Time for a Change: Examining Temporality in Shape-Changing Interfaces

Miriam Sturdee
Lancaster University
Lancaster, UK
m.sturdee@lancaster.ac.uk

Jason Alexander
Lancaster University
Lancaster, UK
j.alexander@lancaster.ac.uk

ABSTRACT

The development of dynamic, shape-changing interfaces as a method of human-computer interaction is receiving increasing attention in both research and manufacturing. The present focus is mainly on hardware development, rather than potential applications. To advance this area, considering temporality in shape-changing displays and interfaces is vital in understanding how to design applications for (and with) such devices. Prototypes within the field range from those which actuate changes at high speed, to the deliberately slow, with a complex range of temporal movement in between. Current research highlights the importance of temporal form in interaction design, and expressive movement, but this is yet to be applied in detail to shape-change. This paper examines the current state of play for temporality in shape-changing interfaces, examines the role of time and design in existing prototypes, and proposes an adaptive methodology for design utilising time, space and shape based on previous research.

Author Keywords

Temporal design; shape-changing interfaces; application design; time;

ACM Classification Keywords

H.5.2. Information Interfaces and Presentation (e.g. HCI): User Interfaces; Theory and Methods, Evaluation/methodology, Interaction Styles.

INTRODUCTION

The passing of time is a constant, measured via a variety of context dependent methodologies. In geology, we might view time in supereons, and in quantum mechanics this could be reduced to *Planck time*. In computing, we think of CPU processing in gigahertz, screen refresh rates in hertz, and data in Megabits per second. When a user clicks on a website link, they expect an almost instantaneous transition between one screen and the next. The passage of time is inexorable in all modalities, so therefore it is prudent to investigate how temporality in interaction with applications might occur when applied to the physicality of a shape-changing interface. Shape-changing interfaces are actuated interactive objects or surfaces with which we can support a complex range of movements and multiple sensory output. We are exposed to the concept of shape-change in organic materials in the world around us, coupled with continually changing textures and colours (Figure 1.). Many current research prototypes look to the natural world for inspiration, making this a valuable starting point to create a methodology of temporal design for shape-change.

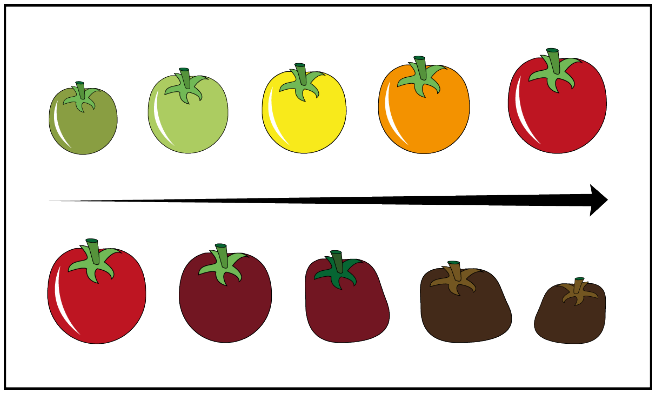

Figure 1. Shape-change, visual-transitions & texture variation across time in the natural world

Although the consideration of temporality has received attention in the field of interaction design and HCI [38] and is mentioned in reviews and prototype papers [5, 32], it has not yet been examined in relation to the field as a whole, and in particular, relating to existing prototypes from a design perspective - although there is growing inspiration to investigate the area of time and temporality [22].

We aim here to highlight the importance of temporal design in the creation of shape-changing applications, and provide the the basic application theory for designers wishing to begin working within this realm. If the design process begins with the current level of shape-changing technology, it can progress in-step with advances in the field, so that the delay between research and practical application can be minimised.

This paper examines the temporality of user-interactions with existing shape-changing interfaces and considers how time affects application design for physical 3D surfaces. It con-

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tributes: 1) An examination of time from the perspective of HCI and shape-changing interfaces; 2) A review of current prototypes outlining three types of time-based interaction, and recommendations for the field; 3) The findings of a workshop exploring notions of temporality in shape-changing interfaces, and 4) A discussion based around the future of time and application design for shape-changing interfaces.

RELATED WORK

Designing with time is not a new subject in HCI, and has received increased attention in the last decade. This attention has often been focused on applying novel temporal interactions to two-dimensional applications such as word-processing (in which text input is coloured depending on when it was input) and digital drawing (where lines become transparent with time, or images are continually sucked toward a central vortex) [21], user-experience studies looking at patterns of engagement with existing technology [17], personal time-lines within computing such as *FutureMe* [23] or memory aides in Alzheimer's patients [33]. However, interaction designers are actively embracing the concept in light of new advances in tangible computing, and time is becoming an important consideration in the creation of shape-changing prototypes and their exploration.

