Study and Design of a Shape-Shifting Wall Display

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ABSTRACT
Wall displays almost universally assume a mostly flat and static shape. We ask two questions: Would people choose a flat display for a given interaction scenario and, if not, what are the display shapes they actually prefer? We conducted a design study around these two questions. Our results show that participants designed different screen shapes that varied based upon peoples' distance from the display and the content shown. Shapes ranged primarily between flat, separated, concave, L-shape and convex displays. Based on our findings, we designed a dynamic display that changes to these and other configurations. Shape-shifting is controlled either by explicit interaction (where the display responds to hand gestures) or implicitly (where the display infers a shape based both on its content and the sensed positions of the people around it). Overall, we contribute: a study that motivates research on shape-shifting wall displays, and a shape-shifting display system that responds to explicit and implicit controls to match particular activities.

Author Keywords
Shape-changing displays, robotic displays.

ACM Classification Keywords
H.5.2. Information interfaces and presentation (e.g., HCI): User Interfaces, Interaction styles.

INTRODUCTION
The research focus on single and multi-display design has tended towards their hardware construction and their interactive capabilities. Yet the physical placement of these large displays within the workplace is also critical: a display's location and orientation within a room and its features, including its position relative to other displays, can afford or inhibit individual and collaborative activities [4,6,7,13-18,24-29]. This is why other domains (e.g., furniture design, interior design, architecture) pay considerable attention to designing efficient and comfortable workplaces. Even so, most display walls are typically configured as a flat display anchored to a particular location. Furthermore, they inhibit manual repositioning because they are unwieldy to move. The result is a fairly static environment that reflects a single expectation of use.

DIS 2016, June 04-08, 2016, Brisbane, QLD, Australia
© 2016 ACM. ISBN 978-1-4503-4031-1/16/06…$15.00
DOI: http://dx.doi.org/10.1145/2901790.2901892

We challenge this status quo. The issue is that people change their activity from moment by moment, and we hypothesize that a given multi-display configuration appropriate for one activity may not be a good match for the next activity. For example, a group of collaborators arranged semi-circularly in an F-formation [16] would likely want a common display in the shared space immediately in front of them. Yet if that group then transitioned to individual activities involving personal tasks, each person would likely want their own separate display to avoid interfering with one another. Individuals may even want these displays angled away from one another to afford privacy or minimize distraction.

One simple remedy is to allow people to manually move displays to fit their activities. This is already afforded by various non-digital displays that can be easily re-arranged. Examples include mobile whiteboards, paper flip boards and even foldable screens. Manual repositioning also exists to a limited extent within the digital realm, usually by mounting smaller displays on display arms or pedestals, as will be discussed in the Related Work section.

Another possibility – and the focus of this paper – is a shape-changing display that *automatically* changes its physical shape or screen arrangement to support the collaborative or individual contexts of people's activities. We were inspired by the entertainment industry, which has developed several impressive shape-changing displays ([3,23]: see Related Work). However, the focus of that industry is on supporting interactive performances rather than work activities. While shape-changing interfaces are an emerging area within HCI, HCI research currently emphasizes surface deformation of a small display into a 3D shape [1,7,10,22] *vs.* large display reconfiguration.

In this paper, we explore the design of a shape-shifting wall display that can dynamically change its shapes to best match particular activities of its surrounding users. Our exploration comprises two parts. First, in order to inform the design of shape-shifting wall displays, we conducted a design study around two questions: would people choose a flat display for given interaction scenarios and, if not, what are the dominant display shapes they actually prefer? As we will see, our findings suggest that people prefer a range of screen shapes – flat, separated, concave, L-shape and convex – where the choice varies based upon their distance from the display and the content shown.

Second, we designed and implemented a working proof of concept shape-shifting wall display, where its dominant shapes were tuned to match our study results. We also experimented with two interaction techniques to control shape-shifting. In *explicit interaction,* shape-shifting is triggered by people's hand gestures. In *implicit interaction,* the display infers a shape based both on its content and the sensed spatial relations between the people around it.

Overall, we make three primary contributions.

1. Our study contributes research on shape-shifting wall display design, where particular useful shapes are suggested for particular situations.
2. Our implementation contributes a shape-shifting wall display that serves as a starting point for others to replicate and enhance.
3. Our explicit and implicit interaction techniques contribute two control methods that match shape shifting to particular individual and group activities.

RELATED WORK

The range of display shapes and their subtle attributes

Many different display shapes have been built and studied: tabletop displays, vertical displays, floor displays, multi-display environments, and so on. They also vary by interaction modality, e.g., touch, a pointing device, a keyboard, and even body presence. An excellent survey [2] classifies many different display shapes according to various dimensions. Considerable research also covers fine-grained attributes of particular displays. For example, E-Conic [18] addresses obliqueness issues arising from extreme viewing angles in a multiple-display environment. Endert et. al. discusses the subtle effects of curvature in multi-monitor office environment [4]. Ichino et. al. looks at the effect of tilt angle on a wall display mounted in a museum [11].

Others have considered display strategies for *mixed focus collaboration* [8], where people monitor what others are doing in order to fluidly transition between individual and group work. Examples in the tabletop realm include PiVOT [13] and Permulin [15]: both provide a display that can present different views to its viewers. Gjerlufsen et. al. describe middleware that allows different views across a multi-surface environment [6]. These efforts confirm that particular individual and collaborative activities are best supported by a matching display configuration.

Our work also supports different display configurations and their subtle attributes, but differs in that it goes beyond a single fixed shape, where it considers how a single system can dynamically and automatically change between multiple shapes.

