User-Defined Gestures for Elastic, Deformable Displays

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ABSTRACT
Elastic, deformable displays allow users to give input by pinching, pushing, folding, and twisting the display. However, little is known about what gestures users prefer or how they will use elasticity and deformability as input. We report a guessability study where 17 participants performed gestures to solve 29 tasks, including selection, navigation, and 3D modeling. Based on the resulting 493 gestures, we describe a user-defined gesture set for elastic, deformable displays. We show how participants used depth and elasticity of the display to simulate deformation, rotation, and displacement of objects. In addition, we show how the use of desktop computers as well as multi-touch interaction affected users' choice of gestures. Finally, we discuss some unique uses of elasticity and deformability in gestures.

ACM Classification Keywords
H.5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous.

General Terms
Human Factors; Experiment; Design; Measurement

Author Keywords
Elastic; deformable display; guessability; gestures; think-aloud; user interfaces

1. INTRODUCTION
Interactive displays that can deform and change their shape are emerging in the field of Human-Computer Interaction (HCI). Due to their elasticity and flexibility, these interfaces allow users to deform the surface dramatically – for instance by stretching, twisting, or folding. Whereas hard interactive tabletops and other flat displays allow only for two dimensional multi-touch input methods, deformable displays can afford interaction that physically extends in depth or in relief [15]. Previous work with deformable hand-held devices [3,5,8,19,22,26] and cloth displays [11] have shown possible applications for displays that deform. Other studies have shown how the size and stiffness of materials can affect users' interaction [5,9].

As suggested by Gründer et al. [4], deformable displays may be divided into two types: (1) *Flexible,* deformable displays, namely displays that are highly flexible and may allow for permanent deformation; (2) *Elastic,* deformable displays, namely displays that are elastic and allow only for temporary deformation. Our work relates to the body of research that investigates the latter. Elastic, deformable displays do not retain shape, and include interfaces like the Khronos Projector [2], where users can push an elastic membrane to interact. The present paper focuses on investigating elastic, deformable displays with the size of multi-touch tabletops (see [2,15,28]), placed at a vertical orientation.
Related work shows applications for elastic, deformable display in virtual 3D modeling [23], map navigation [20], and gaming [28,29]. However, user studies that evaluate interaction with these displays are limited [28] and little is known about how users would make use of deformability for input. Furthermore, while hard multi-touch displays have a well-defined set of gestures (e.g., pinch to zoom), no such set exists for elastic, deformable displays.

To address these shortcomings, we conduct a study of elastic, deformable displays employing a guessability study methodology [25]. The aim is to investigate what gestures users would perform on displays that afford deformation, as well as how and when they would take advantage of deformability and elasticity for input. Using a think-aloud protocol and semi-structured interview, we gather qualitative information and insights on why users choose to perform particular kind of gestures. This work contributes (1) a user-defined set of gestures for elastic, deformable displays and (2) insights into why users choose specific gestures as input.

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2. RELATED WORK
We base our work on research in elastic, deformable displays and on previous guessability studies. In this section we review related work in both of these areas.

2.1 Elastic, Deformable Displays
Table 1 shows a summary of related work on elastic, deformable displays, focusing on five points: (1) material, (2) projection, (3) tracking, (4) applications and (5) gestures. We believe that these are the key points that describe previous work from both the interactive and the technical point of view. Next we discuss each point in the table. Because gestures are performed in the context of interactive applications, points 4 and 5 will be discussed together.

The type of *materials* used in elastic, deformable displays have had a key role in shaping the interactions. It has been described how the action of sliding a finger on the display can become easy or hard, depending on the amount of friction produced by the surface's material [1]. With the hemispherical inflatable multi-touch display [20], the shortcoming of latex (high friction) was addressed by inflation and deflation of the surface, which dynamically changed the stiffness of the material. A PVC inflatable balloon was used to create the surface of Inflated Roly-Poly [7], where users could only punch on the display as input. This approach made it easy and fun to interact with the PVC surface, but resulted in limited gestures. eTable [28], the Kreek Prototype [29], ActiveCurtain [30], CloudPink [31], Firewall [32], and Elascreen [27] all featured the use of fabric, allowing for comfortable pushing, stroking, and sliding. However, because their fabric is slippery, pinching, pulling, and stretching were not used to interact. The Deformable Workspace [23] and DepthTouch

[15] used a mixture of lycra and spandex. These materials have higher elasticity compared to other fabrics, allowing for easier grabbing and pulling. However, finding a material that may easily allow heterogeneous gestures remains a challenge.

In order to create interactive applications, *projection* of graphical contents on the surface is used in many elastic, deformable displays. Only two of the prototypes shown in Table 1 do not use projection [21,32]. Rear-projection is common [2,15,23,28], and it has the advantage of preventing users from covering the projection with their hand's shadow. However, this approach is not always applicable. For instance, Impress [33] used projection from above onto a display made of a thick layer of foam covered with a white cloth; the light of the projector could not have passed through it if placed behind. Furthermore, images projected onto a deformable surface should take into account possible dynamic deformation, and algorithms for the compensation of image deformation should be used if aiming for a realistic effect (see [23]).

