The Design Space of Shape-changing Interfaces: A Repertory Grid Study

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ABSTRACT
Technologies for shape-changing user interfaces are rapidly evolving, but our understanding of the design space of such interfaces is still limited. We report a repertory grid study that aims to describe the design space from the users' point of view by eliciting personal constructs about shape-change. The study is based on six similar-sized, shape-changing artifacts that combine simple sensing of users with actuation that change volume, texture, and orientation. Our results show that the 18 respondents distinguish artifacts on dimensions that differ from those of most models of shape change. For instance, they characterize shape-change in terms of personality, territoriality, and state of mind, in addition to more common categories such as appearance and product properties. We discuss how the dimensions derived from users might be used to design shape-changing interfaces.

Author Keywords
Shape-changing interfaces; organic user interfaces; actuated interfaces; tangible user interfaces.

ACM Classification Keywords
H.5.2 User Interfaces (D.2.2, H.1.2, I.3.6): Haptic I/O

INTRODUCTION
Tangible user interfaces (TUIs) tie digital information to physical objects and allow users to manipulate the information through the objects. In early tangible user interfaces, the physical objects could not reflect changes in digital information and could not be manipulated except by moving them. In recent years, there has been a growing interest in user interfaces that use shape-change of physical objects as input or output. Such interfaces have been called shape-changing interfaces [3,32] or organic interfaces [1].

Relief [29,30], for instance, used 120 motorized pins to show three dimensional shapes and allow the user to manipulate the shape by pulling and pushing the pins; Morphees [33] are self-actuated mobile devices that can adapt their shape to the context of use.

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The majority of research in shape-changing interfaces involves designing, developing, and evaluating point designs. As the body of such research is expanding, researchers are attempting to classify designs and provide descriptive frameworks that will help understand and explore this design space.

Some models and frameworks for thinking about and designing shape-change focus on the technical design possibilities. These models are apt for identifying aspects of the technologies that accomplish shape-change. However, they are less vocal on users' perceptions of the design space and may miss important insights about the user experience of shape changing, rendering them suboptimal for thinking about and designing shape-change interfaces. The present paper aims to address these limitations by studying how users experience shape-change.

We describe 18 repertory grid interviews conducted to elicit participants' personal constructs about artifacts they are presented with [10,26]. The assumption is that participants use constructs to organize and make sense of the world and of their experiences; they provide a way of accounting for the subjective experience of phenomena. Such interviews have been widely used in psychology, but also to study user interfaces [17,18]. Based on the interviews, we analyze how participants describe shape-changing interfaces; we also categorize the descriptions and contrast them with those of existing models of shape-change (e.g., [3,32,33]). The aim is to give insight into how shape-changing interfaces invite to dynamic interactions and develop our understanding of the resulting experience of shape-change. In addition, we intend to develop our descriptions of the experience of shape-change to be a tool for designers that foreground the user's perspective on shape-changing interfaces.

RELATED WORK
This paper departs from work on shape-changing interfaces and repertory grid studies; we review these next.

Shape-changing Interfaces
Shape-changing interfaces are a form of tangible user interface that use shape-change of physical objects as input or output [3,32]. We follow Rasmussen et al. [32] in defining a shape-changing interface as an interface that

"uses physical change of shape as input or output. We follow earlier work that has used self-actuated change as a defining characteristic […]. Additionally, we require that the self-actuation must be controllable so that the object can return to its initial state and repeat the shape-change".

Current research in shape-changing interfaces is mostly about designing and developing shape-changing interfaces. This research has let to a variety of prototypes that explore technical challenges in building shape-changing interfaces (e.g., [9,33]) and papers that evaluate shape-changing interfaces (e.g., [13,20]).

Several papers have attempted to summarize insights on shape-changing interfaces in models of their key components. Coelho and Zigelbaum [3] reviewed possibilities of variation in topology, texture, and permeability. Rasmussen et al. [32] reviewed 44 papers and proposed a framework that characterizes shape-changing interfaces based on the shape-change supported, on the type of transformations connecting different starting and ending states of the shape-change, and, finally, on how shape-changing interfaces use physical transformation as input and output. Several other models exists [31,33]. These models capture the design space primarily based on types of shape and ways of technically generating changes among shapes, for instance using Non-Uniform Rational B-splines to model features of shape-change and illustrating how to design variants of shape-changing mobiles using variants of those features [33]. They do not necessarily capture the users' view of the designs. The present paper attempts to do so using repertory grid methodology, discussed in the next subsection.

Repertory Grid Methodology

Repertory grid interviews have their background in the work of George Kelly [26]. In repertory grid studies, participants are presented with or asked to generate a set of elements. The elements are then rated on a set of constructs, either supplied by participants or by the interviewer. Those constructs can then be analyzed, both to see how participants construe the elements and how the elements relate to each other.

