WindowWall: Towards Adaptive Buildings with Interactive Windows as Ubiquitous Displays

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As architects usually decide on the shape and look of windows during the design of buildings, opportunities for interactive windows have not been systematically explored yet. In this work, we extend the vision of sustainable and comfortable adaptive buildings using interactive smart windows. We systematically explore the design space of interactive windows to chart requirements, constraints, and challenges. To that end, we built proof-of-concept prototypes of smart windows with fine-grained control of transparency. In two studies, we explored user attitudes towards interactive windows and elicited control methods. We found that users understand and see potential for interactive windows at home. We provide specific usage contexts and specify interactions that may facilitate domestic applications. Our work illustrates the concept of interactive smart windows and provides insights regarding their design, development, and user controls for adaptive walls. We identify design dimensions and challenges to stimulate further development in the domain of adaptive buildings.

CCS Concepts: • **Human-centered computing → Displays and imagers**; **Empirical studies in HCI**; *Gestural input*;

Additional Key Words and Phrases: Smart windows, adaptive buildings, elicitation, ambient information systems, see-through displays

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1 INTRODUCTION

Architecture is strongly related to building materials. Walls, roofs, windows, and doors are essential building blocks for homes and offices. These elements are usually static and constitute the "frame" of an experience of a building. Interactive technology can make some of these building blocks dynamic and adjustable. In this work, we experimentally explore how glass panels with controllable transparency change the possibilities for designing homes and offices with smart facades. Fine-grained control of transparency enables combining the function of a wall and a window into one building block; in this view, walls are just windows that are temporarily opaque.

Walls and windows add structure for engineering, aesthetics, and experience. Walls allow the creation of private spaces and windows offer views. Glass allows for natural heating and walls keep heat and sun out. Shutters and blinds are used to change the function of windows and make them in some way opaque and wall-like. Current architectural designs make great use of these elements at design time, but there is little support for altering spaces after the building is erected. Previous work on climate adaptive building shells introduces dynamic elements to buildings. However, adaptation is mostly mechanical and has very limited granularity [49]. Our work and the scientific inquiry reported in this article is strongly inspired by Squama [67] and media façades [22]. Our work builds on the work by Squama and extends the envisioned scenario to the scale of a house. We also derived some of our scenarios from previous work on media façades.

In our work, we investigate adaptive and interactive buildings with smart glass elements, which can precisely control sunlight transmission. In such spaces, the architecture (i.e., the size, type, and position of windows and their properties) can be dynamically adapted to current needs. If privacy is required, all windows can turn into walls. If the sun should heat up a house to conserve energy the window surface can be maximized, and if users like to configure their walls and windows, they should be able to do this effortlessly. Here, we investigate in detail how smart windows can also be used as ubiquitous ambient information displays or to implement mixed reality views.

We systematically explore the opportunities that arise from smart windows. We see windows as fundamentally different than the results from former research that address pervasive and public displays as smart windows offer long-term personalized interactions. In our vision, we depict how self-contained smart glass modules might span the whole outer shell of a building. The smart glass allows changing its visual and thermal properties, and can dynamically adapt to users' needs. We built technology demonstrators for parts of our vision that show how such smart window facades can be implemented. We used different prototypes in our research. One is a single window with four display elements, consisting of in total 1,216 pixels with 16 levels of gray ranging from transparent to opaque. The others are larger structures, including a facade test building consisting of multiple elements. The systems are fully functional and networked; hence, they can be controlled remotely making them a part a smart home infrastructure. With these prototypes, we conducted diff-erent studies with users and explored how people feel about such technologies, how they want to use them, and what issues they see. We have shown the technology demonstrators to potential users and collected rich qualitative feedback in an interview study. The results show that our participants welcomed the possibility of using smart windows as ubiquitous information systems. Further, they appreciated the opportunity to adapt the natural lighting conditions in their homes. Furthermore, we investigated future interaction modalities. We contribute a set of mid-air gestures as well as a smartphone interface. In contrast to gesture elicitation studies in other domains (e.g., large displays), we found that the mental model for interacting with windows leans more towards physicality.

The contributions of the article are as follows:

- A vision of adaptive buildings based on modular and self-contained smart windows;
- A proof-of-concept prototype of a smart window with content display and adaptive shading;
- Two user studies that show the potential for domestication of interactive smart windows and the consequent design constraints;
- An investigation of possible future application scenarios and interaction modalities for smart windows;
- Design dimensions and future challenges for designing interactive windows.

This article offers a broad inquiry into charting the design space of interactive windows. Consequently, we hope that multiple audiences will find this work relevant. HCI researchers interested in understanding how users can interact with smart windows will find our two studies on application scenarios and gestures most interesting. Our vision and implementation description poses challenges that may inspire technical computer scientists. We advise those interested in the interplay between architectural and interaction design to consult our vision and discussion sections. Finally, we hope our contributions can be useful to interaction design practitioners, who will find the gesture set along with findings about future application scenarios helpful for designing for interactive windows.

2 RELATED WORK

Our concept of adaptive buildings with windows as ubiquitous displays relates to various aspects of previous work in the fields of smart windows, see-through displays, ambient information systems (AIS) as well as media façades.

