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論文題目　Actuated Walls as Media Connecting and Dividing Physical / Virtual Spaces

（物理/バーチャル空間の接続と分離を媒介する可動壁に関する研究）

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ACTUATED WALLS AS MEDIA CONNECTING AND DIVIDING PHYSICAL/VIRTUAL SPACES

物理/バーチャル空間の接続と分離を媒介する可動壁に関する研究

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Abstract

Wall-shaped furniture or devices are distributed within a physical space as essential components. The wall-shaped furniture acts as partitions to divide the physical space into smaller individual spaces, which are integrated into the entire environment bounded by the wall. In addition, a vertical display interface presents digital information or visual content, and it can be considered the boundary between virtual and physical spaces. Accordingly, the wall-shaped furniture and display could be considered media that connect and divide two spaces.

This thesis explores the concept of an actuated wall as a medium that flexibly and interactively controls the division and connection of physical and virtual spaces. By introducing self-actuating functions, wall-shaped devices are expected to provide flexible and interactive management of the boundary between two spaces according to the situation. To demonstrate this new concept, this thesis designs and evaluates the following two types of dynamically actuating physical wall-shaped interfaces that intermediate 1) physical-to-physical spaces and 2) virtual-to-physical spaces.

First, to interactively manage the boundary of physical-to-physical spaces, I propose WaddleWalls, a room-scale interactive partitioning system using actuated partitions that allow users to flexibly and interactively reconfigure the spatial layout and optimize spatial functionalities. I focus on supporting work activities that unexpectedly change through flexible workspace layout management. The thesis discusses the design of the interactive partition system and implements a proof-of-concept prototype. It also demonstrates the above functionalities through several application scenarios and fundamental system usability, as well as the system's effect on task load during workspace deformation.

Second, to strengthen the connection between virtual and physical spaces, I propose BouncyScreen, a self-actuating robotic display that enables a display to represent a haptic sensation of virtual content to the user. As additional content representation to the visual information, I focus on providing haptic feedback when interacting with virtual content through the display's physical movement. Here, 1D movement of the vertical display coupled with visual content augments virtual content animation. Manipulating the amount of display movement allows users to perceive various imaginary haptic sensations. This thesis contributes a means to physically augment a pseudo-haptic mechanism by using the display's physical motion to enhance visual content interaction and strengthen the connection between virtual and physical spaces. I conduct psychophysical studies to examine how BouncyScreen's physical movements would affect the user's pseudo-haptic perceptions and interaction experiences.

Through these investigations, I discuss how actuated walls can be effective as spatial media in virtual and physical spatial interfaces. I also mention future directions based on the limitations of existing actuated wall interfaces.

Keywords: Human-computer interaction, Spatial interface, Shape-changing interface, VR/AR, Haptic feedback, Workspace design, Robotic furniture, Social interaction

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Chapter 1

Introduction

1.1 Background

Our physical living spaces and virtual/digital spaces are separated by a wall. Within the physical space, individual areas are separated by physical walls. The physical and virtual/digital spaces are independent, while a visual monitor can work as the interface to provide us with digital information. What if these two spaces could be seamlessly connected? What if digital information and even spatial information could be tangible and thus we could manipulate them ourselves?

This physical world is constructed by walls, and numerous wall-shaped objects are distributed everywhere. An architectural wall configures existing buildings or individual spaces in the physical world. The exterior walls separate the outside and inside, creating our living spaces inside the building. Functional walls, i.e., wall-shaped furniture or devices, such as partitions, barricades, and whiteboards, are distributed in the physical world as essential space components to support our various activities inside a room. Such partitions divide a large space into individual small spaces. We refer to such pieces of furniture as dividers. Conversely, by removing dividers, multiple individual spaces can be integrated into a single space. Thus, dividers are boundaries among individual spaces. The arrangement and composition of wall-shaped furniture significantly impact the relationships among the physical spaces or social interactions among the workers, which have been discussed in not only the architecture and spatial design domains but also human-building interaction(HBI) [59]. The layout or spatial design of the workspace environment affects not only spatial function or comfort but also the occupants' health, performance [14], and social interactions [13, 4, 59, 60]. Due to the multiple effects of wall-shaped interiors, the divider has great potential as the medium that enables us to flexibly adjust spatial functionalities such as connectedness and dividedness among small spaces for various situations. However, most current wall-shaped dividers are anchored or manually movable within the space, so their potential as media has not been sufficiently exploited.

In addition, wall-shaped display interfaces such as TVs, desktop monitors, large screens, and digital signage have been used to represent visual content or digital information. When we consider the visual content displayed on such wall-shaped vertically standing displays, we can say that the display is an entity that connects the visual content and the user who watches it. In other words, the wall-shaped display is a boundary between virtual space with digital information and our physical space.

While these wall-shaped objects are utilized for space configuration or content representation, current standard partitions or display devices have in common with static objects. Although users can move and transform each independent wall-shaped object according to their purpose, their static properties make their functions very limited and less flexible. Therefore, the workspace is semi-permanently divided by partitions since the workspace configuration is basically binary, and the physical and virtual spaces are clearly separated by the display device.

Considering this background, I propose the concept of actuated wall as a medium that flexibly controls the division and connection of virtual and physical spaces. In this thesis, I newly define the term of "the actuated wall as a medium" as a new concept of mediating independent physical or virtual spaces to distinguish it from the existing actuated wall concepts ([104, 96, 121] etc.) that do not focus on the mediation of the different spaces. In the HCI domain, the worth of dynamically device actuating approach has already been explored through workspace optimization with vertical [104] or tabletop displays [54], visual content augmentation with dynamically movable large display [24], and room-scale haptic infrastructure for VR experiences [96, 121]. By introducing these self-actuation capabilities as a wall-shaped devices' operation approach, wall-shaped devices are expected to make it possible to expand their existing ability which includes setting

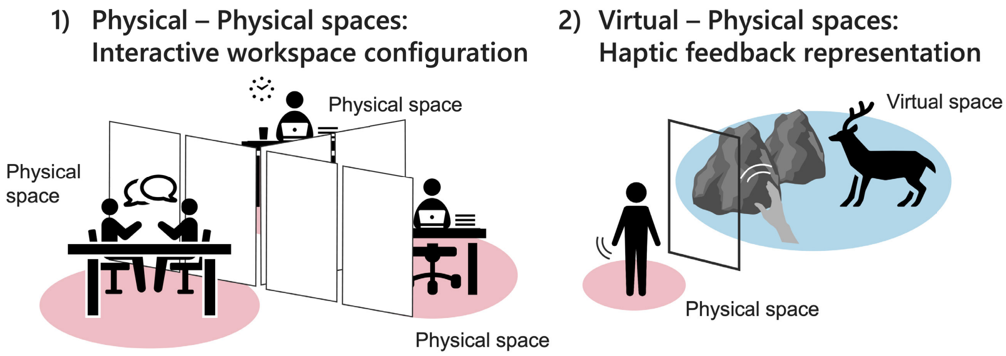


Figure 1: Two approaches of actuated wall

up, removing, or modifying the boundary of two spaces more freely and interactively, which gives wall-shaped devices as a medium. This allows the users to optimize the spatial design (e.g., to maintain one's privacy, to facilitate social interactions), and to augment content representation ability.

To demonstrate the concept of the actuated walls as a medium, I explore two types of actuated wall-shaped interfaces. Figure 1 summarizes this thesis's primary contributions. First, I explore WaddleWalls, which flexibly manages the spatial relationships among the individual physical spaces. WaddleWalls is a room-scale interactive partitioning system using a swarm of robotic partitions, which mediates between multiple small workspaces within an office room (Figure 1 (1)). Second, I explore BouncyScreen, which flexibly connects physical and virtual spaces. The physical actuation of the wall-shaped display, coupled with the user's input and screen animation, is applied to induce imaginary haptic feedback when interacting with the content. The display motion conveys the additional haptic information from the virtual world to the user's physical world, augmenting the user's experience and content understanding (Figure 1 (2)). The primary reason for demonstrating these two approaches is to explore the most fundamental and significant pair of virtual and physical spaces from the physical space user's perspective. These two explorations allow us to broadly discuss how actuated walls can be used in space creation and representation operations.

First, I explore the actuated physical walls that intermediate multiple physical workspaces(Figure 1left). A physical environment, such as an office or lab, comprises various devices and furniture, such as tables, displays, and chairs. The placement of these components needs to be arranged according to the work situation. However, spatial optimization is complicated due to changes resulting from unexpected and unspecified task situations. As personal tasks, occupants compose text, hold discussions online, write code, and implement prototypes. While engaging in such individual tasks, occupants simultaneously multitask with others, in situations including informal or group meetings. Supporting all of the activities happening in the workspace is difficult with a conventional uniform workspace design strategy. Considering the users' continuous interactions with other people, content, and devices, the workspace requires physical flexibility to adapt to various work scenarios. Toward such a flexible workspace, HCI domain researchers have actively explored actuated room-scale interfaces, including re-configurable interactive tabletop displays [102, 54, 32], shape-changing or actuating vertical displays [104, 31, 8, 107], pneumatic actuating furniture [98], and self-actuating chairs [90]. These devices can dynamically transform themselves according to the number of users engaged in a task, their positions, their relationships with each other, and their contents. These devices' self-actuating function enables us to follow their task transitions and create well-suited individual workspaces from the entire space to each user. To achieve reconfigurable room-scale partitioning, I propose WaddleWalls, an interactive partitioning system using a swarm of robotic partitions. This demonstrates a concrete instance of actuated walls that can dynamically divide and connect multiple physical spaces.

Second, I explore the actuated robotic display that intermediates physical space and virtual content(Figure 1right). As one way of physically augmenting virtual content, the approach of introducing the display's dynamic actuation, which aims to expand displayed content, has been developed. By introducing display surfaces' physical deformation [64] or tilting motion[2] and dynamic display actuation [24, 69, 68, 73], it has become possible to successfully augment three-dimensional representation and make visual content more realistic. A different approach, based on augmenting content reality and presenting haptic feedback, has also been explored. However, most approaches need to use particular devices besides the display for tactile feedback presentation, and the cost of preparing such a device is high. Nevertheless, there has been no study on applying the movement of the display itself to offer indirect haptic presentation. Thus, to augment the connection between physical and virtual spaces, I designed BouncyScreen, a physically actuating display allowing the users to perceive additional haptic sensations of the virtual content without physically touching the display. Specifically, I introduce and augment the pseudo-haptic effect[58] by the display's 1D actuation to represent the haptic perception when contacting virtual content and to enrich the user's interactions. This study is an instance showing how an actuated display can connect virtual and physical worlds and how virtual information can be transmitted to physical users.

1.2 Thesis Overview

This thesis proposes a novel concept of an actuated wall that flexibly intermediates physical and virtual spaces. As described in Section 1.1, wall-shaped objects and a display are the essential components of building the physical world and providing digital information. Augmenting the original properties of wall-shaped objects and displays, I explore the actuated wall medium that flexibly divides and connects physical and virtual spaces by introducing physical actuation. To demonstrate this concept, the following two approaches were designed: an interactive partitioning system managing the spatial relationship of physical spaces and a robotic display system flexibly connecting physical and virtual spaces.

First, Chapter 2 explores a method for flexible management of physical space configuration with actuated physical walls. I designed a physically actuated robotic wall-shaped partition system (WaddleWalls) that allows users to interactively construct variously shaped physical spaces. The focus is on simultaneous control of multiple wall surfaces to facilitate workspace optimization and contribute to increasing user privacy and work efficiency. This chapter reports design considerations, a proof of concept prototype, user studies from beginner and expert users, and discussions toward future robotic furniture.

Second, Chapter 3 explores a method for connecting physical and virtual space with actuating robotic displays. I designed BouncyScreen to perceptually render haptic information of the virtual worlds through its 1D physical actuation coupled with the display content. This chapter describes this method's motivation, prototypes, and two studies showing that the actuated wall-shaped display can enhance the user's interaction with the virtual content.

Chapter 4 presents general discussions based on the above two explorations of actuated walls, WalldeWalls and BouncyScreen, particularly regarding the design space of actuated walls and its future directions.

Chapter 2

Interactive Physical Space Transforming using a Swarm-of Robotic Partitions

2.1 Introduction

Workspace design is crucial for optimizing workers' activities, physical comfort [60], productivity [14], social interactions [13, 4, 59, 60], security, and privacy [1, 49, 94, 5]. Traditionally, workspace design has been explored in the domains of architecture and interior design. However, work activities are becoming more diverse, thus making current workspace structures and elements increasingly complicated and computerized with various devices (e.g., desktop, mobile units), data resources (e.g., public, sensitive, secret), and working styles (e.g., solo, team). This diversity makes it difficult for interior designers and occupants to optimize the workplace layout so that it conforms to the occupants' workflows and needs.

Various sensors and robotic technologies have become ubiquitous [117] in current work environments, yet these devices have been primarily used to analyze workers' activities [118, 36] or managing proximity based device interactions [9]. By leveraging such embedded sensing platform and human-robot interaction (HRI) knowledge, we presume that physically transformable offices that achieve flexible layout changes automatically in response to tracked users' activities can offer great potential as the next mainstream technology. This idea allows us to accommodate various activities and user requirements within physically limited work spaces. Toward such a transformable office, self-actuated robotic furniture units [119, 90, 115, 28, 52, 93] have been actively explored, including self-actuated tabletops [102, 54, 32, 31] and moving vertical displays [8, 107, 104] designed to create flexible workspace that can dynamically reconfigure themselves. However, the existing robotic furniture only facilitates interactions in the immediate vicinity of the device, not room-scale workspace reconfiguration.

In this work, we focus on the partition as fundamental furniture that can determine the entire workplace's configuration and functionalities. More specifically, we focus on improving workplace comfort and productivity by controlling visual exposure, that is, balancing the two trade-off factors of their visual privacy and social interaction needs [49, 33]), which is a key problem facing efforts to accommodate multiple workers in an office environment. While auditory privacy is also a critical issue affecting concentration on the task, it is out of the scope of our study because blocking complicated sound propagation with a sound-masking solution or an architectural approach is beyond the functionalities of partitions.

A physical partition is the main tool to control workers' privacy and social interactions, but the current conventional floor-anchored or wheeled partitions have low flexibility, which cannot support dynamically changing interactions. For example, a wholly shielded workspace ensures the visual privacy of the occupant, but such workspaces cannot maintain workers' necessary situational awareness of the surrounding people. Such observations strongly suggest that partitions need to be reconfigured dynamically to maintain the optimal workspace for satisfying the needs of changing privacy and interaction levels; furthermore, manually carrying heavy partitions is totally impractical. Therefore, these visual privacy and social interaction issues are significant in today's open-planned offices, and a few automatic robotic partition devices [75, 63] have been proposed. These studies, however, focused on individual devices, and thus they do not support a room-scale workspace partitioning system.

We propose WaddleWalls, a room-scale interactive partitioning system using a swarm of vertically stretchable robotic partitions (Figure 2(a)). The goal of WaddleWalls is to allow occupants to interactively reconfigure workspace partitions according to their interaction needs. The spatial user interface for target specification adopts an egocentric concept supporting on-site workers' operations and demands where they directly manage the exposure and visibility of the workspace from their own perspective. When the occupant wants to separate the workspace, he can specify an individual partition's target position, rotation, and height with the controller (Figure 2(b)) from his own perspective. Once the user specifies the layout design, the partitions drive to the specified target positions under a collision-free algorithm. The user can also remove partitions to reset the workspaces or change the partition layout for the next situation. In addition, quick height- and position-adjusting functions can be executed with the controller's buttons, which allows the partitions to be fine-tuned for such activities as ad hoc face-to-face interaction with others. The users can also record preferred partition layouts in advance, making it possible to quickly invoke these preset layouts as needed.

In this paper, we first discuss the design considerations that characterizes the major factors of robotic partition hardware and interaction techniques. We then implement a proof-of-concept prototype of WaddleWalls consisting of four robotic partitions and develop software to control multiple partitions simultaneously without collision. We build several application scenarios to demonstrate the functionalities of WaddleWalls in the open-planned office environment. Our technical evaluation clarified the basic system performance in terms of control accuracy and partition-reconfiguration time. Our initial user evaluation shows that WaddleWalls successfully mitigates the user's physical workload and offers smooth workspace partitioning. An additional interview with experts confirmed its novelty, future potential, and possible means of deployment based on their perspectives and expertise. This work makes the following contributions:

- Proposing WaddleWalls as a novel room-scale interactive partitioning system using multiple self-actuated and stretching robotic partitions and a egocentric direct spatial user interface.

- Discussing the design considerations of robotic partitions, including individual partition functions and spatial input methods adopting the egocentric concept for target specification, for designing WaddleWalls' entire set of components.

- Presenting feasible application scenarios to demonstrate WaddleWalls' functionalities.
- Offering insights on an interactive robotic partitioning system in terms of user's physical workload, practicability, and further challenges through user and expert studies.

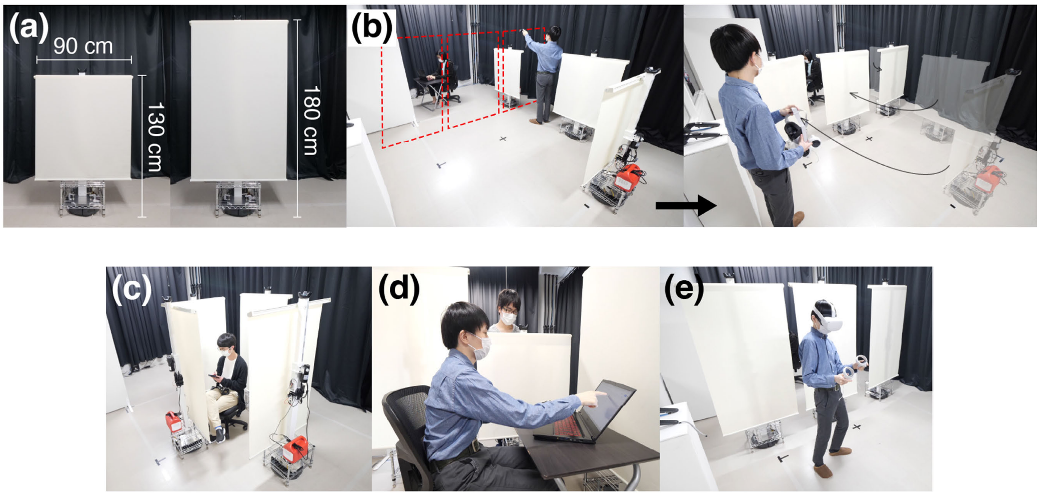


Figure 2: Overview of WaddleWalls: (a) The height-adjustable robotic partition stretching 1.3 m~1.8 m. (b) A swarm of robotic partitions are configured specified layout. WaddleWalls provides example scenarios like (c) building an ad hoc private spot, (d) adjusting partition height for ad hoc face-to-face communication, and (e) separating an entire workspace temporarily.