Temporality in Interaction Design

Interaction design is a mature field and a useful starting point for this discussion. We seek not to build an entirely new theory of design, but to supplement existing practice by emphasising the novel aspects of interaction within shape-change. Vallgarda's [38] *trinity of forms* states how the temporal form is inextricably linked to both the physical form and interaction gestalt, and that traditional methods of making physical form play a part in a practice that also encompasses time. The inter-dependencies discussed form the basis of this exploration of temporality in shape-changing interfaces. Time not only forms part of interaction, but can be examined in terms of histories and traces, as well as intent in the present and future. Vallgarda's paper reviews shape-changing displays and interactive surfaces within the context of interaction design. This temporal form is discussed further in a subsequent exploration, (in terms of the human, society, the computing device and the input/output) in which Vallgarda invites interaction design and arts experts to consider temporal interactions in basic shape-changing interfaces as a qualitative analysis of temporality in shape-change [[37]].

Existing Evaluations of Time in Shape-Change

The concept of time is also evident when exploring the parameters of shape-changing interfaces, such as Roudaut et al's *ten features of shape resolution* [32]. Here however, speed is a feature of self-actuation rather than something that is inflicted upon the surface by the user (as is seen with flexible phones) [25], and *variation* in speed was not then examined as a feature of working prototypes. Rasmussen also highlights *velocity* as one of the kinetic parameters of transformation, as a simple function of shape change, but also to communicate information effectively, or express emotionality. Coelho [5] examines speed as a property of shape-changing materials, in terms of precision and frequency, comparing the fast, non-linear electrostrictive materials with precise linear piezoelectric film. Here however, temporality is merely the result of control, rather than something to be varied as a communication device or as part of the design process. Poupyrev et al. [29] also cites change in speed or motion as a type of actuation to be considered. Norgaard et al. however, view temporality between different shape-changing objects in terms of interaction and user-response, by examining the control of *delay* and *feedback* through time. Here, the link between *natural* movement and time is highlighted [22].

Nature as a Temporal Reference

Natural time (that is, in response to geographic changes or organic forms) has frequently inspired and informed work in shape-changing interfaces. Much as Rasmussen states that shape-change generally plays an important role in nature [31] the temporal aspect of these natural changes in form is of equal importance: the Southern White-faced Owl would not find its increase in size an adequate defense were it to occur over a number of minutes rather than instantaneously — much as Leithinger et al's *Physical Telepresence* would be of less use as a form of instantaneous remote physical interaction if the lag between image and tangible interface response was significantly mismatched [19].

Shape-changing interfaces are now able to both emulate the natural world (such as the relaxed movement of leaves in *MoodFern* [3]) and harness it directly (as in *bioLogic's* natto cells which respond directly to moisture to create changes in form [41]). Yao et al.'s *bioLogic* examines shape-change in conjunction with colour in responsive plants - this blending of appearance and form is of vital importance as we must consider how both aspects might change over time. Figure 1 demonstrates how form, texture and appearance commonly change over time in organic matter (tomatoes).

The perceived *slowness* of such forms of natural movement has been utilised in calm computing displays such as *Lumen* [28] and *MoodFern*, and also in communicative interfaces such as *Shutters* [4] which cannot 'jump' from one state to another. However, the opposite utilisation of time can create a sense of urgency, efficiency or even express qualities such as *anger* [18].

User Reactions to Speed in Shape-Changing Prototypes

Evaluations of user experience for shape-changing prototypes have highlighted speed of change as a topic of importance in the experimental process. Feelings about, and reactions to, mobile phone movements were recorded in a study by Pederson et al. [26], although there was no significant distinction between increased speed of movement and urgency to answer the mobile phone. This was at odds to expectation based upon speed as a feature of *shape resolution* [32], although limited to the specific context of mobile phone notifications.

In comparison, artefacts used in a repertory grid study which changed shape with haste were seen to be more "assertive", whereas those which changed shape slowly were seen as "calm" [22] — a parallel to the ethos of calm computing.

In data physicalisation, transition and animation speed also needs to be optimised, in order to best present data to the user without losing precision [12] — might a smooth slow transition interrupt the flow of exact data, or might a fast transition hinder memory of the previous shape-data? Vallgaarda's recent study [37] builds upon Kwak's research in that visceral responses were gathered in reaction to changes in shape, rather than looking at specific types of interaction or using an application. In conjunction with these qualitative explorations, further structured research into user-reaction to speed of shape-change is necessary to define the boundaries needed for accurate perception when designing with time in mind.

TEMPORALITY IN EXISTING PROTOTYPES

Each shape-changing prototype is subject to its own parameters of interaction, and thus speed-to-change: hence a pneumatically actuated device [8] will have different time constraints than a jamming based model [7]. Existing prototypes also serve different functions, for example, as a mobile phone [25], or as entertainment [8], so the expectations and desires of the end-user in relation to speed must be considered. Finally, each shape-changing prototype is also a computer, and so controlled and built using programming languages - a third influence acting upon temporality.

We can therefore state that temporality in shape-changing prototypes can be affected in three ways: 1) Temporality is defined by the *physical construct of the interface*; 2) Temporality is defined by the *user*; and 3) Temporality is defined by the *programming within the application*. Additionally, there is an interdependence between these three attributes, much as within the *trinity of forms* in the theory of interaction design put forward to deal with form-enabled computing by Vallgaarda[38].

