creature is able to rotate above the play surface.

For extremely fine detail and colour, you may use a set of digital rifflers (scultping tools).

TIP: To get a sense of how your lifeform might move, use the ANIMATE option. You can choose to edit movements using the ADVANCED features

Fig. B.16 Editing your lifeform

3.2.1 Life basics

Limbs, ears, noses and more can all be directly manipulated as if sculpting clay. There are reasonable maximum height/depth limits to keep your lifeform within reasonable parameters (you cannot have a lifeform that takes up more than a certain area of a planet. If you reach the maximums, you will find that your lifeform edge levels off smoothly.

To add internal organs, skeletal structure and reproductive ability, switch to internal view from floating view. This is done via the control edge (see diagram). Switching to internal view means that the outer lifeform shell switches to holographic view (you can see it but you can't touch it).

Trace shapes or lines with your finger or riffler, first pressing the corresponding icon from the control edge. To move around the lifeform, simply grasp it and turn manually.

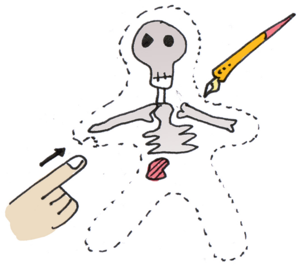


Fig. B.17 Life basics

3.2.2 Physical characteristics

Your lifeform may have any number of appendages, heads, sensory organs or none at all. If starting with a preset, new limbs may be selected and stuck on from the PALETTE, or pinched out of the main body of the lifeform. Detail can be added with your riffler, such as manipulator digits, nails or claws.

When creating a limb, you will be asked to assign a USE. For example, propulsion (legs); balance (tail); flight (wings); attack (any).

To create sensory organs, create the shape of the desired item, then assign an input/output to it (e.g. sight, hearing, taste).

Skin texture can be applied uniformly (select SKIN then apply as base) or in selected areas which you can circle using a finger trace, then select the desired output.

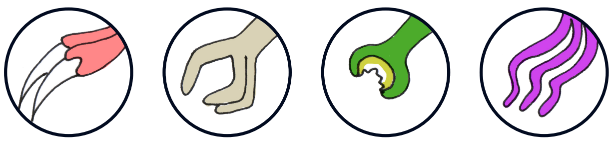


Fig. B.18 Physical characteristics

3.2.3 Biology

Once you have created the basic structure of your creature you can edit the internal structure. You can choose where to have main skeletal features, and which parts of the lifeform might be non-moving. You can select a basic internal biology (i.e. what it eats, how long digestion takes, water percentage) and add features such as extra hearts (for a hardy being) or even pouches for carrying young.

If you wish your lifeform to be non-carbon based, you can choose from several alternative basic biologies, these choices will affect the type of planet you will be assigned.

Brain size is important, but has limitations. If you assign extremely large brains to your lifeform, then you will have a cost in terms of movement and infant mortality.

Base biology takes a large number of interventions to change, hence settling on new planets may require lengthy diversifications (see game play section).

You may switch between the body editor and the biology editor to make changes as you wish. Changes made in either editor will automatically affect the other.

TIP: For more of a challenge, start a game with a 'blob' preset which can gradually adapt to almost any planetary instance but requires lengthy transitions

Fig. B.19 Biology

3.2.4 Colour

Using the COLOUR editor, you can apply tones and block colour to any aspect of your lifeform's surface.

To set a background colour for your lifeform, open the holographic PALETTE and select the desired tone, then push the APPLY icon on the COLOUR editor panel.

Add details by pushing the SELECT button and tracing sections with your finger. This will create an area to colour. Open the PALETTE and select the desired tone, then press APPLY. SMART GRADIENTS can be added to match your lifeform's surface. Turn this on or off by pushing the SMART GRADIENTS icon.

Use your riffler to add finer details, first selecting a colour each time. You can zoom in to add hairlines, or out to mark out larger features. Small colour changes can be made at any time during gameplay without Intervention use.

Fig. B.20 Colour

3.2.3 Features

There are a number of features you can apply to your budding lifeform. These range from telepathic communication (meaning your lifeform has enhanced stealth) to armoured spikes or even gossamer butterfly-styled decorative wings or alternative breathing apparatus.

Basic items can be plucked from the FEATURES panel and placed directly onto your lifeform, or edited individually to suit your lifeform using the ADVANCED options. Items placed directly will automatically blend to match your lifeform colour scheme and texture.

Texture effects can be concentrated in small areas or be graded from a focal point. Plumage or sexual display characteristics can also be added from the textures panel. Each addition can be individually tailored or set to automatic blend.

TIP: Save up Interventions to access specialised adaptations such as chameleonic skin camouflage

Fig. B.21 Features

3.2.6 Advanced

There are advanced options for each editing screen, to access them push the ADVANCED icon on any screen. A full list of ADVANCED options is available in the online manual.

ADVANCED options may normalise themselves to fit in with the ecosystem, but will retain the user-imposed restrictions where the algorithm for the whole system is not compromised.

Explore the ADVANCED options and share your discoveries with friends online!

Fig. B.22 Advanced

4. Game Play

The aim of *First Hand* is to successfully populate your planet and establish a balanced ecosystem and civilisation, and further, to expand into the solar system and galaxy at large. You may make alliances, enemies, find isolated systems, take over manned asteroids. The galaxy is a big place - dare you expand?

You guide your planet or lifeform from its first rotation or breath, to a landscape of beauty and practicality or sentient glory. But be careful, wrong choices can have knock on effects in future generations...

You can be as detailed into your manipulations as you wish, or use presets and basic shapes to speed up the gameplay. Allow the game algorithms to assign purpose to your creations, or interfere with nature's basics. As creator, you may do as you wish - it's your world.

TIP: Interventions that appear to be going wrong can be undone, but using another Intervention to do this will set you back two steps, not just one

Fig. B.23 Game play

4.1 First steps

In both forms of play, your lifeform will be placed in the most appropriate locations for its requirements. You may choose to have the population spread over several areas, or grouped in one large settlement. Both options have advantages: localised populations are more likely to expand swiftly, but may not thrive, isolated pockets indicate preferential conditions for the species but limit growth in less suitable areas.

Choose a number of locations for your species to settle, then choose a level of native life (if you have selected a carnivorous being you must have non-sentient large lifeforms present, although vegetarian lifeforms may have varied native life). You may also choose to have a dense native population or more sparse, again, there are advantages to both.

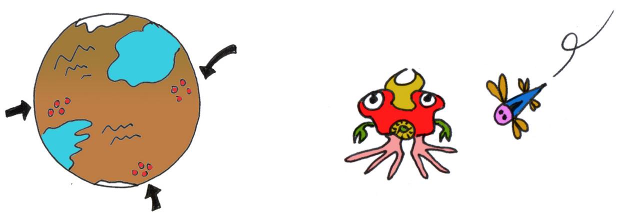


Fig. B.24 First steps

4.2 Basic interactions

Congratulations! Your gameplay has begun. Explore your planet using zoom and rotate.

Survival of the fittest may be helpful in the long run, but your nascent species might need a helping hand to stay out of danger. Retrieve stragglers who may be in danger from native life or planetary features, encourage pairings of stronger individuals to perpetuate the species and more - all using physical *nudges*. If playing as terrain, create natural barriers or safe spots for lifeforms to congregate by manipulating shallow surface features. These basics can be carried out without Interventions. If playing as terrain, you may also assume basic control over native life.

At any time, you may see how any individual is coping by plucking it from the planet surface and placing it in suspension. You will be shown a holographic readout of its vital signs, happiness, age and a percentage suited to its current environment. As the game progresses, interactions and available information may become more complex due to emerging sentience. Sampling of the atmosphere and plant/animal life can also be carried out in both modes of play.

TIP: Inimical native life means danger to your lifeform, use initial interventions to establish defensive strategy

Fig. B.25 Basic interactions

4.3 Earning Interventions

Interventions are allocated for a number of achievements, the most basic of which is one Intervention per a full galactic turn. This is how long your solar system takes to move one light year away from the galaxy centre. You can set your game to run through a galactic turn in a number of different real-times, however, you may miss out on vital species interactions if this is set too high before you have fully established your species.