2.2 Related Work

2.2.1 Workspace and Partitions

There is a long history of workspace design, and an extensive literature suggests that workspace configurations significantly affect total workspace satisfaction [16, 14], the privacy [49, 5, 1, 94], productivity [114, 14], and social interaction among colleagues [84, 59, 60, 4, 13]. According to Altman's definition of privacy [5], when there is neither isolation nor crowding, and social interaction is optimal, a person will feel privacy. In general, privacy can be considered a state in which people are able to concentrate on their work. When privacy is maintained, people feel satisfied with their workspace, and the achievement of workspace satisfaction will, in turn, affect job satisfaction. To maintain privacy for each occupant, physical partitions have become critical furniture [95, 112, 120], and they have been discussed in the context of the territorial office (i.e., partitioned private office space) versus the open-planned office (i.e., without partitions) [122]. Researchers have elucidated the benefits of open-planned workspaces [13], but they have also reported several issues such as the privacy-communication trade-off [1, 49], productivity [14], and ambient noise [11].

Due to the complex nature and diverse understanding [56, 1] of privacy in the office setup, we do not go into detail about every aspect of privacy but focus on ensuring occupants visual privacy. We assume that an occupant's privacy should be ensured by workspace partitioning immediately when they need to visually conceal their information/content, bodies, working areas, and activities from others, or block any visual noise from the surroundings. Partition design is quite challenging; for example, interior researchers carefully design the partitions' dimensions and are particularly sensitive in determining the height of the partition to achieve an appropriate privacy level for workers [112, 120].

2.2.2 Dynamic Workspace Partitioning

The workspace should support not only the occupant's privacy but also their communications. To dynamically re-purpose the workspace, several types of partitions are available. First, the most classical approach uses wheeled partitions that can be manually moved, connected together, and separated to adapt to the in-demand configuration and privacy level. However, this approach causes a major interruption and physical workload for the office workers. The second approach is transparency-controlled partitions, and such partitions have been deployed in confidential meeting setups [20]. More advanced types of programmable partition walls have also been explored [79, 7, 22] to control the wall's transparency and thus support ad hoc social interactions across the partition, but these devices are not capable of protecting occupants moving around them or supporting quick placement and removal. A third approach is the use of VR/AR technologies, where the users can become immersed in a virtual workspace by wearing a headset/headphones, thus excluding real-world visual [62, 83, 61] and auditory [105] information. While this can create a private workspace that others cannot see, the user's body is fully exposed, thus not providing the user full privacy. Another approach is robotic walls that can move and change their length [75, 63], which is the closest type to our own approach. Although both have developed self-actuated stretching partition devices, they have not yet considered room-scale workspace partitioning with multi robotic partitions. Therefore, robotic partitions have not yet been explored for providing an interactive room-scale partitioning experience.

2.2.3 Adaptive Workspace with Robotic Devices

Robotic displays have been increasingly explored to augment spatial motions of the displayed content using their physical movements [73, 74]. Toward a transformable office, recent works have explored making the workspace more adaptive by using moving furniture [103] and shape-changing furniture [93, 3]. Researchers have explored re-configurable interactive tabletop displays [102, 54, 32] and shape-changing vertical displays [104, 107, 31, 8], which actuate according to the task transitions around them. The Shape-shifting Wall Display [104] comprises three mobile vertical surfaces that can reconfigure the workspace based on the information content, number of users, and gesture input. LiftTiles is a shape-changing workspace area where pieces are moved by pneumatic actuators to form temporary furniture (e.g., chair and desk) [98]. Additionally, some works have proposed robotic furniture and explored natural interactions with humans [103, 90, 52, 109, 28]. These moving furniture and robotic devices have great potential to change workplace configurations, but currently they support only the interactions among users within a single workspace. To the best of our knowledge, there is no robotic and shape-changing partition system for ad hoc room-scale workspace partitioning.

2.2.4 Robot and Control Interface

Robot control interface

Intuitive user interfaces to manipulate robots have been actively explored, which could be referred to in designing our system. A famous approach is controlling robots from a third-person viewpoint captured by a video camera, which allows users to accommodate overview of robot movement [92, 27]. This has been extended to more intuitive sketch-based robot manipulation methods [106, 87, 91, 85, 34]. Sketch and Run is a sketch-based interface allowing the user to control robots and design their behaviors by sketching gestures on a tablet displaying a top-down view from ceiling cameras [85]. Another common method involves user-centric interfaces using mobile AR, which enables the users to control a home robot [48] or an indoor robots and drones [19] accurately through direct touch interactions on a live camera display. In addition to these camera-based approaches, there are numerous gesture-based or laser pointer interfaces that give direct and spatial target instructions on how the robot should move [41, 110, 53, 29]. We use prior lessons from a wide range of robotic control interfaces to design our interface for manipulating robotic partitions by focusing on the user's egocentric perspective and experience.

Interaction with Swarm Robot

A swarm robot user interface actuates units of tiny independent robots to represent multi-dimensional information [99, 82]. Zooids is a direct physical interaction platform consisting of a collection of wheeled micro robots [57]. SwarmHaptics was designed using Zooids to additionally provide haptic feedback to the user through the robots' motions and formations [51]. ShapeBots proposed the concept of shape-changing swarm robots that individually change their vertical shapes as well as coordinated robots to represent physical information [99]. While these works are closely related to our motivation, their current prototypes use tiny tabletop-sized robots, which cannot be directly employed for actuated furniture. In terms of controlling the interface for many robots, a set of hand gesture inputs [50] or direct physical manipulations [97] seems promising for such small robots.

The idea of simultaneous use of a swarm of robots is a straightforward way to support a transformable workspace. For example, MovemenTables [103] can be automatically connected or separated a set of moving tabletops to facilitate the users' individual and collaborative activities, but dynamic spatial layout cannot be arranged. Similar efforts using multiple robots have been recently made to simulate the haptic infrastructure of a room-scale VR, where multiple wall-shaped actuated props are coordinated to respond to the HMD user's interactions and to provide encounter-type haptic feedback [121, 96]. Their mechanical setup is similar to ours, but our target is not VR but instead physical partitioning experiences. Furthermore, in terms of the mechanical functionalities, our additional height-changing capability is unique as a way to effectively support the social and privacy needs of on-site occupants.

These existing efforts to develop interactive robots appear to have no direct link to an interactive partition-arrangement system, yet much of the fundamental knowledge involved in them (e.g., control system, control interface, and basic know-how) are indeed related. Therefore, we decided to significantly extend this prior knowledge, particularly the idea of applying interactive swarm robotics to the design of novel human-sized robotic partitions and room-scale interactive partitioning experiences.

2.3 WaddleWalls Design

2.3.1 Goal and Concept

We propose WaddleWalls, a novel room-scale interactive and automatic partitioning system using movable and stretchable robotic partitions. WaddleWalls allows users to interactively reconfigure workspace partitions to meet both privacy and interaction needs by shielding an occupant's workspace/monitor from others. We acknowledge that wheeled partitions are currently the most useful type of furniture for reconfiguring partition layouts, although, unfortunately, they are frustrating, time-consuming, and burdensome to the worker's physical workload (e.g., walking to the partitions' storage, taking them into the workspace, and configuring the layout to fit their space or work style). This costly operation prevents workers from being able to instantaneously re-configure the partition layout to better suit their various needs. Nevertheless, fully automatic partition control is currently not feasible and involves concerns about collisions. Therefore, our goal is to significantly reduce the worker's physical and cognitive workload in dynamically re-configuring partitions by employing robotic partitions and spatial interface technology. To achieve this goal, we intend to design an interactive partitioning system that enables layout design based on on-site occupants' explicit demands and the consent of surrounding colleagues.

Table 2.1: Design considerations of robotic partitions

Parameter	**Elements**
Height Level	**1.3∼1.8m**
Transparency	Transparent (i.e. Glass / Acrylic), **Translucent** (i.e. Magic Mirror / Smart Glass / **Roll-Up Screen**), Opaque
Scale	1∼2: Single User, **3∼5: Multi-User, Room-Scale**
Shape Transformation	**Height**, Width, Thickness, Surface Deformation, Curvature
Locomotion Method	Manual, **Automatic** (**Two-Wheeled**, Omnidirectional)
User Perspective	**Egocentric View**, Third-Person View
Target Specification Method	**Point-and-Click**, Boundary-line Drawing

2.3.2 Design Considerations

Here, we explore the design space in creating an interactive robotic partitioning system and also give the rationale of our design strategy. Table 2.1 summarizes the comprehensive elements of robotic partitioning, with the highlighted factors indicating what we applied to our prototype. This section revisits the key functions of partitions and discusses ways to extend these to an interactive partitioning system using robotic and spatial input technologies.

Height Level

A partition's height determines the ability to shut out others' gaze. The relationship between the height of partitions and the privacy protecting effect has been reported [15, 72]. To increase flexibility, our prototype employs a height-adjustment feature to accommodate privacy protection for both sitting (1.27∼1.32 m) and standing (1.67 m∼1.77 m) users [23, 120].

Transparency

A partition's transparency influences the visual shielding capability. Opaque materials can completely conceal the target, whereas transparent materials have a low privacy-protecting ability. Translucent materials let users interactively switch openness depending on the situation, which is considered an similar effect to dynamic space partitioning. Here, we employed a roll-up screen instead of translucent materials that provides easily controllable openness by changing its height mechanically.

Scale

The number of partitions determines the workspace scale or workspace layout that can be generated. In general, one or two partitions are adequate to achieve partial privacy protection for a single-user workspace. A pair of partitions (3∼5) can form a continuous layout (i.e. line shape, corner, concave) to configure a room-scale workspace for multi-user activity. A larger number of partitions can configure a larger space. Here, to verify the basic functionality of a room-scale workspace partitioning experience, we initially employ four partitions.

Shape Transformation

The partitions' transforming shape affects the workspace appearance. Here, we initially introduce height transformation to tackle the occupants' privacy and interaction trade-off. The width is also a critical form factor determining workspace size, but we initially employ a uniform width in this work.

Although thickness, surface shape, and curvature are also important for appearance, these are less related in the workspace partitioning context.

Locomotion Method

An automatic actuator (e.g., two-wheeled, omnidirectional) is a feasible way to achieve human-effortless furniture locomotion. For rapid prototyping, our initial prototype adopts a conventional two-wheeled actuator that provides 2DoF motion (one-dimensional movement and rotation). This approach with such affordable robots makes our system more scalable and applicable than many other robot platforms.

User Perspective

We classify the user's perspective when interactively designing partition layouts into two types: egocentric and third-person views. An egocentric view allows the user to intuitively understand the partition placement configuration from one's own viewpoint as usual, while a third-person view allows users to see an overview of the position and trajectory of each moving partition remotely. To allow users to manage the exposure and visibility of the workspace from their own perspective, while considering, for example, the on-site workers' operations, we adopt an egocentric concept for target specification.

Target Specification Method

There are several ways to specify the partition states within the concept of an egocentric interface. Here, We consider two methods: point-and-click and boundary-line drawing. Each can be selectively used depending on the required partition length and shape. In point-and-click, the user can directly specify each partition state (position, height, and rotation) using a mid-air pointing gesture. Boundary-line drawing allows the user to easily specify the boundary for separating workspaces, and the target locations are automatically calculated from the defined boundary. To explore fundamental individual partitioning arrangement, we adopt the simple point-and-click method for our first prototype (boundary-line drawing is further described as an alternative interface design in Section 8.2).

2.4 System Implementation

Based on the design space, we implemented a proof-of-concept Waddlewalls prototype.

2.4.1 System Overview

Hardware Design

Figure 3 shows the overall prototype appearance and the installed actuators. The basic components are a roll-up screen (opaque off-white material, 0.9 m × 2.0 m), a metal base unit with four rolling wheels, a height-adjustable lift on the unit, Roomba Create 2 (two-wheeled actuator), and several 3D-printed parts. For the lift, we re-purposed a lift actuator from an electric height-adjustable standing desk and extended its height with an additional 3D-printed pole. The end of the pole suspends the roll-up screen's top unit, and the base unit is fixed to the metal base unit. This structure allows the screen's height to change between 1.3 m and 1.8 m by activating the lift actuator (Figure 2(a)). A low-cost micro controller unit with a Wifi connector (EPS32) is used to automatically manipulate the height of the screen. A portable electric power station (SmartTap PowerArQ, 100V/2A) is mounted on the unit to supply adequate power to drive the lift actuator (59 W input) and other equipment (e.g., ESP32 board and VIVE tracker).

Software and Actuating System

Figure 4 shows the workflow of the WaddleWalls system. We run our software made with Unity 2019.4.16f on a PC (Windows 10 computer with Intel Core i7-7700K 4.20 GHz, 16 GB RAM, and NVIDIA GeForce GTX 1060 6 GB). This PC has a Bluetooth adapter and a WiFi connector to communicate with the two actuators on each partition. The first is a Roomba actuator installed inside the base unit through serial communication via Bluetooth

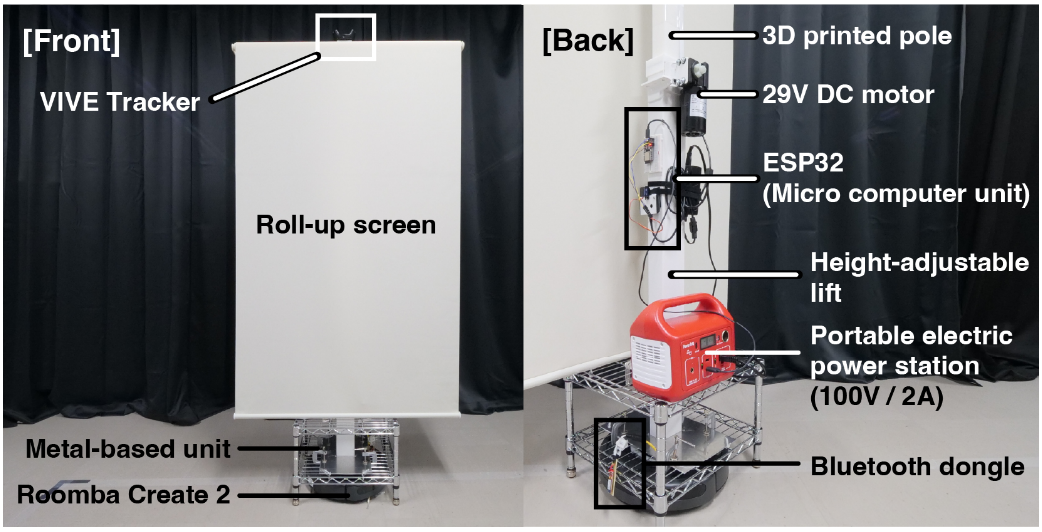


Figure 3: Hardware design overview

(Figure 4 Roomba Create 2). As for movement, each partition can translate up to 50 cm/sec and rotate at 90 deg/sec, which are reasonable parameters for safe operation. The second actuator is a 29 V DC motor-operated lift to control the screen's height, with its operation (up or down) manipulated with an ESP32 (WiFi-integrated MCU) (Figure 4 Lift (ESP32)). The speed of height change is constant at 3.04 cm/sec.

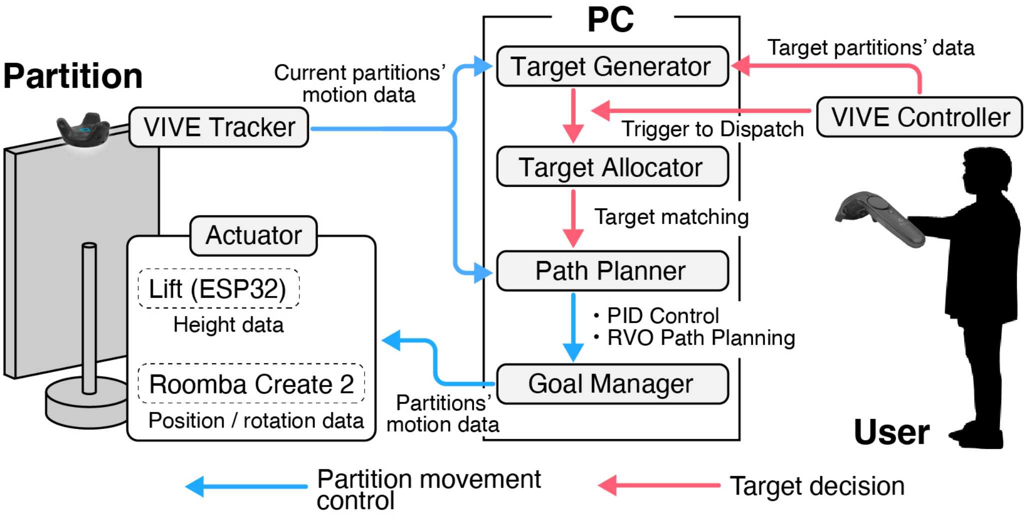


Figure 4: System flow overview

Tracking System

We used a HTC VIVE VR system as the tracking system. A VIVE tracker (ver. 2018) is fixed to the top of the lift, which sends the tracked data of the partition's own position, orientation, and height to the PC at 160 Hz (Figure 4 VIVE Tracker). The hand-held controller is manipulated by the user for specifying the target (Figure 4 VIVE Controller).

Safety Design

We introduced the following four policies. The first is the use of a soft and lightweight material for the partition screens. This was originally aimed at achieving the partition's stretching capability, but it also decreases the risk of injury to the users if physical contact occurs. The second policy is cable-free implementation. Because our system operates multiple partitions simultaneously around the users, use of any cable, even from the ceiling or on the ground, could cause serious danger. To avoid this, we introduced portable electric power stations to make all partitions fully wireless. The third policy is the constant use of an obstacle-avoidance algorithm to control the partitions based on a motion-tracking system. The system also controls each partition's speed, keeping it within a safe range through a PID algorithm. The fourth policy is the ready availability of a physical dead-man switch as an emergency stop mechanism to stop any partition, which can be activated manually by our spotter's keyboard or automatically when any tracking issue is detected.

2.4.2 Motion Control Algorithm

We employed a control mechanism similar to those of previous studies on room-scale robotic systems [121, 96] to effectively and safely manage the robotic partition's movements. The major consideration is safety in simultaneously controlling multiple robots without any collision among partitions and users. The system's workflow is illustrated in Figure 4. First, the system preserves the target's state information from the identified position, height, and orientation data of the controller described in the next section (Target

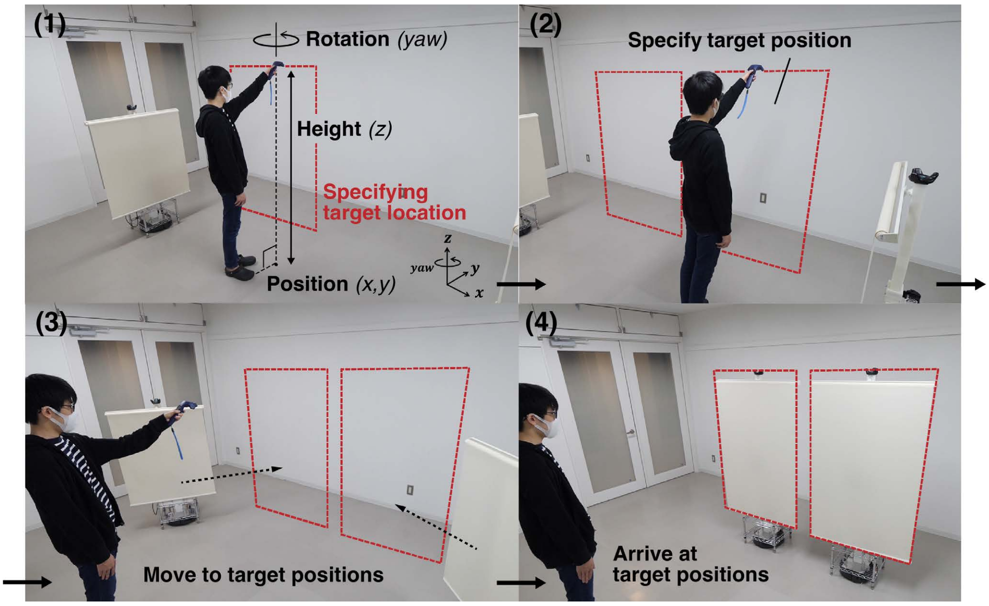


Figure 5: Partition configuration process with point-and-click method: (1)(2) User holds a controller and specifies each target position, orientation, and height of a partition with the controller one by one. (3) Once user pushes the trigger button, the partitions are dispatched, and (4) partitions arrange themselves according to the specified state.