Displays that Change Content in Response to the Spatial Relations of its Users

Various displays dynamically change their content (rather than their shape) to best fit the changing spatial relationship between people and the displays that surround them. This is called *proxemic interactions* [17,28], which is in turn based upon the social theory of *proxemics* [9]. For example, if a person faces towards the display and approaches it (signifying increased interest and engagement), the display will provide progressively more detail [17,28]. As another example, when people orient and move their personal handheld displays towards one other, the interface changes to afford easy information transfer [17]. Another approach uses the social theory of *F-formations* to infer group membership. For example, [16] matches cross-device interaction with particular F-formations, e.g., when people stand in a side-by-side F-formation, they can fluidly share visual content by tilting one device towards the other device. E-conic [18] also uses spatial relations to determine how to present distortion-free content to users viewing multiple displays from different locations and angles. Steerable interface [20] is a projector-based system that dynamically displays movable content on ordinary surfaces in a room by extracting implicit user's needs from their actions (e.g., proximity) or their explicit gestures.

Our work also monitors the spatial relations between people and displays. It differs in that it uses that information to infer a display's *physical* shape that best matches the group's individual and collaborative contexts.

Manually Repositioning Physical Displays

A few multi-display environments include displays that can be manually repositioned. One example is ConnecTable, a horizontal display mounted atop a custom wheeled pedestal [27]. When two people abut ConnecTables together, their interfaces are fused to enable collaborative interaction. A somewhat related example is the Chained Display [14], a public display consisting of six connected vertical Plasma displays, each mounted on a pedestal. Its researchers manually reconfigured the Chained Display to particular vertical display shapes (e.g., flat, circular, hexagonal), and examined the effects of those shaped in a field study. However, they did not examine how users could reconfigure those displays themselves. While these and other works [24] support the idea of manual display rearrangement, our own work goes further, as it examines automatic dynamic re-configuration of physical displays.

Shape-Changing Shared Displays and Robotic Displays

While some small shape-changing displays exist [1,22], there are only a few examples of self-actuated large shared displays that can change their physical shape. TransformTable is a digital table that can change the shape of its single horizontal display, e.g., from circle to square [25], inferring its dynamic shape from the display content and situational contexts. Our work differs as we consider multi-vertical display configurations.

Telepresence robots include a camera and monitor atop a robotic base. The robot serves as a mobile proxy for the remote user that controls its (e.g., [5]).

The entertainment industry has developed several quite sophisticated shape-changing multi-display systems to support interactive performances [3,23]. These entertainment products are inspiring, as they illustrate both the potential and the beauty of robot-controlled shape-changing displays in an artistic installation.

Our prototype implementation follows a similar technical approach (using robots to reposition displays). However, it differs as it examines vertical displays, and rather than exploring artistic expression is aiming to study and support particular personal to collaborative interactions within the workplace. In a parallel project, we are also investing robotic interactive horizontal tabletops that can physically move, assemble or break apart according to the interaction settings [26].

DESIGN STUDY: FREE SCREENS FORMATION

We conducted a design study centered upon two basic questions, whose answers would provide initial insights into strategies for designing shape-shifting displays.

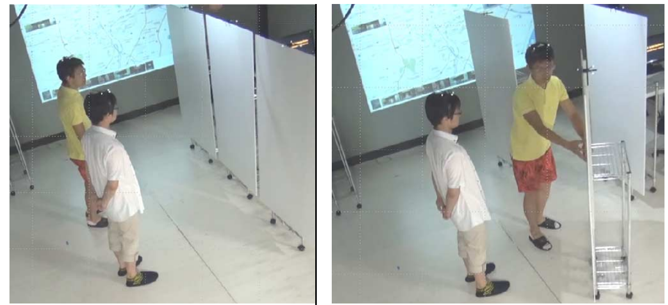
1. Would people choose a flat display for a given interaction scenario?
2. If not, what are the display shapes they actually prefer in particular interaction scenarios?

The first question is important, as its answer *motivates whether different display shapes are useful for particular scenarios*. If that notion is refuted, then it means that a ‘one size fits all’ flat display approach is an acceptable design strategy. If different display shapes are in fact desired, then answers to the second question *provide insight into the design requirements behind such displays*, including how particular shapes should support particular situations.

Method

There are numerous factors that could affect user preferences of display shapes (e.g., the physical environment, the social context of collaboration, particular interaction devices available, screen size, etc.). As this is an initial study, we focused on two critical factors: the location of people around the display, and the particular content being displayed. To facilitate this, we constructed a variety of interactive scenarios that varied by screen content and by participant location (which we call ‘distance conditions’).

For our design study we created a mockup of a simple shape shifting display. The display itself comprised three light-weight separated 80 x 150 cm simulated screens mounted on wheels. Different shapes could be created



a) Initial setting b) During design

Figure 1. Design study: free screen formation

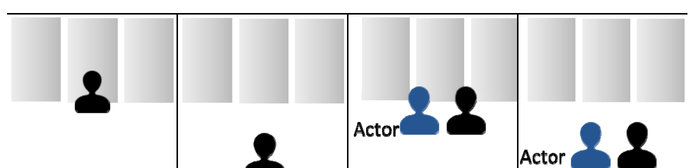
simply by repositioning the location and angles of these three screens (Figure 1). We chose the three screen configuration as a minimum set that could provide basic but reasonable shape expressiveness. We did not use projector tracking during the design study. Instead, we displayed each condition’s screen content on a separate large display on a wall adjacent to the three screens (e.g., Fig 1, side wall). While the two are disjoint, participants were readily able to imagine that content displayed on the three screens.