2.1 Smart Windows

Previous work on smart windows mostly focused on energy conservation by dividing window façades into individually controllable tiles (multiple small windows) and used various technologies to regulate light transmission. Cardoso et al. [19] changed transparency using organic electrochromism and added touch sensors on each tile for user interaction. Applications, where users could *draw transparencies* by touching the window, were envisioned. As switching times of electrochromic glass are comparatively slow (~ 10–15 minutes), other works [46, 75] added inner polymer dispersed liquid crystal (PDLC) films. They applied the films to the inner coating and used IR sensors to detect proximity instead of touch. PDLCs can quickly react to user input whereas electrochromic glass only consumes energy when its state is changing. Kotsopoulos et al. [46] used this combination in a 3 × 9 tile prototype setup for sustainable living. The system can adapt to changes in environmental conditions and user actions. Previous work by Husser et al. [40] investigated sun and glare protection performance for structured switchable glazing based on liquid crystal display (LCD) technology. Although these works included the possibility of user interaction, they did not explore meaningful interaction scenarios and the design space of smart windows with respect to user interaction extensively.

Other work focused on application scenarios for smart windows. Early work by Rodenstein used windows to display short-term weather forecasts [69]. A privacy film and projection were used to display different weather conditions on the film. Squama [67] used multiple 10×10 cm^2 tiles of privacy film applied to a window to form a low-resolution display where transparency can be changed. Scenarios like privacy control based on user location and *programmable shadows* were anticipated. With *programmable shadows*, users can define locations in a room that should be shaded and thus protected from sunlight. PDLCs were also used for shopping windows to direct the attention of passers-by to products in a shop [21]. In contrast, Ventä-Olkkonen et al. [80]

investigated the smart window as an information and communication display in homes using handheld augmented reality prototypes. They found that users preferred pragmatic content to be shown on a smart window and did not want to use it in a social setting. While these works are first steps in exploring the design space of smart windows, we build upon the vision of adaptive buildings by Rekimoto [67] based on smart windows that incorporates both energy conservation aspects and users' needs.

2.2 See-Through Displays

See-through display technology promises higher resolutions and faster response times compared to smart window technologies like PDLC. The previous work on see-through displays primarily used them to augment users' view with additional information. Example use cases are augmented reality systems [59], desktop environments [35], and contact augmented reality [36].

However, see-through displays can also be used as shutters to remove visible content. Kiyokawa et al. [42] built an optical see-through display for augmented reality applications. A see-through LCD is used as a shutter so overlaid content can occlude the real world. Lindlbauer et al. [48] used this concept for *Tracs*, a dual-sided desktop display for two users. Transparency can be changed on a tile basis. Some parts of the screen content can be shared by both users whereas other parts can remain private. Smart windows are similar in this respect as they separate a private space like a room in a building from the public space. See-through display technology is readily available on the market but has not been used for smart windows, yet. However, such displays could form the basis of future smart windows and extend possible interaction scenarios by providing higher resolutions and interactive refresh rates.

2.3 Mid-Air Gesture Elicitation

Gesture interfaces enable interaction at a short distance and have gained increasing interest since consumer devices such as the Kinect or Wii with support for gesture control hit the market.

Wobbrock et al. [88] presented a methodology for deriving gestures from users in *elicitation studies*. In these studies, users are shown the effects of gestures (called *referents*) and are asked to come up with corresponding gestures that would cause the effect. A gesture is then assigned for each referent based on *agreement*. The notion of agreement was extended and formalized in more recent work [78], which allows statistical tests to be performed on *agreement*.

Gesture elicitations have been used in various fields including mobile interaction [71], augmented reality [62], smartwatches [6], and music playback [34]. In the context of large displays, gesture sets were elicited for TV control [25, 77]. Referents for TV control were mainly specialized discrete actions such as switching to the next channel, and are not easily be applicable to other areas.

Closely related work by Wittorf et al. [87] elicited gestures for wall-display interaction and found that gestures tend to be more physically based and larger for large displays. They also found that exact hand postures are less important to participants. Referents were primarily related to manipulation tasks (13/25); however, they focused on typical applications.

Gesture interaction concepts are established for large displays like TVs or wall-displays. However, interaction with smart windows and smart walls is based on a different mental model as they completely surround the user and influence shading in addition to displaying a graphical user interface.

2.4 Ambient Information Systems (AIS)

AIS represent non-urgent information in the periphery of the user's attention on abstract and aesthetic displays [50]. The represented information in AIS should be perceived at a glance from the users [51]. Therefore, the information should be abstracted, e.g., by showing pictorial images. Also, an AIS can represent single or multiple kinds of information [65]. Typical examples of AIS that represent multiple information are info canvases or dashboards. AIS can use visual [33, 90], auditory [5], tactile [64], or olfactory [13, 15] output modalities to represent information. Ambient information can be represented on physical devices developed to show this information, or the information can be added to existing objects using augmentation or on traditional displays such as screens [76]. Another important factor for an ambient notification system is the notification level of a piece of information. The notification level describes the importance of the information, and if the user should be able to ignore. In this case, the system should make him/her aware of the information; otherwise, it should interrupt the current primary task [51]. The transition of an AIS determines how the information will be represented [51]. This includes static information, animations, color changes, fading, and scrolling.

To the best of our knowledge, however, AIS have not yet been physically integrated into buildings.

