Analysis and Classification of Shape-Changing Interfaces for Design and Application-based Research

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Shape-changing interfaces are physically tangible, interactive devices, surfaces, or spaces that allow for rich, organic, and novel experiences with computational devices. Over the last 15 years, research has produced functional prototypes over many use applications; reviews have identified themes and possible future directions but have not yet looked at possible design or application-based research. Here, we gather this information together to provide a reference for designers and researchers wishing to build upon existing prototyping work, using synthesis and discussion of existing shape-changing interface reviews and comprehensive analysis and classification of 84 shape-changing interfaces. Eight categories of prototype are identified alongside recommendations for the field.

CCS Concepts: • **Human-centered computing → Human computer interaction (HCI)**; **Interaction devices**; **Interface design prototyping**;

Additional Key Words and Phrases: Shape-changing interfaces, TUI, GTUI, application design, classification

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1 INTRODUCTION

Shape-changing interfaces are physically geometric dynamic computational systems that 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 human–computer interaction (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

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et al. (2013) and Jansen and Dragicevic (2013)—at present, many applications are either preexisting program types (such as music players or book readers) (Lahey et al. 2011) or designed for one specific iteration of a device as a demonstration of its capabilities (Leithinger et al. 2014). 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 multidimensional devices.

Poupyrev et al. (2007) suggested 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 1). Additionally, while researchers have started to try to make sense of the design space of shape-changing interfaces, in which multiple dimensions must be considered at the same time (Kwak et al. 2014; Coelho and Zigelbaum 2011; Vallgårda 2014), 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 (Ishii et al. 2012) 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 (e.g., Troiano et al. (2014) and Gomes et al. (2013)), 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 (Hardy et al. 2015; Holman et al. 2013) 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 (Coelho and Zigelbaum 2011; Rasmussen et al. 2012; Nørgaard et al. 2013; Kwak et al. 2014), interaction studies (Holman et al. 2013; Nguyen et al. 2014), prototyping tools for shape change (Hardy et al. 2015), 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, hybridization, limitation in design, future use cases, emotionality and user experience, future use cases, perception theory, and the notion of temporal design and ethics, while considering how speculation might inform future work.

Tangible User Interfaces (TUIs) are swiftly making inroads into retail reality (e.g., Nokia's *Kinetic Device* (Kildal et al. 2012)), merging with shape-changing displays to create proto-GTUIs (Graphical-Tangible User Interfaces). Holman and Vertegaal (2008) 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. Thus, 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 the first to provide a comprehensive analysis and categorization of existing prototypes. The latter is necessary in order to begin to formalize design for the field and should be used to inform detailed application design for current shape-changing interfaces in the research context.

This article contributes a contemporary meta-analysis of shape-changing design theory, a detailed database of shape-changing prototypes, and a categorization of types of shape-changing interface (*Enhanced 2D, Bendable, Paper and Cloth, Elastic and Inflatable, Actuated, Liquid,* *Malleable, and Hybrid*). The aim of the article 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 RELATED WORK

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 1. The contribution of this article 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 categorization of prototypes within this context. This is the first time that the field of shape change has been examined in as much breadth and depth, building upon the valuable contributions made by the researchers discussed below.

The review of shape-changing interfaces in Rasmussen et al. (2012) 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 (2014) states, a "new expectation of the computer is already being formed," we 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, in which 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 et al. (2014) 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 that 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 that cover a range of deformations and actions (*Piega, Gato, Yeti, Fantom, Squeezy, and Bulge*). These prototyping devices mirror the most common deformation styles found in shape-changing interfaces (barring 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 *Nonuniform Rational B-Splines*, Roudaut et al. (2013) propose a framework for shape resolution aimed at assisting engineers in creating high-resolution displays. This framework is only as good as the technology allows, though, and its advanced features will need to be applied gradually. It also applies only to those mechanisms that can be thought of as having nodes/loci of control (as seen in a mesh overlay) and thus applies only in part to shape-changing materials, which also require thinking in other dimensions that may not be so constrained.

Coelho and Zigelbaum (2011) focus on all possible realities for shape change in a speculative manner and further provide an interesting overview of the field as it was in 2011. By combining the multiple dimensionality of shape-changing interfaces, they begin construction of a soft mechanical alphabet for HCI (after 18th-century engineer Polhem) with which designers can orient themselves for this conceptually complex research area. This notion supports this review in regard to the need for a modular design theory for those wishing to engage in application design for GTUIs.

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

2015)), 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.

3 CONSOLIDATION OF SHAPE-CHANGE THEMES

A meta-analysis of papers from Coelho and Zigelbaum (2011), Roudaut et al. (2013), Taher et al. (2016), Rasmussen et al. (2012), and Kwak et al. (2014) was conducted, alongside complimentary information from Nørgaard et al. (2013), Schmid et al. (2013), and Hardy et al. (2015) 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 simultaneoulsy to ensure that all dimensions of change were covered. The categorizations provided by each researcher have been mapped alongside one another in Figure 1. Following analysis of these papers, it was also found that the types of change that one needs to consider when thinking around the topic of design followed closely to Vallgårda (2014) "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 summarize the sections in Figure 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 et al. (2013)—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 multifaceted aspect of a GTUI and requires a more detailed overview (see Rasmussen et al. (2012)). Rasmussen et al. (2012) suggest three types of interaction in shape change: direct, indirect, and remote. These types have been used in applying classification to the existing prototypes in Tables 1 to 8, as well as including types of input/output. These are discussed in the next section.

Temporality is a relatively new concept in 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.

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 formalize the nature of this area—all these categories are discussed in more detail in Section 4. The information in Tables 1 to 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 article.

4 APPLICATION TO EXISTING PROTOTYPES

Having condensed current theory into a meaningful summary (Figure 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 regard to design and applications. The category descriptions in the previous section have been 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 that give additional information (such as 2D/2.5D/3D).