Generator). Second, the system matches each partition to its optimal target by solving an assignment problem of distances among partitions and targets by applying the Hungarian Algorithm (Target Allocator).

Next, based on the above role assignment of partitions, the system computes the motion path of each partition based on the simple Reciprocal Velocity Obstacle (RVO) algorithm [113] (Path Planner). RVO avoids collisions between robots and users, and it has been successfully employed in closely related work [121, 96]. The Path Planner also calculates the direction vector and preferred velocity vector to the target location, and it optimizes these vectors to avoid collision in the simulation. Based on each partition's optimized behavior by the RVO algorithm, the system controls each Roomba unit's movement (Roomba Create 2) toward its target location through a PID algorithm at 40 Hz (Goal Manager). The Goal Manager sequentially calculates each wheel's speed and drives each partition to its target position and orientation.

In parallel, the system can continuously calculate the height error as well as a distance error between the partition's current height (Path Planner) and the specified target height, and thus the system actuates the lift (Lift (EPS32)) accordingly to minimize height error (Goal Manager).

2.4.3 Interface Design

Design Considerations

To design a spatial user interface that permits users to freely specify the partitions' target positions, we adopted an egocentric concept derived from on-site users' operations and practices. Our egocentric interface allows user to directly design and specify targets' positions for managing the visual exposure or workspace visibility from their own perspective. Within this concept, we designed two target specification methods: point-and-click and boundary-line drawing, as specification strategies for individual and grouped targets, respectively. Here, we focus on the point-and-click method for the first prototype, and later we explore the other method in Section 8.2.

Components

The spatial interface consists of two components: a hand-held controller and a visual monitor. The controller (Figure 6(a)) lets the user directly specify target states within a 3D space. We adopted the VIVE hand-held controller, which is capable of three-dimensional pointing with multiple physical buttons. The additional visual monitor (Figure 6(b)) provides a top view of the room and visualizes the current partitions and the specified partitions' target positions, helping the user gain spatial awareness of the surrounding environment. The light and dark blue circles in Figure 6(b) indicate the safety areas of already specified partitions and the target of the partition being currently specified, respectively; these areas are not allowed to overlay each other as a way of preventing collisions among partitions. Sound feedback is also employed to indicate whether the target is successfully specified: An error sound alert is played when the controller's target candidate area overlaps the already assigned targets' safety areas and the user cannot place a new target there, whereas an accepted sound alert indicates successful target assignment. A simple setup of a hand-held controller with sound feedback may be adequate for rough partitioning design. The visual monitor on available devices (e.g., monitor or mobile screen) provides the user with spatial awareness of specified invisible partitions, helping to smooth out partition layout design.

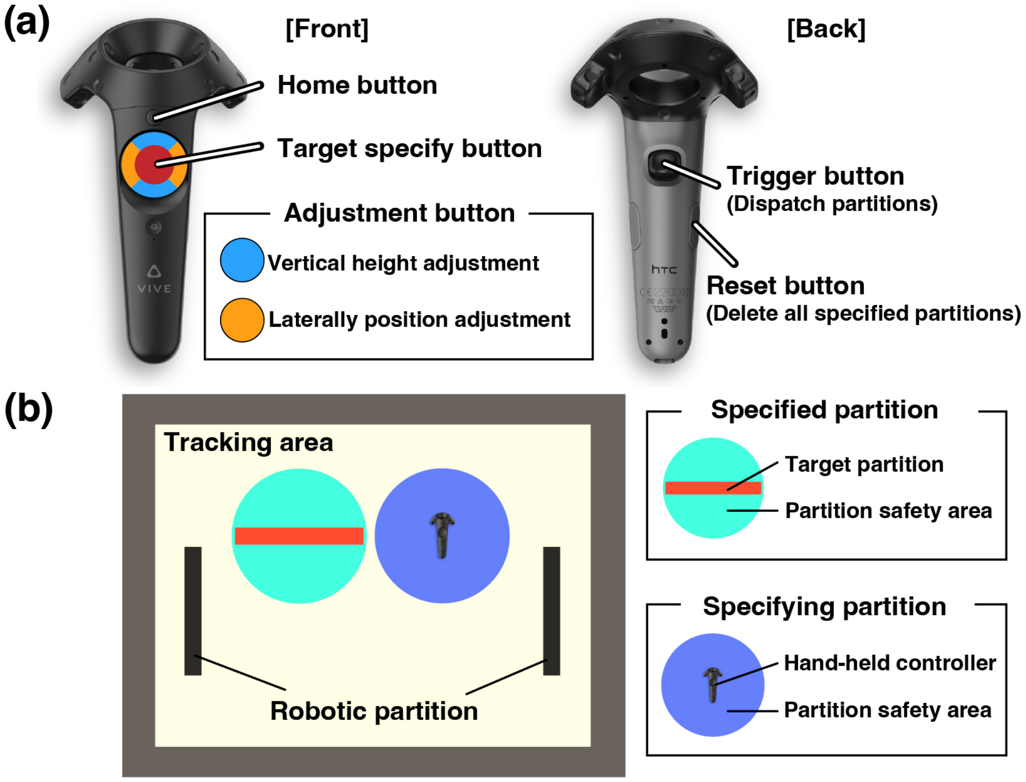


Figure 6: Overview of interface: (a) controller, (b) visual monitor

Interactive Arrangement

Our spatial interface is deployed to complete a set of actions. First, the user specifies the target's position, height, and rotation with point-and-click action using the hand-held controller (Figure 5(1)(2)). The controller's position and posture data are converted and recorded as a target's states: the x and y axis coordinate is the target's position, the z axis coordinate is the target's height, and the yaw rotation is the target's orientation. The users can specify each target state by clicking the center of the controller's track-pad (red point in Figure 6(a)), and the system records the specified targets' information immediately. While specifying and recording the target status, the user is able to confirm the layout on the visual monitor (Figure 6(b)). Once the necessary target states are recorded, the users can dispatch the partitions by pushing the trigger button of the hand-held controller (Figure 6(a) Trigger button). Each partition then moves to its target position (Figure 5(3)) so that its top (i.e., tracker position) matches the specified target position and orientation (Figure 5(4)).

Preset configuration and Height/Position Adjustment

The user can permanently record the frequently used layouts as presets. This mode is quite useful, since the user can immediately obtain a needed workspace partitioning with a one-button click. For our default, we defined a home-position preset (Figure 6(a) Home button), where all partitions return to an initial state (i.e., around the edge of the tracking area as shown in Figure 13).

We additionally designed a remote interaction to adjust each partition's height/position using the hand-held controller's trackpad (Figure 6(a) Adjustment button). The edge around the trackpad is divided into four areas: top, bottom, left, and right. The upper and lower parts are assigned to raising and lowering the partition height by predefined amounts, and the left and right parts are assigned to moving the partitions laterally. These manual adjustments are activated only for a single partition that is indicated by pointing the controller's head. The user is able to use this adjustment function for changing workplace openness (by height changes) or diminishing partition gaps (by lateral actuation) among partitions after initial automatic partition arrangement. This interaction is separately designed to provide users with remote interaction and thus allow them to adjust the partition's status from their working position and perspective (e.g., from their own desk) without making physical contact with the target partition.

2.4.4 Control Performance Evaluation

We conducted a brief technical assessment to verify the current prototype's motion control accuracy and speed. First, we measured the position, height, and rotation control accuracy by comparing the target states and the partition's final states in 15 attempts for 4 partitions. Table 2.2 summarizes the positioning errors for each parameter, showing a sufficient control accuracy under the WaddleWalls' tracking system (HTC VIVE VR System). Next, we measured the time needed to complete the reconfiguration in 15 attempts to reconfigure 4 partitions in a 3 × 2.3 m area at the most stable actuator speed. The average time to complete the four-partition reconfiguration from the initial arrangement was 11.58 sec (*SD* = 2.47). This will be further improved with more powerful actuator and sensing platforms, but even the current platform can save the user time in comparison with manual arrangement.

Table 2.2: Control performance with four robotic partitions

Parameter	Average Error
Position	1.53 cm (*SD* = 1.13)
Height	2.76 cm (*SD* = 1.96)
Rotation	2.39 deg (*SD* = 0.64)

2.5 Application Scenarios

Here, we describe several application scenarios that demonstrate how our WaddleWalls partitions can perform in various office situations. These scenarios generally involve operations to temporarily modify the user's privacy and space zoning.

Ad hoc Private Spot Builder

Our self-actuated partitions can coordinate themselves to produce an instant private spot at anytime and anywhere for a user who wants to conceal his/her private actions (e.g., changing of clothes, napping, telephoning, handling confidential materials). Figure 7 shows an example scenario of quickly building a personal private spot that blocks visual exposure to those in the surrounding area. One of the partitions can act as an automatic door using the position adjustment function. This private spot can be instantly built for use as a telephone or zoom room or even a temporary changing room, and it is dismantled by the user's home button command when the task is finished as well.

Figure 7: Ad hoc private spot builder: A) A user designs the partitions' layout. B) The system creates the designed layout. C) A private spot is configured using four partitions.

Ad hoc Meeting Booth Creator

Under the pandemic circumstances, video meetings are held anytime and anywhere in the office. During video meetings, the user needs to handle the risk of both "shoulder surfing" by on-site colleagues and exposing the surrounding environment to remote people. Therefore, it is advantageous to protect the user's monitor from the surrounding environment. Although using a virtual background hides the actual background environment from remote people, it still does not solve the visual exposure of the monitor to on-site colleagues. Figure 8 shows the simple and straightforward solution of creating an ad hoc meeting booth by providing a physical background behind the user. In addition to privacy protection, this explicitly conveys to those in the surrounding area that this space is being used for a personal chat.

Figure 8: Meeting booth creator: A) A user focuses on a personal task at his desk. B) He invokes a preset layout before starting an online meeting. C) He gets a neutral white background that protects his monitor from "shoulder surfing."

Ad hoc Workspace Protector

The interactive partition placement and height adjustment allow a user to easily protect his/her workspace from the surrounding visual noise. As shown in Figure 9, when others enter the room and start group activities near his desk, the user can quickly arrange partitions around the desk to isolate himself from them. This ad hoc partition is beneficial to maintaining the concentration of both the user and the group.

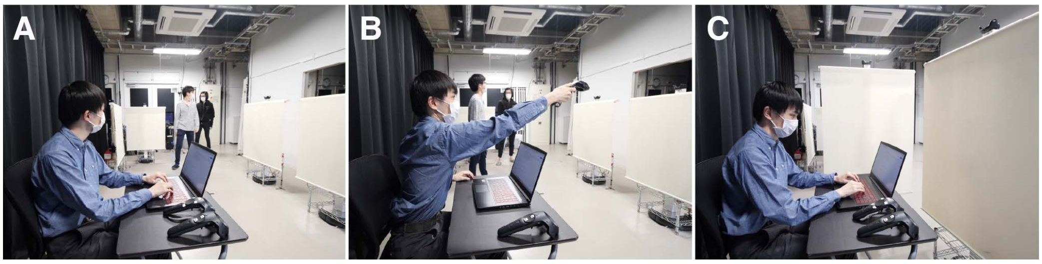


Figure 9: Ad hoc workspace protector: A) A person recognizes a small group starting a discussion near his desk. B) To conceal them from his view, he arranges partitions around his desk. C) L-shaped high partitions are configured to prevent the user and group from seeing each other.

Ad hoc Collaboration Supporter

This example takes up the situation discussed in the previous scenario (ad hoc workspace protector). Even when the shields are configured around the desk, the shielding effect can be controlled by the user. Figure 10 shows an example of a shielded desk user who decides to perform a face-to-face chat with colleagues by changing the height of the partitions. This use scenario clearly demonstrates the impact of partition height on social interaction. The user can easily switch between individual and collaborative workspaces without changing the partition formation.

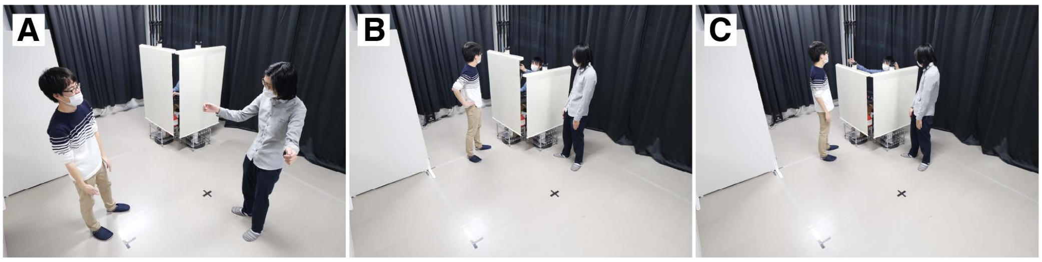


Figure 10: Ad hoc collaboration supporter: A) A user is at a fully shielded desk and others have a discussion in the same room. B) To ask him for feedback, they call to him over the ad hoc booth. (C) He lowers the partition to accommodate face-to-face discussion with them.

Exhibition Layout Editor

Another use case is creating a temporary exhibition space. Figure 11 shows that our system can provide a temporary poster presentation layout. The zig-zag shape can create a unique personal place for each presenter, and this example shows that the surface of the partitions can be used to display a poster or projected content. Our system would be extremely useful for a huge exhibition hall where many partitions are positioned. Depending on the number of visitors around the posters, each space can be interactively customized by altering the partition formation. If a conference banquet is held after the exhibition session, the partitions are automatically rearranged to accommodate the spatial needs of the banquet.

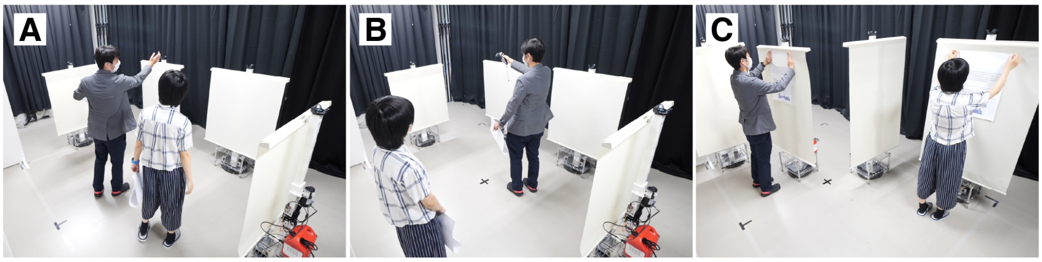


Figure 11: Exhibition layout editor: A) Two presenters discuss the presentation layout in an exhibition hall. B) A man arranges the partitions with the controller. C) The partitions form the poster booth layout, and presenters attach their posters to the partitions.

Ad hoc Physical Shielder

This example shows the creation of a physical shield and explicit territories to protect non-moving users from moving users in a situation where one of the users sharing the room makes physical movements. Figure 12 shows an example of using a physical shield to create a safer workspace. Here, a newly joined user starts debugging VR software using full-body gestural interactions. He dynamically arranges partitions for separating the entire room to secure his physical workspace for the full-body motions. This scenario is a particular case, but it illustrates how the partitions' shield can help to avoid collisions between users.

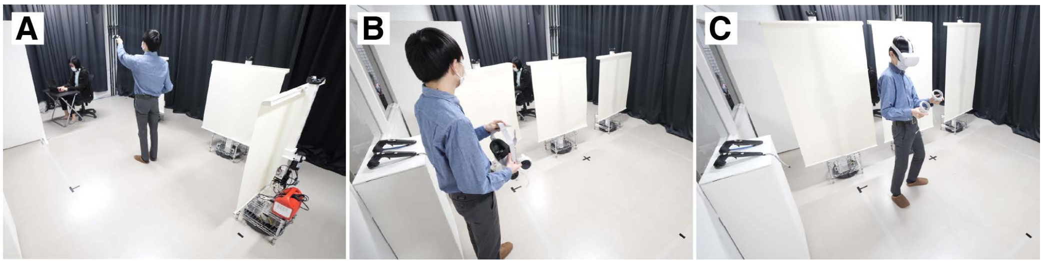


Figure 12: Ad hoc physical shielder: A) A user enters the room where another user is already working, and he starts arranging partitions. B) The configured partitions separate the room. C) While the HMD-wearing user performs VR interactions with full-body gestures, each user can safely concentrate on his task without the risk of collision.

2.6 User Evaluation

We conducted a preliminary experiment to investigate how WaddleWalls affects the user's ad hoc partitioning experiences. From our several functions and use cases, here we focus on three main functions as tasks: interactive partitioning, height-changing, and automatic preset partitioning. Participants experienced these three tasks under two partition conditions: WaddleWalls and conventional wheeled partitions. As an initial evaluation, we investigated how an interactive partitioning system affects physical workload and overall experience during partition arrangement through the NASA-TLX questionnaire and SUS (system usability scale) score as well as subjective preferences. We did not examine the privacy-protection level of

WaddleWalls since the related effects are inherently ensured by the opaque physical partition materials. We used our prototype with four robotic partitions, which allows the user to configure several types of layouts for a single user or multiple users.

Our study strictly followed the university's COVID-19 infection prevention protocols, and the study design was officially approved by our university's ethics committee. We gathered 10 participants (age: 19-55 years old, 4 females and 6 males) who agreed to our institute's virus-prevention requirements. Five of the participants were familiar with the HCI domain, while the rest were not. All participants work daily in an open-planned office environment. They received payment of about $30 after the experiment.

2.6.1 Apparatus

Figure 13 shows the entire experimental environment, and its central 3 × 2.3 m space (in red dashed lines) was the valid tracking area in which two HTC VIVE base stations could stably recognize trackers. We used four WaddleWalls partitions (H: 1.3 - 1.8 m, W: 0.9 m) and four wheeled whiteboard partitions (H: 1.8 m, W: 0.9 m) as the baseline condition to which we unified their form. All of the four partitions were initially placed around the edge of the tracking area. Each participant used one VIVE handheld controller (see Figure 6) to manipulate WaddleWalls. For safety, an on-site assistant was always ready to stop all partitions if any unexpected event occurred. All actions in the experimental space were video-recorded for post-experiment analysis.