2.5 Media façades

Media façades transform passive buildings into interactive spaces by showing additional information on the façade. Various display technologies such as projection or LEDs may be used to represent information on the façade. Depending on the technology used, the type and amount of representable content varies significantly. This includes buildings that can only change a single color floor-wise as well as high-resolution projections with text and images. Offenhuber and Seitinger investigated how information has to be designed in terms of low-resolution media façades [58]. In contrast, MobiSpray uses projection to allow passers-by to draw graffiti onto a façade by using their smartphone as a spray can [73]. Boring et al. extend this idea by providing a real-time video interface for smartphones for multiple users in the context of a drawing application and a game [14]. *Hybrid* media façades combine low resolution LED output and high-resolution screens and provide a toolkit for rapid prototyping [38]. Dalsgaard et al. provide an overview of approaches for designing media architecture in general [22]. Most work on media façades focuses on aesthetics when viewed from the outside. In contrast, our work focuses on user comfort by, e.g., modulating sunlight and using windows as interactive spaces for inhabitants.

Previous smart windows research focused on reducing energy consumption and maximizing user comfort in various sunlight conditions. In contrast, work on see-through displays explored new interaction possibilities that are made possible by adding transparency to displays. Dynamic façades based on smart windows completely surround users and, such as AIS, they should not permanently draw the attention of inhabitants but still provide them with useful information. When people look at such a building from the outside, they may also allow interaction with others from outside comparable to media façades.

Although previous research approached the topic of smart windows from various directions, a consistent vision of how adaptive window façades can be realized is still missing. In particular, there is missing knowledge about technical aspects like minimum resolution as well as for designing user interfaces to make buildings adaptive through smart windows. Further, it has not been explored how smart windows can contribute to and augment reconfigurable smart spaces that foster creativity and communication, such as the swisshouse [39]. In our work, we address this with a top-down approach. We present our vision of adaptive and informative buildings based on smart windows. With technical limitations in mind, we derive functional demonstrators for various aspects of the vision. Based on these demonstrators, users' needs for domestic use of smart windows are assessed with two user studies: an interview and an elicitation study.

2.6 Public Displays

Our work is also inspired by an extensive body of work that addressed the design of public displays. These devices are placed in public spaces to display information or advertisements to users passing by. Many public display applications support interactions with the user's smartphone [4], touch interactions [4], mid-air gestures [30, 32, 83, 84], or the user's posture [56, 82]. Former research identified various application scenarios for public displays including displaying user-generated content [3] as well as user-specific or personal content [74, 86]. Given the possibility that other users could see someone's private content on a public display the use of interaction techniques that protect privacy is important [74]. Therefore, public displays usually adapt the displayed content based on the environment [47, 81]. For instance, Langheinrich et al. postulated that public displays should involve users in the environment by adapting the display content based on the visitors in front of the public display [47]. This inspired us to investigate the possibilities and requirements in terms of adaptability for displays located in private homes.

Furthermore, users value private content that is displayed on a public display if they can configure their own privacy settings [86]. Vogel and Balakrishan developed an interaction framework that changes the level of detail of the displayed personal content for a user based on the his/her distance from the public display [81]. Brudy et al. investigated approaches that mitigate shoulder-surfing problems including increasing the user's awareness by adding visual cues informing about shoulder-surfing, offering easy-to-perform actions to hide or move the displayed content, and automatically masking information when shoulder-surfing is detected [18]. While a significant body of work addressed privacy issues for public displays, it remains a challenge to see if similar phenomena can be observed when interacting with large displays in private spaces. That is why our work explores users' perceptions and requirements for smart windows that any findings about public displays are directly applicable to interactive windows.

Display blindness and interaction blindness [16, 52, 56] are major challenges for designing public display applications. Brignull and Rogers found that users judge public displays from a distance and that these should be designed to display the activities in an attractive and easy to pick up manner [16]. This includes positioning public displays near a traffic flow and at least partially above head height to gain the attention of many users from a distance. Furthermore, public display applications have to be designed clearly and support low-commitment activities that are quickly accomplish-able to reduce the threshold for participation. Peltonen et al. investigated a multi-user and multi-touch public display installation in Helsinki and observed that strangers came in contact during interacting with multi-user public display applications [60]. To reduce the interactions with public display applications using mid-air gestures, visual guides for performing these gestures were integrated into public display applications [2]. Müller et al. found that public display applications should use effective ways of communicating interactivity. Furthermore, they reported that users recognize the interactivity of a public display often after they had already passed by (known as landing effect) or when they observed other users interacting with the public display (known as honeypot effect) [56]. While different effective interactions techniques for public displays were developed, past research shows that the choice of the right technique is dependent on usage context. That is why our work addresses input methods for interactive windows from a fundamental standpoint, without copying techniques from public displays.

These examples show that research in HCI generated a considerable understanding of public displays that share many similarities with windows. However, there are two key differences between public displays and interactive windows. First, smart windows create two distinct interaction spaces with partly opposite requirements sharing a single display. We envision that smart windows will become a ubiquitous part of buildings and users will attend them in their everyday lives with long-term usage. Therefore, they should not distract users from their current primary tasks at work or in their homes, but they may also grab the short-term attention of passers-by on the outside. Hence, needs for attention management for interactive windows are highly different than for public displays [56]. Second, users might still want to look through the window without the content of the window interfering with the view outside. When adapting findings derived for, usually opaque, public displays past considerations may not be fully valid for smart windows. Thus, it is necessary to study smart windows as private devices that may pervade architectural spaces.