Figure 2 shows directionality in influence/limitation between the three attributes outlined above (*Hardware defined*, *User defined* and *Application defined*) at a base level. These three attributes interact together, but the direction of influence is limited or defined depending on the needs of the user, the upper and lower limitations of the hardware, and the programming within the application - which is designed *for* the user, and therefore must operate within the perceptual limits of a human being. However, as the diagram shows, the user can act upon the hardware (shape-changing surface) and vice versa, but the application is pre-set to operate within its imposed limits and therefore the user cannot directly control this part of the temporal form. The exception here is the *temporal feedback loop* which allows the user to feed back into the program to create interactions within those parameters: The user makes use of the *temporal feedback loop* to inform, rather than limit the application. These attributes are explained in more detail within the sections below.

Material/Hardware Defined

Material qualities and hardware constraints are a major influence on temporality in prototypes using SMA (Shape Memory Alloys) such as some of the *Morphees* iterations [32] and where bi-directional actuation arrays are employed as a method of deformation, as is the case with *Shape-Clip* [9] which has a maximum speed of 80mm/s. Although SMA based prototypes do offer some control over extent and velocity of change, they are limited by how fast they can heat up, and then subsequently be cooled. Speed of movement in liquid and other malleable substrates is more likely to be user-led, rather than defined by their nature, although in the case of *Mudpad* [13] the magneto-rheological fluid can be controlled to change state within 5ms.

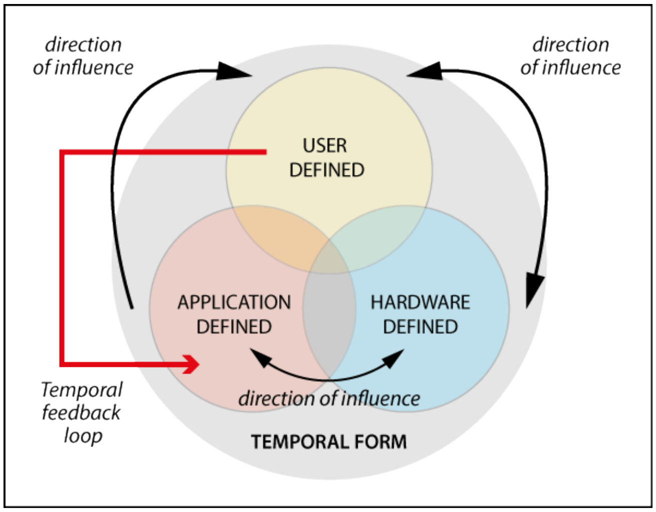

Figure 2. Unpacking the Temporal Form

User Defined

Examples of prototypes where shape-change is primarily user defined are *Bookisheet* [39], *Paddle* [30] and *Xpaaand* [14]. With *Bookisheet*, the speed of scrolling through information increases as the user makes a more pronounced deformation of the interface surface. The flexible plastic sheet has minimal material constraints and is only changed by the user. *Paddle's* re-formation/de-formation relies upon the user to flip back, forward and between states and application screens: here, the programming is a passive actor upon the change in shape, only needing to respond to the speed of the user. This is also the case with *Xpaaand*, where the screen unrolls at the whim of the user, and elastic deformable displays [36].

Apart from the previous examples, the user must operate within the constraints of the material/hardware used, and/or with any programmed *rigidity* imposed. Limits on speed of change as actuated by the user vary within the population. A theoretical *stress-ball* application [32] for example, may deform more quickly under the hands of someone with strong fingers (and could respond via programming to increase or reduce resistance).

Application Defined

Aegis Hyposurface is an example of a primarily programmed temporality [8] in which actuators can display anything from a mathematical formula to falling typefaces. Imagery is overlaid using projection, and a number of sensors can convert extraneous data into a deformed response. Due to the wide range of speed (0-25m/s) available to the device, multiple