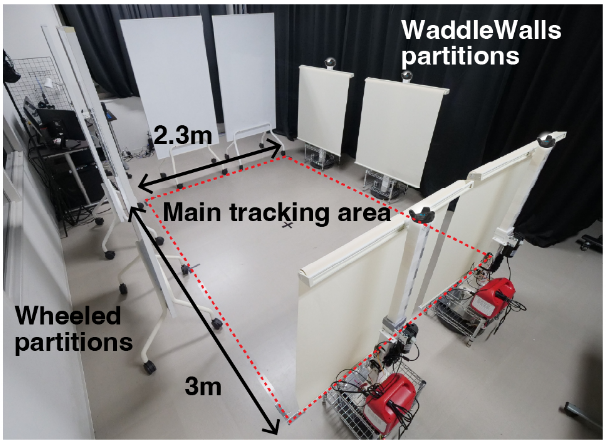


Figure 13: Experimental environment

2.6.2 Procedure and Design

First, participants received an explanation and signed a consent form. They then received instructions on WaddleWalls' manipulation, and they had practice sessions for five minutes. After that, three task sessions began (details described below). Each session took approximately 15 minutes.

Each participant completed six trials: two partition types × three tasks. The order of partition types was counterbalanced, while the order of the three tasks was fixed: 1) interactive workspace partitioning, 2) height-adjustment for face-to-face interaction, and 3) automatic preset partitioning. Dependent variables involved subjective physical workload, which was measured with NASA-TLX at every trial. We additionally obtained the SUS score and an overall subjective preference rating on a 7-point scale at the end of the experiment. Finally, we performed a semi-structured interview to get further thoughts about our system. The experiment took about two hours in total.

2.6.3 Tasks

Task 1: Interactive Workplace Partitioning

The first task was conducted to verify the interactivity of partition arrangement. Participants arranged partitions into the three types of layouts illustrated in Figure 14: squared (e.g., for a private spot), two corners (e.g., for

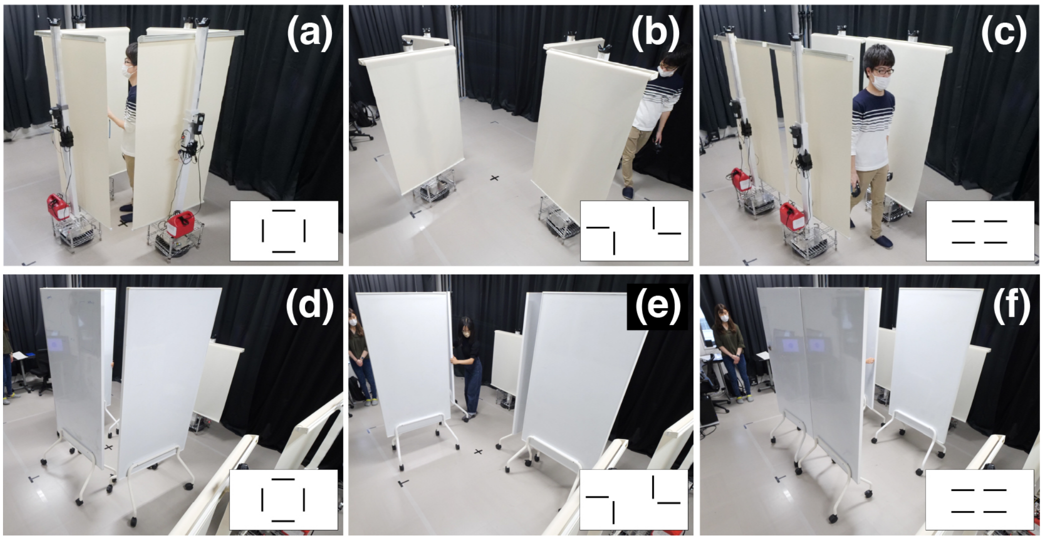


Figure 14: Task 1: Interactive workspace partitioning scenario. (a-c) WaddleWalls, (d-f) wheeled partition.

segmentation), and two lines (e.g., for route guidance). Once they arranged partitions, they walked around to actually experience the created layout. They then returned all partitions to their original positions. This process was repeated for each layout. During the task, participants carefully performed the new partition design process and avoided rushing and rough layout design.

Task 2: Height Adjustment for Face-to-face Interaction

This task verified the ability of spatial openness management, which is a novel feature of WaddleWalls. In this task, the participant first performs a regular typing task at a surrounded desk (Figure 15(a)), and then he/she is required to lower the partition to accommodate ad hoc face-to-face communication with a bystander (Figure 15(b)(c)). After the interaction, the participant restores the partition to the initial height and returns to the typing task. This scenario illustrates that spatial openness provides a smooth transition to an ad hoc social interaction. For the WaddleWalls condition, participants can adjust the partition's height by one-tap button operation (Figure 6(a) Vertical height adjustment). For the wheeled partition condition, they manually remove a part of the wheeled partition to make space for face-to-face communication(Figure 15(e)(f)).

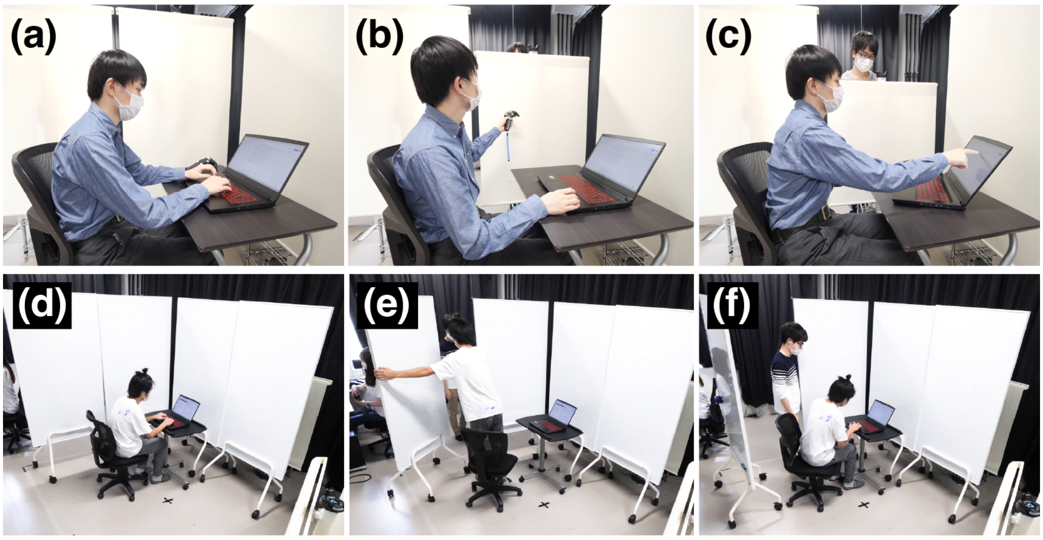


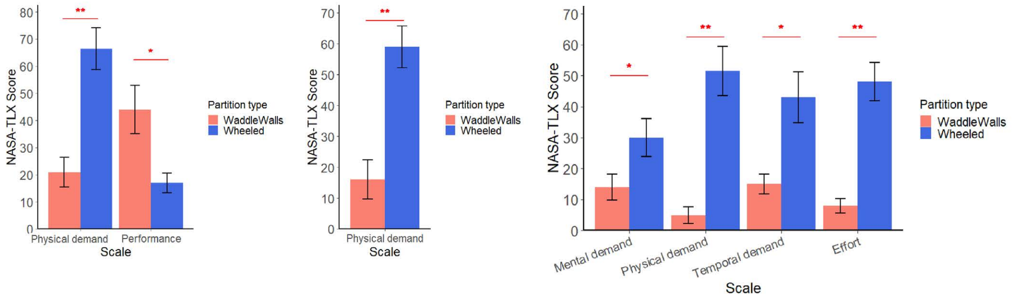
Figure 15: Task 2: Height adjustment for face-to-face interaction. (a-c) WaddleWalls, (d-f) wheeled partition.

Task 3: Automatic Preset Partitioning

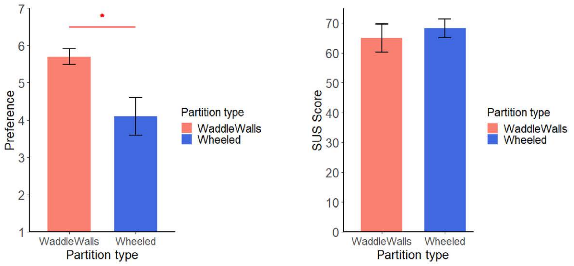
This task verified the preset automatic layout arrangement usability. Among many present options, we employ an ad hoc meeting booth creation example (as discussed in the application scenario) because it is a representative case that requires protecting the user's privacy and security in an open-planned office. Furthermore, this case's desired layout is one that can protect the user's backside to prevent "shoulder-surfing" and unnecessary room exposure. In this task, the participant first performs a normal typing task in the open area (Figure 8(A)), and then he/she sets up the predefined

Figure 16: Task 3: Automatic preset partitioning. (a-c): wheeled partition.

ad hoc meeting booth before starting a video meeting (Figure 8(B)(C)). After completing the video meeting, the participant returns the partitions to their original position. For the WaddleWalls condition, participants can invoke the pre-defined layout by one-tap button operation. For the wheeled partition condition, they manually form the same layout as that done with WaddleWalls (Figure 16).



(a) Interactive Partitioning **(b) Height Changing** **(c) Automatic Partitioning**



(d) Preference **(e) SUS Score**

Figure 17: NASA-TLX score of each task: (a) Interactive partitioning, (b) Height changing, and (c) Automatic partitioning, and the score of (d) preference, and (e) SUS score (*: p < .05, **: p < .01). All bar charts show mean with standard error.

2.6.4 Results

Figure 17(a-c) shows for all tasks the scales for which there were significant differences in NASA-TLX scores between WaddleWalls and the conventional wheeled partitions. Figure 17(d), (e) show the results of subjective preference score and SUS score, respectively. These graphs show mean values, and their error bars indicate standard deviation. A * is a mark of significance detected by Wilcoxon signed-rank test applying the collected non-parametric data.

Task 1: Interactive Workplace Partitioning

Figure 17(a) shows the NASA-TLX scores of physical fatigue and performance. WaddleWalls significantly reduced physical demand 68.4 % compared to the wheeled partitions ($p < .01$, $r = .85$), which clearly supports our fundamental motivation for mitigating users' physical workload. However, we also found that WaddleWalls had lower positioning performance than the wheeled partitions ($p < .05$, $r = .69$).

Task 2: Height Adjustment of Partition

From the NASA-TLX score, we found a significant difference only in physical demand, where WaddleWalls had an approximately 73.0 % lower score than the wheeled partitions ($p < .01$, $r = .89$) (Figure 17(b)). We observed that WaddleWalls required a longer time ($M = 13.8$ sec. $SD = 4.07$) than did the wheeled partitions ($M = 10.8$ sec. $SD = 4.8$) to start face-to-face chat due to the slow lift actuator.

Task 3: Automatic Preset Partitioning

We found significant differences in four of the NASA-TLX scales: mental ($p < .05$, $r = .80$), physical ($p < .01$, $r = .89$), temporal demand ($p < .05$, $r = .71$), and effort ($p < .01$, $r = .89$) (Figure 17(c)). Looking at physical fatigue, WaddleWalls achieved a 90.3 % reduction compared to the wheeled partitions. From our video analysis, we confirmed that WaddleWalls took 14.3 sec. and 10.75 sec. for configuration and resetting, respectively, which were considerably faster than the wheeled partitions' performances of 29.7 sec. and 24.1 sec.

Overall Preferences and Usability

From the results of preference on a 7-point Likert scale (Figure 17(d)), we found that participants significantly preferred WaddleWalls over the wheeled partitions ($p < .05$, $r = .75$). However, overall SUS scores (Figure 17(e)) show that WaddleWalls and the wheeled partitions attained almost the same level at $M = 65.0$ ($SD = 9.79$) and $M = 68.3$ ($SD = 14.77$), respectively.

These results are within the C level (= Okay) [12]. Looking at the individual questions in SUS, participants highly valued how well WaddleWalls integrated the various functions compared to the manual approach, but this multi-functionality of WaddelWalls required a higher initial system-learning cost than manual operation for beginners.

2.6.5 User Feedback and Discussion

WaddleWalls was also found to be effective in reducing cognitive load during path planning for partition transport. The software performs an allocation-optimization algorithm to minimize each partition's travel distance, and it also calculates real-time routing design to avoid collisions of partitions. This helps by avoiding the need to manually determine the partition's path planning (P10). From the NASA-TLX scores, there were no significant differences, but the levels of mental and physical effort were lessened in the interactive layout task and the video meeting task.

Unexpectedly, many participants complimented the high convenience of the functions that accompany fully automatic partition reconfiguration, including deciding layout and carrying partitions (P1, P2, P3, P4, P5, P7). Invoking the pre-defined layout did not interrupt the on-going task and simply required pushing a button (P2). This feature would also be appreciated when the user is tied up and cannot leave the immediate workspace (P3). However, some participants were still bothered that the pre-defined layout did not match where they wanted to place a partition (P3), and a user often needed to adapt to the layout provided (P1).

From SUS and subjective evaluation, we found that participants prefer WaddleWalls, which effectively integrates multiple functions. Currently, the overall SUS score of WaddleWalls is the same as that of the manual approach, but we believe its overall usability will significantly increase after users get used to operating the WaddleWalls system.

2.7 Expert Interview

We conducted an additional expert interview session to discuss the novelty, potential impact, and future directions of WaddleWalls in real-world workspace design contexts.

2.7.1 Method

We recruited three experts (E1: architect (female, 5 years experience), E2: architect/workplace designer (male, 20 years experience), E3: spatial interior designer (female, 10 years experience)) from among acquaintances of the author. Although we initially planned an on-site demonstration and interview to get realistic feedback, we followed the university's COVID-19 infection prevention protocols and shifted to separate online interviews of the three experts. The experts first viewed our video showing WaddleWalls' system details, all application scenarios, and the three scenarios used in the user study. We then conducted a semi-structured interview, mainly asking about three viewpoints: 1) the novelty of WaddleWalls in practice, 2) the validity of our use scenarios, and 3) any insights based on their expertise. After that, we held an open-ended discussion session so they could elaborate their thoughts. The entire study took about an hour, and they received $100 in payment after the interview.

2.7.2 Insights and Feedback

All of the experts first confirmed the clear novelty of WaddleWalls as a system on the market and as seen through their real-world practice. One of them mentioned, "*Although the idea of a robotic partition is easy to come up with, I have never seen any implemented automated partition before (E2)*." In addition, all of our use scenarios were accepted and seemed to be valid to meet real-world workspace needs. The following is a summary of our discussions and the experts' insights.

Use Environment

All of the experts suggested that a larger environment is a better field to drive robotic partitions. In particular, they suggested a public space in the city hall (E1), a cafe (E1 ∼E3), a library (E2), or a university's active learning space (E3).

Providing New Experience

E2 and E3 mentioned that most office occupants have little knowledge about how a workspace can be optimized, even using wheeled partitions and furniture. Therefore, they expected that this system could provide users a new perspective and opportunities to think about workspace optimization. In particular, most people have no chance to change a partition's height (no such device exists on the market), so this system would offer new workspace design and use opportunities (E3).

Group-Work Facilitation

Another perspective is that height manipulation of the partition could be applied to adjusting the workspace's openness, which would facilitate group-based creative activities (E3). For example, distracting the mind through an open workspace usually promotes brainstorming performance (i.e., bringing out a lot of ideas), while a closed workspace would lead the users focus to summarizing their ideas.

Social Problem

E2 was generally positive about our direction but expressed a concern that our partition's introduction in actual workspaces would bring about a sensitive social problem: Partition users could claim a distinct territory with the partitions, which might unintentionally exclude partners. This action might not be socially acceptable depending on the group's features and work styles. Thus, he suggested first using this system in public spaces (e.g., library, cafe) where no sensitive social connections exist. His general suggestion was to explore how to establish valid rationale among workers for physically separating a workspace, specifically when using it among colleagues in an office, and the need for understanding social connections in the group.

Improvement

E1 expected a width-adjustment function that could expand the size of the created workspace. She also suggested replacing the upper part of the opaque material with a transparent sheet, which would also work as a shield that enables users to engage in face-to-face communication as they sit at their desks.

2.8 Discussion

2.8.1 General Discussion

Through our work, we confirmed the fundamental effect of a room-scale workspace-partitioning system toward the development of transformable workspaces. Based on observations from the user evaluation and the expert interview, we suggest the following use cases of WaddleWalls.

First, our observations imply that diminishing physical load is highly expected as the robotic partitioning system's fundamental feature. In addition, it was found that reduction of cognitive load during the overall partitioning experience was also valued by users. Therefore, WaddleWalls promotes interactive creation of various workspace layouts anytime and anywhere with low physical and cognitive effort.

Second, the automatic preset partitioning feature was highly evaluated, since the user could complete the specific layout configuration without any work degradation (i.e., time-consuming steps and lost concentration caused by walking around for set-up planning and confirmation). Assuming the office environment where the user constantly involves any task, designing a system that does not interfere with the main task could be rather important factor of an interactive workspace configuration system. Based on this observation, we could also consider designing a layout recommendation function based on previously recorded layouts or prepare a list of known common layouts in the instant workspace creator. It suggested that this layout recommendation function could work as a part of the main functions of WaddleWalls as well as the layout specifying method. To determine the appropriate workspace layout, it would be worth conducting a design study exploring suitable layouts according to scenarios. Prior researchers have conducted similar design studies that explore the optimal layout of vertical [104] or tabletop display [54], we could further utilize such protocols.

Third, WaddleWalls' unique interactive height-adjustment feature proved useful for a variety of standing and seated users in our various applications. For further development, we also consider a group activity facilitator as another use case, in addition to the ad hoc spatial opening function for face-to-face interaction tested in the user evaluation. More specifically, group work could be facilitated through workspace height adjustment depending on the activity process (i.e., divergent or convergent ideas), since the spatially open workspace was reported to promote imagination [26]. This is an interesting aspect beyond the privacy context, leading to a new research topic in social and environmental psychology.

Finally, our designed applications and user evaluation sessions showed that four partitions were enough to enable room-scale partitioning, since they can configure a variety of workspace layouts to accommodate a single workspace relative to the surrounding environment. To enhance the configurable scale, we will attempt to operate the system with more than five partitions, which we assume is necessary to support a multi-workspace configuration.

2.8.2 Interface Improvements

Based on the study observations and interviews, we designed an alternative spatial input method for WaddleWalls in place of the proposed one-point specification method. Assuming a space-separating scenario like that in Figure 12, specifying a space boundary-line seems more natural than specifying each individual partition's position one by one. Additionally, the users seemed to have difficulty confirming the partitioning status with the visual monitor fixed to the desk, according to user evaluation results. Therefore, we introduced two additional designs regarding 1) the partition specification method and 2) a mobile visual monitor to further increase the usability of the WaddleWalls system.