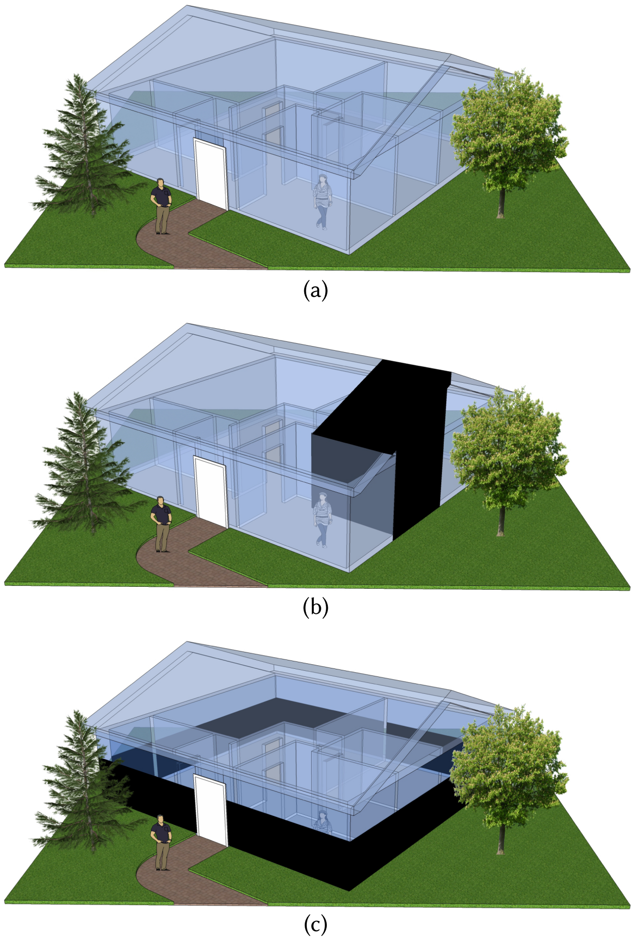
Previous work addressed public displays as architectural elements. In the Media Architectural Interfaces (MAI) framework coined by Behrens et al., public displays and media facades create specific interaction spaces depending on their surface, mediator, and context [10, 11] which may guide the design and implementation media architectures. The framework has been applied to various projects with a tangible interface used as mediator. The framework may be extended to smart windows, which create two distinct interaction spaces instead of a single one: One for inhabitants inside the building and one for passers-by on the outside. Both interaction spaces may differ considerably in the mediator (or interface) and context but share the same (mirrored) surface. Consequently, this work investigates whether and to what extent the past extensive lessons from the public display field can be applied to interactive windows.

3 A VISION OF ADAPTIVE BUILDINGS: WALLS ARE JUST OPAQUE WINDOWS

In traditional buildings, the shape and look of windows are decided upon by architects and building and construction related professions. Currently, it is decided at design and construction time where windows will be and what optical properties these windows will have. However, requirements on windows are constantly changing based on various factors such as time of day, weather, or privacy needs. In today's buildings, such changes are accommodated by external shutters or window blinds that only provide limited degrees of freedom. For example, if the shutter is closed for privacy reasons or to reduce glare, artificial lighting is needed in the room as the shutter covers the whole window. With smart glass technologies, there is an opportunity to fundamentally change this and make the window layout dynamic and allow adaptation to specific situations. The Squama system [67], for example, is a wall of tiled PDLC patches that allow changing visibility per patch. Parts of such a wall can act as a window, whereas others block sight. Adaptation is also possible with traditional walls and windows. Previous work on media architecture resulted in various installations in primarily public buildings where walls and windows are augmented to create digital media spaces [22]. However, we envision smart windows to become a part of homes and help people in their daily routines rather than being an installation in a public space.

3.1 WindowWall: Replacing Walls and Windows with Modular Smart Windows

In this work, we extend the vision of adaptive architecture formulated by Rekimoto [67], where elements of the physical architecture, especially smart windows, change their physical features in real time according to the users' current demands, for example, privacy issues, as well as environmental conditions. In addition to adapting the architectural space to precisely the control environmental conditions, the environment can act as an ambient display to convey information to users subtly and unobtrusively [20, 67]. WindowWall is a modular and self-contained system where a building might consist of various separate windows, as well as the whole outer shell of a house, uniformly made of smart glass panes, as illustrated in Figure 1(a). The smart glass of each module allows pixel-level control of both the optical and thermal properties. It includes a wireless interface and a processor that provides an interface for control and to retrieve its current status. Each pane harvests and buffers energy required for its operation. This makes retrofitting of existing buildings possible and combining multiple modules into a larger area easy.


(a)

(b)

(c)

Fig. 1. Vision of a dynamic architecture: (a) completely transparent, (b) all walls and the ceiling of one room are opaque, (c) lower part opaque for privacy, upper part transparent.

From a user's perspective, the WindowWall is more than a ubiquitous see-through display. It can show in-situ information like weather forecasts or appointments, and provides privacy for inhabitants as well as dynamic glare and sun protection without having to rely on artificial lighting. Furthermore, ceilings and roofs can be made of WindowWalls for regulating the room climate and precisely casting dynamic shadows, much like the Squama system.

3.2 Usage Vision and Scenario: Explicit and Implicit User Control

With a simple multimodal user interface, the inhabitants can directly control the glass. With a multimodal interface, they can define transparent areas that act like windows and opaque areas that act as walls. Based on sensors and algorithms, the control can also be automated.

Scenario 1. It is a warm and sunny day. Lisa comes home with her baby son from grocery shopping in the morning. The entire house is opaque, the way she set it in the morning when she left the house. Opening the door, it is still cool within the house, even without air conditioning. As the sun is still shining, Lisa changes the house to transparent to absorb the sun's thermal energy. At noon, it is time for her baby's nap, so she sets his room to opaque to support a refreshing nap (see

Figure 1(b)). In the evening, she switches all higher parts in the house to windows, only leaving the lower areas opaque for privacy (see Figure 1(c)). She likes this, because it gives her control over many architectural features of her house and even allows her to display information she cares about directly on the wall. She can change the appearance and function of her place according to her current needs, rather than being restricted to the architectural decisions made before building. She has a choice of ways to set the transparency levels, including a smartphone application or by using gestures inside the house.

