Interacting with actuated walls: Exploring applications and input types

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Graphical Abstract

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Highlights

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- Investigated the benefits of shape changing walls in two studies.
- Furthered our limited understanding of how to interact with large vertical actuated interfaces.
- Proposed five themes of possible shape-changing walls applications.
- Users were more likely to use gestures to indicate the shapes and movement when close to walls.
- When facing an actuated wall with bigger cubes, users would use their hands more than their fingers.
- When the cubes were smaller, users would interact and perform operations more with their fingers.

Interacting with Actuated Walls: Exploring Applications and Input Types

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Abstract

Previous literature on small-scale shape displays demonstrated the benefit of shape-changing interfaces and adaptive environments. However, research with large-scale implementations is limited to specific equipment. Thus, there is little understanding of how they can enrich user experience in a larger scope, especially from an interactive perspective. We proposed using pin-array large-scale implementations made of linear actuators matrix as vertical structures to replace static and planar walls and conducted a two-fold exploration to extend the understanding of potential applications and showcase users' behaviors and preferences to inspire researchers. We summarized 14 potential applications for shape-changing walls, and presented users' interaction preferences with such a wall of different sizes and interaction distances. We concluded with recommendations and guidelines for practitioners to design large-scale actuated walls.

Keywords: shape-changing interface, actuated walls, interaction design
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1. Introduction

Shape displays, or sometimes called 2.5D actuated shape displays, are shape-changing interfaces (SCIs) consisting of a matrix of linear actuators that can together generate dynamic physical forms (Leithinger et al., 2011). Shape displays could largely enrich interaction because they not only allow users to physically visualize digital information in a more intuitive, informative, and engaging way (Taher et al., 2015), but also allow them to mold and feel tactile data, as well as to actuate other objects in the vicinity.

Despite many advantages of shape displays and the rich literature accompanying them, there are only small-scale setups that have been explored so far from an interactive point of view: tablet size displays (Hardy et al., 2015; Everitt et al., 2016; Siu et al., 2018); handheld devices (Kim et al., 2018); tabletop systems (Leithinger and Ishii, 2010; Follmer et al., 2013; Leithinger et al., 2011); or on the larger scale, we have TRANSFORM (Ishii et al., 2015), which consists of three InForm displays (Follmer et al., 2013), combined to form a larger actuated countertop with 1,152 motorized pins.

On the other hand, existing larger-scale vertical installations of shape displays have also been proposed, although mainly focusing on hedonistic purposes. For example, Hyper-Matrix (Yang, 2012) is composed of thousands of cubes driven by stepper motors to form a 180-degree actuated setup with 8 meters tall and 45 meters wide. This project and many similar implementations (Rogers and Design Studio, 2010; Goulthorpe et al., 2012; Khan, 2014) demonstrate the technical feasibility of large-scale shape displays, but only exhibit artistic installations.

We believe that large-scale shape displays could offer interactive features that go beyond hedonic ones. We envision this new technology could be used as vertical structures to replace static and planar walls, motivated by the proven benefits of adaptive environments (Aryal et al., 2018) and walls augmented with flat displays (Ball et al., 2007; Liu et al., 2014, 2017; Guimbretière et al., 2001), including increasing occupants' satisfactory and productivity in working (Aryal et al., 2018). The walls could, based on previous applications, display physical information and deform to split spaces. That being said, designing large actuated interactive shape displays brings new research challenges that their smaller counterparts do not take into consideration. Their scale and how users relate to it (proximity) may influence the way users would control the wall. Potentially, users may want the wall to react differently than traditional systems, e.g., waiting for the users to move away from it to avoid hurting or frightening them. Such an assumption is particularly motivated by research in Robot trust (Hancock et al., 2011), showing that there is a complex dynamic between a human and a robot, particularly when the robot is the same size as the human or even larger.

Motivated by the limited research in utilitarian purposes for large shape displays, as well as essential differences with their small counterparts, our project aimed to broaden the design space for interaction and usability, and contribute design guidelines for practitioners. Thus, to achieve these, we raised two research dimensions:

- **What** applications could be enabled by large shape display walls? We are particularly interested in exploring utilitarian purposes.

- **How** do end-users want to interact with such walls? We are particularly interested in how the scale and proximity impact users' interaction.

We conducted two user studies that respectively address these research dimensions to extend the understanding of potential applications and showcase users' behaviors and preferences that would inspire researchers' further explorations, instead of simply finding the ultimate answers. In terms of designing for SCI, there are many formats and form factors that could be investigated. Thus, we chose to investigate a self-contained type of shape. Looking at related work of large-scale SCI, we found that a large majority are pin-array displays either in research or installation (e.g. Alexander et al., 2018). Among them, cubes could make the space of variables more manageable. Based on all of these, we chose cubes as low-fidelity setups with end-users to gather feedback and generalize the result to other shape-changing systems. The exploration of content generation from a user's perspective (Everitt et al., 2016) allows researchers to gain creative input on the design process (Crabtree et al., 2013) and new suggestions for the design of direct interactions (Watanabe et al., 2008). Our methodology resonates with the culture of lean UX (Gothelf and Seiden, 2013) and the use of elicitation study, which are proven effective for interaction design in various contexts (e.g. Wobbrock et al., 2009; Metatla et al., 2015)). The two user studies we conducted are:

- Exploration 1 (**What**): We conducted a structured brainstorming with 12 participants from relevant creative backgrounds (architecture, creative technology, design, and human computer interaction) to gather ideas of applications and contexts and investigate how shape displays could improve user experience as actuated walls.

- Exploration 2 (**How**): We conducted an elicitation study with 20 end-users to better understand the impact of cube sizes and user proximity on the choice of input modalities. We projected visualization of a 3D actuated wall onto a white wall and asked participants to act out interaction for a series of referents [1].

Our two studies offer new insights into the design of actuated walls, and we invite the reader to embrace the full extent of these findings within the paper. We highlight our most practical insights here: as planned, we uncovered a variety of utilitarian purposes going beyond hedonic ones and we found that participants preferred to use the body (gestures and postures) to interact with the wall, suggesting that larger installations invite body interaction. As expected, the proximity of the users to the wall also affected their interaction styles. Our results suggest that there is a design space to explore in terms of the movements of the wall (or individual parts of the wall) to convey different states of the systems.

In summary, we are the first, to our knowledge, to explore the applications of large actuated walls beyond the aesthetic purpose and their related interaction, and we contributed: 1) an exploration in which we have discovered a list of potential applications for vertical shape-changing walls, 2) an analysis of participants' intuitive actions for two zones (close to and away from the wall), two sizes of actuators, and thirteen furniture-related tasks, and 3) design recommendations and implications to inspire researchers and general designers in practice.