For the improved method (Figure 18), we design the boundary-line drawing method using a boundary drawing action, where the user specifies two endpoints to describe the boundaries of the workspace separation. The user specifies these two endpoints by pushing the center of the hand-held controller's trackpad button. From these two specified endpoints, the system automatically calculates the number of partitions that can be placed and quickly lines up the target partitions along the specified line as shown in Figure 18 left. The average of the two endpoints' heights determines the final height of the partitions. This approach allows the user to not worry about the number of partitions to place, and it might be helpful in setting a long boundary of workspaces, e.g., separating the entire room into two work studios.

Considering the scalability for multiple users, we employed a mobile visual monitor, where the users can see the partitions' arrangement in real time in a hand-held display. This mobile monitor allows each user to simultaneously view and specify a target from their desk position. In the future, this mobile monitor and even the VR hand-held controller could be integrated into a personal smartphone application, which would simplify the overall setup and also possibly enable multi-user manipulation.

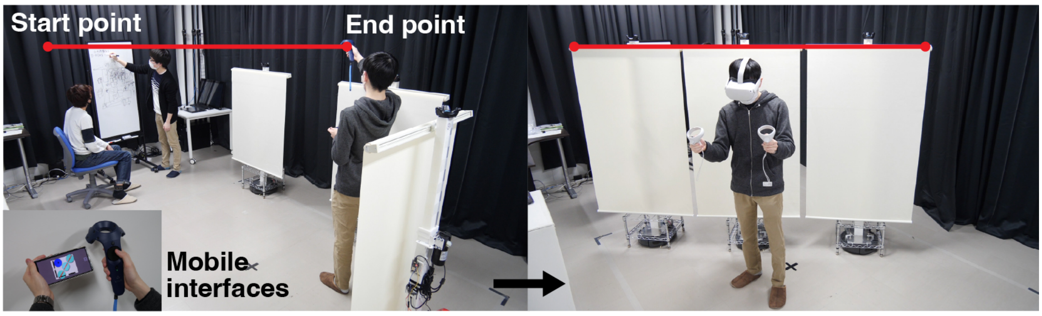


Figure 18: The user specifies targets with the boundary-line drawing method.

2.8.3 Limitations and Discussion

Here, we discuss WaddleWalls' limitations for further exploration of a robotic partitioning system.

Positional accuracy

The first limitation is the physical break between partitions produced after automatic reconfiguration. This issue is caused by the safety concern of avoiding collisions when WaddleWalls' two-wheeled actuators rotate for orientation matching after reaching the target area. The experimental results imply that some level of placement accuracy is required in the initial arrangement to improve overall usability. As one solution, we could introduce an omni-directional actuator that requires less rotation after reaching the target area or improving the partition-controlling algorithm from a simultaneous arrangement to a sequential one-by-one arrangement.

Height-adjusting Speed

Another mechanical limitation is the slow height-adjustment speed. This slow speed made users feel slightly frustrated. A basic solution is to equip the system with a more powerful motor, which would roughly match the satisfactory speed of a conventional automatic door (approximately 0.35∼0.5 m/sec [45]) to achieve both safety and user-accepted operation.

Tracking System

The current WaddleWalls system employs a virtual reality system for rapid prototyping and safe operation, which in turn limits the operational area size. To make the robotic partitions stand-alone, we could employ a camera-based position-tracking system such as LiDAR or other depth sensors. In addition to this, sophisticated smartphones or recent Roomba with spatial tracking capability would be a promising alternative to the hand-held controller in terms of room-structure scanning and mobile AR-based target specification and editing.

User Evaluation

Our user evaluation was conducted in a controlled lab environment where there were no other obstacles or users in the tracking area. Our collision avoidance system will work fine in environments where the spatial structure is known. However, from a practical point of view, usage under limited environment verification is not sufficient. Therefore, our next step must include (1) study in a larger environment to validate the partitions' control capabilities and (2) an in-the-wild study to explore the effect of this robotic partitioning system in real-world work experiences.

Practical Use Issues

Through user interviews, we found two major challenges regarding the application of our system in a real environment: mechanical actuation noise and user concerns about collisions. For the former, the noise may interfere with task concentration, thus the system will need to be equipped with lower-noise actuators. As for the latter, the automated partitions' behavior still seemed unexpected to beginners, even if they knew a collision-avoidance algorithm was running. This may be resolved as the user become accustomed to using the system, so we would like to investigate the long-term effects in the future.

Psychological apprehensions

There is a chance that WalldeWalls' operation may cause the user to have psychological apprehensions. A typical example is an unintentional blind spot or security hole (i.e., unconcealed area) that may be due to failed or incomplete automated partition arrangement. Another psychological apprehension might arise when the user is automatically isolated by high partitions in a closed workspace layout. To avoid these risks, we suggest the reasonable solution of effectively using the height-changing function of WaddleWalls to maintain comfortable openness while partitions are being reconfigured. Partitions can be initially configured at a lower height and be subsequently raised once confirming the layouts are satisfied. Providing such an intermediate step might mitigate user apprehensions by maintaining an appropriate spatial awareness of the changing arrangement and by occluding surrounding areas. Another, more straightforward, approach to increasing the user's situational awareness is to install additional sensors on the outer faces of the partitions that can record any event in the surroundings (e.g., strangers' approach or uncomfortable proximity) and visualize them on the user's monitor.

System transfer to real environments

To transfer our system to real offices, we first need to consider how to make it more affordable. If a longer waiting time is permitted, partitions can be sequentially actuated using fewer actuators. However, considering the results of our technical evaluation, we recommend that each partition have its own actuator to ensure immediate workspace adaptation. Another approach would be a hybrid system set up by replacing a portion of the conventional partitions with our robotic partitions, where the actual wheeled partition arrangements could be manually configured as the base partition formation while the rest of the partitions could be later configured by robots. The second step is to progressively install our system in co-working spaces that have a strong demand for practical partitioning as a field-based approach. Our automated workspace optimization experiences will increase familiarity with robotic furniture. In addition, we could use more familiar input devices in the early stages, such as mobile phones equipped with AR techniques. Such progressive approaches that start with existing familiar practices will be a key to future full deployment.

2.8.4 Future Work

As long-term future work, we will (1) use more WaddleWalls in larger workplaces to investigate further logistic benefits, (2) explore collaborative use with other self-actuated furniture (e.g., [103, 31]) for a fully robotic workspace, (3) explore a automated workplace optimization system that leverages the users' activity tracking data, and finally (4) employ the robotic stretchable partition screens for different purposes (e.g., recreational badminton net, automatic sun shield, airflow manager, telepresence avatar system).

2.9 Conclusion

A workspace must be flexible to accommodate the desired privacy level and other user requirements. The partition unit is a critical element of space partitioning in the office environment. We proposed WaddleWalls, a room-scale interactive partitioning system using a swarm of robotic partitions that allows users to interactively reconfigure workspace layouts to adapt to their privacy and interaction needs. The WaddleWalls system enables the reconfiguration of partitions by specifying partitions' states with the user's hand-held controller. We created a design considerations to implement a proof-of-concept prototype of robotic partitions and, moreover, demonstrated its effectiveness through running application scenarios in an open-planned office environment. To evaluate WaddleWalls' functionalities, we conducted an initial user evaluation, which found that WaddleWalls could provide workspace partitioning experiences that were more physically and cognitively effortless. We also clarified the potential usefulness of WaddleWalls through an interview with experts. Future work includes modifying the robotic partitions for use in more extensive workspace partitioning experiences.

Chapter 3

Interactive Multi-sensory Content Augmentation using Physical Display Movement

3.1 Introduction

Even with the existence of stereoscopic head mounted displays (HMDs), the flat screen remains a typical interaction platform. While it offers only monoscopic visualization, it allows affordable and HMD-free 3D interaction experiences (e.g., Nintendo Wii[71], Switch[70], and PlayStation Move[40]). The users rely on indirect interaction where mid-air controller or gesture inputs are performed to manipulate virtual objects. However, this interaction lacks haptic feedback because there is no physical contact between the manipulating cursor and the targets. A typical solution is to activate a vibrator inside the controller to provide tactile feedback when the user touches a virtual object[39], but this cannot simulate the desired haptic cues. The use of wearable or grounded haptic devices is not suitable, as each requires additional wearing costs and large external mechanics to represent force feedback to the user's skin[30, 37]. If a flat screen can also represent force feedback for the users while retaining its affordable setup, it promises to achieve a multimodal and HMD-free 3D user interface.

To this end, we focus on two approaches. The first is the use of a pseudo-haptic mechanism that provides imaginary haptic feedback, inducing different force perceptions or multisensations of an object's properties in the user (e.g., mass[25], weight[77], stiffness[78], or shape[10]) by manipulating visual output relative to the user's motor input [58, 55, 67].

This pseudo-haptic approach could be a concrete way to induce fundamental force feedback if no external haptic device is available. However, this given interaction relies strictly on visual information and is still not sufficiently realistic and tactile. The second approach is to introduce an actuated display, which is motivated by the recent increasing availability of actuated displays (e.g., telecommunication[38], services, advertisements, live performances, and games). Research reports that 1D actuated displays enable augmentation of 3D content representations spatially (e.g., depth, width, and terrain)[89, 2]. Prior efforts also demonstrate that even a small amount of the screen's physical movements, coupled with the animation, provides stronger motion cues [69, 68]. Thus, combining these two approaches would effectively offer clear and realistic pseudo-force feedback during indirect interaction with the flat-screen content.

In this work, we explore BouncyScreen, an interactive 1D actuated display system. Our basic idea is to physically enhance the existing pseudo-haptic feedback approach by actuated display movements, which would enrich the user's indirect interaction in a flat-screen-based 3D interaction experience. We rely on a movable, flat monoscopic screen mounted on a mobile robot. When the user manipulates virtual objects shown on the screen using a controller, such as by touching a virtual object with a cursor, the screen also moves physically in accordance with the virtual object (Figure 19). We believe that this pseudo-haptic mechanism using control-display (C/D) ratio manipulation would create a basic illusory force perception and the synchronous physical screen movements would enhance it by providing clearer motion cues during user input. This novel interaction style with flat-screen content would make indirect interaction more realistic and tactile. To test our idea, we implemented a concept prototype of BouncyScreen and conducted a psychophysical weight discrimination study with object pushing interaction. We found that this allows users to feel pseudo force equal to the traditional vision-based pseudo-haptic effect. We conducted a follow-up study with a weight magnification discrimination task to explore further possibilities of BouncyScreen with two primary interaction styles (pushing and bumping interactions). The results show that BouncyScreen provides different force representations from visual-based pseudo-haptics depending on the interaction styles and significantly enhances the realism. We then discuss the potentials and use suggestions of BouncyScreen as nonstereoscopic interactive 3D displays.

This paper offers three contributions. Specifically, we:

1. Introduce BouncyScreen; an interactive actuated 1D display that expands the pseudo-haptic approach and achieves realistic indirect interaction by physically moving the screen.
2. Conduct psychophysical studies to show that BouncyScreen induces illusional force feedback resembling a conventional pseudo-haptic effect and gives different force representations depending on the interaction styles.
3. Discuss the potential and future applications of the concept of BouncyScreen.

3.2 Related Work

3.2.1 Force-feedback Devices

Previous research has proposed various wearable and hand-held device approaches that provide force feedback, but most of these have been designed for virtual reality (VR) with HMD. For example, Aero-plane is a hand-held force-feedback device that reproduces a weight-shifting illusion on 2D planes using force produced by jet propellers [46]. FacePush is an actuated HMD that applies pressure to the user's face by alternating torques from two motors that press on the face [17]. Impacto simulates physical contact during boxing by combining tactile simulations with electrical muscle simulation (EMS), where the sensation of being hit is simulated by tapping skin using a solenoid [65]. Pedro et al. actuated a user's shoulder, arm, and wrist muscles using EMS, creating a counterforce for carrying or lifting objects in a virtual environment [66]. These approaches consider simulating force feedback in VR, but we focus on enriching indirect interaction experiences with a flat-screen platform.

On the other hand, physical actuating devices employing monoscopic display have also been explored to simulate force feedback. TouchMover is a flat-screen surface that can be actuated to provide physical force feedback when the user touches or pushes 3D content on the screen. This differs from our system, as it relies on physical contact between the user's hand and the screen surface [89]. Jetto and RetroShape are smartwatch types of pin-based shape-changing display. The deformable surface on the back of the watch face extends into a 2.5D physical surface to provide vertical or lateral force feedback synchronizing visual animation [30, 37].

While these approaches try to simulate force feedback by directly providing tactile feedback, they still require the cost of preparing and wearing specific devices. We explore another approach for providing force feedback that uses a standard controller and gives illusory force feedback by employing a cross-modal pseudo-haptic effect and physical screen actuation.

3.2.2 Pseudo-haptic Force Representation

Pseudo-haptic feedback, proposed by Lecuyer et al. [58], induces an illusory tactile perception by manipulating the proportion (C/D ratio) between the user's hand and the rendered cursor's position. This proportion changes the illusory stiffness[55], mass [25, 43], weight[77, 35], resistance force[100], and object's texture. Also, the object's shape, size [10], and softness [78] can be altered by appropriately manipulating the visual and tactile stimuli. Touchscreen-based pseudo-haptic feedback has also been considered[21, 111]. Moreover, recent pseudo-haptic research focuses on enriching haptic experiences in VR. Samad et al. simulated the relationship between perceived weight and physical work represented by mass, height, and gravity [86]. Rietzler et al. enabled simulating weight perception of a VR object by introducing perceivable tracking offset[81]. The same group also successfully conveyed the perception of kinesthetic feedback in VR[80]. Some works have attempted applying pseudo-haptic theory to the augmented reality (AR) environment. Taima et al. controlled perceived fatigue during object-lifting tasks by evoking a pseudo-haptic effect through visual manipulations in augmented reality (AR) [101]. Chen et al. explored the approach of providing physical properties of augmented objects in an AR environment with a touchscreen interface[18]. While much work proves the benefits of pseudo-haptic approaches for VR and AR, there has been no exploration of indirect interaction with virtual content on an actuated flat-screen.

3.2.3 Actuated Displays

Researchers have paid great attention to actuated displays as a new display platform. Reconfigurable dynamic environments, composed of shape-changing displays, interactively suit the task or content. Takashima et al. demonstrated shape-changing displays that automatically reconfigure depending on the displayed content [104]. MovemenTables are moving digital tables that can be separated and joined when a single large shared display space is required for collaboration [103]. Similar reconfigurable displays that optimize the space have been widely considered [31, 32, 88]. For single-user scenarios, LivingDesktop comprises an actuated desktop display and peripheral devices whose positions and orientations change according to the user's positions, postures, and activities [8]. Therefore, screen actuation and reconfiguration successfully augment the entire workspace, including screen content and physical space. While these actuated displays provide us with a new platform for content augmentation, they currently do not focus on augmenting VR and 3DUI experiences.

3.2.4 Presenting Physical Information using Actuated Displays

The physical actuation of screens coupled with content animation enhances the content's physical properties, especially their multidimensional or volumetric information and depth cues. Tilt Displays illustrated that the tilting actuation of the pieces of tiled displays could physically express 3D information (e.g., height) or motion of the displayed content [2]. A live performance by Bot and Dolly featured large displays moved by 6-DoF (six degrees of freedom) industrial robot arms, demonstrating the high potential of actuated displays in visually and physically representing 3D visual effects in interactive content [24]. Nakanishi et al. confirmed that a display's physical movement also extends the displayed person's social presence by physically representing her spatial or body behaviors [69, 68]. FlexFace explores the reconstruction of head-gestural motions in telecommunication systems using flexible screens that deform in a stretch-and-squash fashion [44]. While these works explored how the screen's physical movement effectively represents 3D information of the content, the effect on the user's perception was not sufficiently assessed. Living Wall Display is most relevant to our work[73, 76]. This is a human-sized wall screen that moves physically during interactions such as hitting an enemy or catching a ball, to visually and physically represent the impact of collisions. Although it also explores interaction augmentation using the screen's physical movement, the user's force perception during content interaction has not been quantitatively investigated. Our approach is built on the Living Wall Display, but we go beyond it by introducing the pseudo-haptic mechanism, understanding the user's force perception, and deriving design implications for interacting with robotic screens.

3.3 BouncyScreen

3.3.1 Approach

To offer force feedback for indirect interaction, pseudo-haptics is a promising approach as it does not require special devices, but is effective in creating different levels of force perceptions by manipulating the motion of the target objects. Our idea is to enhance this pseudo-haptic effect by the screen's physical movements. We expect that the screen's responsive movements will bring two benefits: 1) assisting users in understanding when or how interaction events happen (e.g., when or how a cursor touches an object), thereby making indirect interactions more realistic and tactile; and 2) helping users perceive more real object motions (e.g., how much the object moves for depth direction), which would enhance the pseudo-haptic effects.

BouncyScreen is a proof-of-concept prototype that realizes our idea and is named for its bouncy behaviors when responding to the user's input. As a first step, we investigated providing force feedback of depth direction during pushing and throwing interactions.

3.3.2 Force Representation Techniques

Table 3.1 shows three force representation techniques: Visual, Physical, and Visual + Physical. Table 3.1 also summarizes the status of the visual content animation and screen movement for each technique. The Visual condition is defined as the original vision-based pseudo-haptic representation, where only screen animation is performed to respond to user input. Physical and Visual + Physical conditions are our techniques that work as BouncyScreen. Physical employs the screen movement only, while Visual + Physical uses both visual content animation and the screen's physical movement. Figure 19 and 20 illustrate how each works for a manipulated virtual object.

Table 3.1: Force representation techniques

	Virtual object	Screen
Visual (typical pseudo-haptic)	Dynamic	Static
Physical	Static	Dynamic
Visual + Physical	Dynamic	Dynamic

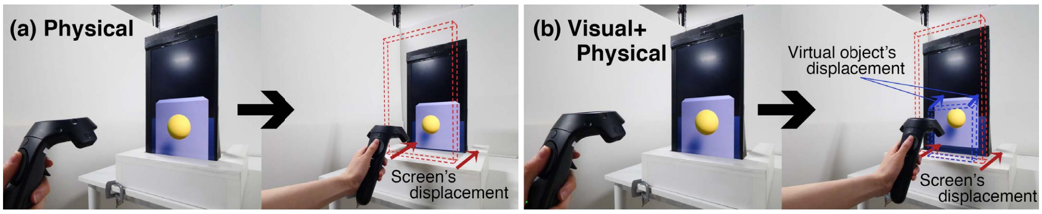


Figure 19: BouncyScreen's Force Representation Techniques: Yellow, red, and blue arrows represent the movements of the controller, physical screen, and virtual object, respectively. (a) In the Visual condition, the displayed virtual object's displacement only occurs by the controller's displacement; the physical screen is static. (b) In the Physical condition, the displayed virtual object is static on the screen; the physical screen's displacement only occurs by the controller's displacement. (c) In the Visual + Physical condition, both the physical screen and the virtual object displacements occur during the interaction.