You can also achieve Interventions each time your population increases. In the beginning of the game, this is achieved for each new birth, as the game progresses the targets become higher (e.g. per 1000 births). Other methods of achieving interventions can be as subtle as a new source of foodstuffs being found, to surviving a natural disaster (such as a mudslide or volcano erruption).

Inital Interventions can be used for small modifications to the landscape directly surrounding your population(s) (Terrain Play) or small modifications to the lifeform's physical appearance. Later Interventions become more epic, in that you may use them on a planet wide scale.

Interventions can be saved if your population is thriving, and evolution observed until it is necessary to Intervene. There are many ways to earn extra interventions - you will discover these as you play the game...

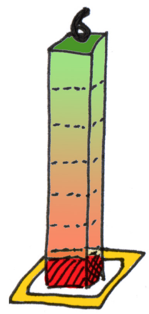
Fig. B.26 Earning interventions

4.4 Using Interventions

When you earn an Intervention, a holographic Intervention bar will appear to the side of the play area. The higher the level of this bar, the more powerful the Intervention. If you are stockpiling Interventions, you will see a number at the top of the bar which indicates the multiplyer.

To use an Intervention, open the Editing Suite (this is similar to the initial editing panel you used to start creating your planet or lifeform). Choose an individual life form (or area of the planet) and pluck it (outline it) from (on) the planet surface, or select GENERAL. You can choose to alter PHYSICAL characteristics (landmass/liquid or appearance/limbs), BIOLOGICAL characteristics (native life/atmosphere or internal biology/mentality) and affect either the whole planet/species or a narrow area/population.

Once you are happy with the change, push APPLY on the editing panel. Your Intervention will take effect immediately, you should see initial results after half a galactic turn.



TIP: Making detailed Interventions in small areas or populations can have interesting knock-on effects, or choose GENERAL to make small homogenous changes

Fig. B.27 Using interventions

4.5 Tips and tricks

- You can't be everywhere at once. If you need to be away to manage a space campaign, your home planet can be set to automatic evolution/terraforming, or left static. Balanced ecosystems and stable species (no major *Interventions* needed within 100 turns) are more resistant to attack by other players, so if this balance is attained, *Interventions* can be banked and saved for use elsewhere.

- Your *First Hand* species or planet can be exported to a 3D colour printer for you to keep, at any stage of its evolution. You can even share your print patterns online within the *First Hand* community pages.

- Talk to individual lifeforms when they reach full sentience by plucking them from the surface and asking how they are, select thriving individuals for special attention to create a generation of scientists, free thinkers and artisans. Beware over-interference however!

- DIVERSIFY your species within one planet if there are inimically distinct habitats which can support a large population, but unmanaged, this may create factions and imbalance at later stages of the game when collaboration is necessary.

- Detailed and accurate sculpting work can result in faster interventions, enhanced species or planetary ecosystem, and also assist in attack/defence of your planet when coming up against a less well developed species.

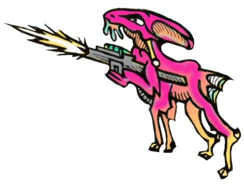
Fig. B.28 Tips and tricks

5. Collaborative play

First Hand can be played either solo in a computer generated universe, as a multiplayer using individual play-platforms or within an open online universe, against an unlimited number of players. In all types of game, players start at a sufficient distance from sentient and space faring life, in order to establish their world and species.

In solo and multiplayer games, fixed goals can be set according to desired length of play (e.g. *single world* play, *colonisation* play, *balance* play - see in game MANUAL for more details). In the open universe, play can be infinite, or players can set their own goals and desires.

You can play with, or against your friends
- but your species must prevail!



TIP: Want to practice Terrain or Life play first? Use the DEMO setting for a basic introduction to tangible digital sculpting.

Fig. B.29 Collaborative play

5.1 Open universe

The *First Hand* universe was launched in April 2021 and has a growing player base. All players start with a world a set distance from the previous most recent start-up, with worlds at the centre of the galaxy being the most established, and thus, most difficult to conquer/approach.

Players may log on or off at any time, unless engaged in battle. Once a battle has been won or lost, and balance restored, that planet is under quarantine and the player who controls it may log off without penalty.

Whilst offline, players' home planets exist in the space *between* stars (Dark Nebulae), meaning they cannot be attacked. Upon re-entry to the game universe, home planets are re-spaced near systems of similar advancement, to prevent annihilation as a result of non-play. To ensure play is possible within your friendship group, players can log into the same instance of the galaxy using a unique code generated by the first entrant.

Unoccupied planets may be settled using only colony ships, those occupied with a sentient race require an attack using at least one navy ship. Once taken, each new planet forms part of your network, supplying goods and services, enhancing intervention generation and species strength. Beware though! When online, you must be prepared to protect all of your planets from attack, overreaching yourself might result in great losses. There is more information about the open universe online at www.firsthandgame.com/guide

Fig. B.30 Open universe

5.2 Space flight

Space flight capabilities can be activated after the first 100 Interventions, although the longer your species has to adapt and evolve, the stronger they will be during encounters, and the more adaptable they will be during colonisation.

Terrain players have an advantage that they can alter terrain to create areas for space ports and provide natural resources close by. Life players must work harder to bring appropriate resources in to the most appropriate area, but can be evolved mentally/physically to work more efficiently on technical aspects. The ship can be manually scultped by either player type when construction starts.

Decision to launch can only be made when at least one ship is completed, and the success depends on ship design, atmospheric/weather conditions, and confidence/dexterity of the species for example. *Interventions* may be used by either player type during the first flight to combat issues and ensure successful insertion into vacuum.

After first flight, modifications to basic ship design can be made, and the program focus can be weighted in favour of either navy or colonisation ships (e.g. 80% 20%).

TIP: Players begin on a isolated planet at the edge of the Open Galaxy, but can expect contact from another *First Hand* after around 1000 Turns.

Fig. B.31 Space flight

5.3 Attack & defence

Planetside Invasion

Terrain players may use *Interventions* to alter the landscape or atmosphere of the target planet. This can be done covertly to prime for invasion, or during battles. Whilst zoomed out, you may use your hands to influence multiple landscape features, crush multiple armies with rockslides, or create violent weather systems. When zoomed in, specific battles may be joined with more force than if multiple landscape points are influenced.

Life players can use *Interventions* to direct armies of their species by pushing the battle mass toward a target. This can be done over multiple points during planet-wide invasions, or whilst zoomed in to influence specific command units during major conflicts. *Interventions* can also be used to directly crush opposing command units, though the scale is limited. Impact ranges from demotivation, to death of units, depending on *Intervention* strength and pressure during the attack. The stronger the opposing player, the harder it is to manipulate their species or terrain.

Space Invasion

Terrain players may create inimical weather systems in order to prevent ships landing, and use pressure to push enemy ships away from the planet if there are sufficient *Interventions* available. Life players may affect the life support systems of enemy ships, move their own ships around and in/out of firing range. Mulitple *Interventions* at this stage can demotivate or destroy an enemy advance and prevent planetary invasion, however, in the event of a successful landing, *Intervention* options may be then be limited.

Fig. B.32 Attack and defence

5.4 Alliances

First Hand allows you to take advantage of real world alliances and friendships and use them to the advantage of multiple species. Successful alliances are often composed of diverse species to avoid planetary competition and to enhance attack capabilities. Alliances in single player are possible with computer generated races.

Alliances of 5 or more species are declared Confederations and are allocated *Joint Interventions* to use for the advancement of species or planets in collaboration. *Joint Interventions* allow unsuitable atmospheres to be converted more quickly, or species to be evolved at a faster rate. *Joint Interventions* may be used for confederations composed of any player type.

If an ally requires assistance in an attack/defence, Interventions may be gifted to that player. In this case, the next Intervention earned by the gifting player will be of greater effect, regardless of the success of the gifted Intervention.