2. Related Work

Our work relates to the usage of current shape-changing interfaces, the usage of large-scale shape displays, and similar adaptive environments design.

2.1. Shape-Changing Interfaces

A shape-changing interface is an interactive computational device that dynamically transforms its physical form into a range of shapes relevant to the context of use (Alexander et al., 2018). The research community has proposed numerous systems (Roudaut et al., 2013; Coelho and Zigelbaum, 2011; Rasmussen et al., 2012; Poupyrev et al., 2007; Economidou et al., 2021a; Roudaut et al., 2014, 2016; Goguey et al., 2019; Kaspersen et al., 2019; Petersen et al., 2020) that have explored a variety of shapes, forms, interactions, and implementation techniques. These interfaces have great potential

[1] Gesture could be triggered for simulating operations(Wobbrock et al., 2009). Referents mean the *functions* that triggered *actions*(Tang, 1991)

in enhancing the experience (Grønbæk et al., 2020), and their interaction capabilities are beginning to be explored (Rasmussen et al., 2012); Yet, due to lack of quantitative evaluation, there is still limited understanding of their impact on user experience (Alexander et al., 2018; Everitt and Alexander, 2017). The design of shape-changing interfaces is still a relatively new area of research, and the community's understanding of potential applications for this new generation of devices is still developing (Sturdee and Alexander, 2018).

Most shape-changing displays consist of an array of solid actuation pins (Follmer et al., 2013; Ishii et al., 2015; Jang et al., 2016; Leithinger et al., 2013; Leithinger and Ishii, 2010; Poupyrev et al., 2004) or deformable surface material (Dand and Hemsley, 2013; Sahoo et al., 2016; Tsimeris et al., 2013; Yao et al., 2013; Everitt and Alexander, 2019). Pin-actuated displays, often called shape displays, are the most widely adopted mechanical implementations (Taher et al., 2016). Alexander et al. (2018) noted the complexity of the hardware required limited current research on shape-changing interfaces. This is reflected in the restricted scale of shape-changing displays (e. g., tabletop) due to a lack of scalable actuators that can be robust, cheap, and easy to implement (Taher et al., 2016). As a result, shape-displays are limited to smaller-scale tabletop implementations (Sturdee and Alexander, 2018), and design-led explorations of application and interaction for those interfaces are small (Grönvall et al., 2014; Park et al., 2015). Inspired by all these implementations, we applied the pin-actuated technology to the large walls, and we aimed to find the differences in applications and interaction with small-size interfaces.

2.2. Large-Scale Shape Displays

While investigations of small-scale shape displays have been thorough - from handheld (Jang et al., 2016; Alexander et al., 2012) to tabletop (Leithinger and Ishii, 2010; Follmer et al., 2013; Leithinger et al., 2011; Siu et al., 2018; Taher et al., 2015; Hardy et al., 2015) - comparatively, little research explores large-scale shape displays, even though different scales have proven to be able to impact user experience (López García and Hornecker, 2021). Work like TilePoP (Teng et al., 2019), LiftTiles (Suzuki et al., 2020), KINEIN Economidou et al. (2021b), and Elevate (Je et al., 2021) is beginning to explore this new design space for large-scale shape displays. In these projects, researchers created floors made of pin-array cubes moving up and down.

These are the largest setups of shape displays we found that consider interaction (the floor could be used as furniture or in combination with a VR setup), though it focused on a horizontal orientation of the implementation. Another work (Takashima et al., 2016) explored interaction with actuated walls consisting of three flat panels next to each other, moving on wheels.

Most existing shape display installations are limited to the artistic field (Rogers and Design Studio, 2010; Yang, 2012; Goulthorpe et al., 2012; Khan, 2014). For example, at the Milan Design Week in 2010, Francesca Rogers and Daniele Gualeni Design Studio displayed Light-Form (Rogers and Design Studio, 2010), a system consisting of an array of lights on a wall that could be turned off by covering the lights with wood boards. In 2012, architects at MIT School of Architect and Planning created HypoSurface (Goulthorpe et al., 2012), which was made from thousands of triangular faces. The installation's goal was hedonic rather than accomplishing specific tasks for end-users. MegaFaces developed by Khan (2014) was a large-scale shape-display consisting of 1000 actuators in a public environment, though this was only a one-off installation for a particular event rather than a long-standing architectural structure. Similarly, Hyper-Matrix (Yang, 2012) is an art installation shown in the 2012 Yeosu EXPO Exhibition. In this artwork, Hyundai Motor Group displayed different patterns on the interface by moving cubes, while the audience sat in front and watched silently. Again, this large-scale installation only served hedonic purposes. Though some studies have investigated the interaction with large horizontal displays, to our knowledge, none have focused on vertical displays except for in the artistic field. Therefore, we aimed to explore the interaction design of large vertical displays and their possible applications other than hedonic functions.

2.3. Adaptive Environments

Coyne (2015) stated that architecture has great potential to enhance interaction. Research on Human-Building Interaction has highlighted the benefits of using space to affect human behaviors and interactions (Alavi et al., 2019). Examples of systems include playful interactive floor (Lim et al., 2019) and structures that move to enhance exercise breathing (Moran et al., 2016). Schnädelbach (2016) developed the idea of a dynamic architecture action-reaction feedback loop, where user input directly generates feedback from the architecture to facilitate interaction with environments.

Adaptive environments may be controlled directly by users. Research has (Aryal et al., 2018) highlighted how users are more fulfilled, gain productivity, and even become healthier when they can control environmental conditions directly. Dynamic Terrain (Pönisch, 2006) is an interactive floor-like surface that supports customized adjustment by users. Similarly, to enhance tangible interaction with architecture, Ingrid and Lian (Pohl and Loke, 2012) developed a folded and geometric structure with a kinetic framework. This was able to move dynamically, and change shape and temperature according to tactile input.

Robotics researchers have also developed adaptive furniture (Sproewitz et al., 2009; Sabinson et al., 2021). Spröwitz et al. (2010) present Roombots: modular robots for reconfigurable furniture. For example, changing from a stool to a bench or a tabletop. From a human-computer interaction perspective, WindowWall (Bader et al., 2019) builds on the vision of adaptive architecture and environments through an interactive window in a ubiquitous display. Features of the smart window can change in real-time based on specific aspects such as privacy, and environmental conditions, e. g., changing from semi-transparent to opaque. Since no literature reveals how adaptive walls can improve the living experience, we investigated how people would think of and treat large-scale adaptive walls.

3. Exploration 1 (What): Applications

We conducted the first exploration to gather ideas on the possible applications of a large-scale actuated wall.