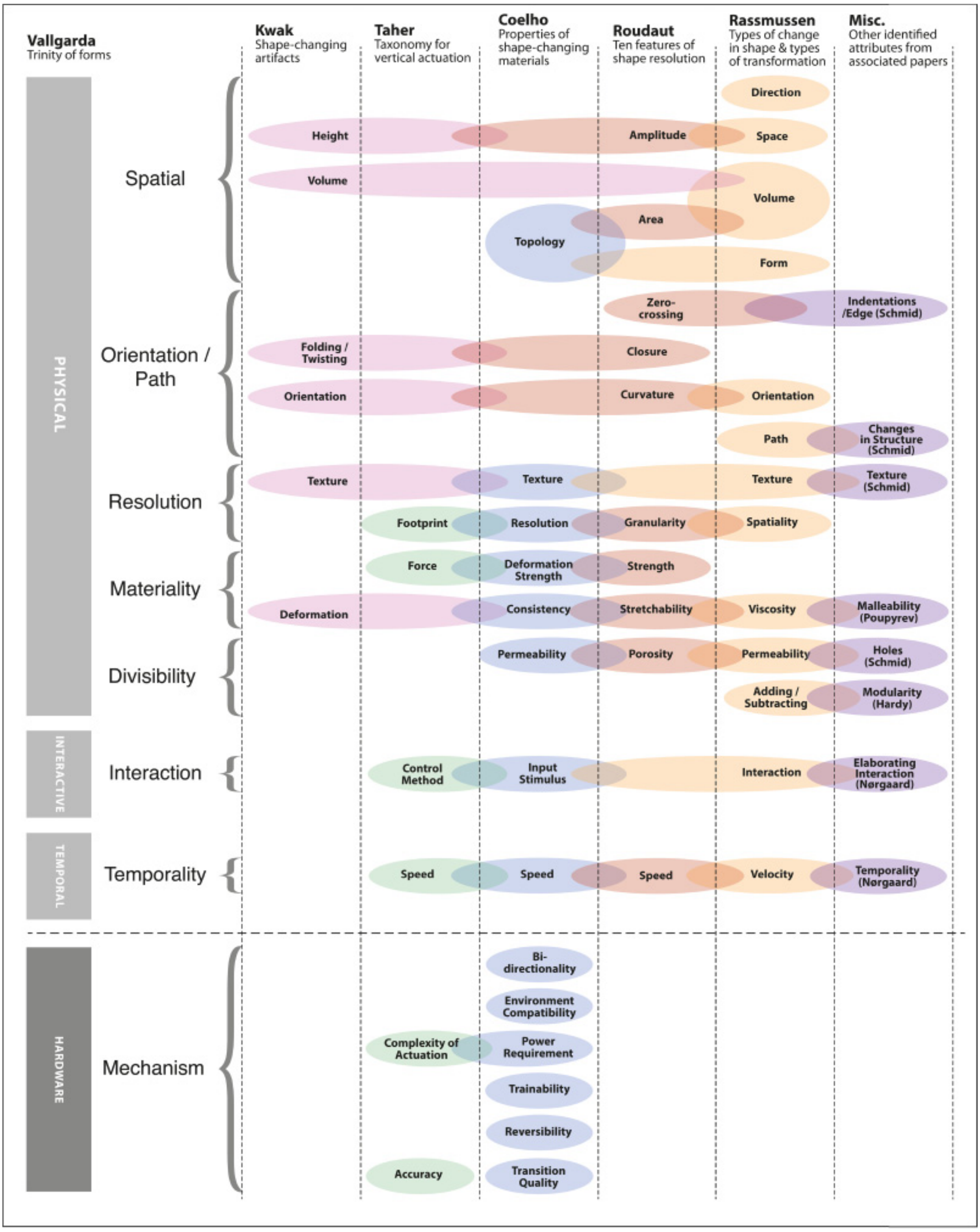

Fig. 1. Meta-analysis of shape-change review papers, taxonomies, and categorizations.

Tables 1 to 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 the review of 44 papers on shape-changing interfaces in Rasmussen et al. (2012) but with more refined criteria for inclusion and a tabulated analysis that compares the field. Figure 3 provides a graphical overview of this categorization in order to compare bgroups at a glance. Further to this, a summary table (Table 9) outlines the main features of the display categories.

4.1 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* (Follmer et al. 2012) and *Behind-the-Tablet Jamming* (Follmer et al. 2012) 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 (Follmer et al. 2012). The same reasoning applies to TUI input-only devices such as *BendID* (Nguyen et al. 2014) and *AR-Jig* (Anabuki and Ishii 2007). Additionally, although Asif Khan's *Megafaces* (Khan 2014) is an exemplar of a hydraulic actuated display—reflecting 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 *Garden Agua* (Guo et al. 2013)—despite being described as a shape-changing display in the literature—as it deals only with movable solid objects and not surface deformation. The same premise also applies to *Ariel Tunes* (Alrøe et al. 2012) 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* (Nakajima et al. 2013).

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 utilized in order to establish something novel. The same also applies to nondeformable 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 criteria 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.

4.2 Dimensions of Shape Change

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

4.3 Hardware

The mechanism, or hardware, of each device is directly linked to its shape-changing properties (see Figure 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 have been identified from current prototypes, which can be combined to create amalgams of shape and display. Each table outlines a primary and/or secondary mechanism in which this is integral to the interaction of the prototype. Incidental structural materials, such as latex or wood, are omitted from this list.