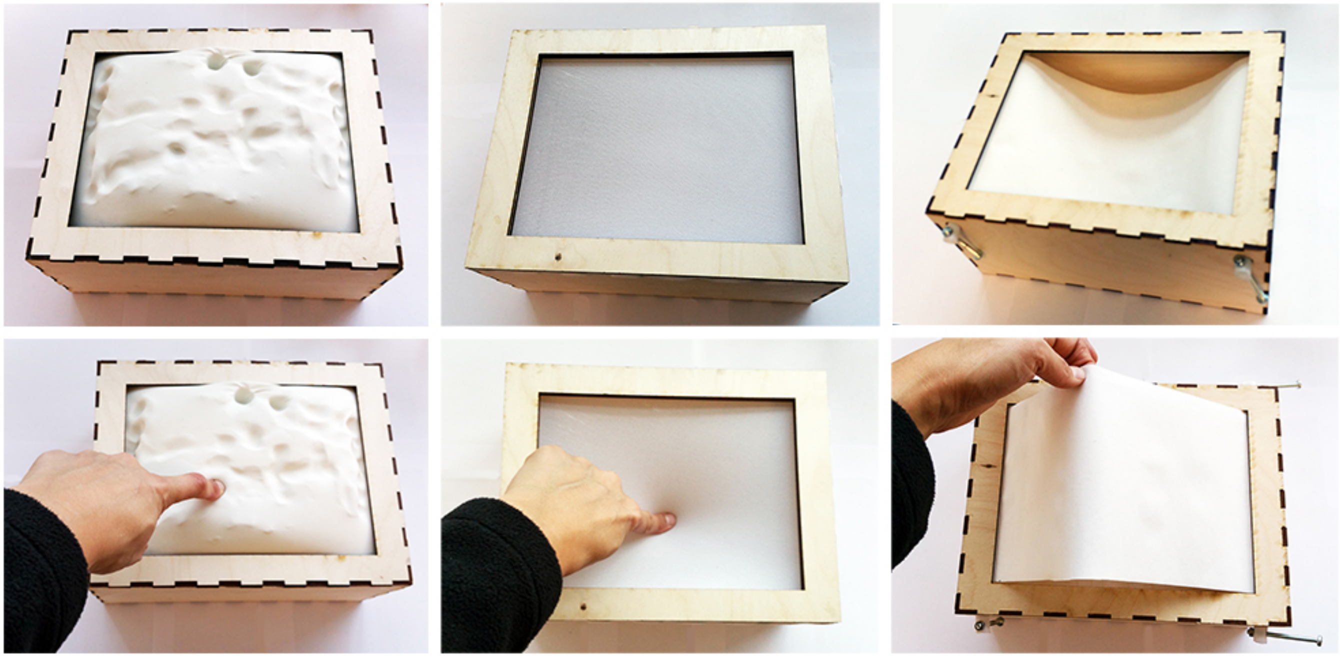

Figure 3. White-surface low-fidelity box prototypes to mimic material and user-defined temporality in shape-changing prototypes. From left to right: Clay-based surface; Elastic-based surface; Paper/Cloth-based surface.

temporalities are possible. Contrasting these kinds of high velocity transformations are examples of calm computing such as *Lumen* [28] which are programmed to engage the user in a less frenetic manner. Slow changes can be enforced by increasing *rigidity* in areas of the interface, thus rendering the user to act within the temporal limits set by the program, instead of freely deforming at speed.

New programming languages are being developed to deal with the challenges of shape-change, such as *Shape Display Shader Language* (SDSL) which include an option for a maximal and minimal update speed, though this is yet to be explored [40]. The influence of application programming upon temporality is at its greatest when the maximum speed available in an interface is high. Interfaces with low maximum speeds are mainly influenced by hardware limitations.

Multiple Temporalities in Shape-Changing Prototypes

Designing for temporality is at its most difficult when potential exists on all of the above dimensions simultaneously. 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. Programmed *slowness* and rigidity in some areas can be contrasted by increased speed and malleability in others.

Human beings, on average, take between 150m/s and 300m/s to react to a stimulus, and can move their hands at a rate of around 65m/s per second. Actuated displays can move between a static state of 0m/s and 25m/s (*Hyposurface*) [8]. Programmed temporality must work within the hardware imposed limits and anticipate interactions that work also within these limits, but may occur close together. Additionally, interaction design considers the time *in-between* input and output to be as important as the time taking during a specific interaction [20]. This links in with the concept of the *temporal feedback loop* in Figure 2, which not only informs the application of how long it took to carry out an interaction, but also how long the user took *between* interactions.

Summary

The above sections outline several types of primary temporal influence within current research prototypes. It is useful to know the range of each of the three temporal influences for the platform that is being designed for, as this will give minimum/maximum parameters between which the application will work. Knowing where the hardware constraints overlap with the users needs and abilities will help shape the advanced programming phase. Identifying these parameters is a practical step to take in conjunction with the initial development phase of any shape-changing application. Except for the instances where only one domain is the primary limiter for temporality. Speed will always be somewhat restrained by the material used, though it is more likely that the movement of the user will be slower than the give/constraints of the material.

This breakdown of the *temporal form* enables us to consider how different prototypes might prioritise time within the design process. The above text outlines a selection of the 100+ shape-changing prototypes currently in development and research, and how they fit into our current exploration of time

	Temporal Influences, Interaction Factors & Speed Attributes						
Prototype	*Primary Influence*	*Secondary Influence*	*Interaction*	*Speed*	*DFB*	*SFB*	*RTB*
Bookisheet [39]	User	Hardware	Direct	*User*	*Hardware*	*User*	*User*
Elastic Displays [36]	User	Hardware	Direct	*User*	*Hardware*	*User*	*Hardware*
Emerge [35]	Application	Hardware	Direct	0.2m/s	100mm	0.5s	0.5s
Hyposurface [8]	Application	Hardware	Indirect	25m/s	500mm	0.02s	0.02
Lumen [28]	Application	User	Direct	*Application*	*Hardware*	*Application*	*Hardware*
Morphee-Couture [32]	Hardware	Application	Direct	0.013-0.04/s	40mm	1-3s	1-3s
Paddle [30]	User	Hardware	Direct	*User*	*Hardware*	*User*	*User*
Shape-Clip [9]	Hardware	Application	Indirect	0.08m/s	60mm	0.75s	0.75s
Tilt-Displays [1]	Hardware	Application	Indirect	0.02m/s	9.1mm	0.45s	0.45s
Xpaaand [14]	User	Hardware	Direct	*User*	340mm	*User*	*User*

Table 1. Examining a selection of existing prototypes by temporal influence, interaction type, speed, distance from baseline, *speed from baseline* state (STB) and *return to baseline* state (RTB) *(where no exact value is available, the attribute which primarily controls that value is stated)*

in design. The next section outlines a discussion-based workshop group in which these ideas were further examined.