3.1. Participants

Wilson (2013) recommends at least 10 participants for a brainstorming activity. To ensure a broader scope for ideation, we recruited 12 participants (7 females, 5 males; age 21-30, mean 24.6) via social networking and the local university's mailing list. Among them, 3 participants majored in creative technology, 3 in architecture, 3 in design, and 3 in human-computer interaction. All of them had at least 5 years of study experience, meaning they had specialized knowledge and were open-minded and creative. We grouped them by their specialties to get in-depth discussion results.

3.2. Design and procedure

This exploration took place in the form of a structured brainstorming (V.Hill, 2019) where we asked participants to envision the possible applications of large actuated walls and used group brainstorming to generate

Figure 1: Brainstorming Cards. The cover (bottom left card) shows the time for individual brainstorming is 10 minutes. When opening the cards, participants could see the other seven cards, which demonstrated seven aspects, including the five Ws (Where, When, What, Who, Why), and each has two attributes with the following keywords: places, situations, residents and visitors, activities, measurement, materials, and environment.

as many ideas as possible. In total, we organized 4 groups, and each of them had 3 participants with a similar educational background. We purposefully grouped the participants by their educational backgrounds because we wanted them to have in-depth discussions related to their major subject. This helped provide a wider range of ideas from professional perspectives. We assigned each group to a different context (at home, at work, in a public space, or at school) to diversify the discussion topic and ultimately expected to get different opinions. To help with the ideation, we also provided some design probes: Lego © bricks to help form ideas by manipulating physical artifacts and a set of foldable brainstorming cards to facilitate the design thinking process (Figure 1). The participants could use the cards freely as they were displayed on the table. With this help, participants could think about the different factors and contexts in which the actuated walls could be used, and they were free to generate ideas with or without the provided probes.

We first explained the purpose of our study, introduced the available materials, and asked participants to fill in basic demographic information and sign a consent form if they agreed to participate. We then displayed several wall-related pictures to warm their brains up and played a video of a previous artistic project using the large scale actuated wall (Yang, 2012) to give them an idea of the setup and to demonstrate the existing technology. However, we did not ask them to be constrained to a single wall: they are free to imagine using any space. After presenting the context of the exploration and distributing necessary materials, participants started to brainstorm the idea for 10 to 15 minutes. They were asked to write down their ideas on sticky notes and share their notes with others after brainstorming. We also asked them to write down the four most interesting ideas from their discussions on a pre-designed form. The whole procedure took about half an hour. The experimenter stayed in the same room with the participants during the entire session, took notes, and answered questions when needed.

3.3. Results

We extracted $4 \times 5 = 20$ ideas from the four brainstormings, and grouped them into a series of themes, summarized below and illustrated in Figure 2 based on the functionalities and proposes in reference to the previous work Sturdee et al. (2015).

3.3.1. Theme 1: Architecture

Architecture includes all the ideas related to the large-scale dynamic structure of buildings. It includes two ideas mentioned four times by people from creative technology and architecture backgrounds. Shape-changing abilities could support changes in building forms and make interior alterations. Architects imagined a very large wall, changing a stepped lecture hall into a basketball court or a playground. Kids would be able to play actively indoors, at home, in dynamically created playgrounds. Additional suggestions include the use of the wall to adhere to electronic devices so that these appliances could be used while charging vertically and the shifting of wall shape to reduce light transmission in summer or to create air inlets.

3.3.2. Theme 2: Augmented Living

We grouped all the ideas related to enhancing the living experience with small-scale building parts into this group. Three groups contributed four different ideas for this category. Actuated walls could improve general life quality by contributing to convenience and efficiency. One example mentioned was for item delivery, where cubes could pop out in order and move items for a certain distance. In the school or working environments, participants envisioned a guide system with customized 3D direction instructions formed by popping cubes. It also allows for tangible navigation in darkness or for people with visual impairment. Here the actuated wall could indicate physical 3D directions, unlike the digital screens which could only provide

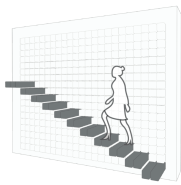
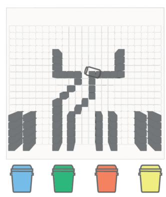
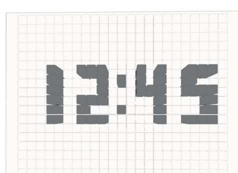
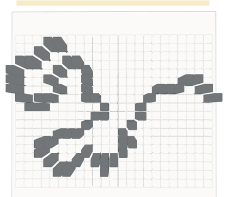
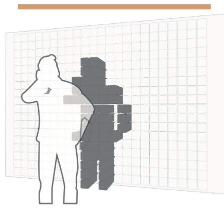
Architecture		1. Change the structure of the architecture, like to open different air inlets for different wind directions and to transform a lecture hall to a backetball court. (G1, G2) 2. Walls could adhere to electronic devices like smart phones. (G1)
Augmented Living		1. Use cubes to deliver items. (G1) 2. Provide customized tangible navigation in darkness or for people with visual impairment. (G2) 3. Perform and educate garbage classification. (G3) 4. From and hide furniture of any size, like chairs, closets, or stairs. (G2)
Communication		1. Display real-time data with poping cubes such as weather and time. (G1, G2, G4) 2. Provide braille for people with visual impairment. (G2) 3. Use every cube attached to a small screen to create adjustable screens. (G1) 4. Use cubes' states as computer logic 1 and 0 to facilitate computer architecture learning. (G4) 5. Visualize individuals' behaviors, like the movement and gathering. (G3)
Entertainment		1. Form entertainment equipment, such as chess boards. (G1, G4) 2. Create the rhythm with moving cubes. (G2) 3. Use the shadow of people to interact with the wall. (G3)
Aesthetics		Interactive decoration and art installations. (G2, G3)

Figure 2: Five applications of shape-changing wall systems. G1, G2, G3, and G4 represent the group from creative technology, architecture, design, and HCI background respectively.

2D navigation. Another example was to use the wall to perform and educate about garbage classification. The wall could construct different paths vertically, and the garbage would be visibly sorted by following the paths. The last idea was that the wall could form and hide furniture, like temporary chairs or tables of any size. Hollow cubes could function as a dynamic closet or a cabinet. Once the furniture was not needed, cubes could move back. Similarly, the actuated wall could implement smart storage by forming an object-specific container. Users can add a customized tag for each container to make it easier for the user to find items.

3.3.3. Theme 3: Communication

The third theme indicated the wall's ability to display information and serve as a communication medium and this is the most popular category. In public buildings, the wall could display real-time data such as weather and time or help with long-distance communication. Moreover, with tiny components in certain parts of the wall, it could provide braille for people with visual impairment. Other suggestions included combining the wall with electronic screens so that each cube has a small display fixed on one face. In this way, users can adjust the size of the screen. One of the participants added that if screen angles could change, users could have a clear view regardless of position. Another idea was to encode cubes' two positions to present computer logic 1 and 0 so that the wall could be used to facilitate computer architecture learning. Also, the wall could help visualize the individuals' behaviors, including how the crowd flows in a train station.