Repertory grids have been used previously in studies of human-computer interaction [17,18,23,24,35] and, more broadly, information systems [6]. Early uses focused on repertory grids for knowledge elicitation [11]. Later studies focused on capturing users' understanding of digital artifacts through eliciting users' constructs about those artifacts. For instance, Hassenzahl and Wessler [18] studied how 11 users described their personal constructs of differences among seven prototypes of a water pump. Hertzum et al. [23] used repertory grids to study how users understood the usability of six systems they interacted with on a regular basis. They also contrasted the repertory grids across participants with different national and professional backgrounds.

In relation to models of shape-changing interfaces, the potential of the repertory grid methodology is that it allows us to study users' perception of shape-change. That perception might differ from what is captured in current models of shape-change. This could potentially advance our understanding of the experiences that shape-changing interfaces can engender and of how we can design for such experiences. Next we present the foundation of the present study, six interactive, shape-changing artifacts.

DEVELOPING ARTIFACTS FOR THE STUDY

Repertory grid studies structure the repertory grid interview around elements, in our case interactive, shape-changing artifacts. The interviewees' personal constructs about the elements are uncovered and analyzed. In our case, we aim to use the analysis to discuss the design space of shape-changing interfaces more generally. To do so, we need artifacts that are heterogeneous enough to capture the variety of such a space: a convenient way of generating such artifacts would be to presuppose a model of the design space (such as those discussed in the previous section) and use that to generate the elements. Obviously, this would create a chicken-and-egg problem, assuming a model even though it is supposed to be the outcome of the repertory grid interviews.

Our approach to developing elements is instead to task advanced design students with generating artifacts within specific restrictions; the input to those design students is general, yet generative ideas on how users may explore the artifacts. Based on the students' work we selected six concepts, enhanced their designs, and developed them into artifacts. Next we present the three parts of this approach (the restrictions, the generative framework, and the design processes) and argue why we believe it gives a heterogeneous set of artifacts that are not directly derived from any of the models we wish to discuss.

Restrictions on Designs

Several restrictions were placed on the designs to ensure that they did not differ in accidental details and to help the design process. First, we worked within a restricted form factor (see Figures 1-7). Second, the artifacts were designed without a specific context in mind to be able to focus on the fundamentals of experiencing shape-change. Third, we focus on artifacts that react directly to user input, rather than autonomously or based on input from other sources.

Generative Framework

In the examples of shape-changing interfaces described by Rasmussen et al. [32], shape-change is mainly considered as a reaction to the user's behavior casting the interaction as isolated pairs of user input and system output. However, when the properties of a product, such as its shape, change, our perceptions will follow these changes through a process of adaptation [12]. A product that changes its shape can potentially give rise to a feedback loop playing on the action-perception possibilities, offering a dynamic interaction between the action of the user and the reaction of the product, which has been named interactive materiality [34]. Our perspective on designing shape-changing interfaces and evaluating emerging interactions takes this broader perspective.

The focus is on interaction supported by manipulation, gesture, and touch, with medium sized (hand scale) objects. Lederman and Klatzky [28] provided a systematic framework for analyzing hand movements and manipulations that are conducted in the context of the active explorations people make to perceive with touch, what Gibson [12] called active touch. Specifically, Lederman and Klatzky [28] identified the necessity and demonstrated the appropriateness of a small set of stereotypical movements for perceiving the shape of different objects: lateral motion, pressure, static contact, unsupported holding, enclosure, contour following, function test, and part motion test. This framework is not directly related to shape-changing interfaces or current models thereof; yet it helps generate design ideas and identify ways one may engage with shape-changing interfaces.

Design Processes

In a one week-long design boot camp, we invited 20 advanced Master level students in industrial design to use a parallel design process to develop shape-changing interfaces that feature variations on the interactive action-perception loop. The shape-changing interfaces were to sense the explorations that the user makes through active touch [12] and adapt their physical properties. Students were instructed to design artifacts that support different explorations of users along the classification of typical movement patterns for exploratory procedures (EPs). A collection of ten shape-changing artifacts was created (Figure 1). Videos of the artifacts can be viewed at http://www.ghost-fet.com.

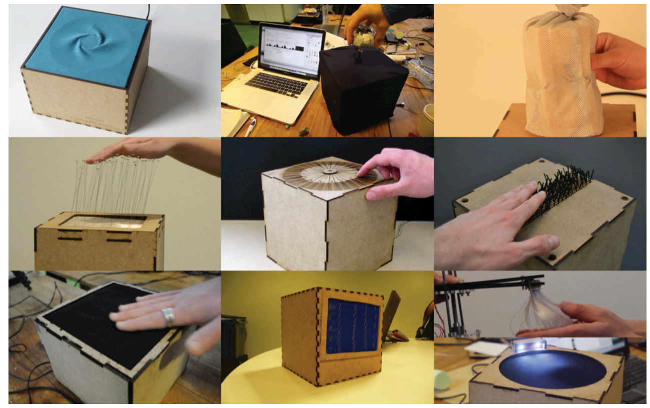

Figure 1. First generation of shape-changing interfaces, exploring dynamic orientation, form, volume, texture, and spatiality in one and two degrees of freedom. The bottom-right figure shows two artifacts.