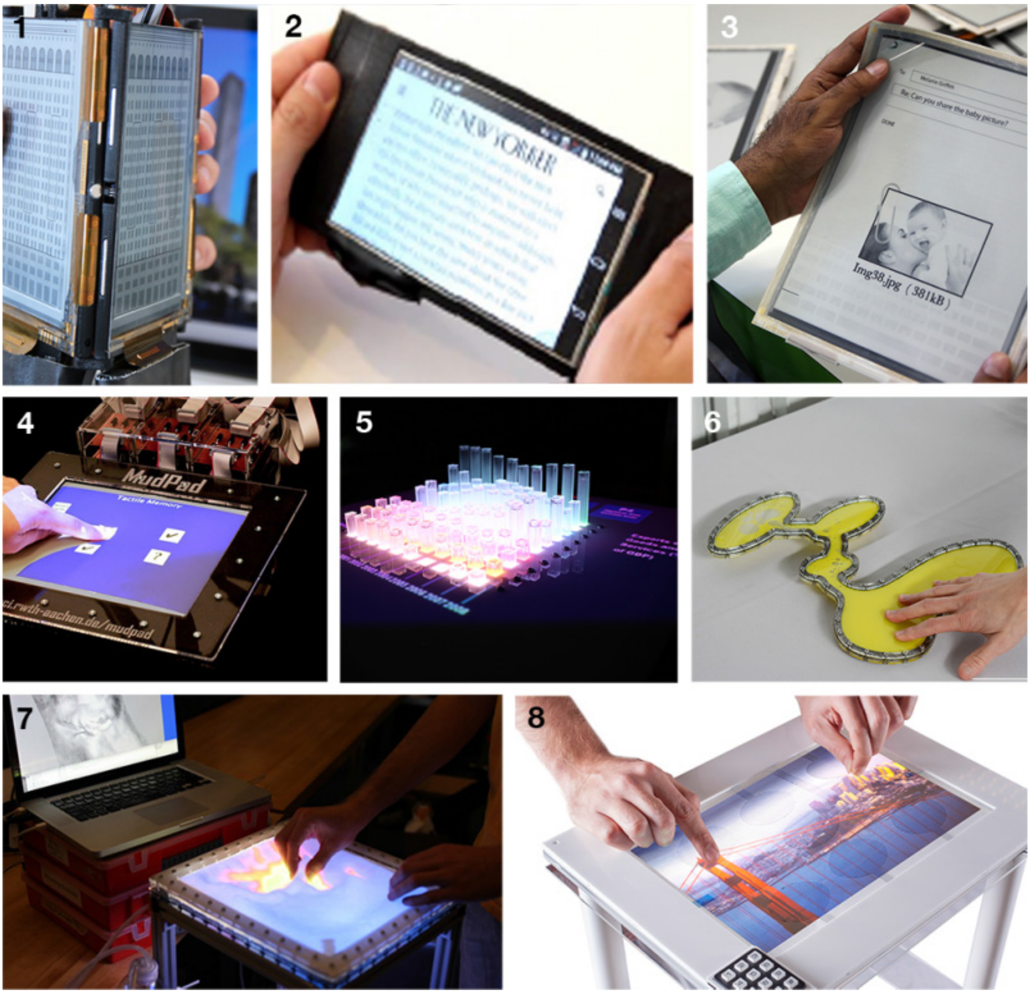

Fig. 2. Current prototypes corresponding to the 8 categories of shape-changing interfaces identified by this review: 1. Enhanced 2D – *PaperFold* (Gomes and Vertegaal 2015); 2. Bendable – *Reflex* (Strohmeier et al. 2016); 3. Papers and Cloths – *PaperTab* (Tarun et al. 2013); 4. Elastics and Inflatables – *Mudpad* (Jansen et al. 2011); 5. Actuated – *Emerge* (Taher et al. 2015); 6. Liquids – *Linetic* (Koh et al. 2013); 7. Malleables – *Tunable Clay* (Follmer et al. 2012) *(courtesy of MIT Media Lab Tangible Media Group)*; 8. Hybrids – *TableHop* (Sahoo et al. 2016).

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 commercialization phase) or would require additional levels of detail and discussion for each individual prototype, which is not possible within the scope of this article.

4.3.1 Bidirectionality. Whereas Coelho and Zigelbaum (2011) stated that bidirectionality is specifically important for designers, it is not an exclusive construct within shape-changing prototypes and thus has not been applied to the list. Bidirectionality 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., nonbidirectionality might be seen in the case of clay-based interfaces, in which the user can deform the surface but the surface itself is passive, in which case it must be manually "reset").

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* (Ramakers et al. 2014), which utilizes purely user-controlled deformation. For *Paddle* to exhibit bidirectionality, 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 bidirectionality in limited ways, however: *ShapeClip* (Hardy et al. 2015) is bidirectional 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* (Everitt et al. 2016), however, which uses the same base mechanism). The same applies to *LightCloth* (Hashimoto et al. 2013), 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 bidirectionality is not a given and, as such, not essential in the design of shape-changing applications, as meaningful interactions can be had across modalities.

4.3.2 Environmental Compatibility/Power Requirement. Environmental compatibility (the suitability of a device for its environment (Coelho and Zigelbaum 2011)) and power requirement are important considerations for the future of shape-changing devices, but at present are not included because of the prototypical nature of the examples due to the immaturity of the field. Therefore, these are future considerations. The application of shape change in real-world scenarios must come before situational problem-solving at this stage.

4.3.3 Reversibility, Transition Quality, and Accuracy. Of the remaining aspects of the hardware, reversibility is a given for shape change in this case; 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, we 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.

4.4 Interactive

The interactive aspects of shape change have been expanded from Figure 1 as these are the most important aspects of shape-changing interfaces: without the user, a prototype is passive or remote (Rasmussen et al. 2012). Interaction is primarily defined by Rasmussen's initial review of shape change and can be defined as *direct*, *indirect,* and *remote*, tdiscussed below. Interactive shape-changing art installations are included if they fulfill the earlier criteria (such as *AegisHyposurface* (Goulthorpe et al. 2001) or *Protrude, Flow* (Kodama 2008)).

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* (Sato et al. 2014)), without the need for an additional item such as a ring or wand (as is the case with *Linetic* (Koh et al. 2013)). *Indirect* proximity requires an additional construct for the user to interact (such as a connected laptop, as with *Flexkit* (Holman

Fig. 3. Overview of shape-changing prototype categories.

et al. 2013)) or the user can use midair 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 table records only current iterations. Smell, for example, has been used in *clayodor* (Kao et al. 2015) 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 nonvisible, 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 (Gomes et al. 2013) or visual imagery (Olberding et al. 2014)); gesture (Hardy et al. 2015; Koh et al. 2013); touch/haptic (Tsimeris et al. 2013; Nojima et al. 2013); light (Steimle et al. 2013); sound (Goulthorpe et al. 2001); and deform (separate from simple touch sensitivity, this implies that some force or movement is applied to change the shape of the available surface, whether it is bending (Tarun et al. 2013), pushing (Follmer et al. 2013), or more advanced deformation (Sato et al. 2014)).