3.3.4. Theme 4: Entertainment

This theme described how actuated walls could function as entertainment devices. Walls could form entertainment equipment for children, such as chess boards, slides, and climbers. Participants also proposed creating a rhythm with moving cubes so the wall could move with music or according to people's gestures. Designers also proposed a new interaction to use their shadow to control the wall.

3.3.5. Theme 5: Aesthetics

Participants also mentioned that the wall could be served as interactive decoration and art installations. We, however, chose not to detail this theme because, as discussed above, it has already been widely used in existing large-scale shape displays.

Our findings are different from previous work and inspirational for the following reasons: first, we extended the knowledge of the potential use cases with wall shape-changing interfaces beyond the aesthetic purpose, (e.g., Rogers and Design Studio, 2010; Yang, 2012; Goulthorpe et al., 2012; Khan, 2014). Though researchers developed various types of systems to demonstrate the great potential of using shape-changing systems to meet all kinds of purposes (Suzuki et al., 2020; Gross and Green, 2012; Je et al., 2021), we summarized and emphasized possible applications for researchers and designers to explore in the future. Such knowledge is essential as designing applications and content has been argued to be one of the major challenges of shape-changing interface research (Alexander et al., 2018). Second, by explicitly categorizing the ideas into several themes and discussing them concerning their unique properties, we went beyond the previous research from a public ideation (Sturdee et al., 2015) that only discussed broader scenarios. We provided a deeper understanding of how these applications in a theme are envisioned to be used differently from the others. Understanding such differences will also help ensure good user experience while designing different applications. And third, participants' considerations that we have learned from this study could inspire the interaction design (for example, using shadows as an interaction prop is rarely seen elsewhere) to ultimately help overcome the challenge of integrating interaction with shape-changing interfaces (Alexander et al., 2018).

4. Exploration 2 (How): Input Modalities

While the results of the first exploration give us ideas about how large actuated walls can be used to improve user experience, it remained unclear how to interact with them. We then conducted a second exploration to understand users' envisioned interaction modalities and patterns.

4.1. Design

We chose to conduct an elicitation study to explore the interaction techniques because this method is commonly used to generate vocabularies for various interfaces (e.g. Downs and Hausenblas, 2003; Wobbrock et al., 2009) and fit well to our purpose. Specifically, in our study, users were asked to envision their preferred interaction modality and technique, and then perform it for given referents. Besides the referents, we also introduced two independent variables: the size of the cube on the wall and the distance between

Table 1: Summary of referent tasks of exploration 2.

Operation		Description
Form		Pop-out a pre-set regular pattern in the center.
		Pop-out a irregular shape in the center.
		Form a pattern in the low place of the wall.
		Form a pattern in the upper place of the wall.
		Form a pattern on the side of the wall.
		Add a new pattern to the current pattern.
Transform	Move	Move the pattern to a specific place.
	Rotate	Rotate the pattern for a specific degree.
	Scale	Scale the pattern.
	Reflect	Reflect the pattern.
	Reverse	Reverse the pattern.
Remove	All	Remove the whole pattern.
	Part	Remove a part of the pattern.

users and the wall. These parameters were extracted from literature (Follmer et al., 2013; Ghare et al., 2018; Yang, 2012) combined with the considerations raised from Exploration 1.

Referents: We created 13 referents based on previous work (Wobbrock et al., 2009) and the properties of large walls using the most mentioned theme of the first exploration: dynamic furniture. The 13 referents, summarized in Table 1, include three types of operation: (1) form a pattern of furniture in a certain place on the wall; (2) transform the pattern, including moving, rotating, reflecting, scaling, and reversing it; (3) remove the whole or part of the pattern. We specifically designed furniture patterns with simple geometries that were easy to be identified by participants to lower the difficulty and let participants focus on the interaction parts. We believe that the three types of operation do not only apply to the studied theme, but also benefit others since all types of application require forming, transforming, and removing content on the wall.

Size of Cube: The size of elements on the wall may cause different interaction techniques (López García and Hornecker, 2021) to accomplish the same task. We thus use two different types of cubes to investigate if the size affects users' interaction choice. We used a setup composed of 120 $\times$ 120 cubes of 12.7 $\times$ 12.7 mm to imitate the setups from previously studied small-scale shape displays (Follmer et al., 2013) and one with 30 $\times$ 30 cubes of 50.8 × 50.8 mm, similar to the size of the Hyper-Matrix Cube Wall (Yang, 2012).

Distance: We were also interested in how the interaction would change depending on proximity since the distance between users and the wall could influence what direct manipulations are possible. Moreover, the distance may affect how users would perceive the wall. It has been pointed out in the robotic community (Hancock et al., 2011) that environments play an important role while interacting with large devices. In this experiment, distances between user and wall were divided into three zones: 0—1m, 1—1.5m, and further than 1.5m according to the concept of proxemics (Ghare et al., 2018). We chose to focus on the first two (noted as zone1 and zone2) since the third is often considered as social space (Hall, 1990), and social functionality was not often mentioned in our application study. We marked these two zones by putting tapes on the floor.

Thus, the experiments had four conditions (2 sizes × 2 distances), each with the same 13 referents. Conditions were randomly ordered to be presented to participants.

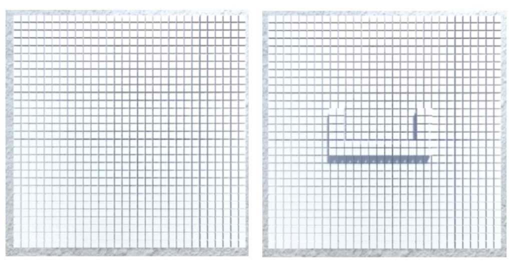


Figure 3: Example of the animation we created to simulate an actuated wall. Only the first and last state was used in the study as referents.

4.2. Apparatus and setup

Since we aimed to explore interaction rather than the implementation of an actuated wall, we simulated a wall shape display using a BENQ W1210ST 1080p, short-throw projector. We projected images of 1524 × 1524 mm, 45 cm above the floor as shown in Figure 4. Though occlusion happened, participants could move around to avoid the effect. We used Unity to create 3D animations of an actuated wall (Figure 3) made of linearly moving cubes. In the end, however, we only used still pictures of these to create the referents (before and after state) following the pattern of previous studies (Wobbrock et al., 2009). The study was run in a meeting room, with video and audio recorded under participants' permission.