We recruited 16 participants (5 females and 11 males, average age 22.9) from local universities. Each participant was introduced to interaction conditions (within-subjects) as described below. For each condition, the participant was asked to design their ideal display using the three screens, where they could grab, manipulate and change the positions and angles of the screens as desired (Figure 1b).

Each participant went through a total of 24 interaction scenarios. Each scenario was crafted from a cross-combination of 6 different screen content types, and 4

(a) Large map content (b) Privacy-sensitive credit card information (c) Immersive video game (d) 3 multi-task windows: mail, browser, map. (e) 3D volumetric model viewer (f) 16:9 film

Figure 2. Screen content conditions



(a) Individual, near (b) Individual, far (c) Group, near (d) Group, far

Figure 3. Distance conditions

distance conditions. Each scenario reflected different individual and collaborative activities that are normally performed on a large display (data exploration, multi-tasking, collaboration, and immersive game).

Figure 2 describes and illustrates the six screen content conditions used in this study. Figure 3 shows the four distance conditions across individuals and groups. For the first two, the participant was told they would be standing alone at a position either near or somewhat far from the screen. For the second two, an actor joined the participant at those near and far conditions to simulate a group.

Screens and participants were tracked with OptiTrack markers in order to precisely capture their positions and spatial relations, and to record the designed screen shapes. We video and audio recorded the entire design processes, including capturing participant's comments. We also conducted intermediate and final interviews.

Each interaction scenario began with the three screens initially aligned as a conventional continuous flat arrangement around the center of the tracking area (Figure 1a). Each participant was instructed to act as a designer and to freely design their desired screen shape in order to match the presented interaction scenario (as being done in Figure 1b). We asked them to use all screens, and to present an arrangement for each setting within two minutes. To minimize a methodical bias that may lead participants to always change the shape, we instructed them to not change the screen shape if they believed flat was the best formation. We then verbally explained the interaction content visible next to the movable screens. Finally, the participant was asked to reflect on that content and, when ready, to start their design.

Participants were asked to design for 'near' and 'far' interactions. We did not give them precise positions but rather explained that 'near' is standing either directly in front or in reach of the display, while 'far' is somewhat back from it.

In case of group conditions, a silent actor entered the space to serve as a proxy of a collaborating colleague, where he stood at a predefined location in front of the screens (e.g., the white-shirted person in Figure 1). The actor did not otherwise interact with the participant. The participant was instructed to consider how the presence of their colleague in the particular scenario and at particular user's distances would affect their screen design.

The order of the 24 interactive scenarios was counterbalanced among the 16 participants using customized Latin square. Following each design outcome (for each of the 24 interactive scenarios) the experimenter conducted a short interview in front of the designed screen in order to elicit the participant's design rationale. Afterwards, the experimenter reset the screen to its default flat position and briefly explained the next scenario. After the complete set of scenarios, the participant was interviewed about their overall experience, and asked to complete a questionnaire regarding the design of shape-shifting screens. The study took approximately 90 minutes to complete and participants were compensated for their effort (an equivalent of $10).

Results and Discussion

Participants produced a variety of screen shapes. Using the data from our OptiTrack sensors, we measured the exact position and angle of the screen shapes. Using those measures along with participant comments on their design rationale, we were able to code all the 384 designed shapes (24 scenarios x 16 participants) into several major shape categories (described shortly).

For example, while we saw different concave shapes, we could classify them into major two major concave types: narrow and wide concaves. We determined which concave shapes fit these categories by using the measured angles of the two sides screens. If the angle was less than 45°, we regarded that shape as wide concave. If greater than 45°, it was classified as narrow concave. The 45° threshold determination was based on the design rationales of participants. Screen separation was determined by the gap size between screens which, based on participant comments, were considered separated when the gap was 10 cm or more.

Figure 4 illustrates the 11 major shape categories produced by our coding analysis as well as how frequently they were seen across all conditions.

Recall our first research question: would people choose a flat display for given interaction scenarios? Our results

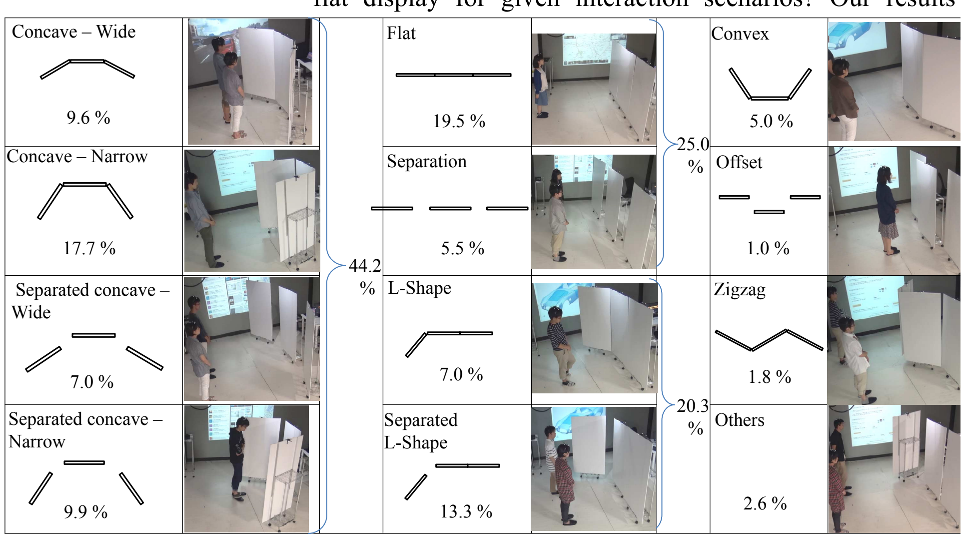


Figure 4. Designed shapes, by categories with sample design snapshots

Table 1. Shape categorizations per scenario
***top 1*: most popular shape; *flat*: the popularity of the flat shape**