Detecting and *tracking* gestures, as well as surface deformation on a deformable display, are hard. The Khronos Projector [2] used an infrared source and a camera with an infrared filter to acquire a grey-scale image. The gray-scale image was used to compute the size of the area deformed by the user, and then mapped onto depth coordinates. The same authors later used a sensing mechanism based on projecting an array of 1,100 spots on the back of the display, and then computing the coordinates of a 3D point for each spotlight in the pattern [23]. With the use of this technique, multi-touch detection was possible. Multi-touch could also be detected by Stevenson et al. [20] with the use of an infrared camera and a strip of infrared emitting lights. A similar technique was used with Inflated Roly-Poly [7], whereas Metamorphic Light [12] and Impress [33] used a camera-based approach to detect deformation. Thanks to the commercialization of the Kinect, recent prototypes take advantage of the depth sensor to rapidly detect multi-touch input in three dimensions. However, many challenges remain open (e.g., how to effectively detect complex deformations and multi-touch on the display at the same time).

Table 1: Five Characteristics of Related Work

Papers	Material	Projec-tion	Tracking	Applications	Gestures
Khronos Projector [2]	Lycra	Back	IR dots array	Video exploration, image navigation	Push
The Deformable Workspace [23]	Lycra	Back	IR dots array	3D modeling, image navigation, 3D rotation, 3D displacement	Push, Grab, Squeeze, Stroke
DepthTouch [15]	Lycra, Spandex	Back	Kinect	Physics simulation, entertainment	Pinch, Pull, Push
Impress [33]	Foam, Fabric	Above	Camera	Music, RSS feed navigation, 3D modeling	Push
Elascreen [27]	Fabric	None	Kinect	Multi-dimensional data navigation	Push
Metamorphic Light [12]	Paper	Above	Camera	Image manipulation, animation	Push, Grab, Tap, Stroke
An Inflatable Hemispherical Multi-Touch Display [20]	Rubber, Latex	Back	IR camera, FTIR	Map navigation, fMRI navigation	Push
Inflated Roly-Poly [7]	PVC	Back	IR camera, IR LEDs	Gaming, entertainment	Punch
A Malleable Surface Touch Interface [21]	Latex	None	Camera	3D modeling	Push
eTable [28]	Fabric	Back	Kinect	Gaming, fMRI navigation	Push, Grab Expand
Firewall [32]	Fabric	Back	Kinect	Entertainment	Push
Kreek Prototype [29]	Fabric	Back	Kinect	Entertainment	Push, Expand
Active Curtain [30]	Fabric	Back	Kinect	Rehabilitation	Push
Cloud Pink [31]	Fabric	Back	Kinect	Entertainment	Push

Early prototypes of elastic, deformable displays showed potential *applications* and *gestures* for such displays. Khronos Projector [2] allowed for simple push interaction to explore the spatio-temporal volume of videos. A 3D modeling application, where a virtual spring mass could be deformed by pushing on a malleable medium, was proposed by Vogt et al. [21]. The idea of manipulating virtual objects through a physical deformable display seemed to enhance virtual 3D modeling. A similar concept was proposed with Impress [33], where users could model virtual 3D objects by simply pushing onto the display. The Deformable Workspace [23] featured a virtual 3D modeling application, where users could push and squeeze the display to deform objects.

Pushing was used for multi-dimensional data navigation [27], to explore multi-dimensional fMRI images [28], and generally in most of the prototypes [29,32,30,31]. DepthTouch [15] adds pulling gesture to pushing, where both can be used to influence the physical behavior of virtual spherical objects. Inflated Roly-Poly [7] introduced the punch gesture, whereas Metamorphic Light [12] allowed users to poke the display to animate the picture of a human face, press or stroke it to play videos, or grab and squeeze it to create real-time animations. However, a well-defined set of gestures for elastic, deformable displays has not been developed yet, and no systematic investigation has been made of which gestures are preferred by users.

2.2 Guessability Studies

The guessability study methodology has been used in previous work to elicit users' gestures for various types of devices and interactive contexts. It has been used for generating user-defined gestures in mobile interaction [18], for interaction across devices [6], and also to understand deformation-based gestures on hand-held devices with various level of flexibility [10]. It consists of eliciting an unbiased input from users by prompting them with specific stimuli, and gathering qualitative information by making users think aloud.

Wobbrock et al. used it in a study for symbolic input guessability [24] and to elicit user-defined gestures for surface computing [25]. The same authors later evaluated the user-defined gesture set against a gesture set created by designers [13], showing that the user-defined set, compared to the designer-defined, was easier for other users to assimilate and master.

Previous work on guessability also shows how users would focus on familiar gestures even if explicitly asked to create new ones [14]. Recently, this method has been used to develop a user-defined gesture set for augmented reality (AR) applications [16,17]. We believe that this methodology can help us investigate gestures for elastic, deformable displays by letting participants suggest fitting gestures for specific tasks, as well as understanding the nature of their choices by the use of a think-aloud protocol.