Scenario 2. Carol has set her house to optimize energy consumption while she is at home. Now during the winter months, the system switches the windows to transparent to warm up the house similar to a greenhouse. Once the desired temperature is reached, the smart glass turns less transparent, so light transmission is reduced to keep the temperature at this level. Just before she leaves home in the morning, the window in her living room displays the temperature outside and notifies her that she does not have to hurry since her train is running late. When she comes home, the house recognizes where she is in the house, and the windows are set so that she has good lighting at all time. It feels very much like adaptive lighting. During the night the lower parts of the house are opaque to ensure privacy, but from her bed, Carol can always see the stars.

3.3 Use Cases and Applications

Our vision of WindowWall allows various ways of interacting with buildings and opens new ways for self-expression.

- Controlling natural indoor lighting becomes feasible on a very fine-grained level. Users can have a wall with many light points (similar to a wall with many LEDs) or delimit dedicated spots by having larger openings. Such an approach supports direct as well as indirect lighting. Sun can also be blocked to protect inhabitants from glare without having to dim whole rooms. Thus, users are put in direct control over exposure to light. Future technologies may also enable using the energy from the blocked light.
- The expression of the building becomes adaptive, and aspects traditionally seen as architectural features can be programmed and changed. Buildings turn into media façades and ambient displays, with the outer parts becoming public displays and allowing public communication. The inner parts can be used to provide context-adaptive information to inhabitants just like AIS but without the need for additional devices in the room.
- The outer shell of the building can augment and alter the view outside. Environmental conditions that normally cannot be seen can be overlaid, or the window can provide a view of another point in time or location.
- Smart windows support sustainable energy usage. By being able to control how much light and warmth is let into the building, the energy consumption can be reduced, either through allowing natural heating by creating a greenhouse or by blocking sunlight avoiding the need for cooling.

3.4 Summary

In the vision of adaptive buildings, windows are smart and modular parts. Their shape and look change dynamically according to users' current needs and environmental aspects [67] and is not decided beforehand. Smart windows allow fine-grained control over which part acts as a wall and which part as a window. We envision that interaction with adaptive buildings will be a combination of implicit interaction based on sensor data and explicit interaction by users through various modalities. This vision forms the basis of our further investigation.

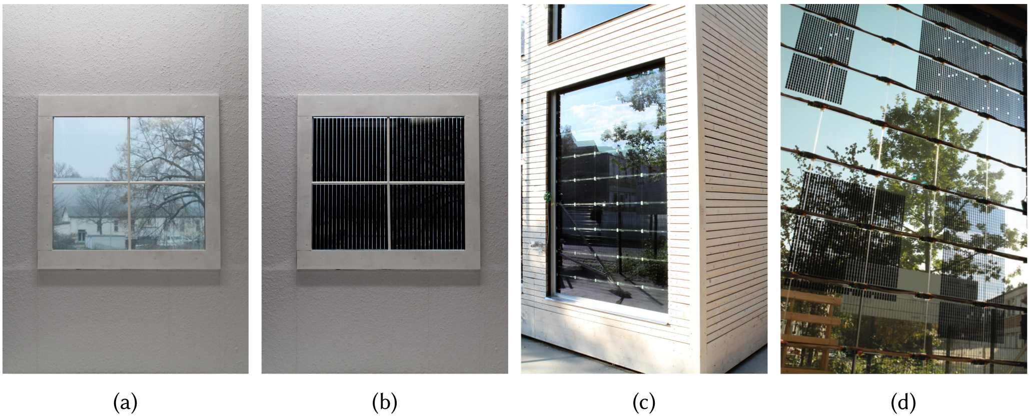

(a) (b) (c) (d)

Fig. 2. Images of our smart window prototype that we used for the use case demonstrations in its fully transparent (a) and fully opaque (b) state and part of the façade test building that we used for the elicitation study as seen from the outside (c) and inside through the window with some opaque regions (d).

4 IMPLEMENTING THE VISION: A FUNCTIONAL PROTOTYPE

Through prototyping, we explore whether our vision of buildings becoming adaptive with the use of smart windows as ubiquitous information displays could be implemented using technologies available today and what is needed for implementation. We provide a comprehensive description of a fully functional proof-of-concept prototype of an interactive smart window, which shows that our vision can be implemented. This prototype serves as a basis to investigate with users various aspects of our vision later on.

Before we describe our prototype in detail, we will cover some of the basic technologies available today to build smart windows. We briefly describe interaction technologies, which may be used to control smart windows and show that an energy self-contained smart window based on LCD panels can be built with state-of-the-art technology.

4.1 Basic Technologies

Smart windows in previous works were built using different technologies and combinations thereof. In this section, we provide a short overview of the benefits and downsides of these technologies. For a more thorough review of smart window technologies, we refer the reader to previous work by Baetens et al. [8]. Electrochromic glazing changes its optical characteristics through reversible chemical reactions. These reactions (ionization) are caused by applying an electrical current to an electrochromic layer (mostly based on tungsten oxide WO_3) inside the glazing.