	Individual – Near		Individual – Far		Group – Near		Group – Far	
	Top 1	Flat	Top 1	Flat	Top 1	Flat	Top 1	Flat
Large Map	31.25%	6.25%	56.25%	31.25%	56.25%	12.5%	31.25%	37.5%
Private/ Sensitive View	50%	0%	37.5%	12.5%	25%	6.25%	25%	12.5%
Immersive Game	50%	6.25%	25%	25%	50%	6.25%	50%	12.5%
Multi-task Windows	62.5%	0%	25%	6.25%	31.25%	6.25%	50%	0%
16:9 Film	43.75%	31.25%	18.75%	68.75%	37.5%	18.75%		62.5%
3D Model	31.25%	12.5%	18.75%	43.75%	25%	18.75%	18.75%	31.25%

show that the conventional continuous flat shape was designed 20% of the time. That is, flat is only preferred a minority of the time, albeit still a significant minority.

Our second question was, what are the display shapes users actually prefer in particular interaction scenarios? We see that the top 8 shapes in Figure 4 dominated the 344 shapes participants made (90% of all shapes). In order, these are: flat, concave narrow, separated L-shape, separated concave narrow, concave wide, separated concave wide, and L-shape. (Later sections will reveal how we use these eight shapes to inform our prototype design of a shape-shifting wall display). Figure 4 also reveals other lesser done shapes that may be important for niche situations, including convex, off-set and zigzag shapes.

Shapes for scenarios

Yet this is not the whole story emerging from our design study. We cross-classified all 11 measured shapes to the 24 scenarios. Each distance condition is described by a pair of columns in Table 1. The column labelled 'Top 1' identifies the most popular shape we saw in that condition, where it shows the percentage of times that shape was designed. For comparison, the column labelled 'Flat' shows the percentage of time the conventional flat display was chosen. (Percentages do not sum to 100% as the table does not show less popular configurations.) Each row specifies the screen content condition, and is discussed in detail below. The discussion is based both on the shape categorizations (as in Table 1) and on participants' design rationales as captured in the interviews.

Large map application content (table 1, first row)
Participants preferred continuous or separated L-shapes to view a display of a single large application such as a map. They said that L-shape reflects how they already work with such applications on dual workstation screens. However, proximity had an effect: the popularity of the flat screen increased when participants stood far from the screen.

Private/sensitive content (table 1, second row)
When sensitive content is displayed and people desired privacy, they clearly preferred the concave shape in the individual condition. Participants said the concave shape somewhat shields the view from passers-by, while also enhancing the feeling of privacy. However, shapes for the group condition were more difficult to interpret, where the separated L-shapes and zigzag shapes somewhat dominated. We believe that there is no clear result for the private views in the group condition because the role of the actor was somewhat unclear to some of the participants, i.e., whether the actor was supposed to be privy to that information or not. Even so, a few participants creatively designed several zig-zag shapes, where they said the zig-zag shielded private views for each person. Although not the most popular configuration, we also saw participants tilt a single screen to completely hide the workspace from their partner's view (illustrated in Figure 4, under 'others').

Immersive video game (table 1, third row)
Participants generally used concave screens for gaming, where that shape seems to provide an immersive experience. The degree of concavity was affected by proximity: narrow concave when near the screen, and wide concave and even flat when far from the screen.

Multiple windows (table 1, fourth row)
Participants predominantly designed separated concave screens across all conditions. Interview comments suggested that screen separation was a more important factor than the concave shape. The main reason given was that the physical gaps between screens helped create explicit separations between tasks and windows.

While not the most popular, we also saw convex shapes (Figure 4 convex) designed for the group condition (18.7% in group & near condition). With a convex shape, a user can see only one or two screens and must move around the center screen to see the third screen. The apparent motivation for this shape is to provide a separate screen for each user (i.e., each of the outside screens) with a common screen in between (the middle screen).

Wide 16:9 film (table 1, fifth row)
Somewhat similar to our immersive video game results, participants preferred concave screens to immerse themselves into the film when near, but opted for the more flatten screens in far conditions. This is why the table has a blank in the far condition for that scenario, as flat is preferable (62.5%) over others. Participants kept all their designed screens connected in this scenario.

3D Model view (table 1, last row)
Designs in this category varied considerably, and are thus inconclusive. We simply state that concave and flat screens were produced somewhat more frequently than others depending on the condition.

Table 1 also highlights contrasting results in the near *vs.* far conditions. Participants in both individual and group conditions generally chose not to use the flat arrangement when near the display. This suggests that a shape-shifting display is particularly beneficial when people are in close proximity to it. However, when people are far, flat shapes are often comparable, or even preferable, to other shapes.

Limitations

The free screen formation design study is not intended to be definitive, and certainly does not cover all the relevant social, technical, environmental, and other factors that could influence how people consider shape-shifting displays. Rather, we view our study as a starting point. It is meant to provide preliminary insight on an uncharted design space, and to help inform the design of our shape shifting display prototype as discussed next.

SHAPE-SHIFTING DISPLAY PROTOTYPE

The results of our design study reveal that most participants preferred customized shapes adapted to the interactive content at hand: the traditional flat screen is chosen only a fifth of the time. This begs the question of how a user can reconfigure the display shape to fit their changing interactive setting. While the simplest way appears to do this is manually [27,14], this can be problematic. Moving large screens can require time and considerable physical effort, and people may be rightly concerned about fragility. Even if light robust displays are used, manual positioning is effortful, where each screen would have to be moved to a new position. The result is that people will likely not reconfigure their screens unless the payoff is high.