3. STUDY

This section describes a guessability study performed on an elastic, deformable display. We base our method on the guessability studies mentioned above, in particular the work of Piumsomboon et al. [17], and Wobbrock et al. [25]. The goal is to investigate what gestures users produce on an elastic display that affords deformation, as well as how users take advantage of deformability and depth for input.

3.1 Participants

Participants were recruited among students and professionals at our university. A total of 17 people participated in the study, 13 participants were male and 4 were female. 14 participants had previous experience with multi-touch devices. The average age was 24.7 years (*SD* = 4.8) and all participants were right-handed. At the end of the session, participants received a gift as a compensation for their time.

3.2 Apparatus

We developed a prototype of elastic, deformable display for the study. To choose the material for the surface of the prototype, a pre-study was run with 10 participants to test five different materials. The materials were (1) a rubber sheet made of latex, (2) a mixture of cotton and elastane (95% cotton, 5% elastane), (3) a mixture of cotton and spandex (90% cotton, 10% spandex), (4) a mixture of polyester and spandex (92% polyester, 8% spandex) and (5) a mixture of lycra and elastane (90% lycra, 10% elastane).

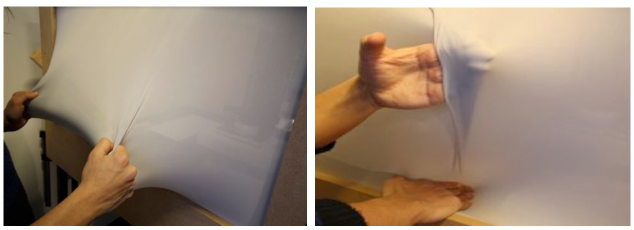

Figure 1: Two pictures that show the elasticity of the material.

Participants chose the mixture of lycra and elastane (90% lycra, 10% elastane) as the best material due to high resistance, stretchability, and smoothness. Figure 1 shows the material. The final prototype to be used in the study was made with a rectangular piece of lycra and elastane attached to a wooden frame. The surface was measuring 76×47 cm, with visual contents rear-projected at 1280×768 pixels.

The software Preview was used by the experimenter to easily switch between tasks using a remote clicker.

Four cameras placed at four different angles were used to record each session. The cameras were placed (a) to the right of the display, (b) to the left of the display, (c) behind the display, and (d) on the side of the display. Figure 2 shows both the prototype and the video recorded by the cameras.

Figure 2: The prototype of an elastic, deformable display used in the study (left). The video recorded by the four cameras (right).

3.3 Tasks

Participants were presented with 29 tasks. For each task two pictures were shown, indicating the *start-state* and the *end-state* of a certain action. After being shown the pictures, participants were asked to perform a fitting gesture. To make each task clear, a text at the top left of the display showed information indicating the purpose of the task. For instance, if the task entailed taking a cube and moving it closer, the text on the display would show the sentence "Bring the Cube Closer". Figure 3 shows an example of a task.

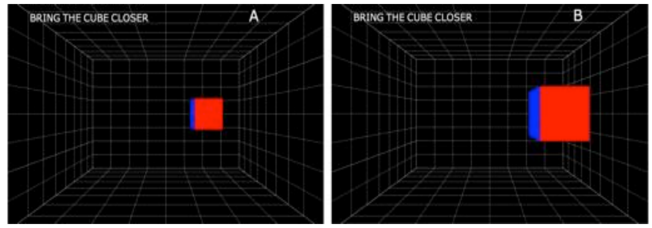

Figure 3: An example of a task. Picture A (left) shows the *start-state*; picture B (right) shows the *end-state.*

To create the set of tasks for the present study, we have used 2D tasks, 3D tasks, and tasks based on previous work on elastic, deformable display. 2D tasks entailed navigating maps, scrolling text, and editing objects (e.g., select, copy, cut and paste). 3D tasks were inspired by 3D modeling applications, as well as applications used in previous work with elastic, deformable display. They included displacing and rotating geometrical shapes in 3D space [23,33], spreading and gathering small objects [15,29] and creating magnifying lens effect [2].

Table 2 shows the 29 tasks used for this study. The objects that the participants manipulated during the tasks were all generic geometrical shapes (e.g., squares, cubes, circles, spheres).

3.4 Qualitative Data Collection

During the task, participants were asked to explain their choices by thinking aloud. After the completion of each task, participants rated their gesture on two 7-point Likert scales: (1) The gesture was a good match for its intended use (2) The gesture was easy to perform. The scales were taken from Wobbrock et al. [25].