Electrochromic glazing achieves high changes in transmittance in the order of 0.6[1] and only consume energy when changing transmittance. However, time taken to change transmittance is in the order of multiple seconds to minutes and glazings cannot easily be tiled into small, individually controllable regions.

PDLC change the orientation of liquid crystal molecules by applying an electric field, and primarily influence haze instead of transmittance. In contrast to electrochromic glazing, switching occurs in a few seconds. However, voltage (approx. 100V) has to be applied constantly for a clear view. With a comparatively high power consumption in the range of 10W/m^2 and little influence on transmittance, PDLCs are primarily used as privacy glasses an in-door applications.

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[1] Transmittance describes how much light can travel through a material with 0 meaning all light is blocked and 1 meaning all light passes through the material.

Twisted nematic liquid crystals (TN-LC) are primarily used in displays. They consist of two polarization filters with orthogonal polarization directions and a liquid crystal layer in between. The first polarization filter only passes light polarized in a specific direction. Then, the liquid crystal layer rotates the polarization direction by applying an electrical field. Depending on the amount the polarization direction is rotated, more or less light will be blocked by the second polarization filter. TN-LCs can be produced either with minimum (black) or maximum transmittance (transparent) when turned off. In contrast to all previously described technologies, fine-grained control of transmittance is possible as TN-LCs can be substructured into individually controllable pixels as is done for display applications. They also allow fast switching times (<20ms) and consume less power (1.5W/m^2) than PDLCs [31]. However, maximum transmittance is lower due to the polarization filters blocking parts of the sunlight, which is initially not polarized.

4.2 Window Prototype

Our vision of smart windows as ubiquitous displays requires windows to control sunlight transmittance on a fine-grained level as well as the ability to display additional information. However, it requires high refresh rates to allow quick response times and enable interactive applications based on a user's location, so we built a smart window prototype using monochrome passive matrix LCD panels that use TN-LC technology. In contrast to active matrix LCD panels, which are used for most screens nowadays, no transistors have to be placed on the panel itself, and no additional color filters are used. On one hand, this increases maximum achievable light transmission and simplifies the fabrication process, thus reducing production cost. On the other hand, it significantly limits achievable resolutions, since each pixel has to be wired individually whereas only one wire per pixel column and row is needed in an active matrix setup. With smart windows, however, the reduced resolution is compensated with large screen space and resolution is still better than alternative technologies. We expect our LCD based smart windows to be comparable in price to current solutions with external shutters and blinds despite higher initial costs (approx. $< 400\$/\text{m}^2$) if maintenance is taken into account. Since the panels will be integrated into double glazing, no maintenance is required as opposed to mechanical solutions which suffer from weather conditions and wear out. Our prototype is sketched in Figure 3. We chose GV286 passive matrix LCD panels with MTC1 driver and GMCC5 gray scale controller from BMG | MIS.[2] These panels are usually used for large display boards in train stations. The prototype consists of 2×2 panels with 19×16 pixels each. The opacity of each pixel can be adjusted in 16 steps with our current controlling electronics. The panels are placed between two sheets of PLEXIGLAS® LED; a special acrylic which is transparent and allows edge lighting.

We implemented edge lighting both as a backlight and also to colorize parts of the window, as the LCD panels themselves are monochrome. A total of 334 RGB-LEDs were installed around the edge of one of the acrylic sheets. We chose Adafruit DotStar Digital LED Strips[3] so we can set the color and brightness of each LED individually.

The assembled window is $61.5 \times 54\text{cm}^2$ large excluding the framing and depicted in Figure 2(a) and (b). We installed the prototype in a wooden wall with wallpaper and added sash bars to make it look like a regular window. The wall was placed directly in front of a window façade in one of our offices.

4.3 A Smart Window System

We integrated our prototype into a more general smart window infrastructure consisting of both hardware and software components, illustrated in Figure 4. Each LCD panel is driven by a panel

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[2] Manufacturer website: https://www.bmgmis.de/en/products/lcd-displays/.

[3] Available here: https://www.adafruit.com/product/2241.

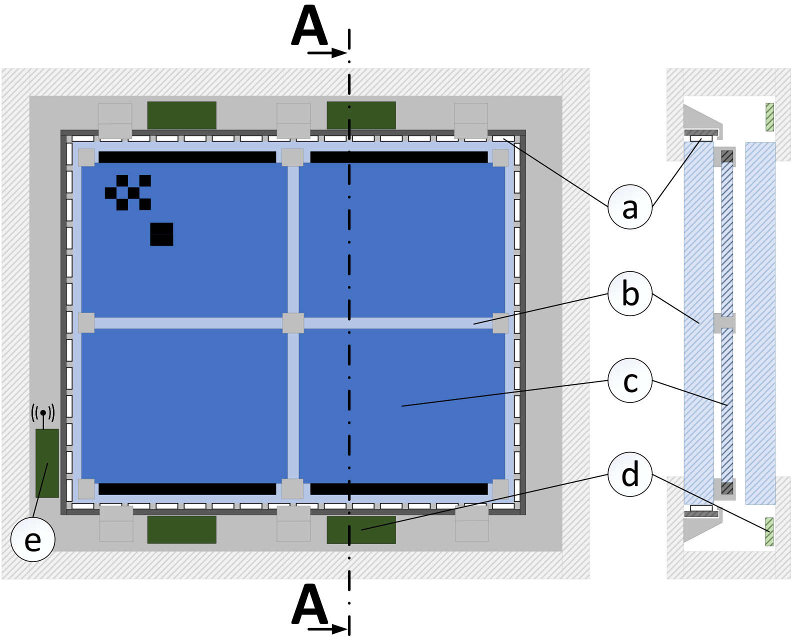

Fig. 3. Schematic cross sections of the window prototype showing the LCD panels (b) between PLEXIGLAS® LED sheets (c), the LED strips for edge lighting (a) around one of the acrylic sheets, and the electronic components consisting of display drivers (d) and controller for WiFi connection (e).