TEMPORALITY AND SHAPE-CHANGE WORKSHOP

In order to augment the theory being outlined here, a 2 part workshop and discussion group was held using 7 expert participants from design, computing, and HCI. The workshop methodology is outlined below, followed by a summary of the key themes and findings.

Method

Participants

Each participant had a set of skills which could be related to the topic of temporality in shape-change. The breakdown of core skills was as follows: P1, Sense-making, problem-solving and creativity; P2, Design research; P3, Co-design, Open design and tool design; P4, Sustainable HCI and social practices; P5, Trust, decision-making and criticial innovation in computing; P6 and P7 were HCI professionals, specialising in building shape-changing hardware and user testing.

Media

Participants were initially invited to watch recordings of existing prototypes such as *Physical Telepresence* [19], *Aegis Hyposurface* [8] and Kodama's *Protrude, Flow* [16]. The recordings of existing research served to familiarise all participants with shape-changing technology and user interactions, and show how programming can act upon the user at different speeds. The recordings were also chosen to reflect differing materials or hardware, shapes and sizes.

Prototype Examples

Additionally, participants interacted with *low-fidelity* prototypes which mimicked shape-changing materials, these items can be seen in Figure 3. The materials were chosen to have either user-defined temporality (paper/cloth), material-defined temporality (elastic) or a combination of both (clay/latex construct). These material choices are based upon existing prototypes or studies, e.g. Paper/Cloth, such as *Lightcloth* [10] or *FluxPaper* [24]; Clay/sand, such as *Illuminating Clay* [27] or *deForm* [6]; and Elastics, such as Troiano et al.ś *User-defined gestures for elastic, deformable displays* [36] or *ElaScreen* [**?**]. These objects were of the same size and with a plain white surface to minimise distractions brought about by differences in appearance, this both reflects and supports the work of both Kwak [18] and Vallgaarda [37] in their recent workshops involving designers and artists. The difference here is that the items used in their studies looked at programmed movements, rather than at simple material properties as are used within our workshop.

Part 1

The first part of the workshop entailed familiarising each participant with the technology and theory behind shape-change and temporality via watching recordings and interacting with the example objects. Discussion around pin-pointing important themes and problems was then initiated, with participants invited to write down or sketch their thoughts, as well as to debate ideas with the other participants. Voice recordings of the proceedings were made, and key points were written down on a white board so that the discussion could be mapped out as it happened.

Part 2

In part 2, participants were asked to imagine a scenario of use in which they were asked to design a shape-changing application to be used to teach children shapes and numbers. They were asked to focus on the temporal aspects of the design process, and to think how this could be built into existing design processes.

Results

Part 1

The first half of the workshop identified 7 major themes that were thought to be of importance for temporality in the design of shape-changing interfaces. These are listed below.

Temporality in Physics: Theories of velocity, relative speed and changes in resistance should be taken from existing theory as applied to different materials and applied to the design process.

Engineering & Hardware: Designers must have an understanding of different mechanisms and constraints when designing for temporality across platforms - this may require extra training.

Emotional Affect: Different speeds in change and types of movement can cause emotional and perceptual differences - designers must consider how tangible, shape-changing interfaces influence mood and visceral response. For example, sudden movements toward the user can be seen as an invasion of personal space.

Temporal Contexts: Time of day as well as time to change as playing a role in how applications must be programmed - ie. light levels, direction of light source, user-fatigue, user-familiarity.

User-Centred Design: The user is the limiting factor in temporality, applications must always operate within the perceptual and multi-sensory range of the individual. Applications must be adaptive to each user - there is no "one size fits all" - including tempo increases as users become more adept at interfacing, and decreasing resistance for weaker users.

Safety: Safety limits need to be set by the designer/programmer in order to ensure users are not injured by sharp movements or closure over limbs/digits. The implications of injury in this context are similar to those that are important in manufacturing, and AI research - the responsibility lies within the design process.

Layering: Guidelines must be layered in order of importance during the process, e.g. the initial layer might be the *purpose* of the application, followed by *safety*, followed by examination of *hardware* constraints. The top layers can be rearranged as necessary for the purpose of the application.

Part 2

During part 2, 6 of the 7 participants sketched and wrote about the suggested design scenario, with P5 acting in an advisory capacity. Participants pulled out various aspects of the prior discussion as a point of focus. Figure 4 shows some examples from the session.

P1 Was concerned with the physical limits of young users, and how single age groups can differ largely in strength and movement speed or coordination. P1 also considered an interface that went beyond the table-top or mobile device, to a free-standing, full-body interface, and so speed of movement between areas of interest must allow for bodily movement across a greater distance.

P2 considered the kinaesthetic attributes of shape-changing interfaces, and how temporality in resistance and touch-feedback could support learning in schools and at home. It was then discussed within the group whether applications should also support *planar* outputs in cases where shape-change was of no apparent added benefit.

P3 examined the interplay between colour/light output and how it linked up with the temporality of the change in shape. Time increments between visual, haptic and physical feedback were noted as important, as all three have to work together in a meaningful way.