Table 2: The 29 tasks presented to the participants. Transform, Selection, 3D modeling, and simulation tasks are inspired by [15,23,33]

Category		Tasks	Inspired by
Transform	Move	1. Bring Object Closer 2. Move Object Horizontally 3. Move Object Back	Watanabe et al. [23]
	Rotate	4. Rotate X (Roll) 5. Rotate Y (Pitch) 6. Rotate Z (Yaw)	Watanabe et al. [23]
	Scale	7. Resize Bigger 8. Resize Smaller	Watanabe et al. [23]
	Mixed	9. Rotate and Transform	N.A.
Selection		10. Select All 11. Select Multiple 12. Select Single	Wobbrock et al. [25]
Navigation		13. Pan 14. Pan and Zoom In 15. Pan and Zoom Out 16. Zoom In 17. Zoom Out	Wobbrock et al. [25]
3D Modeling		18. Deformation (1) 19. Deformation (2) 20. Deformation (3)	Watanabe et al. [23], [33]
Editing		21. Create 22. Delete 23. Cut and Paste 24. Copy and Paste	Wobbrock et al. [25]
Simulation		25. Gather 26. Spread 27. Inflate 28. Magnifying Lens	Peschke et al. [15], [29]
Browsing		29. Scroll	N.A.

3.5 Procedure

Participants were welcomed and introduced to the purpose of the study, the structure of the session and the apparatus. Before proceeding to the session, participants read and agreed to a consent form. A brief warm-up phase introduced them to the material. During the warm-up, participants were asked to pinch, pull, push, and grab the display, as well as performing a trial task (i.e., moving a drawing of a car from the right to the left of the display). The warm-up phase was intended to make participants familiar with the material and let them get a sense of gestural possibilities. When ready to proceed, participants were asked to complete the 29 tasks.

The tasks were presented in random order. Each picture was displaying a letter on the top right, indicating picture A as the *start-state* and picture B as the *end-state* (see Figure 3). When the transition returned to the *start-state*, participants were asked to suggest a fitting gesture by performing it on the display. The transition could be repeated as many times as the participant asked for and no restrictions were applied on performing gestures with one or two hands.

While performing the gestures, the participant also explained his/her choice by thinking aloud. After the gesture was performed, the participant rated the suggested gesture on the two 7-point Likert scales. The two elements were presented on the display after the completion of the task. The participant was asked to do rating by pointing with the finger at the score on the scale and explaining the rating.

4. ANALYSIS

The software Observer XT 11.5 was used to analyze the videos recorded during the study. We also transcribed think-aloud explanations and subjective ratings using the same software. The coding of gestures was done using Excel. The video for each participant was divided into short sub-videos of individual tasks and then re-organized in correspondent folders (e.g., all the sub-videos of the task "Bring the Cube Closer" stored in a folder with the same name).

4.1 Coding the Gestures

A coding manual was created through an iterative process. Each task was analyzed, and a new definition of gesture was generated and added to manual whenever needed. The basis for coding was understanding gestures as being composed of *actions*. A single action would be *grabbing* or *pushing*. The table below shows the complete list of actions sorted by frequency of repetition.

Table 3: The type of actions performed by participants during the study (total number of tokens 906)

Action	Freq(%)	Action	Freq(%)
Push	18	Stretch	1
Drag	12	Gather	1
Expand	9	Release	1
Grab	9	Lasso	0,9
Pinch	8	Punch	0,7
Pull	6	Tilt	0,6
Hold	5	Follow the contour	0,4
Rotate	3	Slice	0,3
Shrink	3	Throw	0,3
Draw a shape	3	Draw a line	0,2
Swipe	3	Slingshot	0,2
Tap	3	Round a shape	0,1
Twist	2	Rub	0,1
Squeeze	2	Spread	0,1
Slide	1		

Along with actions, the number of fingers used in the performed action was coded. If more than three fingers were involved in the action, number of fingers would have been coded as *whole hand*. After the coding manual was finalized, one author coded all the tasks, while a second author independently coded a sub-set of tasks (10% of the whole set). An inter-rater reliability analysis was performed using Cohen's Kappa statistic to determine consistency among raters. The inter-rater reliability for the raters on *Actions* was found to be Kappa = 0.84 (p < 0.01), 95% *CI* (0.7490, 0.9406), while *Fingers* was found to be Kappa = 0.76 (p < 0.01), 95% *CI* (0.6084, 0.9124).

4.2 Agreement Score

In order to calculate consensus among the suggested gestures, an agreement score A was calculated with the following equation:

$$A = \sum_{P_s} \left(\frac{|P_s|}{|P_t|} \right)^2$$

where P_t is the total number of gestures performed within the task, t, and P_s is a subset of similar gesture from P_t, and the range of A is [0, 1]. The equation is taken from Piumsomboon et al. [17]. Our definition of similarity is based on previous work [17], where the metrics used to define similar gestures are minor variations of *hand poses* and *path*. Let us consider as an example the agreement for the task *Select Single*. For this task we compute:

$$A_{Select\ Single} = \left(\frac{12}{17}\right)^2 + \left(\frac{4}{17}\right)^2 + \left(\frac{1}{17}\right)^2 = 0.55$$

The agreement score for all tasks is plotted in Figure 4. The maximum score was reached in *Scroll* task (A = 0.58), whereas *Deformation (3)* reached the minimum agreement score (A = 0.05). For certain tasks, participants reached a better agreement in two-handed gestures than they did for one-handed ones. These tasks were specifically: *Gather, Spread, Zoom In, Zoom Out* and *Pan and Zoom Out*.