These first design explorations were followed by a more sustained and in-depth design process, where a design researcher synthesized the initial design concepts, redesigned the initial artifacts to create a collection of six shape changing interfaces featuring very distinct experiences of shape-change.

The processes described above resulted in six artifacts, illustrated in Figure 2 through Figure 7. The accompanying video details the interaction possible with the artifacts. These six artifacts were used in the study presented next.

REPERTORY GRID STUDY

A repertory-grid interview study was designed to discover how people experience interaction with shape-changing interfaces, with a particular focus on active touch. Specifically the study aimed to identify the constructs that are useful for describing end-user's experience of interacting with shape-changing interfaces and in doing so

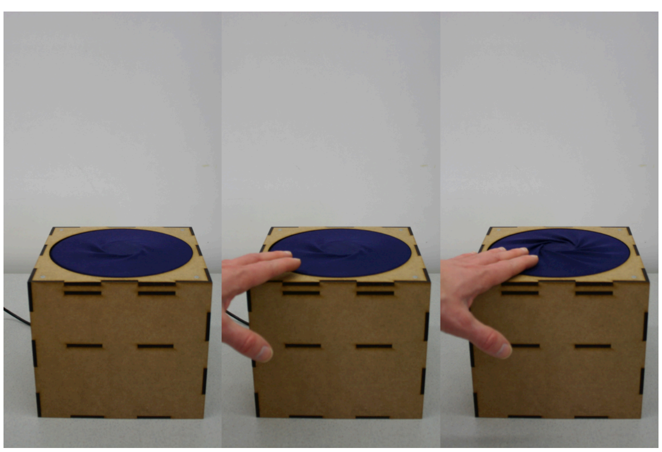

Figure 2. PIEGA explores dynamic changes in form as a response to static contact and consists of a cloth surface attached in the center to a servomotor. The rotation of the servomotor results in folds in the cloth surface. A capacitive sensor is used to determine user presence and static contact.

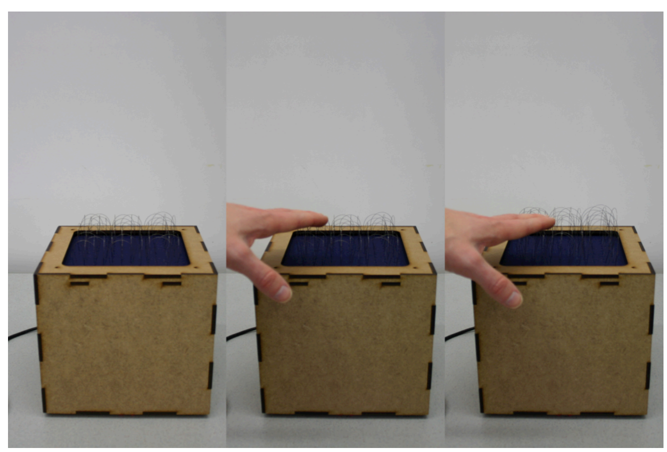

Figure 3. GATO explores dynamic changes in texture as a response to static contact and consists of a platform with spring steel loop 'hairs' that lowers and rises to alter the length of the 'hairs'; short hairs are rougher to the touch than longer hairs. A capacitive sensor is used to determine user presence and static contact.

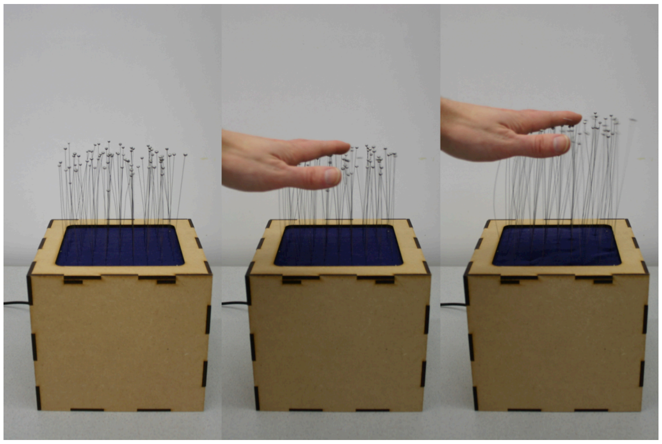

Figure 4. YETI explores dynamic changes in volume as a response to static contact and consists of a platform with beaded wires that lowers and rises to increase the volume of the overall shape. A capacitive sensor is used to determine user presence and static contact.