When an object on a flat surface is pushed by a user's hand, the object moves backward. The user pushes the object with force F, which can be expressed as $F = \mu M g$, where μ, M, and g denote the dynamic friction coefficient, the object's mass, and its gravitational acceleration respectively. We focus on the user's perceived weight that includes all the elements of this equation, rather than its exact mass, as the metric on how the user perceives the force from the object. This weight is perceived based on how easy the object is to move. The more the object moves with the same effort, the less weight the user perceives. In the basic principle of pseudo-haptic effect, the ratio of displacement of the virtual cursor to the user's hand movement is set as the conventional C/D ratio. We apply the physical screen displacement to the Control part of the C/D ratio (= Control/Display). Figure 20 shows a brief overview of our setup and how the Physical and Visual + Physical techniques work in a pushing interaction. In this figure, $D_{controller}$ is the user's hand/controller displacement in the real world. A virtual cursor moves (see the yellow sphere in Figure 19), synchronized with the user's controller on the screen. When the user pushes a virtual object (cube) using the cursor, the cube will move backward in the virtual world to represent that it is being pushed. We define this virtual object displacement as D_{object}. Also, we define D_{screen} as a physical screen movement that might happen during the pushing action depending on the techniques. Thus, our basic algorithm is forming the output values of D_{object} and D_{screen} based on the single input value of $D_{controller}$.

In the Physical condition, the screen physically moves itself to represent the virtual object's corresponding movement when a user pushes it with a cursor. In contrast, the displayed virtual object remains static on the screen (see Figure 19a, Figure 20b), meaning D_{object} is zero. We introduce α (a variable C/D ratio) to manipulate the input-output relationship between the translation amounts of the controller ($D_{controller}$) and the physical screen (D_{screen}). Therefore, the displacement amount of the screen (D_{screen}) and the virtual object (D_{object}) in the Physical condition can be given as follows:

$$Physical \begin{cases} D_{screen} = \alpha * D_{controller} \\ D_{object} = 0 \end{cases} \tag{3.1}$$

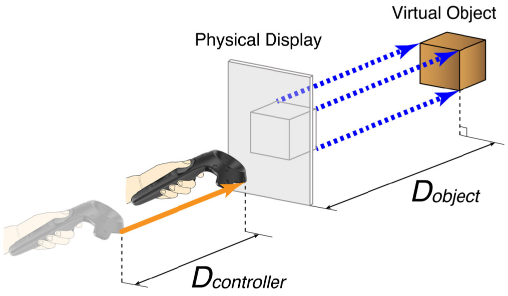
Depending on how we set α between 0 to 1, the screen's behavior responding to the user's input would considerably change.

The Visual + Physical condition combines the screen's physical movement and the virtual object's animation so that the visual and physical cues can be adjusted easily depending on the content (Figure 19b). When an object is pushed, the screen's movement and the virtual object's translation animation are synchronously performed (Figure 20c). We introduce β, a variable C/D ratio, to control the input-output relationship between the translation amount of the controller ($D_{controller}$) and that of the virtual object (D_{object}). To make the combined displacement amount of the screen and the virtual object equal to α*$D_{controller}$ (the same as the physical condition), the physical translation of the screen should be offset by β*$D_{controller}$. Thus, the displacement amount of screen (D_{screen}) and virtual object (D_{object}) in the Visual + Physical condition is represented as follows:

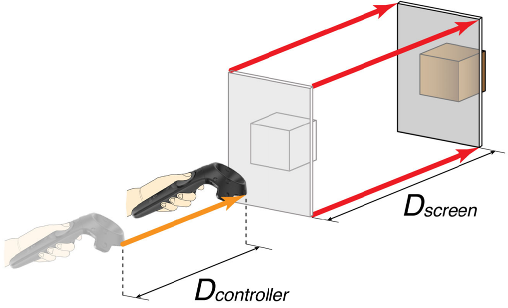
$$Visual + Physical \begin{cases} D_{screen} = (\alpha - \beta) * D_{controller} \\ D_{object} = \beta * D_{controller} \end{cases} \tag{3.2}$$

3.3.3 Prototype Implementation

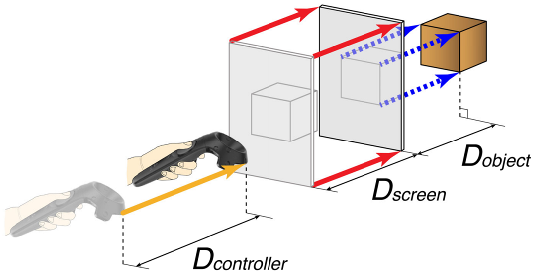
Figure 22 shows our prototype composed of a 17.3-inch LCD (cocopar, 980 g, bezel 2.2cm on left side and 0.7cm on right side, 1920 × 1080 px) mounted on a mobile robot (Roomba, iRobot 500i series), a computer, and a tracked hand-held controller. We needed extra hardware, but such a mobile robot is now quite affordable and controllable using regular computers. The Roomba is connected to a PC using serial communication via a Bluetooth dongle. We used an HTC VIVE controller and two base stations to track the user's input, and developed the experimental software with Unity 3D (2008.4.0 f1). The delay between the detection of contact with the virtual object and the start of actuator motion was less than 0.13 sec. The screen displacement average error was 0.5 cm. These errors were caused by the current inevitable sensor and actuator limitations. We believe that such functionality was adequate for running a perception study.



(a) Visual



(b) Physical



(c) Visual + Physical

Figure 20: BouncyScreen's Force Representation Techniques: Yellow, red, and blue arrows represent the movements of the controller, physical screen, and virtual object, respectively. (a) In the Visual condition, the displayed virtual object's displacement only occurs by the controller's displacement; the physical screen is static. (b) In the Physical condition, the displayed virtual object is static on the screen; the physical screen's displacement only occurs by the controller's displacement. (c) In the Visual + Physical condition, both the physical screen and the virtual object displacements occur during the interaction.

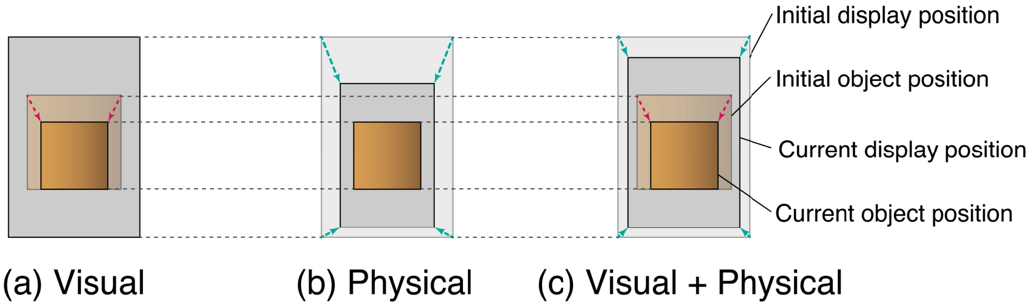


Figure 21: The user perspective and third person perspective of the movements of the virtual object and physical screen for the Visual, Physical, and Visual + Physical conditions. The front view of the virtual object's visual size is identical among the three conditions.

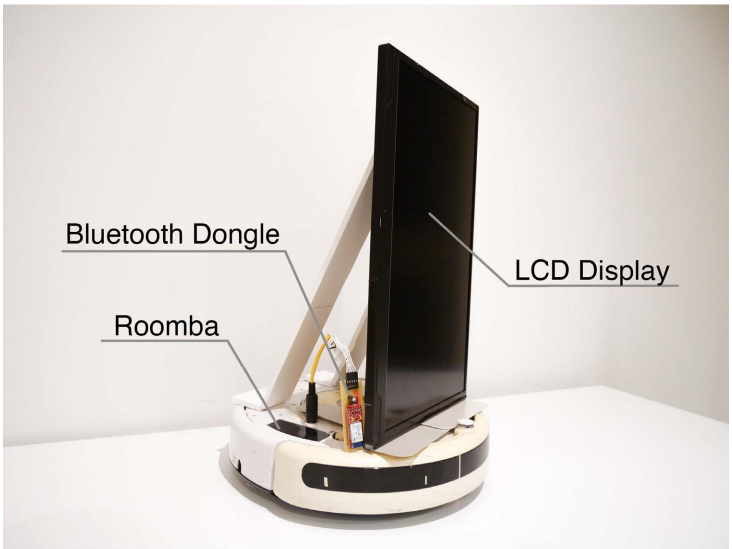


Figure 22: Prototype of BouncyScreen: LCD display is mounted on a mobile robot.

3.4 Preliminary Study: Weight Discrimination

With our prototype, we first conducted a preliminary psychophysical study to investigate whether the screen's sliding movement enhances force perception compared with traditional pseudo-haptic feedback. Following prior research[86, 6], we adopted the two-alternative forced-choice (2AFC) method. Participants pushed a virtual cube within a 5-30-cm movement range. Considering the situation of C/D ratio = 1 as a reference, the participants judged whether the perceived weight for the presented condition with different C/D ratios was heavier or lighter than the reference.

3.4.1 Participants and Apparatus

We collected data from 12 right-handed participants (age: mean = 23.6 years, standard deviation (SD) = 1.31, 3 females) recruited from a local university. They did not know about this research before the experiment. Figure 23 shows the experimental setup. The experimental software ran on an Intel Core i7-7700 4.20 Hz PC running Windows 10 64 bit with 16 GB RAM, NVIDIA GeForce GTX 1060 6 GB. The screen's lower part was covered to hide the Roomba and its movement from the user. The participants manipulated the HTC VIVE controller covered by a box to mask its movement during manipulation, wore noise-canceling headphones to block out the Roomba's noise, and were seated 1 m away from the BouncyScreen during the experiment.

3.4.2 Design and Procedure

The participants completed three sets of trials, including the Visual (original vision-based pseudo-haptic), Physical, and Visual + Physical conditions. To make the virtual object's visual size identical in the three conditions, the translation distances of the displayed virtual object and the physical screen in the Visual + Physical condition were set to half of the translation distance in the other two conditions (Figure 21) (β was set to 0.5α in Equation 3.2). We set α and β to be 1 and 0.5 respectively, as we thought a balanced mix of physical and virtual movements would be the best to obtain an initial

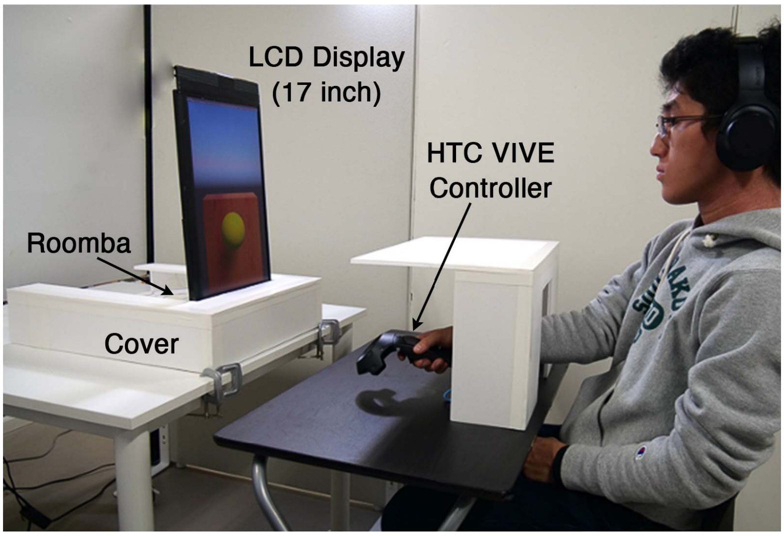


Figure 23: Experiment setup.

understanding of how the three conditions differ. Of course, this balance is worth-investigating from prior work [76].

In the experiment, each trial consisted of two pushing interactions. The first was a reference, while the second was a judging trial where the C/D ratio was set randomly. After completing both trials, the following message was shown: "Was the perceived weight of the second cube heavier or lighter than the reference?" The participants selected their answers by pulling the trigger on the controller. We determined seven C/D ratio conditions (0.7, 0.8, 0.9, 1.0, 1.1, 1.2, 1.3). Each C/D ratio was presented three times in random order for all three screen conditions. The presented order of the screen conditions was counterbalanced among the participants.

Since the screen's physical movement would convey more apparent motion cues, we made the following hypothesis:

H0: The screen's physical displacement (Physical, Visual + Physical) induces stronger illusory force feedback than the traditional vision-based pseudo-haptic approach (Visual).

3.4.3 Result

Before analyzing the data, out of 252 data entries, we removed only one outlier that occurred in the Physical condition when the system was unstable.

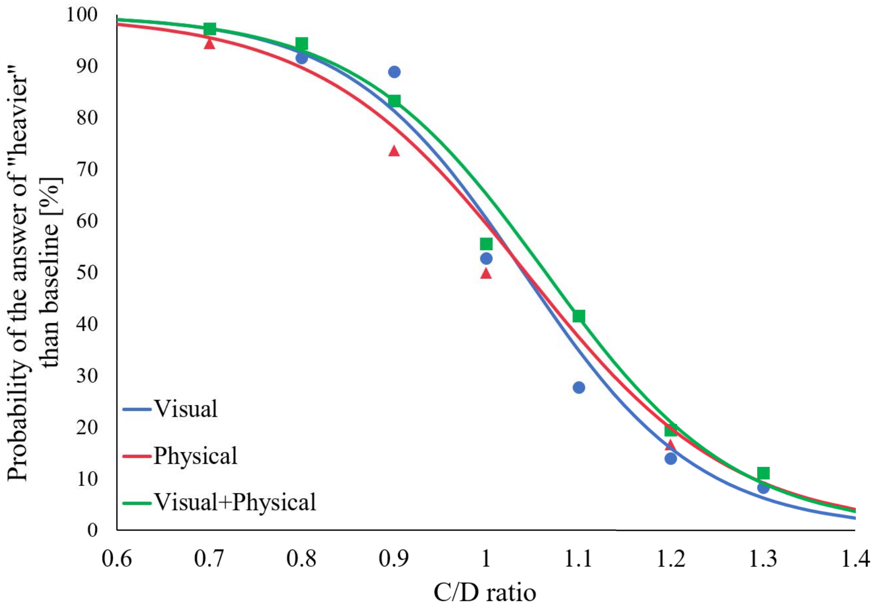


Figure 24: Psychometric function of weight-detection experiment. C/D < 1.0 judged heavier and C/D > 1.0 judged lighter in all three conditions.

Figure 24 shows the psychometric functions in which the collected data were fitted by the following formula:

$$y = \frac{100}{1 + b * e^{-ax}} (a, b \in R).$$

The coefficients of determination R^2 were 0.87, 0.88, and 0.87 in each condition, respectively (Table 3.2). The x-axis in Figure 24 shows the C/D ratio while the y-axis shows the probability that participants perceived the weight as heavier than the reference during the push.

Table 3.2: R^2, PSE and JND of each condition

	R^2	PSE	JND
Visual	0.87	1.04	0.10
Physical	0.88	1.04	0.12
Visual + Physical	0.87	1.06	0.11

The psychometric functions show that the participants perceived heaviness when the C/D ratio was less than 1.0 in all three conditions and vice versa. It was also shown that the Physical and Visual + Physical offer identical pseudo force feedback trends to the Visual condition. We also calculated the point of subjective equality (PSE) and the just-noticeable differences (JND) from the obtained psychometric functions (Table 3.2). PSE denotes the value of the C/D ratio at which the probability is 50%. JND denotes the value of the C/D ratio at which the probability is 75% subtracted by PSE. Friedman's test results showed no significant differences among the three screen conditions for both PSE and JND.

3.4.4 Discussion

Interestingly, the psychometric function curves show that, in both the Physical and Visual + Physical conditions, our new approach using the screen's physical displacement creates pseudo force feedback almost equal to the traditional vision-based pseudo-haptic Visual condition. Users found an object heavier when the C/D < 1.0 and perceived it as lighter when the C/D > 1.0.

In terms of depth cues, different perceptual cues were provided to the viewers in the three screen conditions. The object's movement animation changes the linear perspective, while physical screen movement changes the accommodation and vergence. Interestingly, these different cues did not affect the viewer's perceived depth movement and object weight. A possible reason could be the designed small movement of the object (i.e., 10 cm) within a short viewing distance (i.e., 1 m away from the screen), where these cues do not act much differently. For a larger interaction space with larger object (screen) motions, the impact of each depth cue might differ and the representation of depth cues could be more crucial.

Overall, these results do not support H0 above that manipulating BouncyScreen's physical displacement induces stronger force feedback than the vision-based approach. However, in post-experiment interviews, most of our participants reported that the perceived weight was different among the three conditions. Five users reported that Visual was the heaviest, while two users and one user answered that the Physical and Visual + Physical condition, respectively, were the heaviest. One user felt that the weight was equivalent among the three conditions. Motivated by these comments that are inconsistent with the result, we conducted a follow-up study to investigate the quantitative amount of the perceived force provided by BouncyScreen.

3.5 Full User Study: Weight Magnitude Estimation

We obtained an initial understanding of BouncyScreen's ability to provide illusory force in the preliminary study. To deepen our knowledge, we conducted a full user study that expands the previous study in three ways: method, interaction, and subjective assessment. The first update was employing a magnitude estimation method instead of 2AFC, which gave us a deeper understanding of the user's force perception attributes. The second was additional examination of bumping interaction (Figure 25b) because we expected that such short and discrete interaction would bring different perception trends. The bumping interaction was executed by the user's throwing action (Figure 25b), and the system responded with the same principle of the pushing interaction, where the user's input $D_{controller}$ was set to a constant value. The third was a critical extension that adds a formal post-study questionnaire to assess how the screen's physical movements improved the interaction enjoyment and realism.

3.5.1 Participant and Apparatus

We collected data from 12 right-handed participants (age: mean = 22.3 years, SD = 1.72, three females). None had ever joined any of our prior experiments involving actuated displays. The experimental setup was the same as the preliminary study.

3.5.2 Design and Procedure

The participants were given an outline of the entire experiment and then practiced manipulation to understand how each screen condition and interaction worked and to eliminate first-time bias. As in the preliminary study, the participants interacted with the virtual object twice in each trial. In the first trial, a reference condition with a C/D ratio of 1 was presented and its weight was set to 10. In the second trial, the test condition was presented with one of the C/D ratio conditions. The participants compared the perceived force of the second interaction with the baseline and then verbally estimated the amount of magnitude estimate (ME) value (min: 1, max: 20). Participants also filled out subjective questionnaires regarding enjoyment, the reality of contact, and the sense of the presence of the three-screen conditions using a 7-point Likert scale at the end of each interaction session. We prepared these questions because our previous work suggested that actuated display enhances reality [73, 76, 24].

We set three independent values: screen conditions (Visual, Physical, Visual + Physical), C/D ratio (0.5, 0.7, 0.9, 1.1, 1.3, 1.5), and interaction styles (pushing or bumping: Figure 25). To investigate the trends of force perception in a wider C/D ratio range, we newly set these six C/D ratios. Each C/D ratio was presented two times in random order in each screen condition. While the pushing interaction was the same as the last study, the participants threw a ball and hit the virtual object in a bumping interaction. In BouncyScreen's Physical and Visual + Physical conditions, the screen moves instantly at the moment of hitting a virtual object, which physically represents the impact of the collision. The presentation order of the screen condition and interaction style was counterbalanced among the participants. After all of the trials, we performed semi-structured interviews. The whole experiment took approximately one hour per person. Considering our current results, observation and arguments, we made the following three hypotheses:

H1: The estimated magnitude force values of the Physical and Visual + Physical conditions are heavier than the Visual condition.