Output is currently limited to form (as discussed in relation to bidirectionality), e.g., Roudaut et al. (2014) and Wakita and Nakano (2012); sound (deliberately generated, as opposed to an incidental sound generated by the mechanism) (Koh et al. 2011); light (often as an artifact of projection (Leithinger et al. 2013) or internally generated (Poupyrev et al. 2004)); and text/image (Alexander et al. 2012; Makino and Kakehi 2011).

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* (Khalilbeigi et al. 2011) 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 (Leithinger et al. 2014) is specifically designed to support remote interaction between two users. *Aegis Hyposurface* (Goulthorpe et al. 2001) 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.

4.5 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 (Vallgårda 2014) (see Figure 1). Understanding the limitations of time and speed for each prototype is essential for implementing successful design strategies. While categorizing existing work for Tables 1 to 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* (Goulthorpe et al. 2001), which can move up to 100 km per hour; *material defined*—limitations are placed on the speed with which a change can take place due to material constraints, such as with SMAs (Roudaut et al. 2013) or actuators (Nojima et al. 2013); and *user defined*—the user controls the speed of deformation via direct deformation at a chosen speed (but within the limits of the device) (Koh et al. 2013); or all three (Hardy et al. 2015).

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 that 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.

4.6 Physical

The physical characteristics of shape change emerge as quite distinct from the consolidated dimensions seen in Figure 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 (nondeformed 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 (Goulthorpe et al. 2001) 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 instance (Ou et al. 2014), or due to a device having the capability to be unfolded, such as with *Paddle* (Ramakers et al. 2014).

Bend is most common with flexible displays such as *Morphees* (Roudaut et al. 2013), in which 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 in which a ferrofluid is used (*pBlob* (Wakita and Nakano 2012)) or edges meeting with a static surface (*PaperFold* (Gomes and Vertegaal 2015)).

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 (Khalilbeigi et al. 2011).

Table 1. Enhanced 2D Prototypes Comparison Table Based on the Consolidated Dimensions in Figure 2

		HARDWARE		INTERACTIVE																TEMPORAL			PHYSICAL														
		MECHANISM		*PROXIMITY*			*INPUT*						*OUTPUT*				*USERS*			*CONTROL*			*SPATIAL*		*ORIENTATION AND 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**
ENHANCED 2D PROTOTYPES	*Display Stacks (Girouard et al. 2012)*	OLED		x	x		x	x	x			x			x	x		x				x	x		x					x		x	x		
	FoldMe (Khalilbeigi et al. 2012)	Projection		x		x	x		x			x		x	x	x	x					x		x		x	x					x	x		
	Paddle (Ramakers et al. 2014)	Projection		x					x			x	x	x		x	x					x	x	x		x	x					x	x		
	PaperFold (Gomes and Vertegaal 2015)	Electrophoretic		x	x	x	x		x							x		x				x	x	x	x	x	x			x		x	x		
	Shape Shifting Wall (Takashima et al. 2016)	Roomba Create	Projection	x	x		x	x	x			x	x			x			x	x		x		x			x			x		x	x		
	Transform Table (Takashima et al. 2013)	Projection		x	x		x		x				x		x	x			x	x				x			x					x	x		
	Xpaaand (Khalilbeigi et al. 2011)	OLED		x					x			x						x				x		x				x				x	x		

Table 2. Bendable Prototypes Comparison Table Based on the Consolidated Dimensions in Figure 2

		HARDWARE		INTERACTIVE																	TEMPORAL			PHYSICAL													
		MECHANISM		*PROXIMITY*			*INPUT*						*OUTPUT*				*USERS*			*CONTROL*			*SPATIAL*		*ORIENTATION AND 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 (Lo and Girouard 2014)*	Projection		x								x			x	x	x					x	x	x	x							x	x		
	Bookisheet (Watanabe et al. 2008b)	Projection		x					x			x			x	x	x					x	x	x	x	x						x	x		
	Cobra (Ye and Khalid 2010)	Projection		x	x		x		x			x	x		x	x	x					x	x	x	x							x	x		
	Device Bend Gesture (Ahmaniemi et al. 2014)	OLED		x		x	x		x			x		x	x	x	x					x	x	x	x							x	x		
	Flexkit (Holman et al. 2013)	Electrophoretic		x	x		x		x			x				x		x				x	x	x	x							x	x		
	Flexible Input Device (Gallant et al. 2008)	Projection		x	x		x	x	x	x		x			x	x	x					x	x	x	x	x	x	x				x	x		
	Nokia Kinetic (Kildal et al. 2012)	OLED		x			x		x		x	x	x	x	x	x	x			x		x	x	x	x							x	x		
	ReFlex (Strohmeier et al. 2016)	FOLED	Haptic Actuator	x		x	x		x			x		x	x	x	x				x	x	x	x	x							x	x		
	Snaplet (Tarun et al. 2011)	Electrophoretic		x	x	x	x		x			x	x	x	x	x	x			x		x	x	x	x							x	x		
	WhammyPhone (Gomes et al. 2016)	FOLED		x			x		x		x	x		x	x	x	x					x	x	x	x							x	x		

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 (such as latex) and used over actuators (Harrison and Hudson 2009) or in jamming (Sato et al. 2014).

Divide suggests either a modularity in actuators or components as seen in *Hairlytop* (Nojima et al. 2013), *PaperFold* (Gomes and Vertegaal 2015), and *ShapeClip* (Hardy et al. 2015), or where a solution can be split into parts and reunited, as in *pBlob* (Wakita and Nakano 2012). *Shutters* (Coelho and Maes 2009) 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. (2013) and incorporates the textural element as discussed earlier in Section 3 (Nørgaard et al. 2013). 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 the fact that 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 for which there is sufficient deformation possibility that the design surface would need to allow for form if the display were 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.

5 CATEGORIZATION 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 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 than to an actuated interface (i.e., it is impossible to stretch a solid-state pneumatic pin).

The 8 categories are: *Enhanced 2D* (Table 1), *Bendables* (Table 2), *Cloths and Papers* (Table 3), *Elastics and Inflatables* (Table 4), *Actuated* (Table 5), *Liquids* (Table 6), *Malleables* (Table 7) and *Hybrids* (Table 8). These categories are clear groupings that 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 9 and 10. Additionally, example photographs of prototypical devices within each category can be seen in Figure 2. Each category is discussed in detail below.