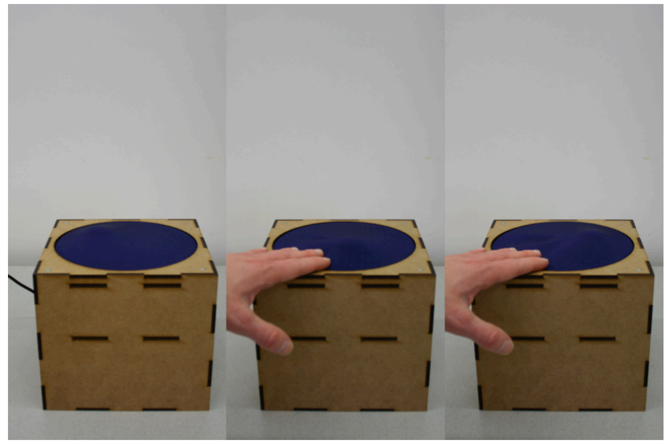

Figure 5. FANTOM explores dynamic changes in orientation as a response to touch and consists of a Perspex semi-sphere mounted on a rotating platform underneath a cloth surface. The orientation of the resulting bulge changes by rotating the platform. A capacitive sensor is used to determine user presence and static contact.

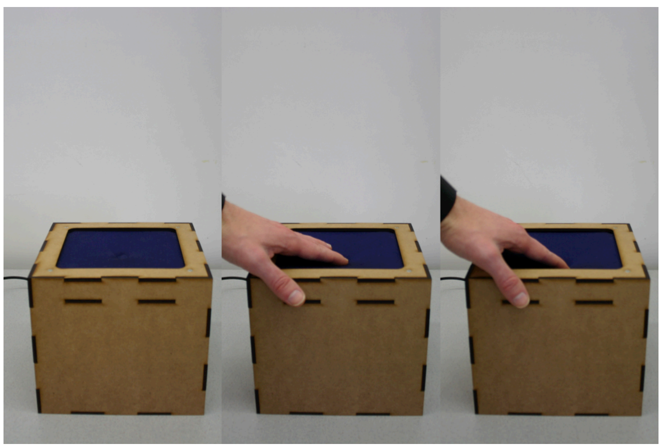

Figure 6. SQUEEZY explores dynamic changes in form as a response to deformation and consists of a foam surface that can be dented in. A force-sensing resistor is used to determine the deformation of the surface.

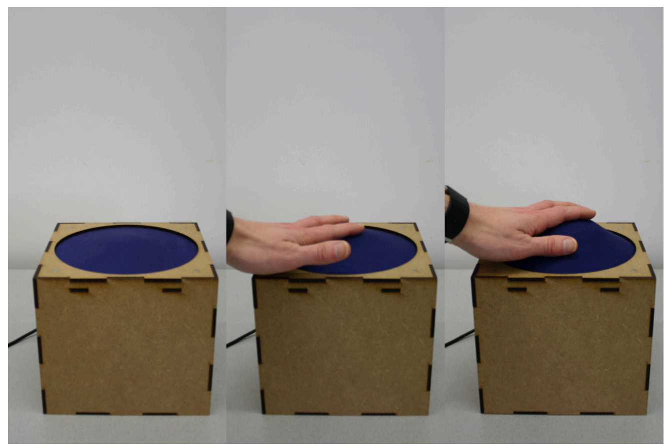

Figure 7. BULGE explores dynamic changes in volume as a response to touch and consists of a Perspex semi-sphere mounted on a scissor platform underneath a cloth surface. The volume of the exposed form increases and decreases when the platform rises and lowers. Five capacitive sensors are used to determine user presence and static contact.

provide an empirically grounded characterization of shape-changing interfaces.

The key elements of the repertory grid interview are the elements that participants judge and the constructs that they use to describe those elements. Next we describe these, the participants, and the procedure followed.

Elements
Earlier papers using the repertory grid method in HCI typically use between 6 and 8 elements [35]. Whereas many repertory grid studies ask participants about elements they are acquainted with before the interview, many earlier studies use novel elements [4,7,18]. In our case, it was not feasible to recruit participants who had experience with a range of shape-changing interfaces, so we used novel elements.

As in the study by Hassenzahl and Trautmann [17] we aimed to use heterogeneous stimuli so as to explore the variety in participants' constructs. We used the six artifacts described in the previous chapter (Figure 2 through Figure 7).

Constructs
Constructs may either be supplied by the researcher or elicited from participants; both approaches have been used in earlier studies ([35] supplied constructs, [18] elicited them). We chose to elicit constructs from participants, so that they use their own words and phrases to describe the interfaces.

Participants

Eighteen Dutch participants (3 female, and 15 men) with a median age of 19.5 (ranging from 19 to 23) were recruited through the study association of the department of Industrial Design. We chose participants with some knowledge of design because they might be better at expressing their experiences with shape change than the average user. We screened participants to not have any visual or physical impairment because we believed such impairments might lead to quite particular perception and exploration strategies.

Procedure

Table 1 outlines the procedure for the interview. Next we describe the parts in turn.

Part	Average Duration	Summary
I	5 min	Introduction to study
II	5 min	Training on repertory grid
III	10 min	Exploring artifacts
IV	60 min	Eliciting constructs
V	5 min	Translating constructs
VI	5 min	Debriefing

Table 1. Procedure for the repertory grid interview.

Participants arrived at the laboratory and were *introduced* to the purpose of the study, the repertory grid technique was outlined, and they provided consent.

An initial *training* on repertory grid interviews was provided with a toy example relating to people and their personalities.