If a player leaves a Confederation, providing the number of members does not go below 5 the Confederation persists. Alliances below 5 players are sustainable, but there are no *Joint Interventions*.

TIP: If a Confederate member leaves, they take tactical and species knowledge with them. Be prepared to defend your planets.

Fig. B.33 Alliances

5.5 Colonisation

If your species reaches planetary capacity, or has completed a new conquest, the option appears to DIVERSIFY your species, i.e. use your Interventions to split and evolve your lifeform to exist in a new solar system. If you are playing as terrain, you must use your interventions to alter the new planet(s) to suit your lifeform.

New planets or planetary conquests that are more than 10 ATMOSPHERE units away from your baseline may not be settled until this difference is within acceptable parameters. Your species must be able to adapt, or have the planet adapted sufficiently within the timescale of finite exploration resources.

During this time, the species must begin evolution in space (Life Play), or the planet must be observed from space whilst the initial Intervention takes hold (Terrain Play) and settled when changes are within acceptable parameters.

TIP: Converting new planets or evolving species for colonisation in populus parts of the galaxy is more difficult whilst your space navy experience is low

Fig. B.34 Colonisation

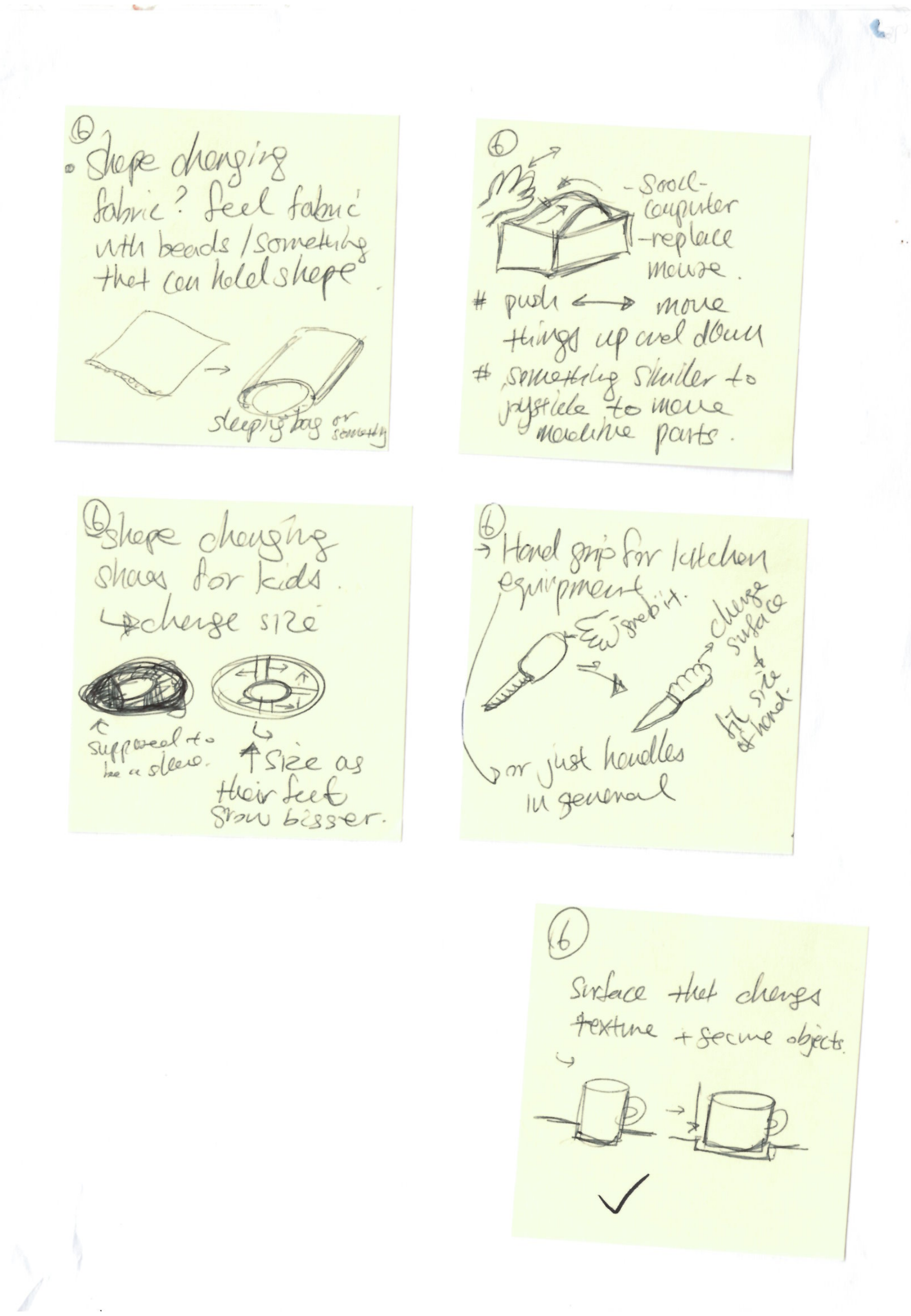


Fig. B.35 Participant 6 ideation

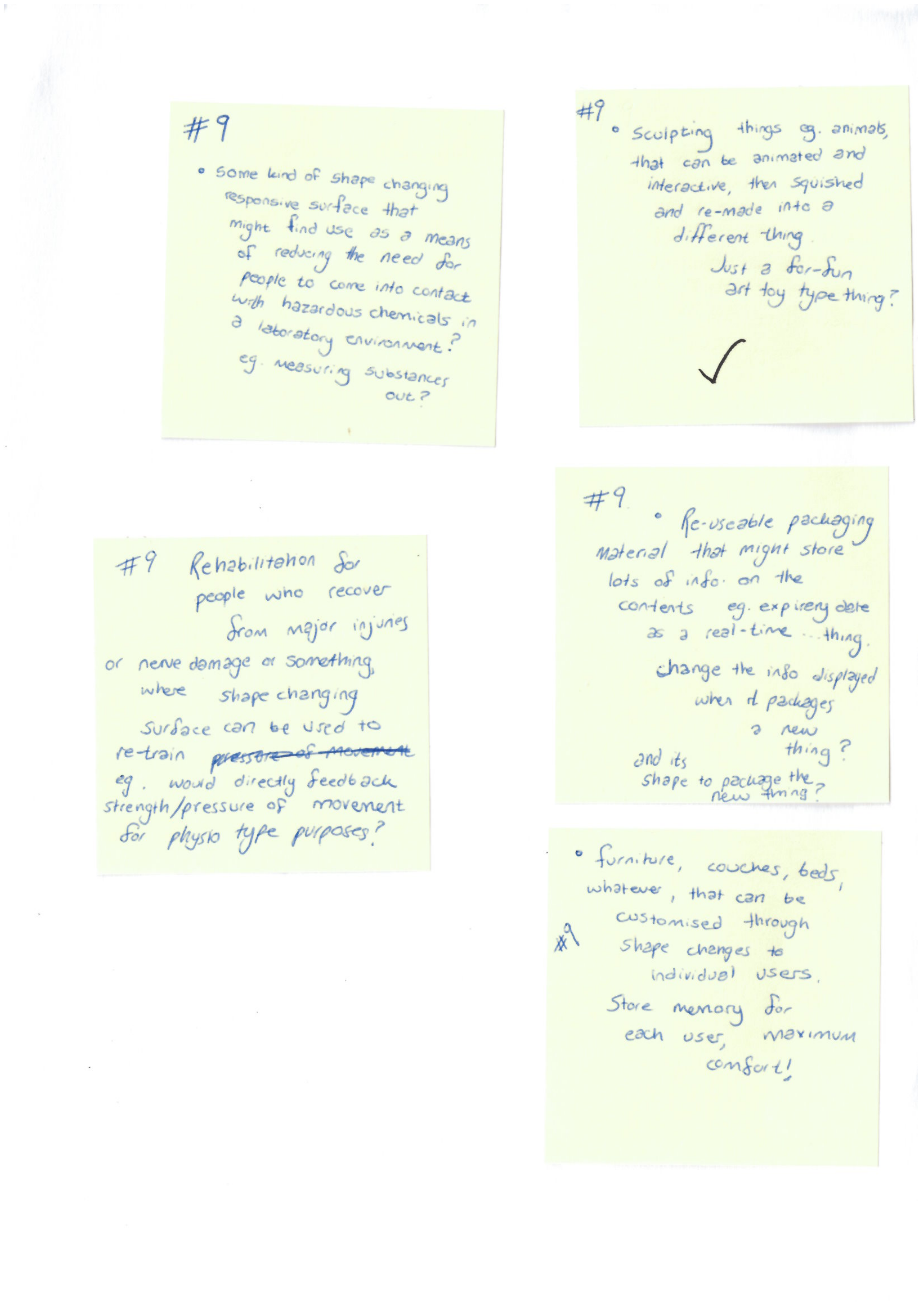


Fig. B.36 Participant 9 ideation

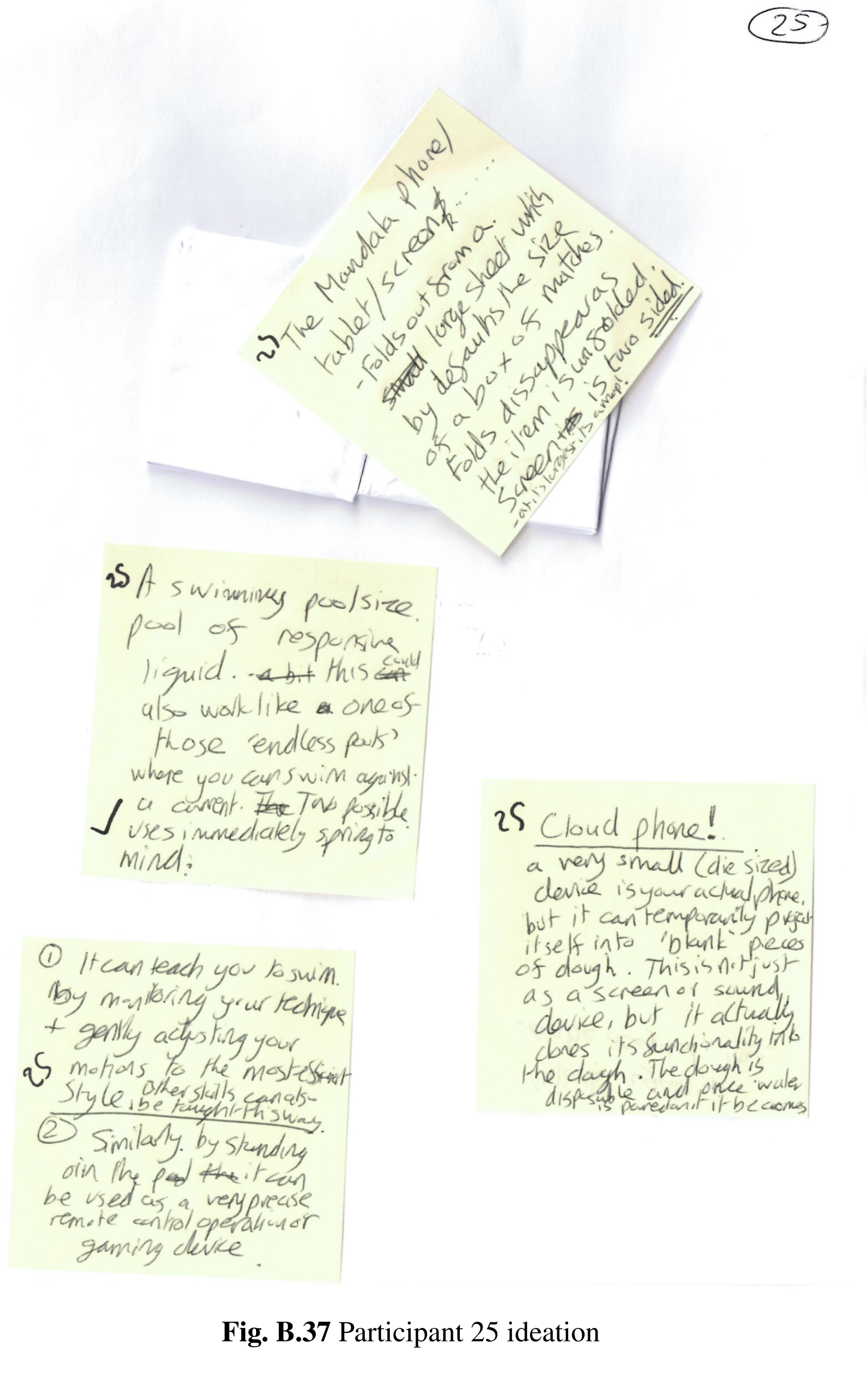