P5 focussed on the importance of feedback, both within applications and how the audience must inform the designer during the process about how they experience time. *Pausing* the flow of the application was also discussed, as freezing time is an important aspect of most applications, be they planar or in 3-dimensional space. Additionally, *rewinding* shapes and moving backward through time was explored.

Of the HCI experts, P6 focussed on the latter part of the design process, and how the speed might be set to increase or slow depending on the aptitude of the user, whereas P7 constructed a highly detailed breakdown of time in the process, with attention on the type of shape constructed in addition to speed - i.e. *speed + output type = variable affect*. P7 also noted that unlike braille readers, shape-changing interfaces can be manipulated with entire limbs as well as fingertips.

Workshop Summary

The group session served to outline the various complex layers within temporal design for shape-change, and was a valuable exploration of how we might integrate temporal thinking into the design of applications for these mechanisms. The major theme was one of User-Centred Design, including being aware of how physical differences can be at odds with perceptual ability, and about defining control. Other ideas suggest that designers in this field must have a competency in not only the mechanical aspects of the platform, but a knowledge of physics, psychology and the ability to think in multiple dimensions and sensory outputs. Thus, the overarching message is to understand the user, and implicitly know the material and mechanical properties of the interfaces in order to apply temporal thinking to the design process.

RECOMMENDATIONS AND ANALYSIS

Knowing how the three temporal influencing factors interact together is vital for starting the design process for any application. However, different interfaces have different priorities, limitations and abilities, which must be accounted for on a case-by-case basis. Establishing which of the three temporal influences is primary is the first consideration, then the factors inherent within that influence can be examined in turn. This section examines the temporal form in context of hardware, the user, and the programming constraints.

Additionally, to apply the context to current research, Table 1 compares ten existing shape-changing prototypes against temporal influences, interaction type and speed, in order to compare the temporal form. A secondary temporal influence is given in each case to show the direction of influence. There are many more types of research prototype currently in use, but the selection is indicative of the total range available (currently there are over 100 shape-changing interfaces documented in the field). Finally, an example design-map based on the scenario explored in the workshop can be seen in Figure 5.

Below, the three temporal limiters are examined in the context of the design process.

Hardware

The hardware will set lower and upper limits for speed (and other attributes) depending on the material and/or mechanical structure. Here, it is useful to categorise devices into types to aid design narrative (see Figure 4). For *elastics*, *cloths/papers*

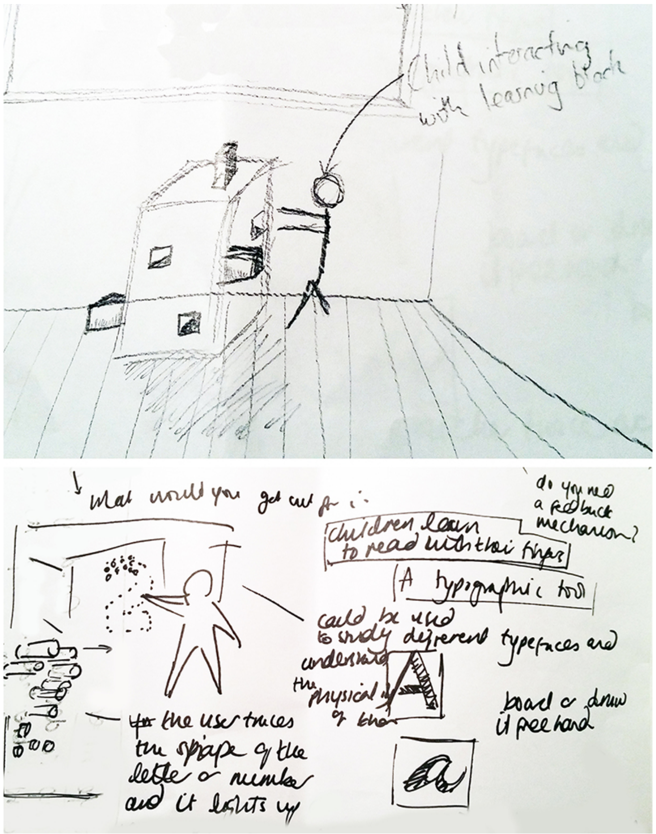

Figure 4. Workshop sketches exploring temporal design in a childrens' learning application for shape-changing interfaces

and *bendables* the speed of deformation is primarily set by the user (although *bendables* could also be programmed to deform). For the *actuated* interfaces the primary influence is the hardware and/or programming, whereas the *liquid* and *clays/putties* are primarily material-constrained. The below list outlines the hardware-dependent temporal attributes.

- Maximum/minimum speed of travel
- Maximum *distance from baseline* (DTB)
- *Speed from baseline* (SFB) to maximum DTB
- Speed to return to baseline (RTB)
- Material resistance *(e.g. elasticity/viscosity)*
- Mechanical resistance to input
- Visual (surface) display refresh rate
- Visual/deformation phasing
- Safe levels of actuation speed to be established

User Defined

The user should always be at the centre of the design process, but cannot always dictate the speed of movement or image within an application. There is a constant flow of information between the user and the programming within the application (the *temporal feedback loop* in Figure 2) which is enabled by the hardware of the interface and acts within its limitations. When considering temporality in conjunction with the user, the following items are of relevance.