As an alternative, we set out to prototype a customizable, efficient and comfortable automatic shape-shifting wall display that can be controlled explicitly by a users' commands via gestures, and implicitly via algorithmic suggestions based on the interactive content being displayed and the sensed user's distance from the display.

Hardware and software

Our prototype, illustrated in Figures 5 and 6, uses the same screen configuration as in the design study. It comprises three vertical slim screens (61 x 150 cm for each), each mounted on a mobile Roomba Create robot. Each screen also has 3D markers atop of it. The position and orientation of each screen are controlled by maneuvering the robot, where a tracking system accurately tracks the position of each display (via its markers) as it is moved. People also wear markers, which allows the system to track their spatial location relative to the display and to each other. People's input gestures (described later) are recognized via a Kinect placed above the display.

As screen positions and orientations change, visual content (image-scrapped from a host computer's display) is adjusted continuously and dynamically via projection mapping. This is done to remove distortion (resulting from tilt and distance changes), and to map content to individual separated screens or to the collective screen as a whole.

Due to the small projection area of the prototype's single projector (Figure 5), and based on the shapes emerging from the design study, our screen angles shifts only between 0°, ±30° or ±45° to represent various flat, concave and convex shapes. For the same reasons, it allows physical gaps of up to 22cm between its screens. However, these values can be easily revised by changes to the robotic movement patterns, or via different projectors settings.

Our control software communicates with the robots via Bluetooth, and with the tracking system and Kinect through TCP sockets at 100Hz. Our projection mapping program is implemented atop of openFrameworks [19] at 30 fps. People interact with the displayed content via a controller, such as a wireless mouse or smartphone, or via Kinect tracked gestures. As projection mapping onto moving displays is difficult, we suppress display updates during shape-changes by using static screen snapshots captured just before movement begins.

Design Elements

Shape-shifting displays are heavily influenced by several design elements. This can affect how they fit into the workspace and how they adapt to intended uses.

First, the number of individual screens and their sizes are important. The more screens, the more shapes possible. Similar to our design study, the current prototype uses three modest-sized screens. This three-screen configuration allows users to create various fundamental and useful shapes (Figure 6) that could be appropriate for individual and small group interactions (1-3 people).

Second, the way multiple screens are connected can constrain the possible resulting shapes. For example, Chained Display [14] and other small shape-changing displays [1,7,10] physically connect screens with hinges to create a single screen whose curve can be altered manually. We used unconnected screens, each controlled separately, as our design study reflected on screen separations being an important component of users' desired configurations.

Third, the robot's ability to move affects the screen shapes possible, and the flexibility of their dynamics. We currently use Roombas, a low-cost differential two-wheeled robot, where the screens are fixed perpendicularly atop of them as in Figure 5 (left). This allowed us to create various configurations of perpendicular displays by horizontally moving and rotating the robots across the floor.

SCREEN SHAPES FROM DESIGN STUDY

We created several screen shapes as our starting point, where the system can easily switch between these shapes. These include flat, separated, concave, convex, L-shape and the other shapes illustrated in Figure 6. Our shapes and the rationale behind them, all inspired by our design study, are described below.

Flat wall displays (Figure 6, top left) are appropriate for many purposes. Uses include a big data exploration, video viewing, as an ambient information wall viewable at a distance, or as a medium for collaborative data exploration.

Separated displays (top mid-left) support one or more people pursuing individual tasks on individual screens. The gaps between the screens emphasize the separation between tasks or users. All affect the perception of these screens as personal or private areas, as well as how one person can glance over to see what others are doing. This horizontal separation could also be used in the concave and the L-shape arrangements screens to add a physical partition feature to these shapes.

Concave connected displays (top mid-right) provide a somewhat physically shielded workspace for a more personal or private user experience. It is also appropriate for immersive content (e.g., games).

Concave separated displays (top right) allow users to maintain a focused and compact workspace while still having individual tasks and information displayed on each screen.

L-shape displays (bottom left) have a primary large screen and a physically separate secondary screen. As Figure 6 shows, the position and angle of the second screen can be further altered for the tasks.

Convex connected displays (bottom mid-left) were not popular in the design study. We included this because it could be suitable to some unique scenarios. Like Cubic display [21], the convex shape's screen can visualizes volume data from three different camera points. Alternately, each screen can display different tasks, where users can perform individual work while monitoring others (i.e., mixed focus collaboration [8]).

Other shapes are included (bottom right side)**.** *Offset rows* may show primary work on the foreground screen and peripheral work on the background screens. *Zigzag* shapes can be customized to particular settings, such as public displays of posters or advertisements. *Tilting* can display distortion-free images to users at any directions.

INTERACTION TECHNIQUES AND USAGE SCENARIOS

We designed and implemented a set of explicit and implicit interaction techniques that can control the display shape. While these techniques are not yet evaluated in a user study, we reflect on our design rationale, present their implementation, and discuss their possible mapping to different interactive scenarios.

Explicit Interaction through Gestures

We allow users to explicitly control the display shape. While this could be done through various means (e.g., commands on a smart phone), we concentrated on gestural commands as a better fit: a person invoking a shape change is not required to touch the display or go through an intermediary device, and gestural actions are easily seen by other collaborators. The explicit interaction technique will initiate movement of the shape-shifting wall display only when the user explicitly initiates the shape change. It thus has fewer risks of unintentional shape changing (assuming that the gesture sensing is accurate and that the user has not made the gesture unintentionally). All gestures consist of grasp-move-release actions, each recognized via the Kinect situated above the display. Our design focused on finding realistic metaphorical gestures that could be easily mapped to the physical action of the shape-shifting wall display screens.