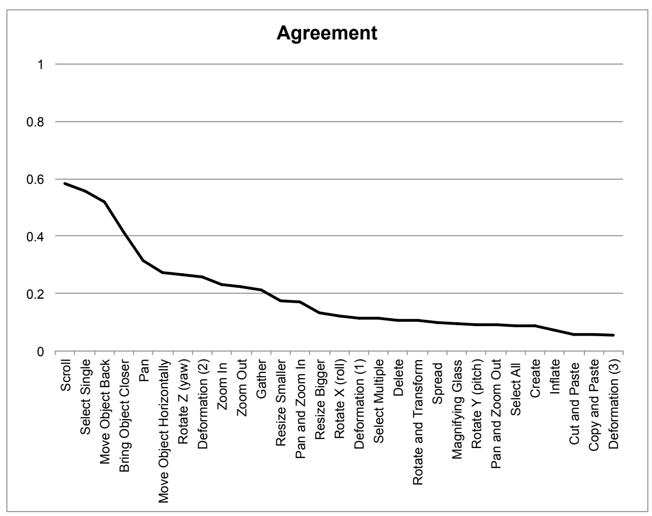

Figure 4: Plot of the agreement score.

5. RESULTS

A total of 493 gestures were generated from 17 participants performing 29 tasks. For each participant, data collection included video and audio recorded from the four cameras placed around them. A user-defined set of gestures is outlined as a result of the study. Also, subjective rating, transcription of think-aloud and qualitative data from semi-structured interviews are reported.

5.1 User-defined Gesture Set

We construct the user-defined gesture set from the group of similar gestures that obtained the largest agreement score for a particular task. We define the gesture identified from the group with the largest agreement as the *consensus gesture*. Therefore, this section describes a user-defined set made of 27 consensus gestures. The 27 gestures are assigned to 25 tasks. The tasks *Cut and Paste, Copy and Paste, Rotate Y (pitch)*, and *Deform (3)* were not assigned any gesture, because participants could not reach an agreement in those tasks.

To make the user-defined gesture set conflict free, consensus gestures that were identical or similar could be assigned to different tasks only if they did not fall into the same category (see Table 2). For the tasks *Delete* and *Pan*, participants reached the same agreement score for more than one gesture. Therefore, these tasks were assigned two consensus gestures.

Of the 27 consensus gestures, 20 were unimanual, 5 bimanual and 2 were a combination of unimanual and bimanual, indicating that overall participants preferred one-handed interaction over two-handed.

By observing the gestures performed by participants, and by reading the comments they provided through think-aloud, we distinguish three main factors that affected the gestures produced during the study: (1) the influence of elasticity and deformation of the display, (2) the influence of previous use of multi-touch technology, (3) the influence of previous use of desktop computers. Next we discuss each of these factors in turn.

5.2 Influence of Elasticity and Deformation

In this section we discuss the consensus gestures that have been influenced by the elasticity and deformability of the display. Seven consensus gestures (26% of the user-defined set) were identified in which participants made use of depth and deformation to solve tasks such as 3D modeling or deformations. They are illustrated in Figure 5 and 6. When having to rotate, displace and deform objects, participants seem to treat the virtual objects as if they were physical, or used a metaphorical approach when lacking a physical reference.

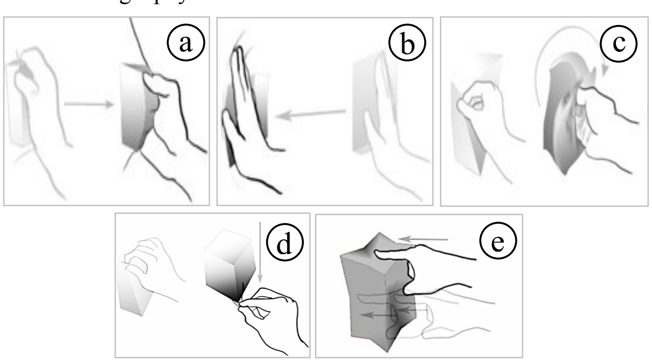

Figure 5: The gestures generated by participants using deformation and depth, where objects were treated physically: (a) *grab and pull*, (b) *push with flat hand*, (c) *grab and twist*, (d) *pinch and drag*, (e) *push with index finger*.

Grabbing, pulling, and pushing on the display (Figure 5a, 5b) were suggested by participants as fitting gestures to displace a cube back and forth in a three dimensional space. 35% of participants found these gestures physically intuitive and easy to perform: *"I can grab the object and pull it because it's an intuitive motion and the material can afford it"* – P3. Twisting the shape by physically twisting the display (Figure 5c) was also described as easy to perform on the elastic display. Furthermore, 41% of the participants said that the cube must be grabbed in the middle to obtain the deformation. A similar concern was expressed when rotating the cube on the x-axis (pitch), where the top corner was used as the point of rotation (Figure 5d). This shows how the geometrical properties of the objects influenced some of the gestures performed.