H2: The display actuation enhances perceived force feedback in the different characteristics as heaviness in the pushing interaction and lightness in the bumping interaction.

H3: The interaction experiences (enjoyment, the reality of contact, and presence) of Physical and Visual + Physical are higher than Visual.

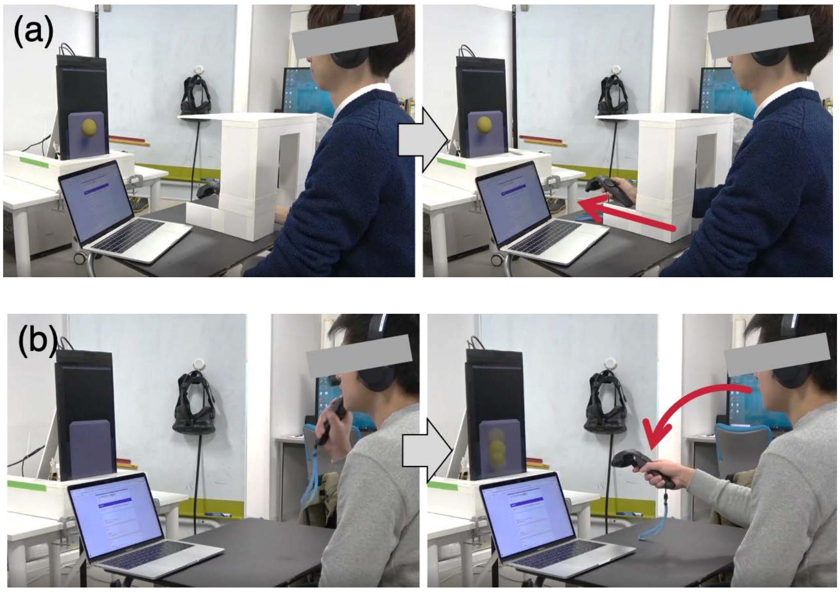


Figure 25: Interaction scenarios: (a) Pushing and (b) Bumping.

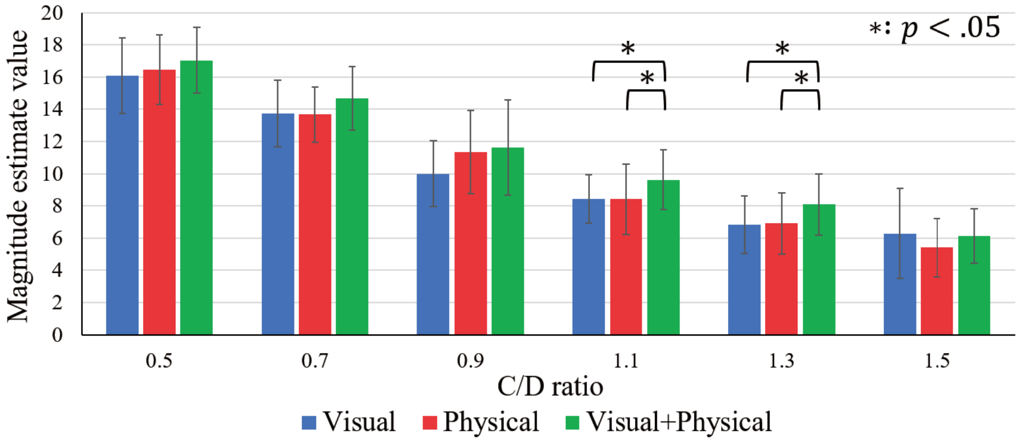
3.5.3 Result

Weight Magnitude Estimation

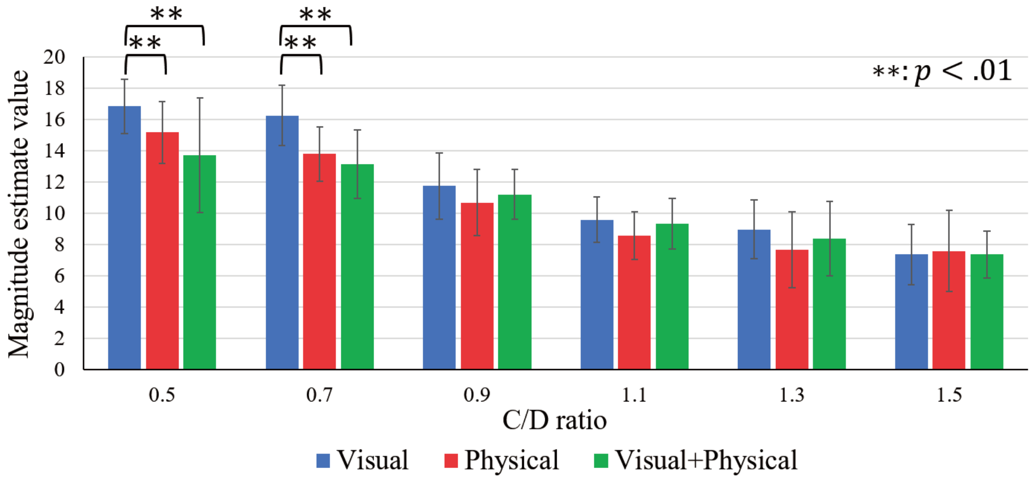
Figure 26 shows the average of the magnitude estimate (ME) value of the weight relative to the screen in different C/D ratio conditions. The error bar represents the standard deviation (SD). Since the collected data did not follow a normal distribution, we used Friedman's test to analyze the effects of screen conditions on each C/D ratio for both interactions. If a significant difference was found, we used Wilcoxon's signed rank test with Bonferroni correction as post-hoc pairwise comparisons.

Pushing interaction (Figure 26a): The screen condition had a significant effect on ME values. Significant differences of ME values were observed at C/D ratios of 1.1 ($p < .05$) and 1.3 ($p < .01$), where the Visual + Physical was perceived significantly heavier than the Visual (1.1: $p < .05$, $z = 2.46$, $r = .50$, 1.3: $p < .05$, $z = 2.30$, $r = .47$) and the Physical (1.1: $p < .05$, $z = 2.14$, $r = .44$, 1.3: $p < .05$, $z = 2.13$, $r = .44$). However, there were no significant differences between the Visual and Physical conditions at all C/D ratios.

Bumping interaction (Figure 26b): The screen condition had a significant effect on ME. Significant differences were observed at C/D ratios of 0.5 ($p < .01$) and 0.7 ($p < .01$), where Visual was perceived significantly heavier than Physical (0.5: $p < .01$, $z = 2.76$, $r = .56$, 0.7: $p < .01$, $z = 3.36$, $r = .69$) and Visual + Physical (0.5: $p < .01$, $z = 3.43$, $r = .70$, 0.7: $p < .01$, $z = 3.57$, $r = .73$).



(a) Pushing Interaction



(b) Bumping Interaction

Figure 26: Magnitude estimate value of weight perception: The baseline (C/D ratio = 1) weight value is 10.

Enjoyment, Reality of Contact, and Presence

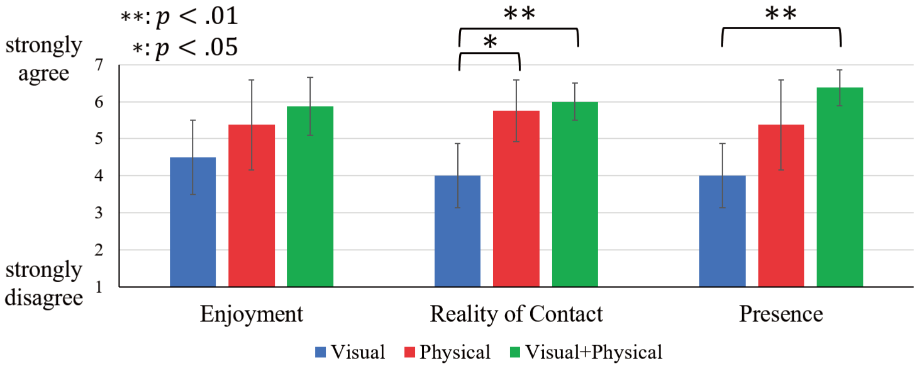
Figure 27 shows the subjective evaluation results regarding enjoyment, reality of contact with the virtual object, and sense of presence. We asked, "How much did you enjoy the experienced interaction?" (enjoyment), "How real was the reality of contact with a virtual object?" (reality of contact), "How much did you feel the sense of the presence of the whole interaction experience?" (sense of presence), respectively. We compared these scores among the three display conditions using Friedman's test. If a significant difference was found, we performed a Wilcoxon's signed-rank test with Holm correction as post-hoc pairwise comparison. We set the significance level as $\alpha = 0.05$.

Pushing interaction (Figure 27a): Physical and Visual + Physical had higher scores than Visual for all three questions. We found significant differences in the reality of contact ($p < .01$) and presence ($p < .01$) scores. A pairwise comparison confirmed a significant difference between Visual and Physical ($p < .05$, $z = 2.39$, $r = .84$) and between Visual and Visual + Physical ($p < .01$, $z = 2.56$, $r = .90$) for the reality of the contact. For the sense of presence question, Visual + Physical was significantly higher than Visual ($p < .01$, $z = 2.56$, $r = .90$).

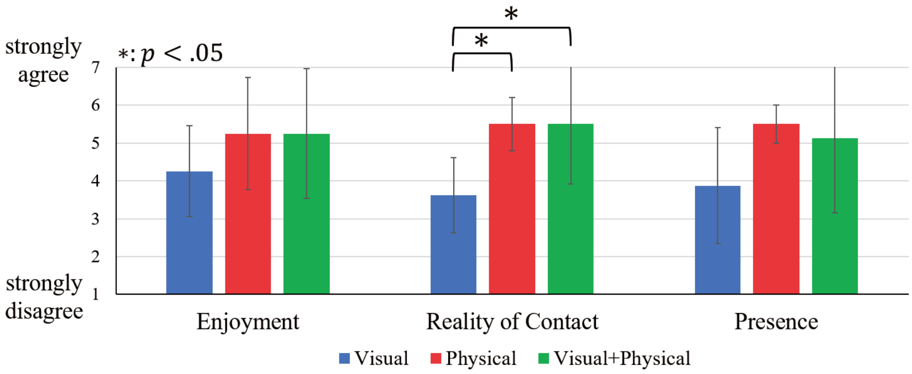
Bumping interaction (Figure 27b): Physical and Visual + Physical had higher scores than Visual for all the questions as well. We found significant difference in reality of contact ($p < .05$). A pairwise comparison confirmed a significant difference between Visual and Physical ($p < .05$, $z = 2.23$, $r = .78$) and between Visual and Visual + Physical ($p < .05$, $z = 1.69$, $r = .60$).

Subjective Feedback

Regardless of the interaction styles, the Physical and Visual + Physical conditions always had higher scores of enjoyment, reality of contact, and presence than the Visual condition. In the interviews, some participants concurred, with comments such as “When the display physically moved, the interaction seemed more realistic. Although it was easy to understand the displacement of a virtual object in the Visual condition, I did not feel that I was operating it by myself” (P2), and “If the screen moved, I strongly felt



(a) Pushing Interaction



(b) Bumping Interaction

Figure 27: Subjective evaluation.

that I was manipulating a virtual object by myself" (P11). These comments suggest that physical screen movements effectively improved the reality of the interaction. Regarding the differences between the Physical and Visual + Physical conditions, a participant commented that "the Visual + Physical condition effectively augmented the experience of manipulating an object, although the Physical condition had a strong sense of pushing the screen itself rather than the virtual object" (P8). There were other related comments: "The Visual + Physical condition is not suitable for estimating an object's weight because the moving distance of an object is difficult to grasp when both the virtual object and the physical screen move" (P12) and "In the Visual + Physical condition, I was confused about what I should use as the reference for weight estimation" (P9). Their comments imply that either screen or visual animation displacement works as a depth cue which induces force perception. Finally, 10 out of the 12 users stated that “physical screen movements increased the sense of object manipulation to a greater extent in the pushing interaction than in the bumping interaction.” The immediate response of the screen movement during continuous manipulation in which the cursor is constantly touching the object might enhance realism.

3.5.4 Discussion

Force Feedback Enhancement

We examined the difference of the perceived weights among the three conditions. First, our users perceived objects in the Visual + Physical condition as heavier than in the Visual or Physical conditions in the pushing interaction. Second, the users perceived that the object weights in the Physical and Visual + Physical conditions were lighter than those of Visual in the bumping interaction. In other words, two exact opposite trends were observed between the pushing and the bumping interactions. We did not find that the screen movement always made the force perception heavier; however, we did find that the screen’s movement had a significant effect on the user’s force perception, so H1 was partially supported. Also, although H2 was not clearly supported, the force perception was enhanced in both interaction styles even though their trends were quite opposite.

Regarding the impact of the C/D ratio, the pushing and bumping interactions had different results. During pushing, with larger C/D ratios (i.e., C/D = 1.1 and 1.3), the Visual + Physical condition offered a heavier perception than the other two screen conditions (Figure 26a). We did not clearly observe a similar trend at C/D ratio = 1.5, which might be because longer object motions could produce complex perceptions, meaning that the Visual + Physical condition diminished the illusion by the pseudo-haptic mechanism. Similarly, Physical and Visual + Physical conditions significantly diminished the illusion with smaller C/D ratios (i.e., C/D = 0.5 and 0.7) in bumping (Figure 26b). Although we built H2 (different force perceptions for each interaction), such reverse results were rather surprising. We interpret this as an interesting phenomenon caused by the users’ different attention strategies for the two interactions, which is described below.

In the pushing interaction, users focused on the screen content: the contact between the virtual object and the cursor and their movements during the interaction. Users' continuous attention to the screen's visual content might weaken their peripheral attention to the screen's physical movement. Since the Visual + Physical condition shows only half of the virtual object movement as screen animation and the rest by physical screen movement (Figure 20c), users' perceived depth-movement might be shortened. This short and slow translation might have an effect on perceiving depth movement and force feedback. In contrast, in the bumping interaction, the user clearly paid attention to the whole event including the screen's physical displacement in real space. Immediate movement of the physical screen effectively makes depth movement stronger, which works to enhance the lightness of the momentary contact impact between the virtual object and the cursor. Therefore, two physical screen conditions (Physical and Visual + Physical) for bumping interaction were significantly perceived as lighter than the traditional vision-based pseudo-haptic approach (Visual condition).

Interaction Experiences Enhancement

Figure 27 suggests that our approach effectively enhances the reality of contact and the sense of presence compared with the traditional vision-based pseudo-haptic approach regardless of interaction styles. This result fully supports H3 and is consistent with the result of the evaluation study of the Living Wall Display [76]. Moreover, the Visual + Physical condition recorded the highest score in these points, meaning that both visual animation and physical transitions contribute to enhancing the interaction experience. While we did not find a significant difference, it might be worth mentioning that the enjoyment scores of Physical and Visual + Physical were also more positive than Visual. Based on these data, our approach significantly enhances such indirect interaction that uses a flat-screen and a mid-air controller, particularly when the interaction requires a strong sense of contact and presence.

3.6 Example Applications

Based on our findings from our two studies, we designed several example applications that are comprised of continuous and discrete impacts for users.

Door-opening Operation

Figure 28a shows the door-opening operation, which could enhance the quality of the experience in many VR scenarios. When the user touches the door through a virtual hand and tries to open it, the BouncyScreen also moves backward to simulate the door being pushed and opened. A small applied C/D ratio and slow screen motion indicates that the door is heavy, and vice versa. This can be expressed, for example, by changing the size of the C/D ratio of the door by varying the weight of the door due to differences in materials (e.g., plastic, wood, and stone). In this application, the users are allowed to feel the weight of the door not only visually but also sensibly during the door interaction.

Pushing Button

We also designed a virtual button application (Figure 28b), which reproduces the sensation of pressing buttons at various degrees of hardness as a 3DUI physical augmentation. When pushing a real button, we normally feel resistance from its mechanical structure. This kind of resistance sensation cannot be represented in mid-air interaction with regular HMD. Our BouncyScreen allows the user to feel the resistance while pushing the virtual button by dynamic C/D ratio manipulation and screen movements. As our experimental data suggest, changing C/D ratios enables manipulation of the button's stiffness or softness, which is considered a 3DUI platform.

Baseball Pitching

As a more specific game application using discrete interaction, we designed a baseball pitching application (Figure 28c). In this application, a catcher sits in the field and catches a ball thrown by the user. The BouncyScreen moves

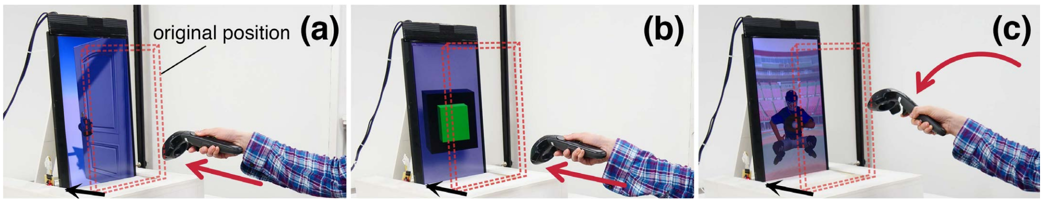


Figure 28: Three example applications; (a) Door-opening operation: The screen's movement represents a door's opening motion and changing the C/D ratio varies the material of the door. (b) Pushing button: Physical screen motion represents the resistance during pushing the virtual button. (c) Baseball pitching: The screen's backward movement enhances the impact of catching the ball and different C/D ratios represent different speeds of the ball thrown by the user.

backward in time with the moment of the catch to represent the impact of the catch. The force the catcher receives from the ball is exaggeratedly represented. By changing the C/D ratio and adjusting the speed of the BouncyScreen, the user can sense the speed with which he throws the ball. For example, if the speed of the screen is fast, it means that the ball is fast and straight, and vice versa. By physical screen movement, we can visualize the momentum of the thrown ball, which is usually difficult to visualize with visual-only content.

3.7 General Discussion

3.7.1 Findings and Usage Suggestions

Our data suggest that a vision-based typical pseudo-haptic mechanism outweighs the screen's physical movements for creating illusional force perception. This result does not support our original expectations, yet the data offer additional insights.

First, physical screen movement is correctly perceived as motion cues and output when interacting with the content. This finding supports prior actuated display knowledge [24, 2, 73, 76], suggesting that display actuation is a unique expression form when presenting the content's interaction-related motion.

Second, the exact physical enhancement appears in representing lighter perception (Figure 26b).

Third, the data indicate the necessity of focusing on balancing visual content animation and physical motions when these happen simultaneously. This balance can be optimized if the system can predict the user's immediate attention. We believe that, without the user's explicit attention to the physical display (i.e., the bezel of the screen), the physical motion is an insufficient motion cue, and turns into wasted behavior. Future work is required with various physical form factors to determine when and where physical information becomes dominant, which would be worth investigating for other actuated display applications (e.g., telepresence robots, etc.).