Example gestures are illustrated in Figure 7. A person selects a single screen by one-handed grasping gesture made in front of it (7a), or all screens by a similar two-handed grasping gesture. Individual screens can be pulled, pushed or tilted via a corresponding single-handed *pull*, *push* or *tilt* gesture (7a). All screens can be simultaneously controlled in the same manner when a two-handed gesture is done. A person can also use a class of gestures to invoke

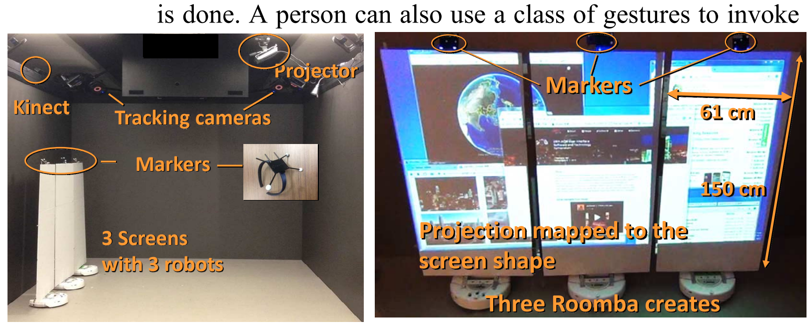


Figure 5 Prototype implementation

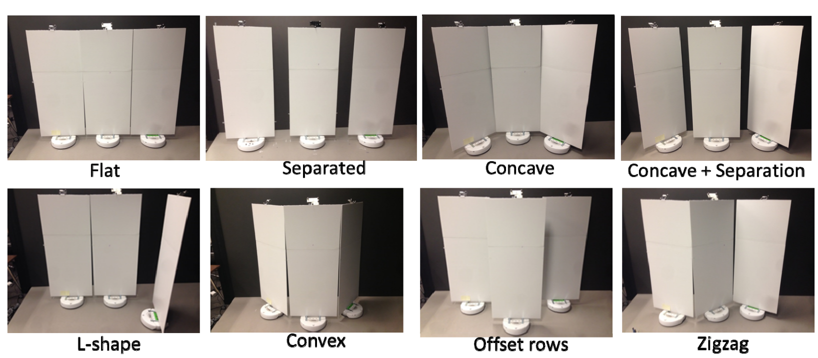
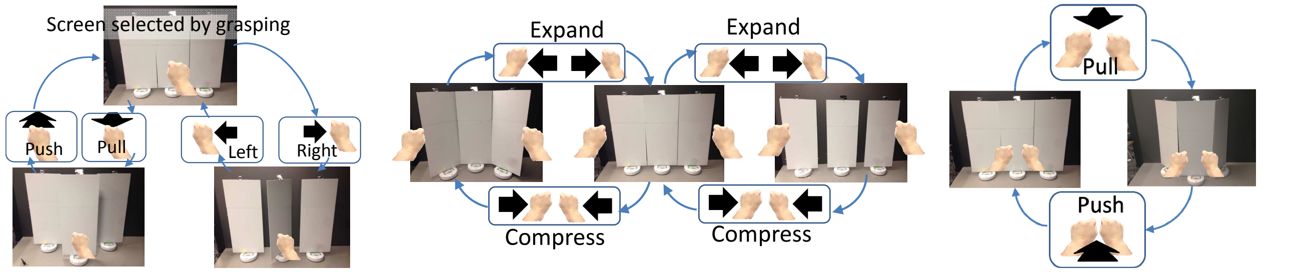


Figure 6 Wall display shapes



(a) Screen selection by grasping, and position and angle controls by gestures

(b) Between concave, flat and separated shapes

(c) Between flat and convex shapes

Figure 7 State transition model of gesture-based shape control

(a) Collaboration

(b) Gestures for expand (upper) and Compress (lower)

(c) Individual tasks

(d) Compress gesture

(e) Private workspace

Figure 8 Explicit shape controls via gestures in individual and collaborative activities.

the stock screen arrangements shown in Figure 6. The basic gestural form creates a more focused convex workspace when the hands are moved sideways towards each other (*compress* gesture), or a more separated workspace (continuous flat, separated flat) when hands are moved apart from each other (*expand* gesture) (7b). Similarly, a two-handed *push* or *pull* gesture in front of the central screen will switch between flat and convex shapes (7c).

Figure 8 illustrates how this works in collaborative and individual scenarios. We see three people that are just finishing collaborating over a flat display (8a). One person invokes the expand gesture (8b upper) to separate the screens to support individual activities (8c). If they wish to move from individual back to collaborative work, the compress gesture (8b lower) will bring the screens back together (8a). Figure 8 (d-e) shows an individual usage situation where a person wanting a somewhat more private setting uses the compress gesture to shape-shift the display into a concave form.

Implicit interaction techniques

Our second approach uses implicit interaction, where the screen shape changes proactively based on inferences made by the system. Our design attempts to initiate an automatic shape-shifting action only if there is mounting evidence that such a change is desirable. This means that, if designed correctly, the screens' physical movements timing and magnitude would enhance the workspace, adapting it to the user's changing task context, rather than disturb the user's task flow. Our design study suggests two contextual cues which can be easily detected by a simple monitoring system to trigger shape-changes: screen content, and the spatial relations of people around the display.