To explain further the rationale behind choosing projection, we should clarify that SCI research, particularly with the large-scale device, is in its infancy. The technologies necessary to build such interfaces are not yet ready, resulting in high development costs. To address such a challenge, various design platforms have been used to simulate SCIs and better understand how users interact with them. Pedersen et al. Pedersen et al. (2014) used 51 videos of an SCI mobile device to investigate how users perceive them. They demonstrated that using video clips can help capture how users would perceive physical devices of a handheld scale. Cano et al. Cano and Roudaut (2019) used Projected Augmented Reality (AR) to investigate the perceived affordances of SCI objects and demonstrated that Projected AR can be a promising platform for studying SCIs. Another possibility would have been to use Virtual Reality (VR). Although it has not been directly used for SCIs, it was for designing interactive spaces Jetter et al. (2020), architecture, and interior design Racz and Zilizi (2018).

All these platforms provide suitable options to gain a better understanding of SCIs, but there is no research that provides a comparative overview of their pro and cons. For example, we can speculate that VR may provide an immersive and engaging experience, while AR (or platforms embedded in the environment) may provide physicality tangibility which may convey the sense of scale. While these questions are attractive on their own, they are out of the scope of this project and require a particular setup to test and compare those platforms. For our project which follows a different goal, we thus looked at current studies on SCI which showed that using 2D interfaces is working Pedersen et al. (2014). Additionally, MorphBenches Cano and Roudaut (2019) showed that projecting onto a real environment is beneficial and could add to physical experience (Pinhanez, 2001). We thus chose to project a 2D interface onto a large wall. We used a single wall as the initial step because most interactive walls are constrained to one planar surface. Similarly, many commonly mentioned ideas from the first exploration make use of a single vertical wall, even though we did not constrain them to it. Moreover, one of the challenges that come with studying shape-changing interfaces is that the design space is huge (e. g., the size of blocks, the wall size, the number of walls, curvature, and distance to users). All these factors could be combined to create an exponential space for designing walls. To lay the foundation for designing such walls, we designed a self-contained set of

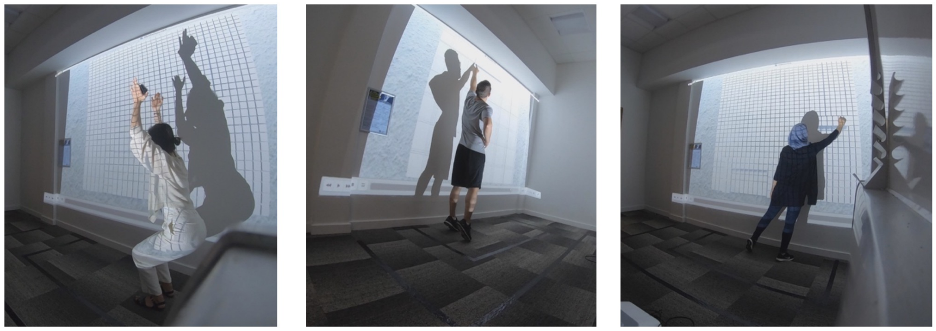


Figure 4: Example of setup with the participants performing gestures in front of the projected simulation of an actuated shape display

factors to limit possible confounding variables.

4.3. Participants

We recruited 20 participants (10 females, 10 males; age 22-37, mean 25.1) via social networking and the local university's mailing list with diverse backgrounds: 8 in Computer Sciences, 3 in Management, 2 in Marketing, 2 in Human-Computer Interaction, 2 in Electronic Engineering, 1 in Japanese, 1 in Nutrition, and 1 in Biology. All participants had at least a bachelor's degree. 19 of them were right-handed. None had visual or hearing impairment.

4.4. Procedure

We began by introducing the experiment and letting participants sign the consent form and fill in basic demographic information if they agreed to participate. We did not compensate participants for their time. Each participant had a 5 minutes training session to get familiar with the task. Trials of the training session had the same type of requirements as the experiment but with different tasks. For each trial, we first showed the participant two images: the "before" referent image and the "after" one. Participants were then asked to act to cause that change to happen (Figure 3). They were encouraged to both act out the interaction and think aloud, explaining their action. The experimenter carefully avoided priming participants for particular interactions and told them to use any type of action they wished (e.g., physical, vocal, or others). The experimenter stayed with the participant during the whole study to take notes and give help when needed.

Once the participants finished all the trials, we conducted a post-study interview to better understand their feeling and the reasons behind their choices. Questions included: **Q1** What is the main difference between the interaction in the two zones? **Q2** What is the main difference between the interaction with cubes of two sizes? **Q3** What are the reasons you chose that type of interaction? **Q4** Have you noticed any difficulties or problems that may occur when interacting with the system? Based on the answers, we adopted a systematic process to code the interactions.

4.5. Results

Each participant took about 60 minutes to finish the experiment. In total, we recorded 1040 trials (20 participants $\times$ 13 $\times$ 4). We discarded four of them because the participants were confused and gave up. We thus analyzed the remaining 1036 results and summarized them in this section. We also paid attention to participants' encountered obstacles and tactics. For the post-interview studies, we kept detailed logs of their experience and preferences.

For the study results analysis, after all the results were read and cleaned up, we categorized participants' actions into four main categories **gestures**, **postures**, **voice** commands, and **tools**. We categorized one action into **gestures** category if the participant used his/her upper/lower limb to interact. If one action involves participants' whole body moving, we categorized it into **postures**. We also classified actions into subcategories as described in Table 2. The detailed descriptions of gesture and posture categories were summarized in Figure 6 and Figure 7. Participants' operations were simple for the voice commands: almost all wanted to say a sentence, and we thus did not further classify or analyze it. For using tools, a mobile controller was mentioned most by participants. Additionally, participants also mentioned several other tools like integrating fixed buttons into the environments, using ray pointer, timer, or augmented reality (AR) headsets to control the wall. To explore whether participants' interaction would be affected by the zone and sizes, we used the chi-square test approach and grouped interactions by referents to find the potential patterns. For the post-interview results, we analyzed the collected qualitative data using thematic analysis (Given, 2008) and an inductive approach.

4.5.1. Zones

We conducted a chi-square test to verify if participants' preferred interaction varies a lot between the two zones. To ensure the validity of the test, we used the four main categories instead of sub-categories to fulfill the basic condition that the number of each observation is at least 5 (Starnes et al.,

Table 2: Interaction categories.