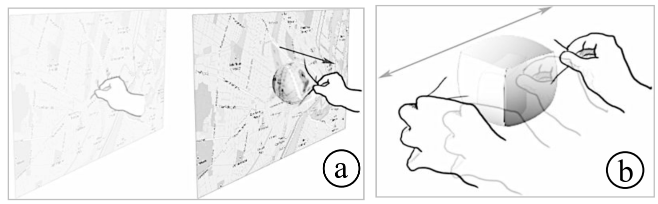

Figure 6: The gestures generated by participants using deformation and depth, where objects were treated metaphorically: (a) *pinch and pull*, (b) *grab and stretch.*

Five participants (29%) pushed with the index finger into the display to deform the sides of the cube in the *Deformation (1)* task (Figure 5e). Among them, two participants (12%) also wanted to deform the top and bottom sides of the cube: *"...I then grab and pull the bottom corner and push underneath, cause I imagine the bottom deforms too…"* – P6. This shows that when modeling 3D objects, these participants extended their perception of the object to the third dimension. Due to its deformability, the display could complement this perception also in a physical way.

A metaphorical approach was used to solve the task *Inflate*, where participants pinched and stretched the display (Figure 6b), hoping that the system would understand the motion and instantly inflate the cube. The deformability of the display was used also to create a magnifying lens on a map, where 18% of participants pinched and pulled the display (Figure 6a), hoping that the system would understand and magnify the deformed area of the display.

5.3 Influence of Multi-touch

In this section we discuss the consensus gestures that seem influenced by the use of multi-touch. We show that, although the prototype used for the study could be deformed, operations like navigation and browsing were solved with multi-touch inspired gestures. The multi-touch inspired gestures account for 62% of the consensus gestures in the user-defined set.

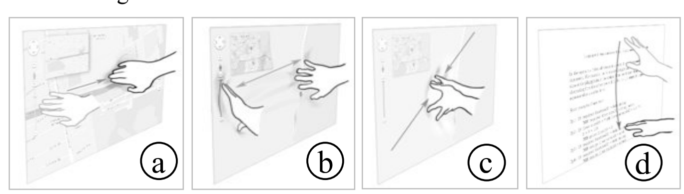

Figure 7: The gestures inspired by multi-touch in navigation and browsing tasks: (a) *drag with whole hand*, (b) *expand with two hands*, (c) *shrink with two hands*, (d) *swipe*.

For navigation tasks participants were mainly inspired by multi-touch interaction (Figure 7 and 8). In order to pan on a map, 52% of the participants suggested drag or swipe as fitting gestures (Figure 7a and 7d), and 30% explained that the use of iPad and Google Maps influenced their choices.

This also had an impact on other navigation tasks, namely *Zoom in*, *Zoom out*, and *Pan and Zoom* (Figure 7b, 7c, 8a, 8b): *"just like as you would zoom on tablet but with a bigger motion"* – P10; *"this is like how you do with maps on touch computers and big touch screens"* – P7. This shows how the massive use of multi-touch devices is shaping user's navigation techniques. However, it can be seen from Figure 7b and 7c how participants, while performing zoom operations, still applied force on the surface and slightly deformed it. In this case we had the impression that, while zooming on the display, participants also wanted to dig into the display. However, the use of depth was not totally intentional according to the participant's feedback, and therefore we did not include these gestures among the ones where the participants explicitly make use of depth.

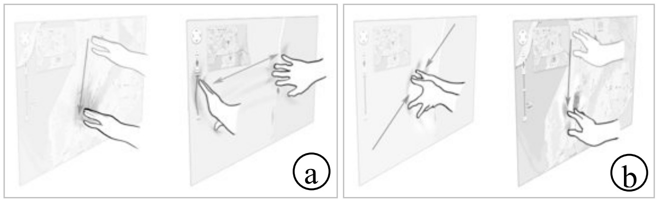

Figure 8: The gestures inspired by multi-touch that combined unimanual and bimanual actions: (a) *drag and expand*, (b) *shrink and drag*.

A swipe motion was suggested as a fitting gesture to scroll a text (Figure 7d), where 30% of the participants explained that they would scroll like in OS X or iOS systems (i.e. scrolling up to go down and vice versa), and 12% imagined a scrolling bar would appear on the side of the display when moving the text.

Gestures performed to resize and rotate objects were also influenced by multi-touch. In order to resize a cube and make it bigger, 35% of the participants chose to do it by placing the index and the thumb from the same hand on the corners of the cube, and expand it by moving two hands apart from each other (Figure 9b). However, only one participant explained that this gesture is similar to how one scales things on a multi-touch tablet.