- Application must operate within operational temporal range of human sensory abilities *(e.g. hand movement/eye-tracking/arm length)*
- User needs and expectations must be met *e.g. application speed must match the use case - physical telepresence should operate at matched speed)*
- User has primary influence over elastic, cloth, paper and physically actuated displays

Program Defined

The application must operate within both the temporal parameters of human sensory abilities (for direct interaction), and within the temporal limitations set by the hardware or material. The full range of movement in between what is acceptable can be influenced by the application programming.

- Application must be able to keep up with the temporal demands of the user
- Application must have variable speed output to match user needs and desires
- Application must fit requirements of software type *(e.g. calm computing = slow SFB, smooth transitioning)*
- Application should impose rigidity on non-movable parts before interaction can occur *(e.g. before the user can create an accidental deformation)*
- Application should infer interaction via movement and visual imagery
- Visual/shape phasing must be able to match if required - compensation for hardware limitations may be necessary

Additional considerations

As well as unpacking the temporal form and analysing each major component, the design process must consider how temporality works on both planar and non-planar surfaces, with multiple sensory input and output, and, notably, how physical time can be coupled with visual time. Shape-change has also been shown to have an emotional impact on users [15, 18, 37] which can be directly influenced by temporal output.

Usage Scenarios

Temporality is of varying levels of importance depending on the application use. For alerts or warnings, speed might increase in accordance with the severity of the event. The difference in movement speed might be between a "nudge" and a "sharp poke". A horror-style game might have the antagonist "creep" around the interface surface before lurching out of the screen toward the user. If small children are using the interface, parental restrictions on hardware speed might be placed, especially if it was before bedtime. The following scenario outlines a possible future application.

Scenario: Educational application for children between 3-5

Application: Application must teach basic counting and number forms in an engaging and enjoyable manner, using form, colour and sound.

Hardware: Actuated interface with shape-resolution of 300x300 shape-pixels and projected visual information. Auditory input and output available, as well as bi-directional touch/deformation. Speed to change is a maximum of 10m/s.

User: Young child with limited dexterity and reaction speed. Basic aptitude with technology. Will be using application with minimum supervision.

Figure 4 outlines the practical steps involved in temporal considerations when designing an application. Establishing the primary temporal influence is the first step in the process. The secondary temporal influence then feeds from the former. User testing follows to develop the timing aspect of the application with an appropriate age group. These steps might be reversed, removed or adapted, depending on the interface. They may also change if cross-platform compatibility is required. This idea of a temporal design narrative is a re-iterative process, and may expand over time to include more complexities as we discover more about the capabilities of our technology, and ourselves. This route through the temporal design process is intended as a rough guide for the design process in this domain.

DISCUSSION

Temporality in shape-changing interfaces is a complex and wide-ranging attribute which is considered by this paper in relation to existing, and future device applications. As interaction designers begin to grasp the varying axes of temporality and shape-resolution [32] there will also come more challenges and opportunities. In response to the documented workshop and paper, the below paragraphs discuss some of the major themes.

Application of Multiple Disciplines

The temporal form has its roots in both physics, physicality and psychology, therefore the designer must have an intimate knowledge of multiple disciplines in order to successfully navigate the layers of the design process. Within modern business, the boundary between designer and programmer is becoming increasingly blurred, with successful candidates expected to have working knowledge of both. The shape-changing interface designer might be expected to take on board many roles in order to create not only usable, exciting products, but also safe ones. HCI is increasingly seen as an inter-discipline, so researchers in this field are well placed to embrace this extension to their skill set.

Display/Output Imbalance

Whereas we are able to design with both the surface-output and shape-output in mind as separate entities, there currently exists a technological imbalance between speed of deformation and speed of visual display in many prototypes. Visual display technology far outstrips its shape-changing counterpart in terms of update speed and resolution. As many existing prototypes currently rely on projected content, there is a definite mis-match in information presentation, especially where actuators are used. This imbalance creates another temporal limiter, although one which will eventually be eliminated as technology catches up with concept.

Expressive Effects as a result of Temporality

Shape-changing interfaces have an advantage over their static, planar counterparts, as movement inevitably creates the impression of expressive output. This has been explored in relation to existing research prototypes [31] and in more depth in a repertory grid study [18]. Expression in shape-change thus is related back to nature (smooth, slow) and mechanics (jerky, fast). Personality traits and qualities are given to the movements experienced, hence a working prototype might be *stubborn* and emphturbulent (takes time to react or be deformed, moves with slow increments) or *playful* and *courageous* (moves toward the user, quick, non-threatening movements). The idea of attributing personality to shape-change fits well with the concept of giving HCI its *human* focus back [2], by humanising the computational part. These attributes also give us an unparalleled extra dimension to with which to design our future applications.

Toward a practice of User-Centred Temporal Design

With the added expressive, physical and ethical considerations of tangible interfaces, adaptive design for specific users is of vital importance. This is especially true when considering the varying physical limitations between age groups. To be inclusive, a *calibration* stage must be incorporated into every application. A co-design process involving the user at the initial stages of design would ensure the ensuing product was both timely, and operated within tolerable parameters. Individuals experience movement and velocity in different ways, and have a wide range of reaction times.