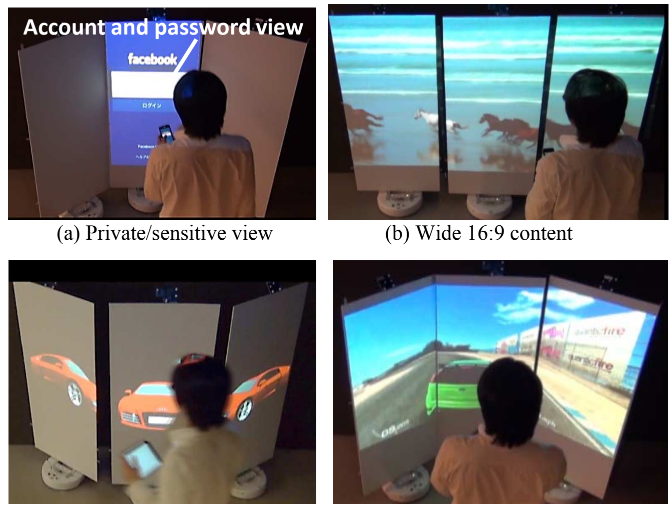
Shape control inferred from screen content

The system can monitor the content that is being displayed (e.g., by monitoring applications and file types selected by the user), and automatically customize its shape to match that content. Figure 9 illustrates some examples of several shape change scenarios that occur on particular content types. When a person's actions require a degree of privacy (e.g., display of a password entry dialog), the shape automatically changes to concave to discourage shoulder-surfing (9a). When the person selects a full-screen application with a wide aspect ratio (e.g., a movie player), the system assumes a continuous flat shape to optimize the viewing experience (9b). When the person displays a volumetric visualization (e.g., showing side, front, side views) the screen becomes convex. While our design study did not explore this scenario, we expect that this may enhance the feeling of depth and encourage multi-perspective data exploration from three camera viewpoints (9c) [21]. When the person is navigating through 3D landscapes (driving simulators, 1st person shooter games), the system becomes concave to create a more immersive experience (9d). While these examples are limited they suggest a rich design space based on the system being able to adapt its shape following dynamic assessment of the content and task the user is interacting with.

Shape control inferred from spatial relationships

Our design study suggests that people's spatial locations and relations significantly impacted what screen shape was desired. Consequently, we implemented an implicit interaction technique where the system infers the positions of people and changes the screen shape based on a proxemic interaction approach [17]. Our technique tracks which of two zones people are in: an *ambient display zone* where people may be just glancing at the display, and an *interaction zone* where people are nearby and thus likely to be interacting with the display's content (Figure 11). Within the interaction zone, the system detects F-formations [16,17]: the physical spatial patterns that people adopt when they engage in focused conversational encounters (e.g., side by side, face to face). While people's positions are currently tracked through head-worn tracking markers (Figure 10a), marker-less methods are also possible [17]. Figures 10 and the video figure illustrate several shape change scenarios that occur when particular spatial relationships are detected. When no one is within the interaction zone, the display assumes a flat single shape so that its contents are viewable by passersby (Figures 11). When it detects a single person crossing into the interaction zone (currently 1.2 m from the screen as suggested from our design study) towards the screen's center (10a), the display assumes a concave shape to reflect personal work (10b). Our findings (Table 1) suggest that this shape shifting approach could be preferable by users in many scenarios.

Figure 10c-f illustrate an example scenario showing how the shape-shifting wall display supports mixed-focus collaboration [8]. Here, people may pursue a mix of individual activities while still monitoring others' activities, up to fully collaborative activities where they work together directly on a shared task. Example mixed-focus collaborations include planning activities, gaming, brainstorming, etc. To support this, when a 2nd user enters the interaction zone and stands to one side (10c), the display flattens that side to afford a degree of collaborative viewing (10d). When people move closer together, the screen flattens completely as it assumes a purely collaborative shape (10e). When people move apart to pursue individual tasks the screen turns convex or separates. When two collaborators need their own private workspaces, the screens could separate (Figure 8c) or reconfigure themselves into a convex shape: individual content placed on the sides provide personal spaces, with shared content placed on the middle screen that both could monitor. Figure 10f shows two people travel planning with a convex screen. Both access personal email and calendars on their own screens, but see a shared map on the central screen. Of course, people can easily shift back from individual to full screen collaboration by moving to a side-by-side formation in front of the display (10e). F-formations can involve more than two people. For example, and similar to (8c), when three people stand apart from each other, the system separates as it infers each is pursuing individual tasks.



(a) Private/sensitive view (b) Wide 16:9 content

(c) Volumetric data (d) Immersive game content

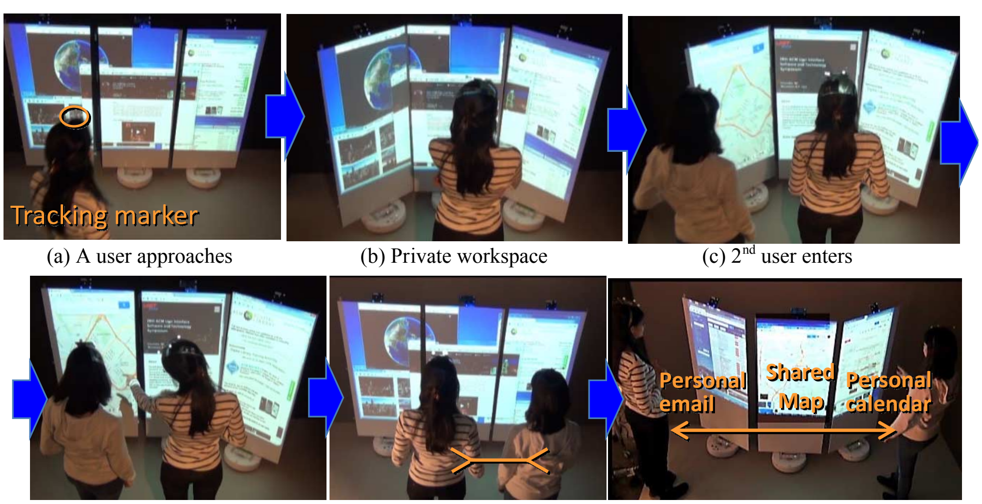
Figure 9 Implicit shape control inferred from screen content

Combination

The system can also consider combinations of content-based and spatial-based mechanisms to provide more nuanced inferences. For example, if a movie is being displayed and people have stepped back into the ambient zone, the system could infer that they are now viewing the movie together and shape the screen accordingly.