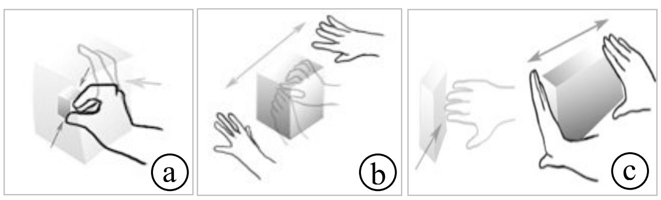

Figure 9. Gestures inspired by multi-touch to resize objects: (a) *shrink*, (b) *expand with two hands*, (c) *drag and expand.*

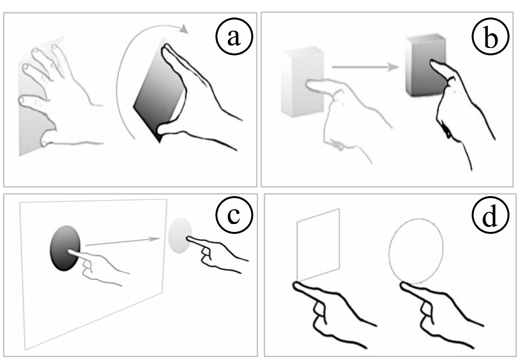

Figure 10: Gestures inspired by multi-touch rotate, move create and delete objects: (a) *rotate*, (b-d) *drag with index finger*, (c) *draw a shape.*

To resize a cube and make it smaller the one handed approach was slightly preferred, where all the five fingers from the hand were placed on the object and shrunk so as to make the object smaller (Figure 9a). To rotate (pitch) and stretch the sides of a cube in the task *Rotate and Transform*, 24% of the participants used a combination of *drag* to rotate and *expand with two hands* to stretch the sides (Figure 9c). The open hand pose was also used to rotate a cube on the z-axis (Figure 10a), where 47% of participants used the wrist as the center of rotation and rotated the hand around it in order to rotate a cube.

Delete, *Create*, and *Move Horizontally* were solved with one-point contact gestures inspired by touchscreen. To move an object horizontally, participants used the index finger in order to drag it (Figure 10b). They did likewise to delete an object (Figure 10c), but eventually dragging it outside the boundaries of the display. For these gestures 40% of the participants talked about touchscreen computers and smartphones, and 12% imagined a bin in the corner of the display.

To create an object, 35% of the participants drew the outline of what they wanted to create on the display the outline of what they wanted to create (Figure 10d). 33% of the participants optionally pulled or pushed the display after drawing the shape so as to extrude the form of the object, showing how the deformability of the display could be used to add third dimension to bidimensional contents. However, 30% wished a contextual menu to appear on the display, which could allow them to either create the object or to choose among options like color, size, and so forth.

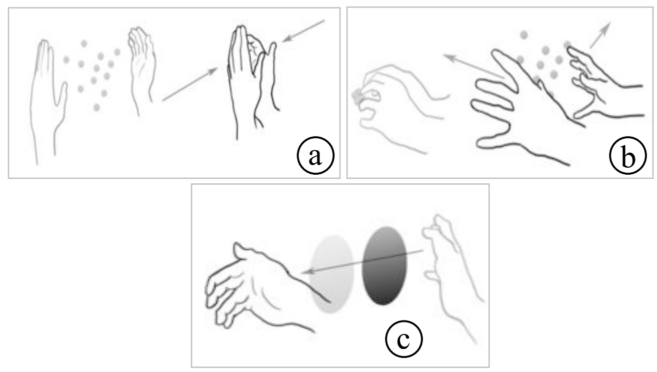

Figure 11: Multi-touch gestures that resembled real physical actions: (a) *gather*, (b) *grab and expand*, (c) *swipe.*

When gathering or spreading objects (Figure 11a, 11b), 47% of the participants referred to real physical actions, like making snowballs, squeezing beads in a plastic bag, or spreading small objects on a table, and two participants also talked about multi-touch gestures. When swiping to delete (Figure 11c), 18% of participants thought they were physically throwing an object out of the screen. This kind of physical approach is probably inspired by actions that participants would perform in the real world.

5.4 Influence of Desktop Computers

In this section we discuss the consensus gestures that have been influenced by previous use of desktop computers. We identified 3 consensus gestures of this kind (12% of the user-defined set). These gestures are illustrated in Figure 12.

In order to select a single object, 70% of the participants pushed onto them directly with their index finger (Figure 12a). This approach was explained by 35% of the participants with reference to point and click from desktop computers or tap selection from touchscreen: *"it is like pointing and clicking, I do the same with my computer, or like when I touch to select an icon on my tablet"* – P17. When selecting multiple objects, participants simply repeated the same gesture as many times as the number of objects to be selected (Figure 12b), while *Select All* was solved by 18% of participants with a lasso selection (Figure 12c). They all explained this gesture as similar to what they would do in a drawing program in order to select an area.