Speeding is dangerous

With the development of more efficient and high velocity shape-changing prototypes, there comes the question of ethics and safety in interfacing with such devices. This has not yet received wide-spread attention, although it is mentioned by Ishii et al. [11]. Currently, *Hyposurface* is the only such public installation capable of speeds that might cause harm, and so is rigidly controlled with smooth transitions that enable a user to effectively "lie" back upon the surface as a wave passes through it [8].

As the technology becomes more refined, more precise edges and complex forms will become feasible, including *closure* [32]. Strict programming procedures will need to be followed to prevent spiking, trapped body parts and bruising - just because an interface is capable of moving at 25m/s it may not be wise to allow unconstrained programmed speed. Despite precautions, there is always the chance of corrupted programming *glitching* and *crashing*, so limiting the maximum speed of hardware from the outset is wise consideration.

Future work

The next step in examining the temporality of shape-changing interfaces should involve conducting user studies examining differing levels of speed with comfort and ease of use, in a variety of scenarios. This can be done with existing prototypes to establish baselines of human interaction on a temporal level, which can then be employed in future research scenarios where applications are being designed for public use.

Individuals with slow reaction times are less likely to enjoy using an application that does not allow for the full range of human movement, and adapt via feedback. Applications for

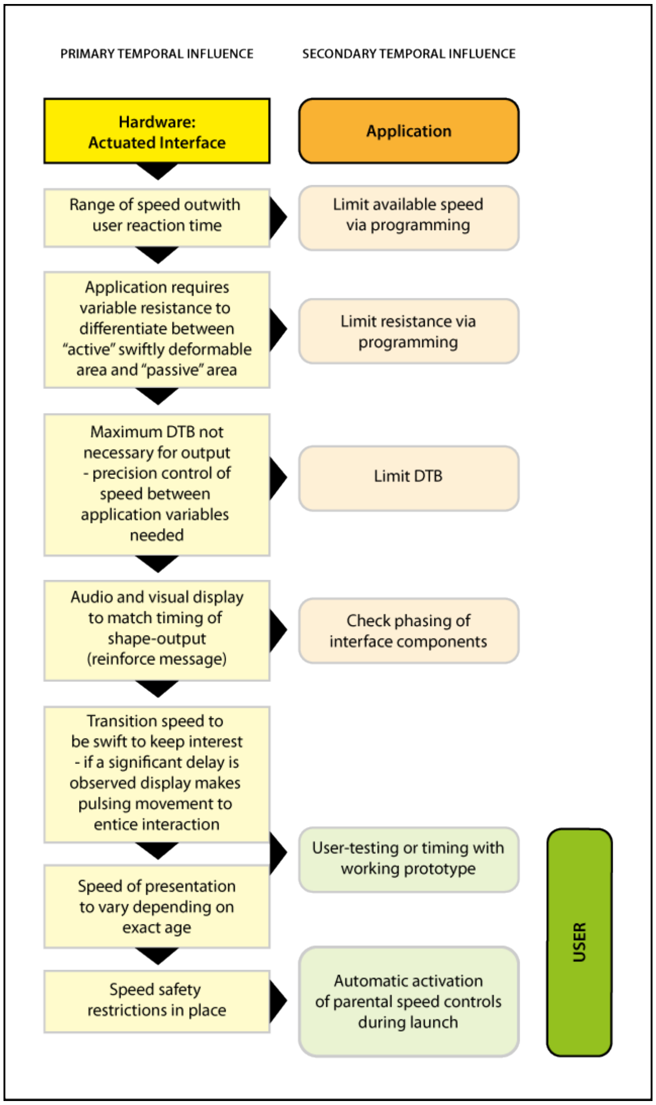

Figure 5. Exploring temporal attributes in the design of a childs' counting application

gaming however, will set speeds appropriate to difficulty levels and the type of game, e.g. a fighting game will rely on high velocity interactions, whilst a city simulator might move in real time; stressed individuals might dislike a jerky transition, preferring a smooth and relaxed change in shape.

Thus far there are few examinations of user reaction as seen in Pedersen et al. [26], and examination of the time *between* interactions as they apply to deformations and programmed changes is another consideration. Understanding and applying temporality in shape-changing interfaces is a vital facet of interaction design in applications for such devices.

In addition to examining the limits of human interaction with shape-changing interfaces, it is worth beginning the design process, and design theory, with the user at the centre. Recent work in public settings has shown the value of non-expert participants in using, imagining and analysing shape-changing interfaces [34, 15]. This work can be capitalised upon in relation to temporal design for shape-change.

CONCLUSION

We have shown here that the consideration of temporality in designing for shape-changing interfaces is a distinct and important part of the process when developing applications for such devices. We have analysed the temporal form and how it relates to hardware, the user and programming. We have also made recommendations for design using examples of existing prototypes, and made steps toward applying temporal design theory to this emergent field via facilitating a workshop and subsequent discussions. It is hoped that the ideas discussed here will add to the growing interest in this field and be of use to others interested in designing applications for shape-changing interfaces.

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