Fig. B.37 Participant 25 ideation

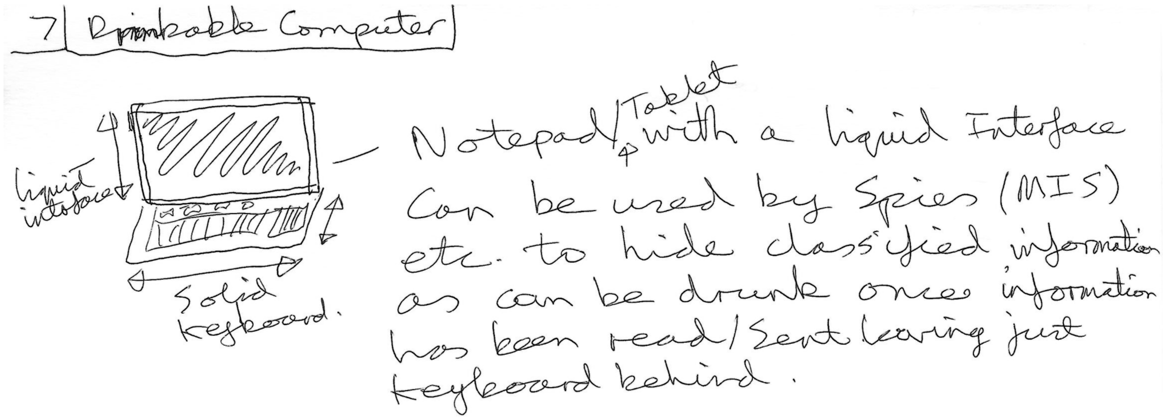


Fig. B.38 Participant 7 diagram

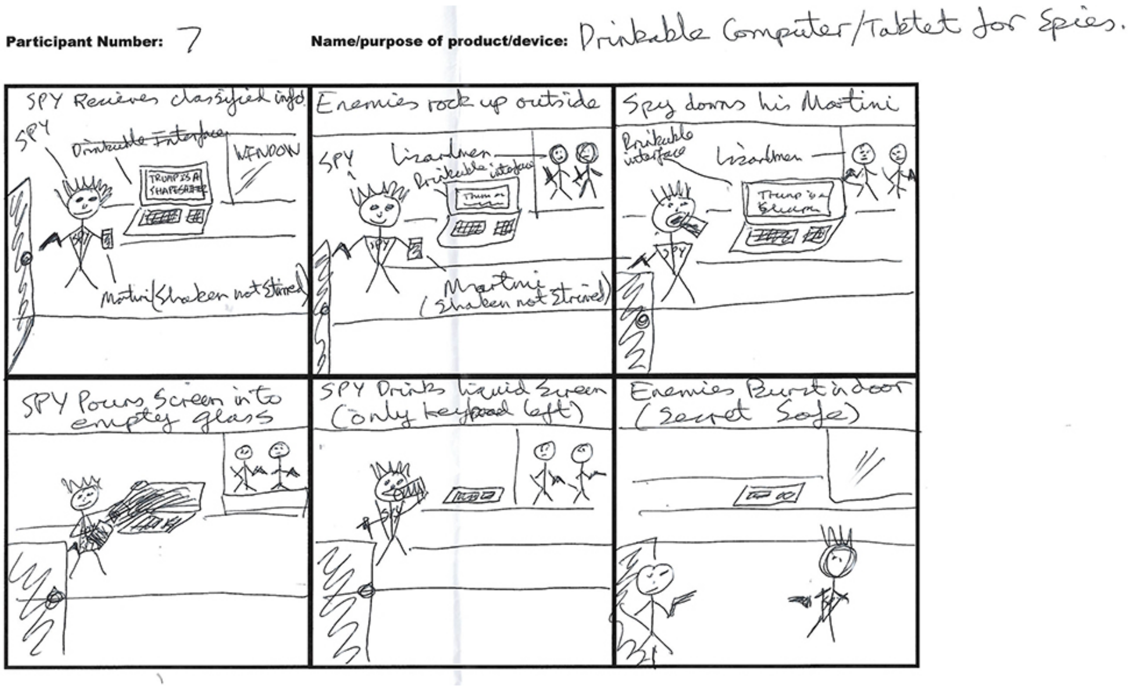


Fig. B.39 Participant 7 scenario

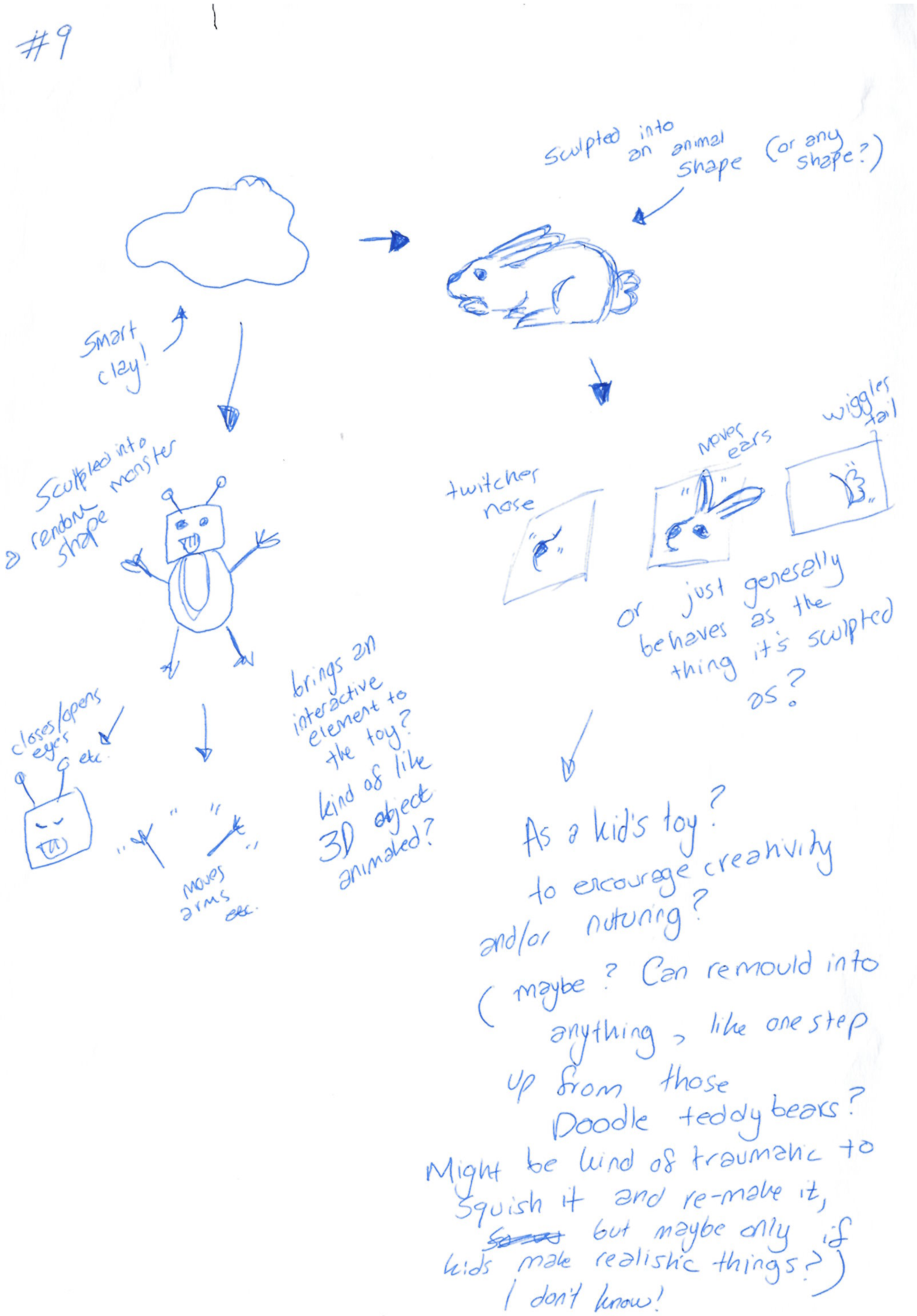
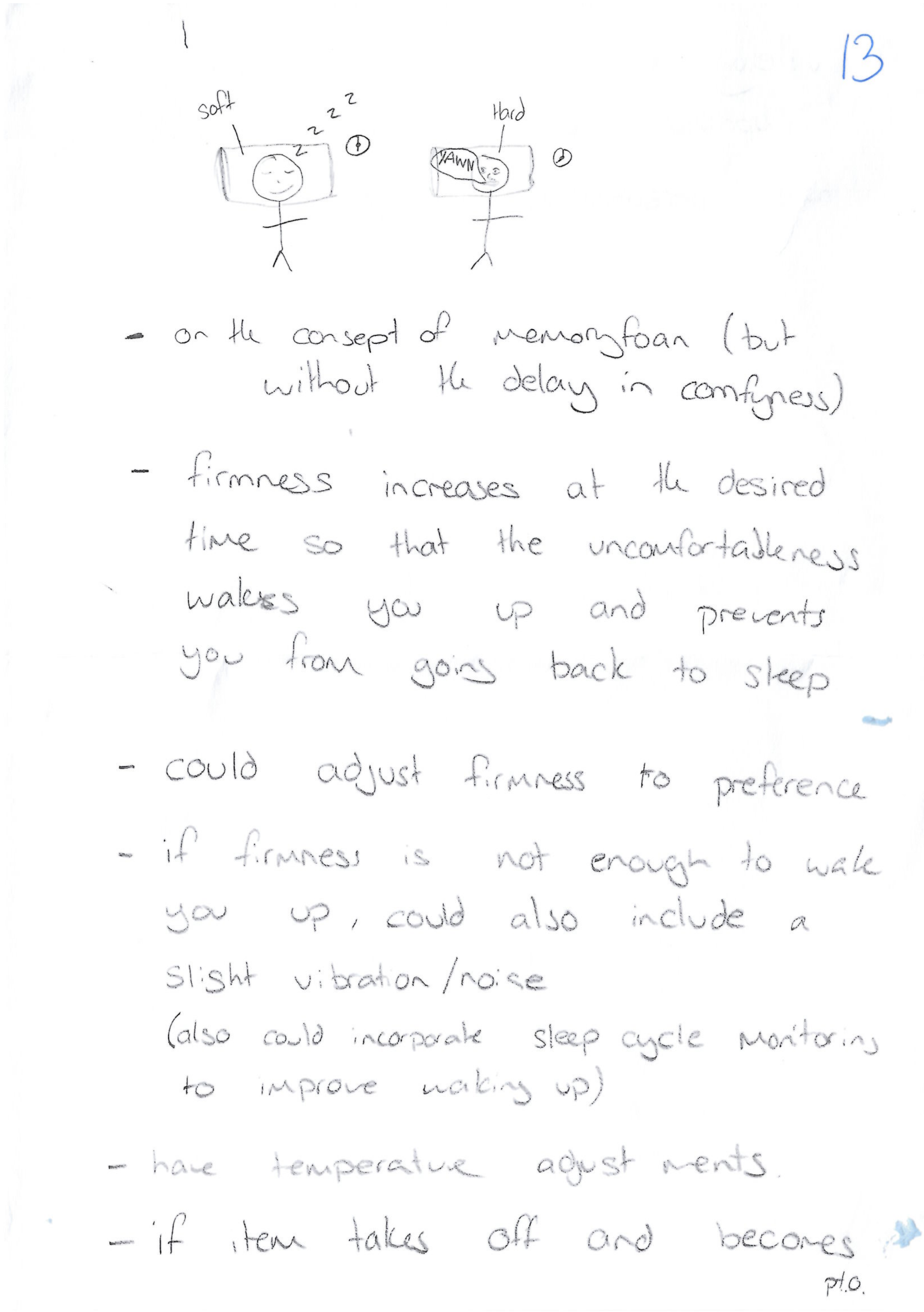


Fig. B.40 Participant 9 diagram

Fig. B.41 Participant 9 scenario



- on the consept of memoryfoam (but without the delay in comfyness)
- firmness increases at the desired time so that the uncomfortableness wakes you up and prevents you from going back to sleep
- could adjust firmness to preference
- if firmness is not enough to wake you up, could also include a slight vibration/noise (also could incorporate sleep cycle monitoring to improve waking up)
- have temperature adjustments
- if item takes off and becomes

p.t.o.