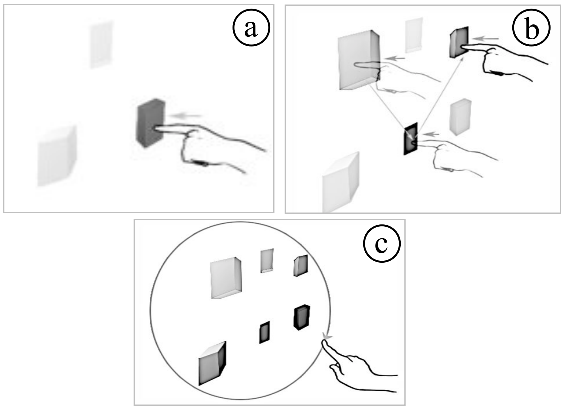

Figure 12: The inspired by desktop computers: (a-b) *push with index finger*, (c) *lasso.*

5.5 Subjective Rating

Subjective rating results show a correlation between ratings of goodness and of ease. The Pearson's correlation coefficient shows a very strong, positive correlation, $r(27) = 0.805$, $N = 29$, $p < 0.01$. This indicates that when a gesture was regarded as easy to perform, it was also perceived as a good match for the task, with goodness rated generally lower than easiness.

5.6 Semi-structured Interview

Comments from semi-structured interviews revealed that most participants (70%) enjoyed interacting with the surface of the prototype, and said that multi-touch gestures were easier to perform on it than on a glass display. Furthermore, 65% of participants explained that they pushed a bit the display also when performing multi-touch gestures because the surface naturally afforded it.

For 53% of participants grabbing or pinching the surface was hard, 23% said they would stick to known gestures from multi-touch and desktop computers, and 30% said elasticity and deformability would greatly enhance gaming. 18% of participants said they would like such a display to be real and commercialized, and two participants noticed that pushing and grabbing became harder if moving towards the corners of the display. Finally, one participant suggested that the deformable display could have the shape of a cube, so that one could interact by fully pushing the hands inside of it.

6. DISCUSSION

Earlier work on elastic, deformable displays have used gestures such as push, grab, pinch, and pull. Our results show gestures that produced more extreme deformation of the display, such as twist and stretch. Watanabe et al. [23] showed how moving virtual objects far from the self in a three dimensional space could be mapped to push gesture. We show that the reverse action can be mapped to grab and pull gesture. Also, we show how participants, when manipulating 3D objects in a 3D context are likely to use deformation and depth for input. This result confirms that interacting with 3D modeling applications, as proposed in earlier work [20,23,27], can be enhanced on elastic, deformable displays.

Similarly to Wobbrock et al. [25], our agreement scores show that tasks involving simple actions (e.g., moving objects, selecting, scrolling) reached higher agreement than tasks involving complex actions. However, our results also show that actions happening in the three dimensional space, such as moving an object back and forth, reached higher agreement. This means that experience with multi-touch has just partially influenced the level of agreement among participants. This becomes clearer when observing tasks that, despite being solved with multi-touch alike gestures, were rated lower because of their conceptual complexity (i.e., create, select all).

Besides gestures from the user-defined set, like twisting and stretching, participants performed other types of interesting gestures, but these were not included in the final results because participants did not agree on them. For instance, some participants used the elasticity of the display to simulate a slingshot, others reached behind the display and pulled it to move objects closer. These gestures were not reported in previous work and they would be difficult if not impossible to perform on flexible displays like Flexpad [19] or Impress [33].

A substantial number of gestures from the user-defined set were inspired by multi-touch. This shows that the influence from already known interfaces had a strong impact on certain tasks. However, most participants accidentally used depth also for those multi-touch alike gestures. This may present issues when implementing a gesture recognition system. Preventing depth interaction from being accidentally triggered when unwanted, could be mitigated by using a threshold for depth or dynamic filtering techniques.

Implementing the recognition of gestures from this user-defined set can present other challenges besides the accidental depth issue. While bidimensional multi-touch gestures and depth detection can be achieved using existing approaches (e.g., blob tracking, depth sensor), detection of stretching, twisting, or folding the hand into the surface of the display would be harder. Developing a gesture recognition system that is able to recognize various deformations efficiently will require more elaborate techniques. The implementation of such system will be paramount to verify the validity of our results, and extend them beyond the present study.

Finally, we must consider sources of error and limitations in our approach. We have used a guessability study methodology, which has the advantage of not biasing users' choices. However, for certain tasks, like 3D modeling or simulation, participants explained that the lack of real time feedback made it really hard to find a suitable gesture. Furthermore, tasks that resembled multi-touch operations may have led participants to perform already known gestures. This suggests that for future studies a set of tasks specifically designed for elastic, deformable displays may be used.

7. CONCLUSION AND FUTURE WORK

We have presented a study of elastic, deformable display that outlines a user-defined set of gestures based on participants' agreement over 493 gestures. Using the agreement among the elicited gestures, 27 consensus gestures were selected to compose the user-defined set. We have also shown how previous use of multi-touch and desktop computers influenced choices in certain tasks, such as navigation, selection and scale. We will also conduct further studies to validate the user-defined gesture set and investigate those gestures that did not reach enough agreement. A new group of participants will try these gestures with interactive applications to confirm the validity of the consensus set, and hopefully better explain the gestures discarded in the present study.

8. ACKNOWLEDGMENTS

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