5.0.1 Enhanced 2D. Prototypes make use of multiple incidences of 2D screens that flex along either axis (see Table 1). Prototypes must have one or more screens or extra surface available that operates independently from its primary interface surface (see Figure 2.1 and Figure 3). The primary method of shape change is touch defined (with the exception of *TransformTable* (Takashima et al. 2013)). 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 multiscreen interactions or applications and either exploit or avoid the ensuing perceptual angles allowed by such prototypes (e.g., when a geometric shape, such as a boat, is constructed (Gomes et al. 2013)). With regard to this, designers should also 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; therefore, there are existing precedents (e.g., *Nintendo DS*$^{\text{TM}}$).

Table 3. Cloth and Paper Prototypes Comparison Table Based on the Consolidated Dimensions in Figure 2

		HARDWARE		INTERACTIVE																TEMPORAL			PHYSICAL												
		MECHANISM		*PROXIMITY*			*INPUT*						*OUTPUT*				*USERS*			*CONTROL*			*SPATIAL*		*ORIENTATION AND 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**
PAPER AND CLOTH PROTOTYPES	*Cloth Displays (Lepinski and Vertegaal 2011)*	Projection		x	x			x	x			x			x	x	x				x	x	x	x	x	x	x	x	x		x				x
	Flexpad (Steimle et al. 2013)	Projection		x	x		x			x		x				x	x					x			x	x	x	x				x		x	
	FluxPaper (Ogata and Fukumoto 2015)	Electromagnetic		x	x		x		x			x	x				x			x	x	x	x	x	x	x	x	x		x		x		x	
	FuSA 2 (Nakajima et al. 2011)	Optical Fiber	Projection	x					x	x		x			x	x		x			x	x	x		x					x		x		x	
	IllumiPaper (Klamka and Dachselt 2017)	Electrochromism	Electroluminescence	x	x				x						x	x	x					x			x	x	x	x		x		x	x		
	jamSheets (Ou et al. 2014)	Jamming	Projection	x			x		x			x	x		x	x		x		x		x	x	x	x	x	x	x	x	x	x				x
	LightCloth (Hashimoto et al. 2013)	Optical Fiber		x	x					x		x	x		x			x				x	x		x	x	x	x			x		x		
	Metamorphic Light (Makino and Kakehi 2011)	Projection		x	x			x	x			x			x	x	x					x			x	x	x	x				x	x		
	Murmur (Rydarowski et al. 2008)	CPU Fans			x						x		x						x	x	x	x	x		x		x					x		x	
	PaperPhone (Lahey et al. 2011)	OLED	Electrophoretic	x			x		x			x	x		x	x	x					x			x							x	x		
	PaperTab (Tarun et al. 2013)	Electrophoretic		x			x	x	x			x				x			x			x			x							x	x		
	PaperWindows (Holman et al. 2005)	Projection		x	x			x	x			x			x	x			x			x		x	x	x		x		x		x	x		
	PrintScreen (Olberding et al. 2014)	OLED	TEFL	x	x		x		x			x			x	x			x			x			x	x		x				x		x	
	Projectagami (Tan et al. 2015)	Projection		x					x			x				x	x					x	x	x	x	x	x	x				x	x		

Table 4. Elastic and Inflatable Prototypes Comparison Table Based on the Consolidated Dimensions in Figure 2

		HARDWARE		**INTERACTIVE**																**TEMPORAL**			**PHYSICAL**												
		MECHANISM		***PROXIMITY***			***INPUT***						***OUTPUT***				***USERS***			***CONTROL***			***SPATIAL***		***ORIENTATION AND 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 AND INFLATABLE PROTOTYPES	*Deformable Workspace (Watanabe et al. 2008a)*	Projection		x	x		x		x			x			x	x	x				x	x	x						x			x	x		
	DepthTouch (Peschke et al. 2012)	Projection		x					x			x			x	x	x				x	x	x		x		x		x			x	x		
	ElaScreen (Yun et al. 2013)	Projection		x								x			x	x	x				x	x	x						x			x	x		
	Emoballoon (Nakajima et al. 2013)	Pressure Sensor		x					x			x			x		x				x	x	x	x					x			x			x
	Flexiwall (Franke et al. 2014)	Projection		x					x			x			x	x			x		x	x	x				x		x			x	x		
	ForceForm (Tsimeris et al. 2013)	Electromagnetic		x			x		x			x	x				x			x	x	x	x						x			x	x		
	Inflatable Hemispherical Multitouch Display (Stevenson et al. 2011)	Projection		x			x		x	x		x	x	x	x	x		x		x	x	x	x						x			x		x	
	Mudpad (Jansen et al. 2011)	Projection		x			x		x			x			x	x		x				x	x						x			x	x		
	Volflex (Iwata et al. 2005)	Projection		x					x			x			x	x	x					x	x	x	x		x		x		x				x

5.0.2 Bendables. These devices have one display and interaction surface, but that surface can bend or flex at the corners, middle, and edges (including twist; Table 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.

Bendables account for just over 10% of the surveyed prototypes (10/84), largely focusing on either input and interaction (Watanabe et al. 2008b) or physical, unobtrusive notifications (Lo and Girouard 2014). 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. (2012, 2013). The prospect of anthropomorphizing 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 (Gomes et al. 2013)).

5.0.3 Papers and Cloths. Table 3 shows prototypes that fulfill the criteria of *Papers and Cloths.* These prototypes have one interaction surface but are highly adaptive in terms of orientation and path, mimicking the characteristics of their noninteractive base materials. Deformation is primarily user controlled. These prototypes can borrow from web design (in that reflowable content to fit the visually available area is used) or can be repurposed into novel interface designs (wearables/furniture).

Around 16% of the prototypes in this summary are *Papers and Cloths* (14/84). Devices of this nature would be beneficial in situations in which 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 in which viewing size is important across a range of scenarios.

5.0.4 Elastics and Inflatables. Elastics and Inflatables are deformable interfaces that are made up of materials with built-in stretch, such as *Elascreen* (Yun et al. 2013). 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* (Nakajima et al. 2013)) but usually have limited shape resolution (with the exception of jamming interfaces (Follmer et al. 2012)). Like *Bendables*, they can also exhibit *emotional* characteristics.