Type	Sub-Type		Times mentioned
Gestures	Upper-limb	Hand	330
		Finger	205
		Arm	454
	Lower-limb	Foot	18
		Leg	18
Tools	Interface	Fixed	1
		Mobile	159
	Other	Pointer	9
		Timer	1
		AR glasses	5
Postures	Move		62
	Squat		3
	Bow		5
	Jump		4
	Sit		2
	Move		6
Voice control	Sentence		158

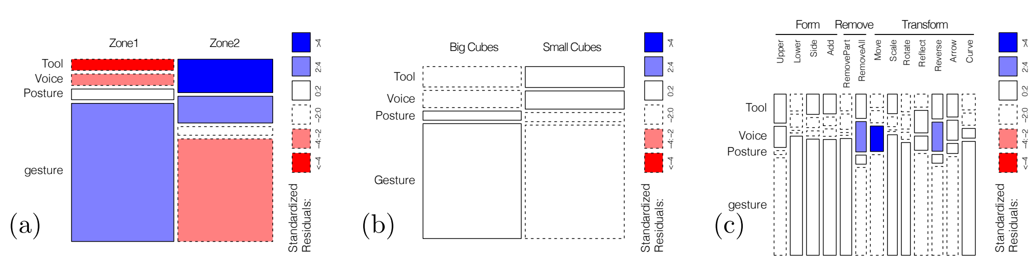


Figure 5: We visualized the results in mosaic plots. (a) represents the effects of zones in interaction methods; (b) represents the effects of cube size in interaction methods; and (c) represents the effects of different tasks in interaction methods.

2010). The result ($\chi^2 = 97.468, df = 3, p < 2.2e{-}16$), with $p-$value less than 0.05, indicates that we can reject the null hypothesis. Thus, strong evidence proved that participants' preferred interaction changed significantly between the two zones. By further exploring the data (5(a)), we observed that participants were more likely to use tools or voice commands to control the system while gestures were less preferred when they were in zone 2 compared with zone 1 (close to the system).

4.5.2. Sizes

The result of the chi-square test ($\chi^2 = 0.19743, df = 3, p = 0.978 > 0.05$) did not give us any evidence of the difference in interaction techniques chosen between two different types of cube sizes. We could also observe from 5(b) that the number count of different interaction categories remains stable for various conditions.

4.5.3. Referents

When grouping the values by referents, we got relatively small numbers. Thus, we did not rely on the results of chi-square and make assumptions based on statistical results. Nevertheless, we explored which type of interaction was more likely to be used in each task according to the initial measurement. According to 5(c), we observed that compared with all other referents, users preferred to use voice control to remove all the contents on the wall or to reverse a pattern, while the body posture was most preferred for moving an object.

In Figure 6, we followed the work Nielsen et al. (2003) to distinguish the dynamic and static gestures. Static gestures are hand gestures without movements, while dynamic gestures indicate movements. We found that the use of a gesture to form a pattern usually contains two steps: 1) draw the shape and 2) give a signal to pop out the pattern. Participants usually drew with hand(s), and used double tapping or pulling gestures to indicate cubes to pop out. To transform the shapes, participants usually first select the target shape and then use gestures to perform the transformation. The gestures were similar to the ones used in digital interfaces, even though hands were more used in operating walls rather than fingers. As for removing patterns, participants chose to press back if the shape was small, while using swipe gestures to erase extensively if the pattern was large.

O	Form	S/D	T
Top	1. (3), and pull out with hand(s)	D	14
	2. (3), and push it up with one hand	D	11
	3. Draw with finger(s)	D	5
	4. Draw with fingers on the ground	D	2
	5. Drag feet in the shape path on the ground	D	2
	6. Touch with one hand and push it up with hand	D	1
Bottom	1. Draw with one hand	D	15
	2. Touch with one hand	D	11
	3. (4), and pull out with hands	D	10
	4. Draw with finger(s)	D	7
	5. (4), and double tap to pop out cubes	D	2
	6. Drag feet in the shape path on the ground	D	2
Add	1. Touch with one hand	D	11
	2. Draw with one hand	D	9
	3. (2), and pull out with one hand	D	6
	4. Draw with finger(s)	D	4
	5. Draw with index finger and double tap to pop out cubes	D	2
	6. Pointing the turning points with the index finger	S	1
Center	1. Draw with finger(s)	D	13
	2. Draw with hand(s)	D	13
	3. Touch with one hand	D	8
	4. (2), and pull out with one hand	D	5
	5. Draw with index finger and double tap to pop out cubes	D	4

O	Form	S/D	T
Side	1. (4), and pull out with hands	D	12
	2. Touch with one hand	D	10
	3. Draw with one hand	D	9
	4. Draw with finger(s)	D	5
	5. (4), and double tap to pop out cubes	D	2
	6. Index and medium finger indicating width, and move along the path with one hand	D	2
	7. Drag feet in shape path	D	2

O	Remove	S/D	T
Part	1. Press back	S	28
	2. Select with fingers and wipe	D	7
	3. Select with index finger and drag outside the edge	D	4
All	1. Wipe with one hand	D	13
	2. Select with fingers and press back	D	10

O	Transform	S/D	T
Move	1. Tap to select and drag with one hand	D	11
	2. use the palm (perpendicular to the interface) to push objects	D	9
	3. Move hands to the position as if carrying th object	D	6
	4. Grab and move to the position	D	4
	5. Move fingers to the position	D	4
	6. Draw a circle to contain objects with index finger and grab to the position	D	2

O	Transform	S/D	T
Scale	1. Both palms squeeze together	D	22
	2. Open palm	D	7
	3. Index finger and thumb stretch	D	3
	4. Index finger, thumb and medium finger squeeze together	D	2
	5. Tap to select, and then do (3)	D	2
Rotate	1. Rotating two palms as if manually rotating	D	23
	2. Twist with one hand	D	7
	3. Rotating index fingers	D	4
	4. Grab two ends of the object and rotate	D	4
Refelction	1. Flip. One palm rotate around the wrist	D	10
	2. Press back and draw a new one	D	5
	3. One palm stay still and the other move from left to right	D	4
	4. Select with index finger, grad and flip the fist	D	2
	5. Select with index finger, and flip with two fingers	D	2
	6. Select with hand and turn body around	D	2
Reverse	1. Pushing in for a while	S	9
	2. One palm stay still and the other palm push to the wall	D	4
	3. One palm stay still and the other pull out	D	4
	4. Turn one hand over	D	2

Figure 6: Detailed Gestures (O indicates Operation as described in Table 1, S/D represents if the action is Static or Dynamic; T means the number of times that one action is mentioned. The first action 1. (3), and pull out with hands means that users prefer to first perform an action described in 3 (draw with fingers), and then pull out with hands. We distinguished touch directly and mid-air gestures with "touch" and "draw".

O	Form	S/D	T
Top	1. Tiptoe	D	6
	2. Bend over to draw the shape on the ground	D	2
	3. Walking in the same shape path	D	2
Bottom	1. Squat and draw with finger(s)	D	2
	2. Jump in the shape path	D	2
Add	1. Walking in the shape path	D	2
Center	1. Walking in the shape path	D	2
Side	1. Strench body to the side	D	8

O	Remove	S/D	T
Part	1. Jump to the corresponding shape position on ground	D	2

O	Transform	S/D	T
Move	1. Walk from the original position to the target position	D	21
	2. Face the target object and them jump to the position	D	4
Scale	1. Jump and open the feet	D	1
Rotate	1. Sit down and rotate body	D	4
Refelction	1. Simulate the shape by body and do reflected gestures	D	12
Reverse	1. Turn around	D	4
	2. Jump in a direction away from the wall	D	2

Figure 7: Detailed Postures (O indicates Operation as described in Table 1, S/D represents if the action is Static or Dynamic; T means the number of times that one action is mentioned.