Then participants were given the opportunity to *explore* the six artifacts freely without an explanation of what each does and why. The only help provided to them was some tips to discover and feel the interaction with the device in the cases where this was not something they discovered spontaneously. Where participants could not figure out the operation principle for each of the devices, this was discussed at the end of the session with them in order to understand how much issues related to intuitiveness affected their experience. We allowed participants ample time to interact with and explore each artifact. The order of the artifacts in the setup was randomized for each participant. As mentioned earlier, the artifacts were unknown to participants before the study and it was important that they had time to form an opinion about them before beginning rating.

Next, the *elicitation* of constructions began. Participants and the interviewer sat on a table perpendicular to the table containing the six artifacts. Participants were presented with cards featuring pictures of the six artifacts labeled with a character (a-f) used also in the setup. These characters were used as the elements in the repertory grid. A standard elicitation procedure was followed [25] that asks participants to consider a triplet of artifacts chosen at random. The participant must then think of a personal construct that helps differentiate two of the artifacts from the third. The construct is then explained in terms of a construct pole (e.g., “light”) and a contrast pole (e.g., “dark”). We talk about these as a construct/contrast pair. The participant then rates each artifact by using a scale ranging from 1 (construct-pole) to 7 (contrast-pole) with respect to the construct/contrast pair specified. These ratings form the basis of the quantitative analysis. A new triplet of artifacts was then chosen and construct/contrast pairs elicited. This continued until participants could not produce any more personal constructs.

The interviews were conducted in Dutch, the native language of the participants. However, at the end of the session *translations* into English of the constructs were discussed to ensure that the interpretation that will be reported in English was faithful to the constructs reported by the participants. Where necessary the interviewer applied laddering down to ensure that constructs were expressed in terms that were self-explanatory and clear.

At the end of each interview, participants were *debriefed* and asked to comment on the session as a whole. These comments were added to the reflections of the interviewer on the process. Where obvious similarities between constructs or artifacts were visible on the grid, interviewees were asked to comment on them to check whether these constructs are overlapping or even identical. They also rated the goodness of each interface on a scale of 1 to 7, adapted from Hassenzahl [19].

The sessions lasted on average 90 minutes, distributed as in Table 1. The interviews were recorded on video to allow researchers to consult them later if necessary. Participants were paid €15 as compensation for their time.

Analysis of interview results

The results of the interviews were analyzed qualitatively and quantitatively.

Qualitative Analysis

A content analysis of the data was conducted with constructs as the unit of analysis. Constructs from all participants were clustered inductively by three coders (the interviewer and two external coders) until we could define nine categories, and less than 5% would be considered as ‘miscellaneous’, that is, not fitting any other cluster.

In most cases the categories reflect overall topics. These topics are similar to what Feixas et al. [8] describe as themes. However, in some cases a set of constructs was more specific and large enough to form a category by itself. In these cases the categories can be viewed as a sub-topic and are similar to what Feixas et al. describe as categories. Three perspectives were evident: approaching the artifacts as if they were other persons; approaching the artifacts as if they were wild animals; and approaching the artifacts as if they were interactive products. These perspectives correspond to three out of the four associative expressive parameters as observed by Rasmussen et al. [32].

The first and second coder calibrated their clustering procedures iteratively until an inter-rater agreement of over 90% could be achieved on 10% of the data (checks were made at 2%, 5% and 10% of the data).

After this the first and third coder classified the data set separately. They achieved an inter-rater reliability of kappa = .72, suggesting substantial agreement [27]. Table 2 shows the categories and examples of the constructs. Also shown is the frequency of constructs in this category. The actual categorization of constructs provided by the participants is available at http://www.ghost-fet.com. For each category a definition was developed by the coders in Dutch and later translated to English.

Quantitative Analysis

The quantitative analysis of grid data was done for each individual case and for the set of grid data as a whole. For the individual grids, we use principal components analysis; its use to understand repertory grids is discussed in detail by Fransella et al. [10] and Bell [2]. Principal component analysis helps reduce the dimensionality of the repertory grid ratings, typically to two dimensions; this makes plotting the ratings possible. When reporting the results of principal component analyses, we include only components with loadings equal to or above ± .7.

To analyze the full set of grids we used Generalized Procrustes analysis [14]. This is a multivariate analysis technique widely used outside of HCI (e.g., to analyze the experience of food or shapes, see [5]) and occasionally in HCI (e.g., [23]). The idea of Generalized Procrustes analysis is to identify a consensus among a set of p points in k-dimensional space. The points are given by the individual ratings. The analysis identifies a consensus configuration by translation, scaling, and rotation; that configuration is a least-squares estimation of the agreement among the set of points. The configuration can then be mapped to a two-dimensional plot by principal components analysis. The analyses were performed in IdioGrid, a specialized software package for analyzing repertory grids [16]. Using IdioGrid for the Generalized Procrustes analysis is described at http://psychology.okstate.edu/faculty/jgrice/personalitylab/GPA_Idiogrid_Example.pdf and in several papers [15,23].