Just over 10% of shape-changing prototypes exhibit criteria that assign them to this category (9/84). Large-scale elastic screens (Troiano et al. 2014) 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 multiple users needing to collaborate on demand.

5.0.5 Actuated. While 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 (Goulthorpe et al. 2001). Some *actuated* prototypes have visual displays built in. These prototypes usually have one repeated movement (bidirectional) and a limited height from baseline (flattened plane).

Actuated interfaces make up the largest proportion of shape-changing interface prototypes at just over one-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 that range from calm, environmental computing (Cheng et al. 2014) to communicative architecture (Coelho and Maes 2009). 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 (Weichel et al. 2015). This is a vital step in giving other researchers and application designers the tools they need to build meaningful interactions for such devices.

5.0.6 Liquids. Liquid prototypes are complex, spanning 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 (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 (Koh et al. 2013)) 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 hybridization with *jamming* (Follmer et al. 2012).

5.0.7 Malleables. Malleables are claylike or jamming substrates that afford the user a pliable, deformable surface with which to create high shape-resolution forms. Jamming does not take center stage here, as other materials have been used to create the same rigidity and control (e.g., *Tunable Clay* (Follmer et al. 2012)). These prototypes have multidimensional input/output, but rely mainly on projection to supply equally high-resolution graphics.

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 visualizing complex graphics means that these devices are not portable yet. In their current state, they are best suited to permanent installations or interactive multiple-user scenarios.

5.0.8 Hybrids. Hybrid interfaces are relatively new in the field, combining 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 that we have on these, they are shown as a final, complex category. *TableHop* (Sahoo et al. 2016), *Obake* (Dand and Hemsley 2013), and the second iteration of *Mephistophone* (Herman et al. 2015) combine an *actuated* base with an *elastic* surface to create additional methods for user interaction. This layering up of mechanisms is reminiscent of the space-suit glove prototype of Seah et al. (2015), which enables those in sealed suits to experience physical textures. However, much attention has been given regarding the three hybrid prototypes to the complexity of interaction *between* layers and in combination. Table 8 shows an overview of the current Hybrid interfaces.

Although some of the other 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, crossing different modalities and 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.

Table 5. Actuated Prototypes Comparison Table Based on the Consolidated Dimensions in Figure 2

		HARDWARE		INTERACTIVE																TEMPORAL			PHYSICAL													
		MECHANISM		*PROXIMITY*			*INPUT*						*OUTPUT*				*USERS*			*CONTROL*			*SPATIAL*		*ORIENTATION AND 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* *(Nakatani et al. 2005)*	SMA		x	x		x		x			x	x		x		x			x	x	x	x									x		x	
	Aegis Hyposurface *(Goulthorpe et al. 2001)*	Pneumatic		x	x	x	x	x	x	x	x	x	x		x	x			x	x			x								x			x	
	BubbleWrap *(Bau et al. 2009)*	Electromagnetic		x	x		x		x			x	x	x			x			x		x	x						x			x		x	
	ChainFORM *(Nakagaki et al. 2016)*	Servo Motor		x		x	x		x			x	x		x	x	x			x		x	x	x	x	x	x	x		x		x		x	
	Changibles *(Roudaut et al. 2014)*	Servo Motor		x	x	x	x		x				x						x	x	x		x	x						x		x			x
	EMERGE *(Taher et al. 2015)*	DC Motor	Projection	x	x		x		x			x	x		x	x			x	x		x	x									x		x	
	FEELEX2 *(Iwata et al. 2005)*	Servo Motor	Projection	x	x	x	x		x			x	x		x	x			x	x		x	x								x			x	
	Hairlytop *(Nojima et al. 2013)*	SMA		x	x		x		x	x		x	x				x				x	x	x	x	x					x		x		x	
	inFORM *(Follmer et al. 2013)*	DC Motor	Projection	x	x	x	x	x	x	x		x	x		x	x		x		x		x	x									x		x	
	Kinetic Tiles *(Kim and Lee 2011)*	Electromagnetic		x		x	x					x	x			x	x			x		x	x						x	x		x		x	
	Lumen *(Poupyrev et al. 2004)*	SMA		x	x	x	x		x			x	x		x	x	x			x	x	x	x									x		x	
	Luminescent Tentacles *(Nakayasu 2016)*	SMA			x		x	x					x	x	x		x			x			x	x	x					x		x		x	
	Mood Fern *(Cheng et al. 2014)*	SMA		x	x		x		x				x						x	x	x	x			x			x				x	x		
	Morphees 1 *(Roudaut et al. 2013)*	SMA	Projection	x			x		x			x	x			x	x				x				x		x					x	x		
	Morphees 2 *(Roudaut et al. 2013)*	SMA	Electrophoretic	x			x		x			x	x			x	x				x				x							x	x		
	MorePhone *(Gomes et al. 2013)*	SMA	Electrophoretic	x		x	x		x			x	x			x	x				x	x			x							x	x		
	PolySurface *(Everitt and Alexander 2017)*	Stepper Motor	Projection	x	x	x	x		x	x			x		x	x			x	x	x	x	x		x		x			x		x		x	
	Pneuxel *(Yao et al. 2014)*	Pneumatic	Optical Fiber	x	x			x	x				x	x	x		x			x			x						x			x		x	
	Relief *(Leithinger et al. 2011)*	DC Motor	Projection	x	x		x	x	x			x	x		x		x			x		x	x									x		x	
	ShapeCanvas *(Everitt et al. 2016)*	Stepper Motor		x	x	x	x	x	x	x		x	x		x	x	x			x	x	x	x									x		x	
	Shape-Changing Tablet *(Lindlbauer et al. 2016)*	Servo Motor	Projection	x			x		x			x	x	x	x	x	x			x			x				x					x		x	
	ShapeClip *(Hardy et al. 2015)*	Stepper Motor	Projection	x	x	x	x	x	x	x			x		x				x	x	x	x	x							x		x		x	
	Shutters *(Coelho and Maes 2009)*	SMA			x		x			x			x			x			x	x	x				x		x			x		x		x	
	SoundFORMS *(Colter et al. 2016)*	DC Motor	Projection	x	x	x	x	x	x	x	x	x	x	x		x			x	x		x	x									x		x	
	Sprout IO *(Coelho and Maes 2008)*	SMA		x	x	x	x		x			x	x					x		x	x	x	x	x	x	x	x					x		x	
	Sublimate *(Leithinger et al. 2013)*	DC Motor	Projection	x	x	x	x	x	x			x	x		x	x			x	x			x									x		x	
	Taxel *(Kyung et al. 2011)*	Piezo-electric	Projection	x	x		x		x			x	x		x	x	x			x		x	x								x			x	
	Tilt Displays *(Alexander et al. 2012)*	Servo Motor	OLED	x	x		x		x				x		x	x		x		x		x	x							x		x		x	
	TRANSFORM *(Leithinger et al. 2014)*	DC Motor	Projection	x	x	x	x	x	x	x		x	x		x	x		x		x		x	x									x		x	