4.5.4. Results of the post-study interview

To analyze the interview feedback, we first open-coded the interview notes and grouped the codes into a list of themes that are identical to the subcategories in Table 2. We slightly adjusted the themes because participants did not distinguish gestures and postures in the post-study interview. Thus, we reported their feedback with both themes as gestures. Participants reported that they were more engaging in zone1 while having a better view of the whole system in zone2. Within each zone, participants would get closer to the wall when the pattern was small and rich in details, while they would step back when the shape was large, or when they could not reach some of the cubes. When participants were in Zone1 and the wall was reachable, sixteen preferred to touch the wall. Two participants mentioned that they would switch motions based on the materials of the wall, and that they would only touch the wall if its surface was clean and smooth. An interesting phenomenon was that four people would use gestures with bigger movements and more motions in Zone1, while two of them used smaller ones. One explication mentioned by four people was that in Zone1, shapes in different positions would require different gestures and standing points, while in Zone2, they preferred to stand in a set position. Participants preferred to use one hand rather than two in Zone2. Since participants were unable to touch the cubes in Zone2, six participants stated that they would be more likely to use tools, and two would prefer to use voice commands. A popular idea mentioned by six participants was that standing back gave them a larger view, and they could form complex shapes with a better interactive experience.

When referring to the differences between the interaction with cubes of two sizes, six participants said smaller cubes made it hard to draw precisely. At the same time, seven mentioned that smaller cubes could express more details. One participant noted that the wall with small cubes reminded him of digital screens. One said he would prefer to use fingers to draw details of smaller cubes better, while another two chose to use tools. One preferred to operate in the distance facing smaller cubes because he wanted a full view with all details. As for the wall of bigger cubes, seven participants thought the movement was more realistic and palpable. Thus, they knew better what to do. Two people considered the cubes were more like furniture. As for gestures, three mentioned they preferred to use the full hand.

Gestures were the participants' most popular type of interaction. Twelve participants used gestures to interact with the wall. When being asked about the reasons why they chose that particular type, participants mentioned the following reasons: Four used them because they had experience in operating digital screens, and they used similar gestures when using the wall system; Three participants chose similar movements to those they used when interacting with the physical objects, and two used gestures to match the movement of cubes. Also, two participants said the gestures were easy to perform. All participants used their upper body and hands to perform the gestures, but one participant also proposed to use their foot. Two said they used gestures because they were not limited by distance.

Nine volunteers used the interfaces (i. e., an external control such as a tablet to control the wall) as the primary type of interaction. Among them, six participants felt that interfaces were more precise compared to gestures. Three thought that they were more efficient because interfaces could have predefined wall patterns to be triggered when needed, and those patterns could also be customized by the end-users. Other reasons mentioned were: computers were frequently used in daily life; interfaces were not limited by distance; operating computers made no noise.

Voice commands were adopted as the main control method by four participants. Voice command was favored because of its convenience and fast expression.

The last question asked in the interview was about the difficulties and problems participants could think of when interacting with the wall system. The most frequently mentioned problem was concern about the accuracy of gestures (mentioned by four people). One participant felt this was particularly a problem when the cubes were small, and the user was required to stand far away from the wall. Two people thought that the gestures were similar and may not be recognized correctly. About three participants were concerned about the efficiency of the voice command since it was hard to describe the exact shape as expected. One participant found that the selection of particular elements was difficult. Last but not least, two volunteers would like to have visual aids to help with confirmation and tracking.

5. Discussion

Exploration 1 (what). We found five themes for applications of actuated walls: Architecture, Augmented Living, Communication, Entertainment, and Aesthetics. These themes represent shape-changing walls' abilities to form dynamic architecture, improve the general living experience, deliver

3D information, provide an intuitive interactive experience, and serve as artwork. We compared our themes with those drawn from general shape-changing applications (Sturdee et al., 2015). Among them, Architecture contains more applications, such as changing interior traffic, which could not be achieved with small devices. Similarly, although our theme shared the same descriptions of the theme Augmented Living with the literature, we included more practical ideas such as item delivery, smart storage, and tangible navigation. Another difference was that we made Communication an individual theme rather than a subset of e. g., Utensils & Tools, since 3D information delivery was significant in all ideas.

Exploration 2 (how). Generally, the most popular way of interacting with the walls was via gestures. This may be because people are more used to directly interacting with the display. Tools and voice control were still adopted when people were far away from the wall, probably since people are familiar with tools to interact remotely. Although our participants tried a variety kind of gestures in the air, they were overall quite similar to touch-based gestures (Wobbrock et al., 2009; Epps et al., 2006). Then, using tools to control the system was mainly related to mobile interfaces and wall-top interfaces. Additionally, the detail of voice commands varied but with similar structures (simply describing operations, shapes, and the position like in the famous "put-that-there" UIs (Bolt, 1980)). When people used tools to draw the shape, they would use the same gestures as they were using mobile phones, possibly due to their familiarity with mobile gestures.

Interestingly, people acted differently even using the same technique, depending on the zone. When people were in the zone near the wall, they were more likely to touch the wall; while standing far from the wall, they used mid-air gestures to interact. Moreover, when they were facing larger cubes, they first used hand(s), but then switched to finger(s) to draw the shape with smaller cubes. This was because, according to the participants, finger(s) were more precise than the hand(s) in their view. As for tools and voice control, they preferred to have a fixed tool interface near the wall, but a handheld device when they were far away from the wall. We see this difference as a result that bigger cubes provided a more engaging feeling while smaller cubes demanded more details. Voice control, in contrast, seemed to have no big differences in different conditions. This is understandable as voice control has no limits in space. We can not find any interaction technique preference differences regarding the different cube sizes in statistics, even though several participants had a different feeling of accuracy in interacting with them, and we observed that people tended to use fingers more in drawing small shapes.

Compared with previous work on using touch or embodied gestures to interact with small surfaces (e.g. Nielsen et al., 2003; Wobbrock et al., 2009; Niiro et al., 2019; Leithinger et al., 2011; Kistler and André, 2013), we observed that the moving paths of hands were similar, but users in our case tended to use the whole hand rather than just fingers. Although users would prefer gestures with large movements in interaction decisively than small ones, they were not sure how to perform gestures. Also, people tended to move closer to the wall compared to vertical digital displays.