Fig. B.42 Participant 13 diagram

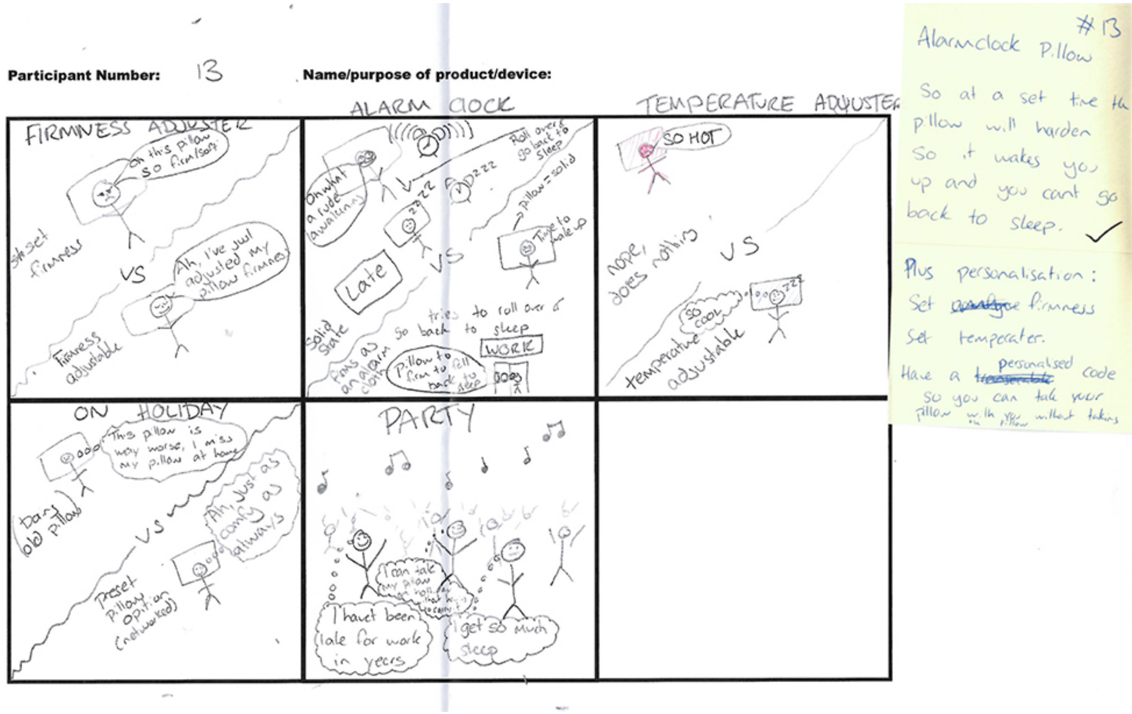


Fig. B.43 Participant 13 scenario

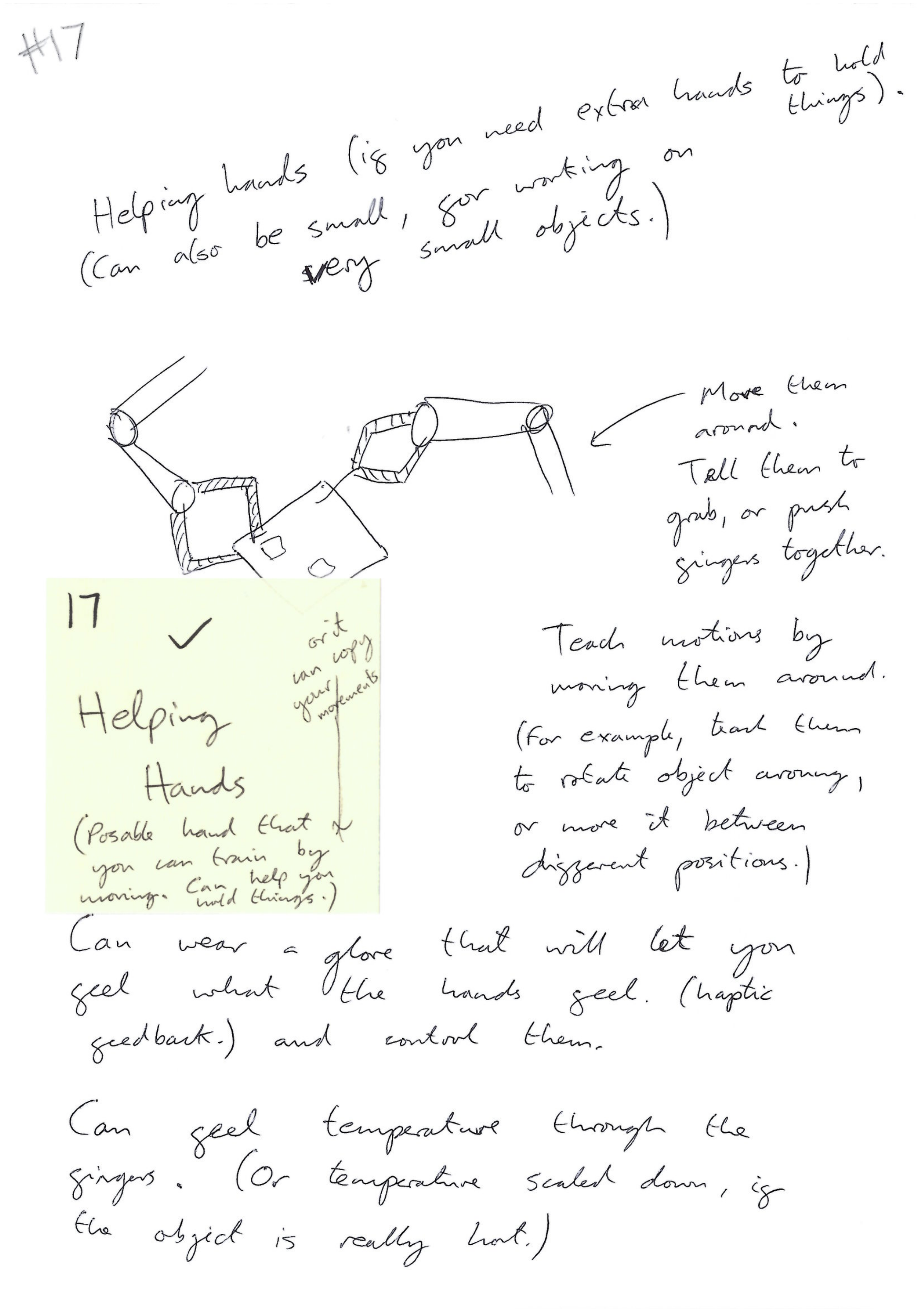


Fig. B.44 Participant 17 diagram