Table 6. Liquid Prototypes Comparison Table Based on the Consolidated Dimensions in Figure 2

		HARDWARE		**INTERACTIVE**																**TEMPORAL**			**PHYSICAL**												
		MECHANISM		***PROXIMITY***			***INPUT***						***OUTPUT***				***USERS***			***CONTROL***			***SPATIAL***		***ORIENTATION AND 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 (Campbell et al. 2015)*	Water	Projection	x									x				x				x	x							x	x		x	x		
	Linetic (Koh et al. 2013)	Electromagnetic	Ferrofluid		x		x	x					x	x			x				x	x	x						x		x			x	
	Liquid Interface (Koh et al. 2011)	Electromagnetic	Ferrofluid	x			x		x			x	x	x			x			x	x		x								x			x	
	pBlob (Wakita and Nakano 2012)	Electromagnetic	Ferrofluid		x		x	x					x				x			x	x		x	x		x				x	x			x	
	Protrude/Flow (Kodama 2008)	Electromagnetic	Ferrofluid		x		x	x					x				x			x	x		x	x		x					x				x

Table 7. Malleable Prototypes Comparison Table Based on the Consolidated Dimensions in Figure 2

		HARDWARE		INTERACTIVE																TEMPORAL			PHYSICAL												
		MECHANISM		*PROXIMITY*			*INPUT*						*OUTPUT*				*USERS*			*CONTROL*			*SPATIAL*		*ORIENTATION AND 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 (Sato et al. 2014)*	Jamming	Projection	x			x		x	x		x	x		x	x			x	x	x	x	x	x	x	x	x		x		x				x
	deForm (Follmer et al. 2011)	Clay	Projection	x	x				x	x		x	x		x		x				x	x	x						x		x			x	
	Illuminating Clay (Piper et al. 2002)	Plastiscene	Projection	x	x		x		x	x		x			x	x			x		x	x	x	x			x		x		x				x
	GelTouch (Miruchna et al. 2015)	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 (Vogt et al. 2004)	Projection		x					x			x			x		x				x	x	x				x		x			x		x	
	Sandscape (Ishii et al. 2004)	Glass Beads	Projection	x	x				x	x		x			x	x			x			x	x							x	x			x	
	Tunable Clay (Follmer et al. 2012)	Jamming	Projection	x	x					x		x	x		x				x	x	x	x	x	x	x		x		x		x			x	

5.1 Categorization Summary

The current state of the art is largely represented by this categorization of shape-changing interfaces (Tables 1 to 8). The field as a whole, however, is constantly evolving—there may be additions or whole new categories within a relatively short space of time. Each interface category has its strengths and weaknesses, which are continually evolving, making designing for such structures an iterative process. Many research papers suggest future design modifications for their existing prototypes; it is these that enrich and take the field forward.

A summary diagram of the prototype categories can be seen in Figure 3. An analysis of feature frequency across all 8 categories can be seen in Table 9. Table 10 provides an overview of the limitations and current uses for each prototype category. The overall comparison of features between categories (Table 9) produces some additional findings that offer another perspective for the analysis contained here. These are discussed below.

5.1.1 The Problem with Projection. Over half of all prototypes included in this dataset rely on one form or another of projection, e.g., back lit as with *TableHop* (Sahoo et al. 2016) or, more commonly, top lit, as is the case with *Metamorphic Light* (Makino and Kakehi 2011). 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. Alternatively, it shows that there is a need for advanced materials that have not yet been developed or are currently being developed, such as *Ultraflexible organic photonic skin* (Yokota et al. 2016). 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. This means that 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.

5.1.2 Multidimensional Change. Hardware and mechanism limitations can also affect the interactive qualities of devices. Poupyrev's notion of *RGBH shape pixels* (Poupyrev et al. 2007) reflects the current state of play but does not leave space for the exploration of multidimensional 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 expand on the interactions available to this subset of interfaces, combining the properties of a paper or cloth interface with the mechanized 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.

5.1.3 Number of Users. User data across the categories shows that just over half of all prototypes analyzed are developed for single users, although there is still a significant number that 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 that are discussed later.

5.1.4 Control. With regard 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*, in which 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

Table 8. Hybrid Prototypes Comparison Table Based on the Consolidated Dimensions in Figure 2

		HARDWARE		INTERACTIVE																TEMPORAL			PHYSICAL												
		MECHANISM		*PROXIMITY*			*INPUT*						*OUTPUT*				*USERS*			*CONTROL*			*SPATIAL*		*ORIENTATION AND 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 (Herman et al. 2015)*	Servo Motor	Projection	x			x	x	x		x	x	x		x	x			x	x	x	x	x		x				x			x		x	
	Obake (Dand and Hemsley 2013)	Linear	Projection	x	x		x		x		x	x	x		x	x			x		x	x	x	x	x	x	x		x		x			x	
	TableHop (Sahoo et al. 2016)	ITO Array	Projection	x	x	x	x	x	x			x	x	x		x			x	x	x	x	x		x				x			x		x	

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.

6 DISCUSSION

The story of shape change so far is one of prototyping within existing technological constraints. By creating content for what we have now, we will be able to lay the groundwork for a future shape-changing application design. With the vision-driven design of Ishii et al. (2012) we look to the future, but this can happen only when we have truly understood the present. Whereas Kwak's framework (Kwak et al. 2014) 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 with Kwak's explorations and toward Ishii's speculation into which this article places itself.