RESULTS

First we describe examples of the constructs elicited, through a qualitative analysis of their content. Then we attempt to capture the relation among the artifacts quantitatively, and finally we remark on the process of doing the repertory grid interviews.

Constructs Elicited

The participants reported an average of 11.6 constructs (SD = 3.58). One participant only gave four construct/contrast pairs, whereas one gave 17. This gives a total of 209 construct/contrast pairs. These were grouped into 9 categories based on their content; Table 2 shows the categories as well as examples of the construct/contrast pairs in each category.

Constructs frequently concerned *Interaction with Others* (about a fifth of the cases). These constructs seem to describe interaction with the artifact through terms relating to people and personalities (e.g., Friendly/Distance, or Indifferent/Attentive). Similar anthropomorphic terms were used in categories *Approach* (e.g., Cautious or Narrow-minded), *Stubbornness* (e.g., Stubborn/Compliant), *Open-Closed* (in particular Introvert versus Extrovert), and *State-of-Mind* (e.g., Happy/Sad). Even the categories that we call Appearance and Energy are cast in anthropomorphic terms like Vulnerable and Sensitive (*Appearance*) and Weak to Powerful (*Energy*). In total, three-quarters of the constructs concern characteristics that are also mentioned in the Classification System for Personal Constructs (CSPC) by Feixas et al. [8]. The CSPC focuses on value constructs, which "include the meanings people give to their own and others' psychological traits or characteristics". That about 75% of the constructs elicited in our interviews fall in this category tells us that the artifacts are perceived as having a personality. This shows that with relatively simple means, in terms of shape-change, diverse and highly interesting experiences can be created.

Only 17% of the constructs (those in the category *Product Properties*) describe shape-change in phrases that refer to product properties and to terms used in the most common models of shape change in the literature. Common constructs concerns predictability (e.g., Random/Predictable) and Mechanical/Organic (even though this latter construct/contrast pair appears only once). Possibly the low frequency reflects the simplicity of the artifacts and their limited interaction possibilities and rudimentary behavior.

Territoriality subsumed a large group of constructs, such as Frightened/Defensive or Aggressive/Coy. About 8% of the constructs were coded as concerning territoriality and the difference to the anthropomorphic constructs above is that they mainly describe meanings that people give to the characteristics of animals. This is not unexpected as the several participants noted that the artifacts appeared alive. Especially in cases where the participants felt that artifacts behaved unexpectedly or in a way that was difficult to understand, they described the observed behavior as similar to that of wild animals.

Consensus Configuration

As discussed earlier, it is possible to construct a consensus configuration of the construct/contrast pairs elicited; Figure 8 shows two dimensions of such a configuration. These two dimensions account for 58% of the variation in the individual ratings. This amount is comparable to other studies (e.g., [23]).

Category	Explanation	Example Constructs	N
Interaction with others	This category specifically concerns how the artifacts interact with others (the participants in this case).	Friendly/Distant, Indifferent/Attentive, Honest/Underhand	44 (21.1%)
Product properties	This category specifically concerns the concrete descriptions of the artifacts that tend to describe product properties. What counts is that you wouldn't couple one or both of the words in the construct to how people or animals behave or come across.	Random/Predictable, Sturdy/Fragile, Mechanical/Organic	35 (16.8%)
Approach	This category specifically concerns how the artifacts (would) deal with certain situations, how they (would) approach matters or (would) respond to things.	Cautious/Ambitious, Narrow-Minded/Progressive, Insecure/Determined	30 (14.4%)
Appearance	This category specifically concerns how the artifacts are according to the participants and how they then come across. This results in how they interact with others and deal with situations.	Unconcerned/Insecure, Vulnerable/Strong, Surly/Sensitive	28 (13.4%)
Stubbornness	This category specifically concerns how stubborn or docile the artifacts come across. On this scale are also constructs like being confident or being easy to influence.	Rebellious/Cooperative, Stubborn/Compliant, Obedient/Recalcitrant	19 (9.1%)
Open/Closed	This category specifically concerns how open or closed the artifacts come across. This is often talked about in terms such as extrovert or introvert.	Open/Mysterious, Boisterous/Introvert, Social/Introvert	17 (8.1%)
Territorial	This category concerns the behavior of the artifacts that has something animalistic. This often describes the offensive or defensive fight or flight behavior of the artifacts. What counts is that you wouldn't couple one or both of the words in the construct to how people or products behave or come across.	Skittish/Affectionate, Frightened/Defensive, Aggressive/Coy	16 (7.7%)
Energy	This category specifically concerns the level of energy in terms of activity of the artifacts. Whether they are active or playful or don not have any energy at all?	Weak/Powerful, Playful/Calm, Restful/Hasty	14 (6.7%)
State of Mind	This category concerns the state of mind of the artifacts. Often these describe temporary moods that influence the actions of the artifacts. For example, few people are permanently sad or up spirited.	Downhearted/Hopeful, Up-spirited/Sad, Happy/Sad	6 (2.9%)

Table 2. Categories and examples of constructs/contrast pairs. Each of the 209 pairs was placed in one category only.