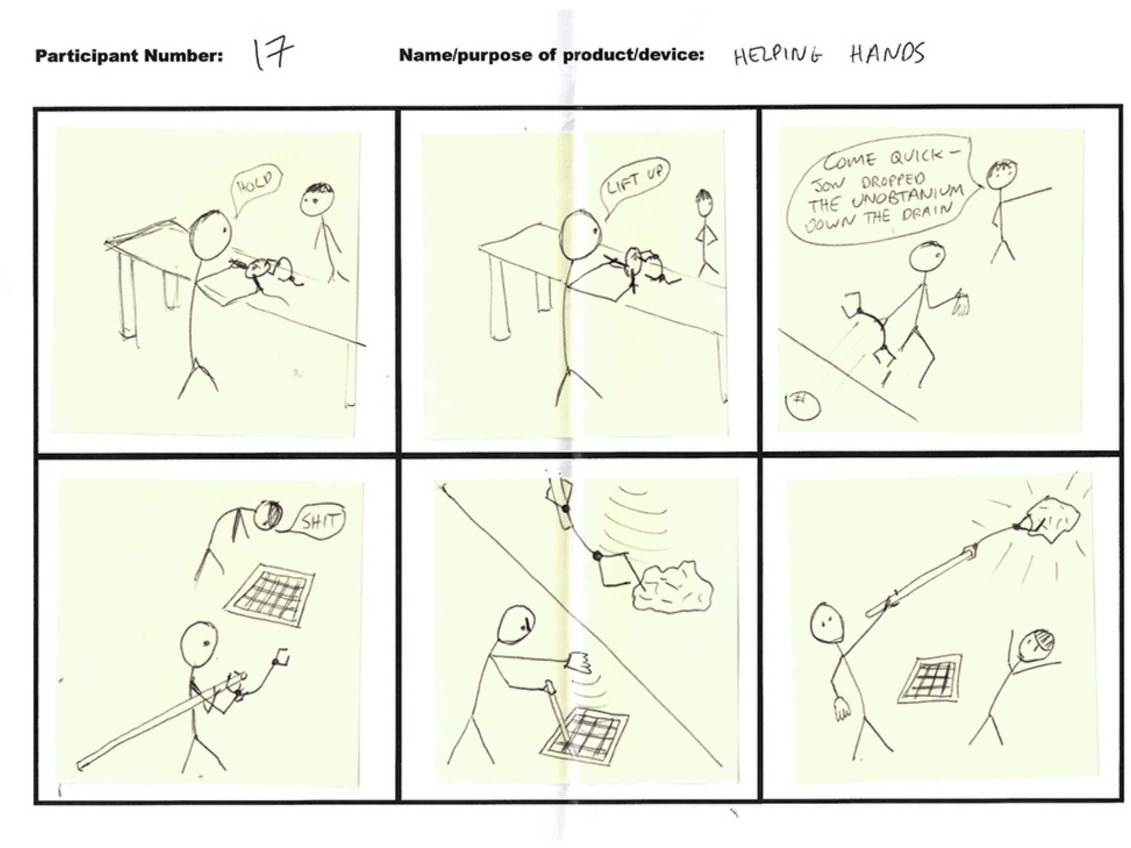


Fig. B.45 Participant 17 scenario

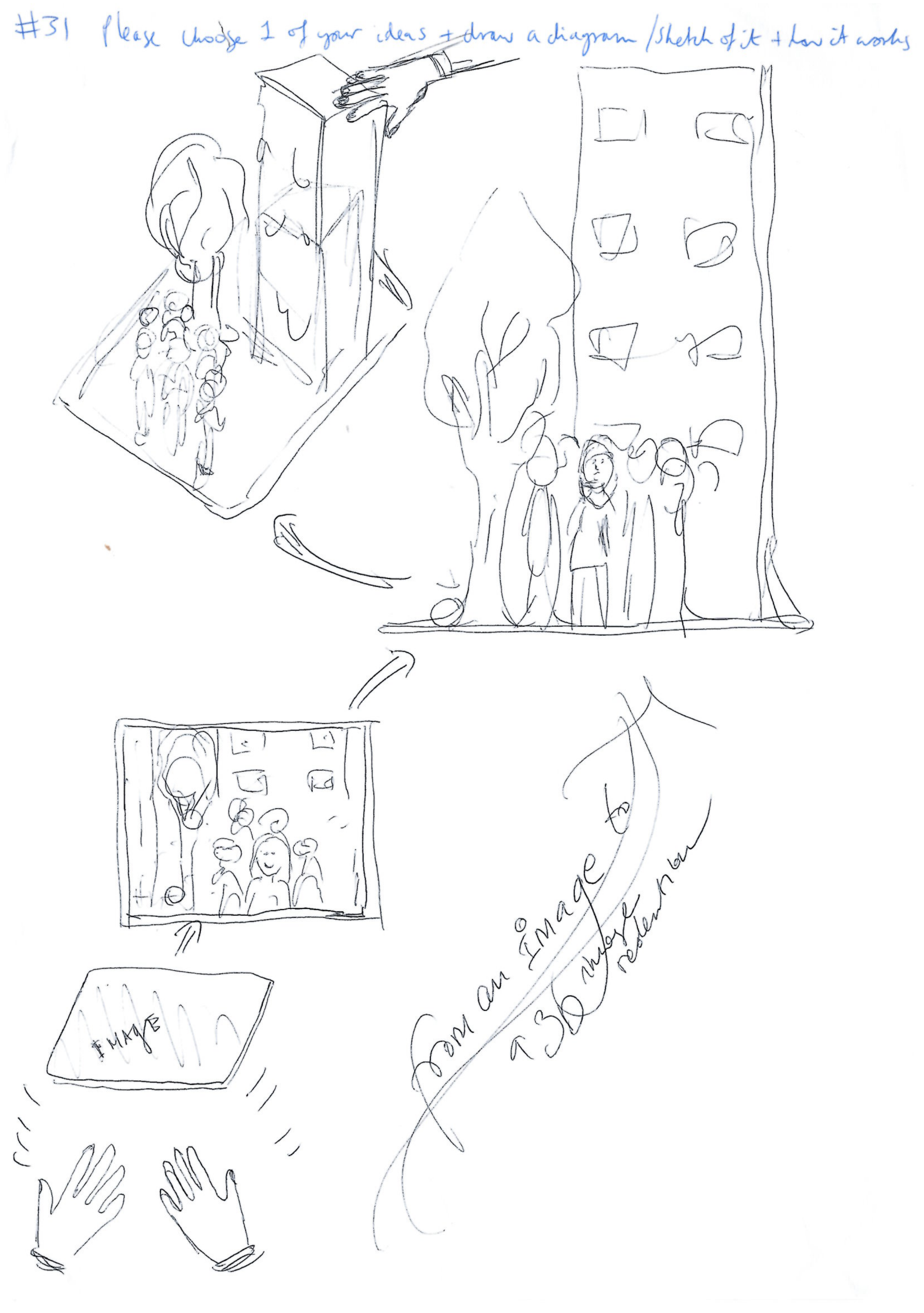


Fig. B.46 Participant 31 diagram

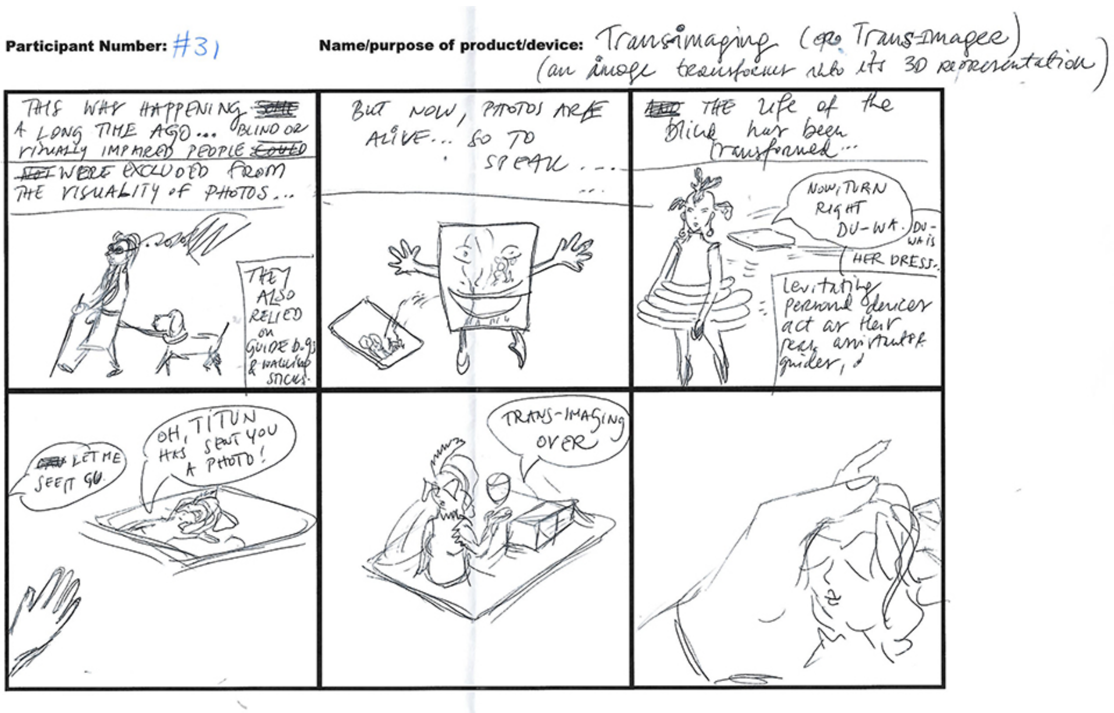