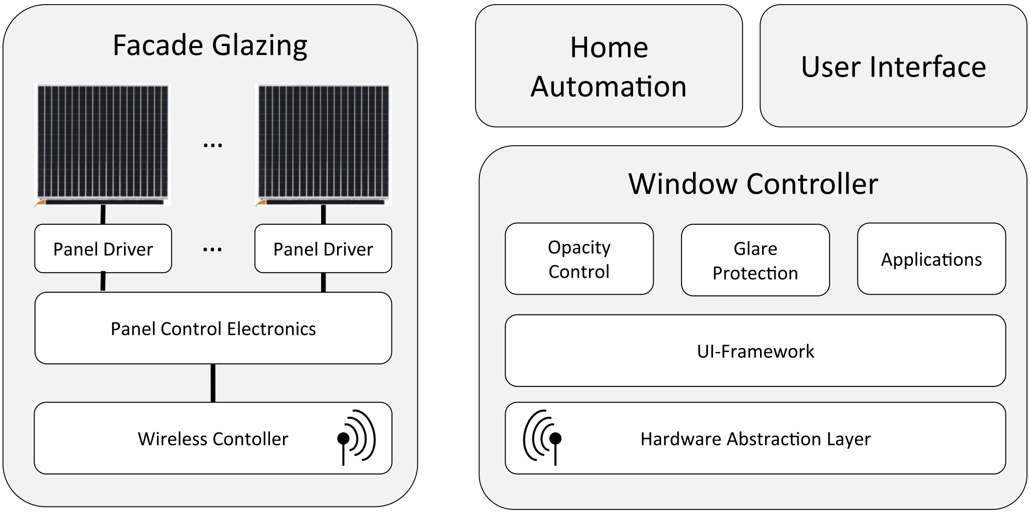

Fig. 4. Schematic overview of the smart window system, including hardware components (left) which are integrated into a window's double glazing and software components (right) for high-level control. The system may be integrated into a home automation system for climate control and provides a user interface for additional applications. Communication between the façade glazing and the window controller is wireless.

driver, and multiple drivers may be connected to one controller using wires. We added an additional controller that provides Wi-Fi communication. Therefore, no wires for communication have to be connected to the window, and existing wireless infrastructure can be used.

On the software side, we implemented a window controller component, which provides all the functionality needed for using our smart windows. A hardware abstraction layer is implemented to decouple high-level application logic from the exact hardware setup like types of LCD panels used, size and orientation of the panels and communication technology. This layer represents all smart windows as rectangular bitmaps. A UI-framework provides a high-level interface for displaying and positioning components like text or images. It handles drawing these components onto the respective bitmaps from hardware abstraction and supports correct blending of semi-transparent components.

The window controller implements an opacity control application. Its main purpose is to communicate with a home automation system to optimize room climate, i.e., temperature and overall brightness. A second application called glare protection is responsible for tracking users and the location of the sun to prevent users from being blinded by the sun. This is done by blocking direct and indirect sunlight towards a user's eyes. Additionally, applications, for example, a weather forecast, clock, or information on public transport are supported and may be controlled explicitly by the user through various interfaces, like smartphones and gestures. Multiple applications can run at the same time on a single window and may be displayed without interfering with each other.

4.4 Façade Test Building

As the previously described prototype is limited in size, we additionally integrated a large window façade built by Haase et al. [31] into our system. It is part of a façade test building; a two-story timber building at our local university. The building includes four test rooms, each $2.00 \times 4.20 \times 2.70\text{m}^3$ large and with a glazed south façade. One of these rooms has the $1.6 \times 2.6\text{m}^2$ LCD-based smart window prototype, which we integrated, consisting of 5 × 9 LCD-panels with a resolution of 130 × 144 pixels in total. Each pixel can be set to either transparent or opaque, see Figure 2(c) and (d). Through our hardware abstraction layer, we only needed to change the communication protocol. A more detailed description of the facility and the smart window is provided by Haase et al. [31].

4.5 Interaction Technologies

Windows and especially shutters and blinds are usually controlled manually either through direct manipulation or with hardware switches located on nearby walls. Although these input modalities may still be usable with smart windows, they are insufficient to utilize their full potential. For example, hardware switches only allow one-dimensional input and could be used to simulate shutter-like behavior on smart windows; however, they do not allow users to define small parts of the window to block sunlight. Furthermore, they have to walk to the switch to use it, and other interaction modalities are needed to make full use of smart windows. These include direct touch and gestures as well as indirect interaction through mobile devices and speech.

Integrated into a smart home environment where the location of people is known, a smart window could adapt implicitly to users' needs based on their location and behavior; however, this requires access to external devices and sensors for tracking users. Many homes already include such tracking devices such as the Kinect® sensor attached to their gaming console. Alternatively, users may also be tracked, e.g., using Bluetooth LE beacons in fitness trackers.

4.6 Self-Powered Smart Windows

Transitioning from regular windows to smart windows has to be as easy as possible for broad adoption in existing buildings. A major issue when adding electrical components to a building is that they usually require running additional cables through walls. This can be avoided by providing smart windows as self-contained components.