Thus, our data suggest that the screen's physical movement and its mixed-use with screen animation significantly improve the user experience's realism. Current data does not explain how this improved realism is related to the users' motion and weight perceptions. However, we consider that a minimum approach exploiting the screen's physicality might be executing short screen motions (e.g., vibration) at the contact timing, potentially making the whole interaction realistic. A considerable design space with screen behaviors might exist. Based on the findings and considerations, we derive the following general usage recommendations according to different object manipulating experiences:

- To make indirect interaction the most realistic with proper force representation, adding a screen's physical movement is strongly suggested. Specifically, Visual + Physical would provide the highest sense of presence.
- To make illusory force perception in indirect interaction, a vision-based pseudo-haptic technique may be sufficient. Physical can also be an option.
- When using a bumping or throwing interaction, additional perceptual effects (e.g., making the object lighter) and higher interaction realism by the screen's physical movements can be exploited.

We believe that our approach can be applied to other robotic displays [2, 24, 73, 76] because of its simple mechanics, and our current prototype is sufficient to demonstrate the potential and early insights. However, the current approach has some limitations for generalization.

3.7.2 Limitations and Future work

First, the flexibility and continuity of the screen motion are limited due to the current single DoF design with a simple actuator. For example, the current BouncyScreen does not support other fundamental actions, such as object rotation or sway, as well as repeated interactions, as its position should be reset after every action to prepare for the next action. An ideal solution could be employing complex actuators such as an omnidirectional robot or a robot arm whose motion speed is adequate to support a user's natural and continuous mid-air interactions. Since this solution is costly, designing interactions and scenarios that adapt the limited actuation capabilities is rather practical (e.g., using a visual effect to let a user wait for the actuator to be ready without annoying him/her [108]).

Second, our study setup and content are limited. Since the object's appearance/functions would likely affect the user's weight perception[78], our study can be expanded in several ways; screen sizes, content types, and content materials (e.g., plastic, wood, or stone), which may promote different perception trends.

Third, we are also aware of the scalability issue. For example, only one object's motion can be physically represented by the current BouncyScreen. To support the motion of multiple objects, one idea is to employ a tile-display approach [2, 42] that gives physical representation for multiple objects displayed on each display. Or, we could take a swarm robots approach, where multiple smaller BouncyScreens are coordinated in a way that physically and simultaneously represents multiple 3D content. This could be rather promising in terms of cost and system complexity.

Lastly, we did not perform a formal comparison between our system and other stereoscopic VR displays like HMD and CAVE (cave automatic virtual environment), which would provide more vital 3D motion cues of the object's movements. Our concept is to establish glasses-free and flat-screen-based VR experiences, but it is worth investigating how much our system differs from such a glass-based VR experience. Possible research questions for such future work could include how differently users perceive and understand the object's motions in the virtual world from the real world. Another study update could compare our approach with the real-object pushing task, which might provide a fundamental understanding of possible force levels. Therefore, various future study designs and research directions can be drawn from the current findings and arguments.

3.8 Conclusion

We explored BouncyScreen; an interactive actuated 1D display system that enriches indirect interactions by applying the physical movement of pseudo-haptic mechanics-enhanced screens. We first configured a proof-of-concept prototype of BouncyScreen with a movable flat screen mounted on a mobile robot. We then conducted a psychophysical experiment to examine the BouncyScreen's ability to provide pseudo force feedback. The results showed that induced pseudo force feedback by physical screen movement was almost equal to the traditional vision-based pseudo-haptic approach. Our follow-up study with a weight magnification discrimination task revealed that BouncyScreen provides different force representation depending on the interaction types (e.g., pushing and bumping), and significantly enhances the reality of contact and sense of presence. Based on these results, we designed some example applications and discussed use suggestions of BouncyScreen as a non-stereoscopic interactive 3D-display.

Chapter 4

General Discussion

The concept of actuated walls was developed and validated through two types of robotic wall-shaped devices. While they offer different contributions, here I present the general arguments for how actuated walls are effective and how they can be modified and deployed in the future.

4.1 System validity and future improvements

4.1.1 Actuated walls' hardware

A critical area of improvement in the hardware of actuated walls is the actuator's capabilities, including the degree of freedom and locomotion speed.

We must give attention to the ISO regulations regarding the safety of robot operation near humans when operating our robotic wall-shaped devices. However, I assume that contact detection sensors, proximity sensors on the moving parts, or more sophisticated situational awareness systems will become available shortly. In that case, it may be possible to employ faster robots, significantly expanding the expressiveness of space in both the partitions and haptic presentations. In particular, the imaginary haptics by BouncyScreen would benefit from a faster robot by improving the reality of contact timing, which may provide more continuous and repetitive contact interactions. As for robotic partitions by WaddleWalls, there is no solid demand to frequently and quickly change the partition layout in the current context of office design and activities, so I assume that the speed of the robot is equivalent to walking people or other current service robots (e.g., food servers or robotic advertisement). The size of the actuated wall-shaped device will affect this speed limit for people's safety considerations.

Therefore, an essential research step will be to investigate the optimal locomotion speed setting of robotic furniture relative to its form factors (e.g., size, shape, and movement range).

For the two wall-shaped interfaces, the freedom of movement direction is also a critical area of improvement. I believe that a two-wheeled robot is currently the best platform for prototyping and even for deployment in a realistic setting. However, if omnidirectional robots are available, the number of possible route choices increases, significantly improving the travel time of simultaneously moving multiple robots and increasing the expressiveness of the spatial content (e.g., animation). The cost of installing an omnidirectional robot would be double that of a home cleaning robot (I used Roomba Create), but I believe the cost is justified. Home robots, catering robots, and warehouse robots are expected to be replaced with such high-quality robots, which support the feasibility of this work's research aims. Along with the robot's speed setup described above, the optimal motion degree of actuated walls relative to their form factors and motion patterns needs to be further investigated.

4.1.2 Interface Design

The above two explorations relied on direct interactions performed from the user's egocentric perspective. This concept was consistent with the partitions' characteristics regarding how the user wants to see or not see objects. In the BouncyScreen application, the user's point of view also matched the interaction scene with the display in front of the user. However, as discussed in each section, the egocentric viewpoint is not the only preferred or adopted way for placing or controlling an object. In the case of BouncyScreen, it might be interesting to see whether the pseudo-tactile sensation can be reproduced differently by using different viewpoints, since the user can perceive the amount of movement on the display differently. Similar to multi-viewpoint content readily available recently, it may be an exciting topic to seek a multiple and adaptive viewpoint system for the moving wall-shaped robotic interfaces, thus improving the robot's motion understanding and controllability.

The interaction design of our robotic interfaces is closely related to VR and AR interface design and technologies. As spatial user interfaces, both WaddleWalls and BouncyScreen smoothly incorporate the benefits of AR and VR elements. The use of VR hand-held controllers was not a compromise. It should be one of the best choices in light of the current VR and AR market trends. However, among the various 3D user interface techniques, gesture input, which is very popular and has become more sophisticated with the evolution of computer vision techniques, is worth incorporating. It can bring another disadvantage of complex problems such as defining gesture commands, but device-free interfaces promise to increase the system deployability. As for spatial sensing, gesture input has much room for improvement, and future studies would benefit from future computer-vision-based human pose detectors to understand the full-body status of the main user as well as bystanders around the moving walls.

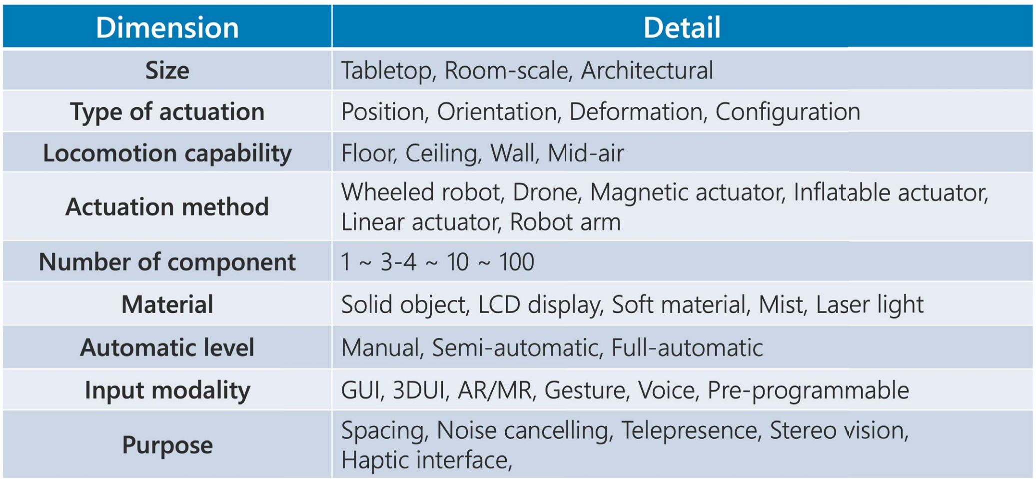
4.2 System Deployment

Actuated walls' concept is generally compatible with the concepts of spatial intelligence, such as ambient interface, ubiquitous computing[116], and IoT (Internet of Things). Through these concepts, smart environments have been realized where everything is connected to the network and can be operated by humans anywhere and anytime. For instance, lighting equipment, air conditioners, cleaning robots, and televisions are already connected to the internet, and we can easily operate them through voice input, gesture interfaces, or even smartphones. In addition to these information devices, programmable and controllable environmental equipment could be expanded in the future. From this point of view, our actuated wall concept is a promising approach. WaddleWalls can provide powerful output of ambient intelligence as long as the related spatial-awareness technology is running correctly. For example, BouncyScreen can also be expanded into a room-scale experience if room-sized sensing and projection systems were available so that the entire room would visualize the virtual worlds (e.g., Microsoft's RoomAlive [47]) and actuated wall's representations could augment the user's focus. Therefore, this work's contributions can be positioned in the context of the existing spatial intelligence technologies.

The idea of actuated walls is not eccentric in the context of the current electrical product and furniture markets. Remote conference robots, cleaning robots, catering robots, warehouse robots, and many other robots are already part of our daily lives. Automatic doors were also a pioneer technology in robotic walls. Based on this background, I believe that the research prototypes of actuated walls are becoming mature. The remaining significant challenges could be the cost and design issues, such as speed and freedom related to the social acceptance of robots and user experiences rather than technical elements.

4.3 Future design space of actuated walls

Through two types of proposed interfaces, I explored the part of the actuated walls interface that interactively connects and divides two spaces. Based on the hardware and interface improvements discussed above, here I discuss possible future design space for expanding the applied fields of the actuated wall. Figure 29 shows the possible dimensions of further actuated wall's design space.



Dimension	Detail
Size	Tabletop, Room-scale, Architectural
Type of actuation	Position, Orientation, Deformation, Configuration
Locomotion capability	Floor, Ceiling, Wall, Mid-air
Actuation method	Wheeled robot, Drone, Magnetic actuator, Inflatable actuator, Linear actuator, Robot arm
Number of component	1 ~ 3-4 ~ 10 ~ 100
Material	Solid object, LCD display, Soft material, Mist, Laser light
Automatic level	Manual, Semi-automatic, Full-automatic
Input modality	GUI, 3DUI, AR/MR, Gesture, Voice, Pre-programmable
Purpose	Spacing, Noise cancelling, Telepresence, Stereo vision, Haptic interface,

Figure 29: Future design space of actuated walls

Size

The size of each actuated wall device is related to the scale of the device operation. Besides tabletop-size interfaces like BouncyScreen and room-scale size interfaces like WaddleWalls, architectural scale wall-shaped interfaces (e.g., door) could also be developed to influence occupants' lifestyle.

Type of actuation

Our two interfaces support three types of actuation: position, orientation, and configuration. Supporting other types of actuation can enrich interaction possibilities. For instance, surface deformation enables the physical representation of multi-dimensional content.

Locomotion capability

Room-scale partitions and desktop monitors required power to operate, so they were limited to moving around on the floor or table surface. However, future actuated walls also could be activated on ceilings, walls, and mid-air. As a unique instance, small and lightweight modules can be distributed and actuated to represent a spatial barrier or 3D content throughout space using a swam of flying actuators (e.g., drones).

Actuation method

Depending on the size of the available space and the size of the device to be moved, there are various possible methods of actuation. A wheeled robot offers a high degree of freedom when moving a large area or an area with many obstacles such as a workspace. On the other hand, a robot arm would be suitable for moving a large object multi-dimensionally and dynamically. Drones are good at allowing small modules to float freely in space. An inflatable actuator would be suitable for soft, deformable materials. Finally, a linear actuator with a motor or the like attached would be suitable for operating a myriad of small modules.

Number of Component

The number of components within single system is related to the size of each device and the scale of the area where the system could cover. With the smaller modules, dozens of components can be combined to form a single system which enables the more expressive and detail rendering. On the other hand, the larger actuated wall device could support applications at large scale with a couple of components.

Material

Non-physical surface material for the actuated wall interfaces is also possible as a future development. For example, a body of fog or an optical laser display could be considered an ambient actuated wall, thus providing a relatively flexible separation for dividing physical space or protecting user privacy.

Automatic level

The proposed two interfaces actuate semi-automatically, which means that the device reacts to the user's input. Combined with sophisticated exterior sensors or spatial recognition systems, the system would enable to automatic operate actuated wall interfaces according to the environmental situation to support users.

Input modality

WaddleWalls introduced 3D pointing operations from the egocentric viewpoint, and AR/MR enables operation from similar viewpoints. In addition, camera-based gesture and voice input have been introduced in recent device operations, and are likely to be easy for users to use. If spatial recognition technology using sensors becomes widespread, it will be possible to realize automatic operation depending on the situation by simply programming the behavior of the device in advance.

Purpose

The space configuration as a method of mediating physical spaces can be applied not only to office environments but also to home interior layouts. In addition to visual privacy, the actuated wall could be used for noise masking to control sound privacy. On the other hand, as a method of mediating between physical and virtual spaces, the movement of wall surfaces could be used to augment the avatar's movements or animations to three dimensions, which enables the enhancement of the presence of remote partners and a three-dimensional content representation.

Chapter 5

Conclusion

This thesis explored the concept of actuated walls as media that flexibly control the dividing and connecting of physical and virtual spaces. By introducing self-actuating functions, wall-shaped devices have been designed to address flexible and interactive management of the boundary between two spaces. Through demonstrations of two types of dynamically actuating physical wall-shaped interfaces, their function as media that interactively control the connection and division of spaces has been presented. This thesis provides the following contributions.

First, I proposed WaddleWalls, a room-scale interactive partitioning system using actuated wall-shaped partitions to demonstrate interactive management of the boundary among multiple physical spaces. I developed a proof-of-concept prototype of an interactive partitioning system, based on design considerations, and demonstrated interactive spatial reconfiguration through workspace application scenarios. The user studies showed that WaddleWalls allows effective workspace partitioning and mitigates the physical and cognitive efforts to satisfy the requirements of ad hoc work activities.

Second, I proposed BouncyScreen, a self-actuating wall-shaped robotic display to demonstrate the flexible connection between virtual and physical spaces. I focused on providing haptic feedback presentation by physical display movement when interacting with virtual content, which firmly connects the virtual content and the users. I configured a proof-of-concept prototype of providing indirect haptic feedback with an actuated wall-shaped display's movement. Our psychophysical studies show that BouncyScreen offers pseudo-force feedback to the user, and the display's synchronous physical movement enhances the reality of content interaction.

These contributions are the initial step toward embodying the concept of an actuated wall as a medium that flexibly controls connecting and dividing between physical and virtual spaces. Considering its demonstrated capabilities and future design space, it is possible to expand this actuated wall interface into a controllable environmental interface for the ubiquitous computing and IoT domains.

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1. **Yuki Onishi**, Kazuki Takashima, Shoi Higashiyama, Kazuyuki Fujita and Yoshifumi Kitamura. WaddleWalls: Room-scale Interactive Partitioning System using a Swarm of Robotic Partitions, *In Proceedings of Symposium on User Interface Software and Technology (UIST'22)*. Oregon, USA, October 2022, ACM, Article 29, pp.1–15.

2. **Yuki Onishi**, Kazuki Takashima, Kazuyuki Fujita, Yoshifumi Kitamura. BouncyScreen: Physical Enhancement of Pseudo-Force Feedback, *In Proceedings of 2021 IEEE Virtual Reality and 3D User Interfaces (IEEE VR and 3DUI '21)*. Online, March 2021, IEEE, pp.363-372.

Peer Reviewed Journal

1. **Yuki Onishi**, Anthony Tang, Yoshiki Kudo, Kazuki Takashima, Yoshifumi Kitamura. Exploring a Living Wall Display that Physically Augments Interactive Content, *Transactions of the Virtual Reality Society of Japan*. 2019, Volume 24, Issue 3, pp.197-207.

Peer Reviewed Conference (Poster, Demo)

1. **Yuki Onishi**, Kazuki Takashima, Kazuyuki Fujita, and Yoshifumi Kitamura. Self-actuated Stretchable Partitions for Dynamically Creating Secure Workplaces. *In Extended Abstracts of the 2021 CHI Conference on Human Factors in Computing Systems (CHI EA '21)*. Online, May 2021, ACM, Article 294, pp.1–6.

2. **Yuki Onishi**, Anthony Tang, Yoshiki Kudo, Kazuki Takashima, Yoshifumi Kitamura. Perception of Spatial Information of Animated Content

on Physically Moving Display, *Asian CHI Symposium: Emerging HCI Research*. Glasgow, UK, May 2019.

3. Shotaro Ichikawa, **Yuki Onishi**, Daigo Hayashi, Akiyuki Ebi, Isamu Endo, Aoi Suzuki, Anri Niwano, Kazuyuki Fujita, Kazuki Takashima, Yoshifumi Kitamura. Be Bait!: Hammock-Based Interaction for Enjoyable Underwater Swimming in VR, *Asian CHI Symposium: Emerging HCI Research*. Glasgow, UK, May 2019.

4. Shotaro Ichikawa, **Yuki Onishi**, Daigo Hayashi, Akiyuki Ebi, Isamu Endo, Aoi Suzuki, Anri Niwano, Yoshifumi Kitamura. Be Bait!: A Unique Experience with Hammock-based Underwater Locomotion Method, *In Proceedings of 2019 IEEE Virtual Reality and 3D User Interfaces (IEEE VR and 3DUI '19)*. Osaka, Japan, March 2019, IEEE, pp.1315-1316. (Invited Demonstration)

5. **Yuki Onishi**, Yoshiki Kudo, Kazuki Takashima, Yoshifumi Kitamura. The Living Wall Display: Physically Augmentation of Interactive Content Using an Autonomous Mobile Display, *In Proceedings of ACM SIGGRAPH Asia 2018 Emerging Technologies*. Tokyo, Japan, December 2018, ACM, Article 15, pp.1-2.

Non-Peer Reviewed Conference

1. 大西悠貴，高嶋和毅，藤田和之，北村喜文，平面ディスプレイの移動による擬似力覚の生成に関する研究，第24 回日本バーチャルリアリティ学会大会論文集, 東京, 2019年9月, 1A-07

2. 大西悠貴，工藤義礎，高嶋和毅，北村喜文，自走式ディスプレイの並進と回転を用いたコンテンツ表現の拡張，エンターテインメントコンピューティングシンポジウム2017, 仙台, 2017年9月, pp.383-384（Best Demo Award）