Fig. B.47 Participant 31 scenario

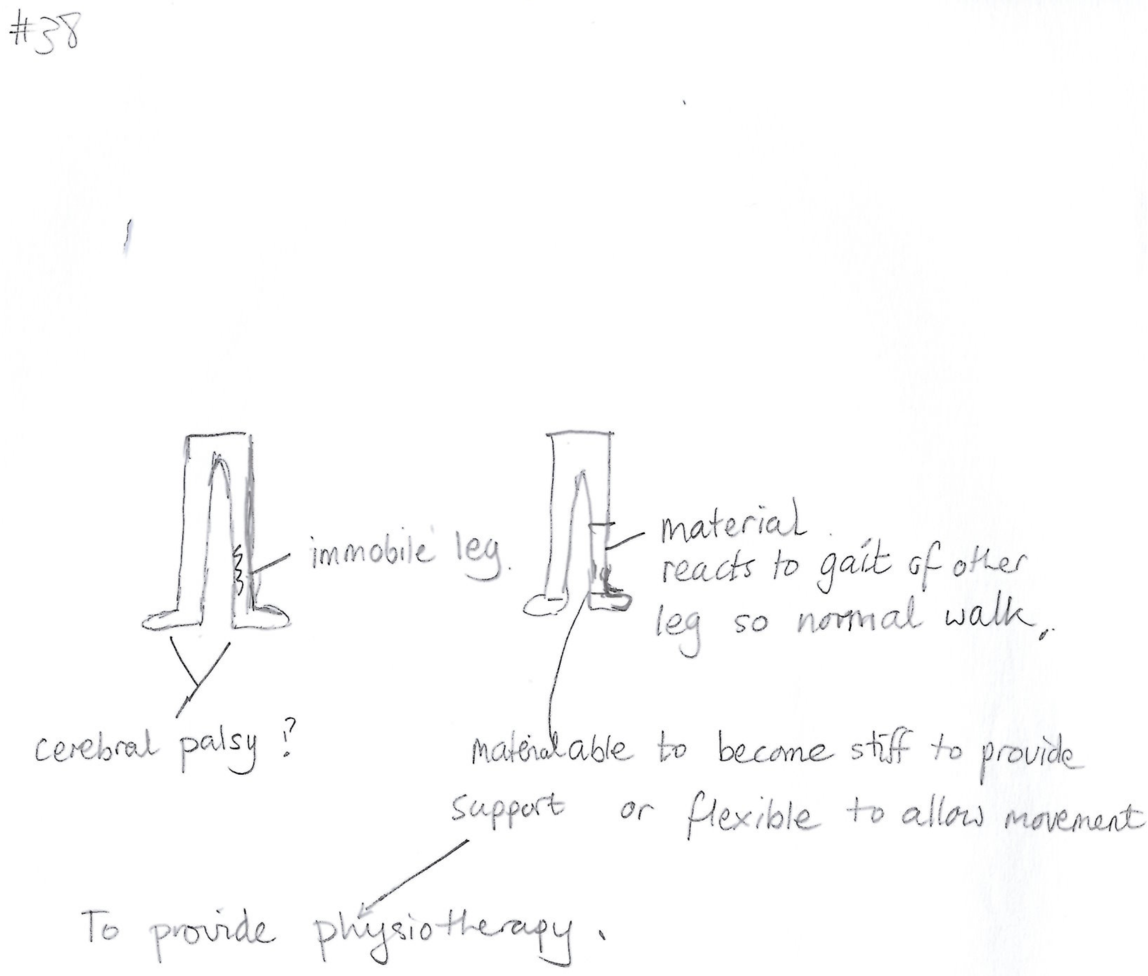


Fig. B.48 Participant 38 diagram

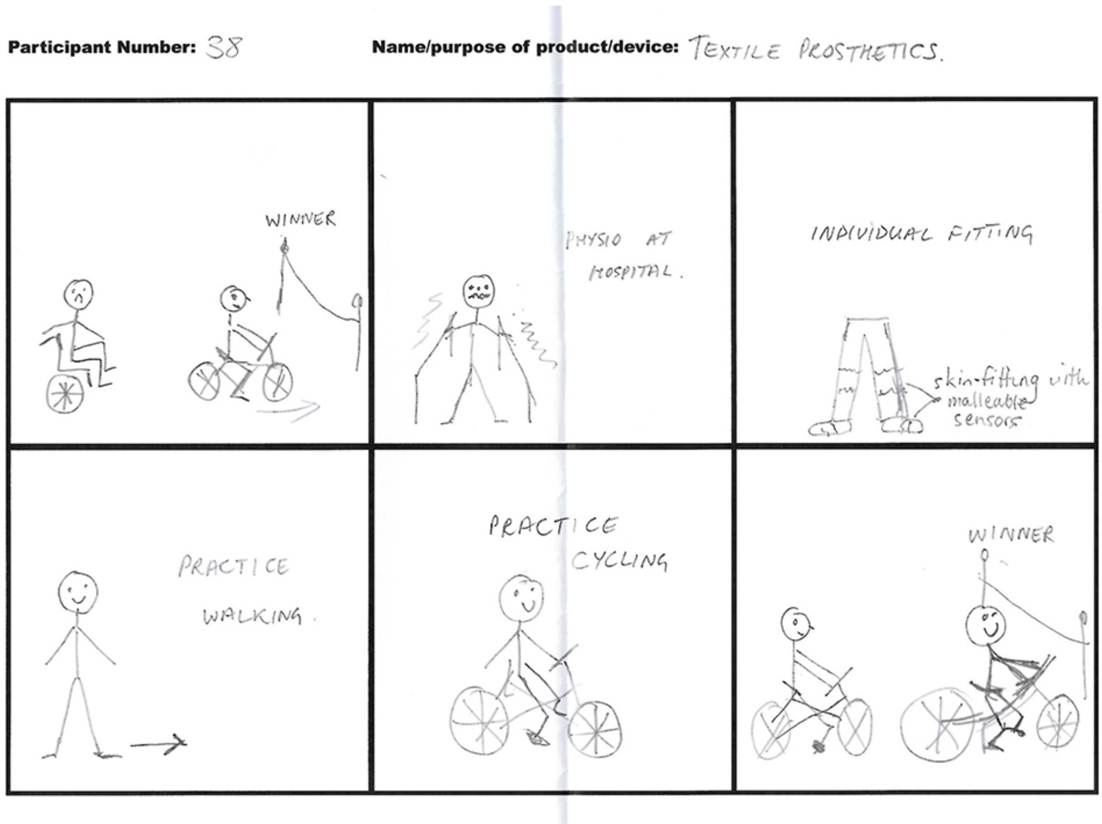


Fig. B.49 Participant 38 scenario