The first dimension of the consensus configuration has high loadings within the categories of *Interaction with Others* (11 items), *Stubbornness* (11), *Product Properties* (10), *Approach* (9), *Appearance* (8), *Open/close* (7), and *Territorial* (7). The dimension seems mainly to concern being open (as opposed to introvert), compliant and open-minded (as opposed to stubborn), considerate (as opposed to unpleasant), and enthusiastic and territorial (as opposed to timid).

The second dimension of the consensus configuration has high loadings on the category *Interaction with Others* (11), *Approach* (10), *Energy* (5), and *State of Mind* (2). The dimension seems to concern being familiar or social (as opposed to uninterested) and being calm (as opposed to quick and energetic). This dimension is also related to being organic or mechanical.

Extremity Analysis and Individual Differences

The literature on repertory grids suggests that constructs that receive extreme ratings are particularly important because they reflect superordinate constructs [10]. In our case, 1254 ratings of an artifact were reported, of which 420 (33%) were either a rating of one or of seven. A principal-components analysis was used to identify the most prominent construct for each individual, resulting in 18 constructs. Those were predominantly about *Interaction with Others* (6), *Approach* (5), and *Stubbornness* (3). In this case, the prominent individual constructs seem to reflect well the analysis at the consensus level.

Goodness of Interfaces

To assess the goodness of the artifacts, participants also ranked the artifacts on a rating scale construct provided by the interviewer, ranging from good (low) to bad (high).

The analysis of goodness differed significantly among artifacts, $F(5, 13) = 3.2$, $p < .05$. Post-hoc tests showed, however, that this difference was due to PIEGA (M= 4.89, SD = 1.49) being rated significantly higher (meaning bad) than all other artifacts (M = 3.37, SD = 1.88). To us, this suggests that the artifacts were mainly considered similar in terms of overall experience, except PIEGA.

From the interviews, several observations suggest an explanation for this. Many participants expressed their appreciation of the aesthetic quality of the shape-change of PIEGA, but were put of because it was considered linear and evasive. PIEGA is the only artifact that hides parts of itself and this was perceived as a clear message that it was not open for interaction. The consensus plot in Figure 8 shows that PIEGA is perceived as the most introvert and timid artifact compared to the other artifacts.

The majority of the participants said they found the artifacts fascinating and that they enjoyed the novelty of all of them. Consequently the scale good/bad might have been interpreted as good/least good. However interpreted, PIEGA seems very different from the other artifacts.

Other Observations from the Interviews

Two observations made by the interviewer are worth noting.

Design Elements

Certain design elements appear to be responsible for the characterization of the artifacts as can be deduced from the analyses and observations. These are:

- Artifacts with segmented shape-changing surfaces (GATO and YETI) are perceived as being more playful.
- Artifacts that approach the user when changing shape (GATO, YETI, and BULGE) are perceived as being more energetic.
- The speed with which the artifacts change their shape relates directly to the perceived assertiveness ('quick' as opposed to 'calm' in Figure 8).
- Artifacts that change shape by means of rotation (PIEGA and FANTOM) are perceived as mechanical.
- Artifacts that change shape slowly and retract (PIEGA and SQUEEZY) are perceived as calm and introverted.

Favorite/least favorite

During the interviews the majority of the participants directly or indirectly expressed having a favorite or a least favorite. While expected to be the favorite for the majority because of its playfulness, YETI was not favored more than the other artifacts.

While participants expressed their appreciation for the aesthetic quality of PIEGA, it was the least favorite for many participants. This is also reflected in the assessment of goodness of the artifacts.

Both the assessment and the observations of favorite and least favorite artifacts give value to the consensus plot in highlighting less favored characteristics.

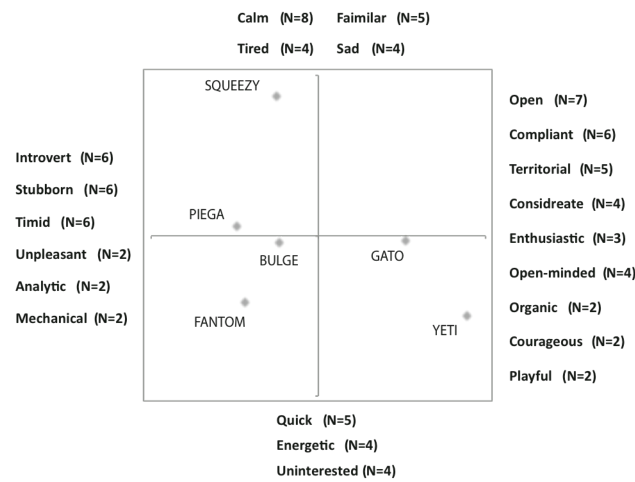

Figure 8. Consensus plot showing the six artifacts and terms that characterize the dimensions of the plot.