A critical finding of the study was that the surrounding environment had great potential to support interaction. This is partial because the system was large-scale, and users were unable to reach every cube in the system. As such, the area beside and in front of the surface becomes essential. Thus, including an associated display to one side or a sidebar on the surface may largely help with the interaction. Moreover, the large space in front of the actuated wall could function more than place tools. Inspired by the participant, we found that the whole ground could serve as the associated input interface. People could step on the ground to draw the shape to form and jump to indicate the transformation. Such interactions are especially suitable for the theme of Augmented Living, where vague and easy instructions are needed. As participants in the brain-storming session proposed, they wanted to fast instruct pre-set stairs to form. Further, the environment may play a role in suggesting the functions of the wall. Socio-material context has regularly been claimed to influence interactions in spaces (Dourish, 2001). For example, interaction modalities and expected functionalities for a shape-wall are likely to be different in the home vs. the workplace, or in functional and recreational spaces, based on contextual expectations. As participants in the second study mentioned, they would perform differently based on the walls' cleanliness. Apart from these standard practices, another interesting interaction observed in the study was taking the floor interface as the associated input interface. The participant chose to drag his feet in a path of the shape he expected. Also, the ground interface allowed for more foot gestures like jumping and kneeling.

Another interesting idea raised by the participants is to use visual aids to guide and confirm the interaction. First, as the mechanical actuators naturally need reaction time when one interaction is triggered, it is a good practice to inform users about its current status visually. Second, because users envisioned multiple interaction preferences, using visual aids to guide them will facilitate the interaction and their memory load. This is also useful when users need to switch among different interaction modalities, which we expect to happen frequently because such a system needs to support many interactive functions.

We used the mechanical pin-array wall as the prop of this study because it is yet the most common way to realize an actuated wall, but our results are not dependent on its physical material. Our results should still hold using other setups (like fordable structures) with a similar setup (application, size, and distance). The choice of an appropriate realization method should be considered with respect to the application and surrounding environments, as we discuss in section 6.

6. Recommendations and Implications

To facilitate the interaction design for actuated walls, we generated recommendations for the whole design.

- **Application.** From the comparison in section 5, we could conclude that the actuated walls have numerous additional distinguished functions compared with small interfaces, including furniture organizing and interior space rearrangement. Walls enable us to freely form, transform, and put back furniture, from small containers to large sofas. Additionally, they could break the traditional limits of immutable interior structures and rearrange the room space. Different features may require different physical materials and realization methods.

- **Interaction.** The most inspiring and interesting input modalities are feet gestures and whole-body postures in interaction. Our participants dragged their feet to draw the shape and jumped to indicate the movements. They also simulated the movements with their body. For example, in instructing the pattern to move or rotate, people would move or rotate their bodies. Some people would even demonstrate the furniture shape, such as a chair by body gesture. Thus, unlike other small implementations, participants are free to use other parts of their bodies besides their hands. We believe that the whole body could increase interaction engagement.

We also concluded several **how-to** steps as guidelines for designing interaction for large actuated walls from our analysis in the two studies.

1. The first step is to **evaluate the surrounding environment**. The surrounding environment first decides and constrains the potential application scenario. As Exploration 1 shows, people would think of different applications and target users for different environments. In the public train station, people would think of using the devices as facilities for the general public, e.g., serving as an automatic garbage classifier, while in the private home, they could probably serve as an adjustable air inlet. Also, the potential physical materials and moving distance would also be influenced by its surrounding environment. For example, Architecture theme, like functioning as stairs, requires lower accuracy and less frequent but deeper movements than Communication theme. The materials should be hard, and the popped-out widths should be reasonable. These require the environment to be able to support the demands.
2. Once finishing the environment, it is essential to **decide on the specific application and analyze its requirements**. From the first study, we found that different applications may require different wall setups, like vertical as a real wall to form furniture. These diverse applications have different target users and thus could affect the interaction requirements. For example, many people could interact with a wall in the public space, while there is usually one or several people interacting with the wall at home. For the case where many people are interacting with the wall, the voice command would be difficult and touching could be a good option for the interaction.
3. The following step is to **define input modality and choose appropriate interaction techniques**. We see a large range of interaction approaches from the results of Exploration 2. As we found from Exploration 2, some participants switched interaction types in different zones. We thus encourage to support multiple interaction methods to fulfill users' interaction preferences and to fully use the space around the wall. Moreover, for children whose height are below the average and people who cannot freely control their upper-limbs, an alternative method such a feet gestures should be equipped.
4. Inspired by the post-interview results of Exploration 2, it seems to be a good idea to **add visual aids** to guide the users during the interaction, to ultimately avoid possible confusion and uncertainty. This would be a way to increase the quality of the perceived affordance of the system. As we have discussed, the system should provide multi-

ple interaction techniques, and users should be aware of the system's current status. Visual aids could help them effectively use and switch interaction types, though only two persons mentioned this idea. For example, it is interesting to note that the participants proposed the use of visual signifiers rather than physical deformation. A possible way is to, for example, project indicators on the actuators or use luminescent technology (e.g., Hanton et al., 2020).

7. Limitations and future work

In our brainstorming session, we conducted studies with people grouped in the same background, but it will also be interesting to have mixed participants in the follow-up studies. For our elicitation study, we used a low-fidelity projection system to simulate the interaction situations rather than implementing a real interactive system. This may influence users' feelings and affect their interaction choices because of the failure to convey physical sensations. Thus, in the future, we would plan to make a prototype based on the results and then investigate the user experience with the high-fidelity wall system. We would also like to investigate different typologies of walls and the interplay between using different modalities for conveying the affordance of the system in the future. Second, we chose the Architecture theme got from the first experiment as the testing scenario, and the interaction may differ in other scenarios. Our future studies would also evaluate different types of tasks associated with other application contexts, beyond those considered in this study. Additionally, even though we analyzed users' preferred interaction techniques to accomplish different referents and concluded some general design guidelines, it would also be a useful extension to finally design a set of interaction techniques in the future, with their usability well evaluated. Besides these interaction techniques, we are also interested in the dynamic of the shape-changing walls. We plan to implement a large-scale shape-changing wall with actuators that have different moving speeds, moving orders, and reaction delays. With such a device, we would conduct another study to evaluate people's preferences using diverse interaction types.

8. Conclusion

We have presented studies to understand how end-users would interact with an actuated shape display wall. We ran two experiments with end-users, with the results of the first experiment informing the design of the second. Based on detailed qualitative and quantitative analysis of results in these experiments, we identified important contributions to research in this area. First, we identified five themes for interaction with actuated walls. We also identified differences in interaction style based on distance-to-wall and size-of-element. Based on these findings, we have presented a series of suggestions that can inform future research and design for actuated walls. We hope our work can inspire designers of large-scale shape displays to explore functionalities that go beyond hedonic features, and we invite them to use our insights for designing such systems.

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