Managing errors

Mistaken inferences will happen, which could lead to unwanted, and perhaps even annoying shape changes. Several methods can mitigate this [12]. The best way to



(a) A user approaches (b) Private workspace (c) 2nd user enters

(d) Partial flat screen (e) Full collaboration (f) Individual and private tasks

Figure 10 Implicit shape control inferred from spatial relationships

manage errors is to minimize their number. One approach is to act very conservatively where the system may change its shape only when it has fairly convincing evidence that it has detected something warranting a shape change. It may also weight some shape changes more than others, i.e., shifting to unusual shapes would require more evidence. It may use timing and hysteresis constraints to minimize excessive screen changes, e.g., as may occur when people are rapidly moving around a display.

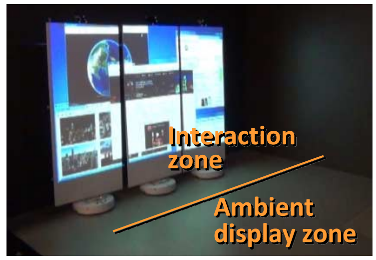


Figure 11 Proxemics zones

Figure 12 Stop gesture

Explicit overrides of implicit actions
People should be able to easily override undesired shape-changes [12]. Our system provides for manual override by detecting a *stop* gesture (Figure 12), an open upright palm moved towards the screen during an implicit shape change.

DISCUSSION
The idea of a display that shape-shifts to support particular individual and collaborative activities is unusual, and thus could be met with some skepticism. Yet our design study shows that display reconfiguration is what people would do if given an easy choice. Our prototype illustrates one way to provide people with that easy shape-shifting display.

Admittedly, this is early work. We have contributed a study where participants designed screen shapes of a wall display for particular interaction scenarios, and implemented a working proof-of-concept system that can shape-shift based on explicit or implicit user actions. Yet we have not yet studied the actual benefits of the total system. This includes verifying the implicit rules over particular situations, and the understandability of the gestures used for explicit control. We will certainly need to: study the nuances of shape-shifting design and strategies; test their actual use; and consider alternate powerful implementations. Yet the benefits of a shape-shifting display can be predicted. In terms of the screen shape, there are common practices and our design study mostly support them. For example, large concave screens are common as immersive screens. Convex volumetric displays are afforded by cubic displays supporting multi-perspective data exploration [21]. Others have explored manually reconfigurable modular displays of various shapes. Reconfigurable Displays allow various quite large panels to be created by modular projection boxes e.g., towers, horizontal or vertical, L-shapes, etc. [24]. Commercially, there are myriads of wall displays comprising odd shapes (e.g., advertising walls etc.). There is no question that both interest and deployment of differently shaped displays is growing. Our work just pushes it to the next step, where shape-shifting is done by user's effortless interface or the system in response to actual individual and group needs, rather than by a person manually and laboriously reconfiguring display components.

Our next steps will be to improve upon our own implementation. First, we will increase the number of screens, which involves a modified multi-projection system. This gives greater flexibility in the shapes possible and will also allow separated screens to have larger gaps between them. Second, we will improve upon shape transition. While the screens' movements are accurate, the movements possible are impacted by limitations in how we can maneuver our robot, as well as the robot's limited degrees of freedom. We foresee an omnidirectional robot, perhaps with a controllable arm to carry actual flat displays and change their roll/pitch/yaw, as a feasible – and physically more stable platform (including more rigid screen support to avoid screen vibrations during movement) to rapidly and smoothly move the screens towards any location, direction and angle. Screen visualizations could also be improved by modifying our projection mapping so that animated content can be displayed even during the shape-changes. This can, for example, express motion cues [26] that help users anticipate screen change intentions before its actual movement.

CONCLUSION
We contributed a shape-shifting wall display that dynamically changes its physical shape to support particular individual and group activities. We presented a design study that shows that participants designed different screen shapes to match varying interactive content and people's position around it. The design study confirmed our motivation of shape-shifting display and suggested several fundamental screen shapes. Based on our findings we implemented a proof-of-concept prototype of the shape-shifting display which can automatically change its shape to one of these fundamentals screen shapes. Our first prototype comprises three vertical slim screens, each mounted on a mobile robot. We showed how we can transition not only between stock shapes (flat, separated, concave and convex) but other shapes. We provided scenarios of how particular shapes can potentially optimize individual, mixed-focus, and fully collaborative activities as well as content viewing. We illustrated three methods for triggering shape changes: explicit shape control based on gestural commands, and two implicit methods based on screen content and the spatial relations of users.

ACKNOWLEDGMENTS
This work was supported in part by JSPS KAKENHI (26730101), Leading Young Researcher Overseas Visit Program, the Cooperative Research Project Program of the Research Institute of Electrical Communication, Tohoku University, the Frank and Sarah Meyer Foundation CMG Collaboration Centre, and NSERC's Discovery Grants.

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