6.1 Supporting Application Design

The categorizations supplied in this article 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 they 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 the 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 and therefore what type of actuation best suits this outcome? A study wishing to analyze latency on moving pins would almost certainly need bidirectional 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 a 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 the context of the latter, if you need 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 shape clips but the advanced material properties of *Transform* (recently examined by Nakagaki et al. (2016)), you will need to decide which property is more salient for the research at hand.

Essentially, this article 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 multidisciplinary collaborations and within the field, although the following question is raised: is it the applications that will drive the technology or the technology that will drive or limit the design of applications?

6.2 Limitation in Design

A successful multidimensional 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 (Ishii et al. 2012)). These limiters actually reign in the design space and offer a firm ground from which to work backwards. A future in which devices have unlimited dimensional potential (such as Ishii's *Perfect Red* (Ishii et al. 2012)) 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 noninteraction, such as 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 user's 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 (Hardy et al. 2015) or width of their device (Khalilbeigi et al. 2011). 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. 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, whereas a projected, high-resolution image will interact in multiple ways with areas of height and deformation, presenting a challenge for users utilizing multiple viewing angles (Poupyrev et al. 2007).

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

Table 9. Category Summary of Prototypical Shape-Changing Interfaces Showing Totals Across the Consolidated Dimensions

		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 AND 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**

Temporality: Speed of change is sometimes limited by the hardware (such as with motorized actuators) and thus 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.

Holman et al. (2013) mentions the current limitations of readily available electrophoretic displays (<1 fps) 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 (Smith 2006) and vice versa (Fishwick 2003). This new space of shape-changing interaction design requires a new generation of multiskilled designer-coders; it is probably not enough to simply be a competent developer or designer when new technology stretches the limits of imagination.

6.3 Future Use Cases

Application of shape-changing prototypes is so far mostly limited to improving items that we already have in 2D, such as phones, tablets, and workspace. 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, Sturdee et al. carried out a study using a participant pool taken from the general public (Sturdee et al. 2015) 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 reimagine 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* (Schnädelbach et al. 2010)) turns our living space into an opportunity for interaction. Within shape change, *BubbleWrap* (Bau et al. 2009) 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 et al. (2012), 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. Hence developing user-experience design for this field is an important step.

6.4 User Experience and Emotionality

User-centered 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 multisensory 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 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" (Rasmussen et al. 2013)), and it is Rasmussen who is attempting to bring focus onto user experience in this field. To successfully create applications for these "magical" devices, designer, researcher, and user must collaborate in first developing a novel practice of user experience.

6.5 Perception

Few researchers make the connection between actuation and altered perceptive state. Poupyrev et al. (2007), however, mention 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

Table 10. Summary of the Features, Limitations and Current-Use Cases of Prototypical Shape-Changing Interfaces

Prototype	**Primary Feature**	**Limitation**	**Current-Use Cases**
Enhanced 2D	Multiscreen	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	Bidirectionality	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 Visualization

display could be altered to make perception easier from multiple locations, which also relates back to optical illusions (such as distorted advertising blocks on football pitches that 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, in which there is a distinction between how something looks and how something works. Fidelity in either one of these areas affects possible interactions and thus the overall look and feel of an application design.

6.6 Ethical Considerations

If our computers become tangible, we open ourselves up to the notion of unwanted tangible interaction, perhaps unsolicited, in the case of 3D spam (Munroe 2012). 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* (Goulthorpe et al. 2001) can move at speeds of 100kph, how can we design to prevent injury? Can closure of a surface cause trapped fingers and 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.

6.7 Future Work

The field of shape-changing interface prototypes as it currently stands is outlined in detail in this article. At the time of writing, researchers were already beginning to combine mechanisms and interactions between prototypes to create hybridized interfaces (Sahoo et al. (2016), Dand and Hemsley (2013), and Herman et al. (2015)). 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 the combined interactions of both interfaces, 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 in which all interactions are possible registers and even more complex problem to users, researchers, and designers. It is hoped that this categorization 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.

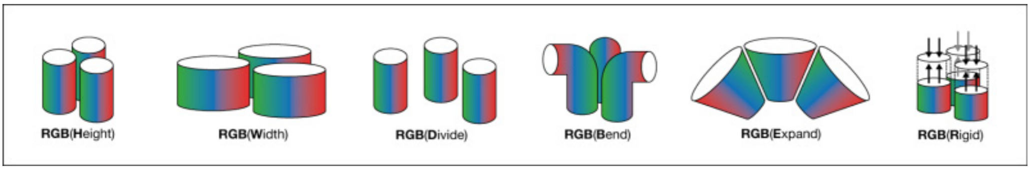

Fig. 4. Possible development of shape pixel states based on the RGB-H principle (Poupyrev et al. 2007).

Poupyrev et al. (2007) discuss the notion of RGBH graphics, in which color information is as we expect to find in GUIs but with pixel height as an added numerical component. 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 4 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 in future research.

The community surrounding these advances is often a highly specialized base of researchers and students; as such, user testing and the resulting inferences might be biased. Bannon (2011) mentions that the human side of HCI has been lacking in recent years, and Rasmussen et al. (2012) call for more high-quality data on user experience for shape change. By eliciting input from nonexpert users, we might realize new directions for shape change and nurture the design space. Finally, it is anticipated that the categorization of shape-changing prototypes will be added to as the field moves forward in coming years. Thus, there will more complex aspects for designers to consider along with the implications for the user.

7 CONCLUSIONS

This article has consolidated multiple reviews for shape change, mapped existing prototypes onto this 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 have been further reviewed in relation to application design for GTUIs and guidelines suggested to make the first steps toward a standardized future practice. The analysis and classification of shape-changing interfaces will be an ongoing task as these technologies develop. It is hoped that this review of the field will enable designers to make decisions about designing for these devices and carry out user studies relevant to specific applications and hardware. It is also hoped that creating transparency in the field might elicit new collaborations and prompt interdisciplinary research, as there are many opportunities. Future iterations should include investigation of nonstandard interface technologies, detailed user-experience analysis, and collaborative practice to inform a new paradigm of user-experience design and sample application design based on new guidelines that spring from the categorizations presented here.

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