DISCUSSION

We have designed a set of six artifacts and used them to elicit personal constructs from 18 participants. Those constructs have been classified and analyzed. The key insights from the study are that (a) constructs to a large extent can be described by anthropomorphic terms, (b) product properties play a relatively small role in talking about the artifacts, (c) territoriality was used to describe interaction, and (d) the main differences among artifacts related to openness/closeness and being timid/shy. Next we discuss four points raised by the study.

Relation to other Models of Shape-change

A key motivation for the study was to investigate how existing models of shape-change (e.g., [3,31,32,33]) would compare to eliciting personal constructs from prospective users. How do our findings differ from those models? First, the anthropomorphic categories from the content analysis and the consensus plot do not correspond to dimensions of the existing models. On the one hand, this is to be expected as the highly technical dimensions of some models (e.g., that of Roudaut et al. [33]) might not be visible or understandable to users. On the other hand, we think that the low frequency of product properties among the constructs raise optimism for complementary models of shape-change; models that emphasize the experience of such interfaces. A few earlier papers have explored dimensions related to some of those that we elicited (e.g., Hemmert and colleagues in [21,22]), but we believe the categorization of constructs in the present paper is the first systematic mapping of this space. Note that the repertory grid procedure does not automatically result in non-product properties; Hertzum et al. [23] also used repertory grid interviews on interactive products and found many more product properties than we do.

Second, it seems to be possible to map some constructs to existing models. *Energy*, for instance, seems to concern movement speed as evidenced by constructs like Hasty and

Calm. *Territoriality* relates to approach and avoidance behavior, and may be mapped indirectly to movement (like Hemmert et al. [21,22] have done). How to map many of the other categories to shapes and transformations among shapes remains hard. For instance, how can we use the dimensions of Roudaut et al. [33] to create an impression of Friendly/Distant or Vulnerable/Strong?

Using the Categories for Design

The analysis of the constructs shows that there is a considerable degree of generality in these constructs. While they are shown to provide some descriptive and analytical leverage for characterizing interactive experiences, future design work needs to explore how such a characterization of the user experience of shape-changing interfaces can inform designers. To this end it would be interesting to see how designers and/or design researchers would categorize the constructs in terms of design relevancy. In other words, how operational are these constructs? Can they be used to guide the design process of shape-changing interfaces immediately or is some form of analysis necessary to either abstract or concretize the constructs? Such an exercise would also allow us to verify if the participants perceived the design elements.

From a design point of view we see that subtle differences in the design and the behavior have a large impact on the resulting interaction. This suggests that designers of shape-changing interfaces should also have experience in programming behavior, that is, the transformation from one shape to another as response to user-input, when designing for interaction. We think that the sensitivities classical designers develop when working with materials and shapes in product form giving are also required to successfully program behavior and find a balance between these. In this we agree with Vallgårda [36] that the task of programming behavior should be seen as a form giving practice and with our work we demonstrate that, in highly interactive designs, design and behavior are inseparable and the interdependencies between these two make for a highly complex practice. Herein lies the challenge of versing future designer with the opportunities of shape-changing technologies.

Particularities and Limitations of the Study

Several particularities of our study need to be discussed because they shape our results and the conclusions that can be drawn. First, the artifacts used and the specific way they are designed of course impact our results greatly. The artifacts are relatively simple, react on direct touch (as opposed to merely approaching them), and reflect the restrictions that we employed to focus the design process.

Second, even though we achieved substantial agreement in categorizing the constructs, some improvements seem possible. Some construct/contrast pairs have a construct among one of the associative expressive parameters (anthropomorphic, zoomorphic, or mechanical), while the contrast represents a different parameter. Dealing with this was hard.

Third, another difficulty is that the meaning of the constructs and contrasts can actually change depending on whether the coder focuses on the Dutch word, the English translation, or the interplay between these. There are numerous cases where the Dutch word gives a general idea of the experience, but is nuanced by the English translation and vice versa.

Future Work

We see several avenues of future work. First, given the frequency of anthropomorphic contrast/construct pairs, it would be natural to employ hierarchies like CSPC [8] even more. A more thorough comparison between the CSPC and the categorization of the present paper is required to determine a suitable hierarchy and possibly come up with a more thorough classification system for shape-changing interfaces. All of the constructs can in fact be placed in the 45 categories as put forward by Feixas et al. [8]. Our motivation to do our own categorization and keep the amount of categories under 10 was to ensure that each category consisted of enough constructs to be able to say something meaningful about the category, its relation to other categories and its relevancy for design.

We believe that a vocabulary for discussing a set of behaviors and examples is crucial in communicating while developing the skills for designing subtleties in shape-changing interfaces. Touching an interface and being able to express your experience helps in explaining the effect subtle differences have on the affective experience. As a consequence, follow up studies should support designers in developing their own shape-changing interfaces and considering possible applications using said vocabulary.

CONCLUSION

We have described a repertory-grid study of the experience of six shape-changing artifacts. The study has resulted in a catalogue of personal constructs about such artifacts, emphasizing anthropomorphic descriptions and complex behaviors compared to existing models. We have discussed the potential of these descriptions for design and for research in shape-changing interfaces.

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