Our previously described smart window prototype is self-contained with respect to communication, i.e., no external wiring is necessary to control the smart windows, and it integrates into existing Wi-Fi infrastructure. However, it is not optimized for power consumption and requires an external power supply. Measurements showed that on average 2.5W is consumed by the panels and control electronics and an additional 0.5W by the wireless controller. Taking window size into account, this results in a power consumption of 8.0W/m^2.

To minimize effort and cost for replacing existing windows with LCD-based smart windows, self-contained solutions are required. Such windows would not need any wiring and can be installed by glaziers like regular windows. With current technology self-powered solutions are feasible. Haase et al. achieved 1.5W/m^2 power consumption with an LCD-based window façade [31]. We expect there is further potential for optimization with LC-panels that are custom designed for smart window usage. If normally black panels are chosen the window is opaque when turned off. This allows the window to be completely turned off as people typically close their shutters during nighttime. The power consumption of the wireless controller can also be reduced when no change in the window state is necessary. It can also be sent to a deep-sleep mode which consumes below 0.1mW most of the time and only occasionally be woken up.

An LCD-based smart window can then be made self-powered using current photovoltaic modules by adding 10% to the window area. If the photovoltaic modules are integrated into the window framing, no additional space is required. For our next calculations, we assume a window size of $1.6 \times 2.6\text{m}^2$ (4.16m^2) like in the façade test building. As a worst case, we assume a day in December in a central European city like Prague. The average solar irradiance is $0.94\text{kWh/m}^2\text{/day}$ onto a vertical façade not facing north.[4] Photovoltaic panels are integrated into a 10cm wide framing resulting in a total area of 0.88m^2 for the modules. Assuming an efficiency of 15% for the modules results in 124.08Wh per day, which is enough energy to supply the smart window for 19 hours. As day length in December in Prague is below 8 hours, the remaining energy can be used to charge batteries in the framing, which supply the window during cloudy days.

4.7 Summary

Our functional smart window prototype implements our vision of adaptive buildings using windows as ubiquitous displays with the well-established technology available today. It is integrated into a more general system for smart windows that abstracts over specific hardware details and can support additional smart window technologies in the future. The prototype is self-contained with respect to communication, and we show that building self-powered smart windows is possible. This prototype serves as a proof of concept and also forms the basis of our exploration of future domestication possibilities for smart windows.

5 EXPLORING DOMESTICATION POSSIBILITIES FOR SMART WINDOWS

So far, we have shown that smart interactive windows can be built using existing technologies. Consequently, it appears that future buildings that include smart windows may begin to appear. However, in order to validate our vision, we are eager to investigate whether users can see the possible benefits of smart windows. More importantly, we ask whether smart windows can be

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[4] Calculated with the solar irradiance calculator provided by Greenstream Publishing Limited (http://www.solarelectricityhandbook.com/solar-irradiance.html), which is based on data from the NASA Langley Research Center Atmospheric Science Data Center Surface meteorological and Solar Energy (SSE) web portal supported by the NASA LaRC POWER Project.

Table 1. Overview of the Participants in Our Domestication Study

ID	Age	Gender	Profession	Rental type	Household	Housemate(s)	Scenario order
1	34	Male	PhD student	Own	Flat	Wife	S1, S2, S3
2	31	Female	PhD student	Sublet	Room	Flat's owner	S2, S3, S1
3	42	Female	Sociologist	Own	House	Husband and two children	S3, S2, S1
4	31	Male	Office worker	Rent	Flat	Two friends	S2, S1, S3
5	23	Male	Student	Own	House	Parents (house owners)	S3, S1, S2
6	23	Female	Office worker	Rent	Flat	Boyfriend and two friends	S1, S3, S2
7	26	Male	PhD student	Rent	Flat	Girlfriend and one friend	S1, S2, S3
8	28	Male	PhD student	Rent	Flat	Wife and baby	S2, S3, S1
9	25	Male	Student	Rent	Flat	Eight friends	S3, S2, S1
10	33	Female	Manager	Rent	Flat	Alone	S2, S1, S3
11	33	Male	PhD student	Rent	Flat	Girlfriend	S3, S1, S2
12	22	Female	Student	Own	House	Parents (house owners)	S1, S3, S2

used in the domestic market and eventually become a useful part of one's personal interactive artifact ecology. To that end, we conducted a user study where we used the prototype described in the previous section to gather feedback on whether, why and how users would imagine using smart windows. Our goal was to build a preliminary understanding of the constraints and limits in the design space of smart windows.

In order to make our vision more tangible and enable gathering scenario-oriented feedback from users, we created three usage scenarios that formed the context of our study. Our vision inspires these scenarios and is driven by the current capabilities of the prototype. First, we proposed that future smart window applications could use the window to display *in-situ information* beyond the information that users would usually expect to perceive when they look out of a window. Second, we investigated whether users could imagine using the window as an *ambient information display* to communicate information either inside or outside a building. Finally, we looked at *adaptive shading* to change shading on a per-pixel basis depending on the environmental conditions outside or the presence of users.

We conducted a qualitative study where we focused on feedback provided by the participants when presented with the different scenarios using the prototype. In the study, we explored the design space of smart windows that have the potential for domestic use and endeavored to identify the user needs and design within the constraints involved when designing smart windows.

5.1 Participants

We recruited a total of twelve participants (five female, seven male) through a snowball sampling procedure. Participants were from 22 to 42 years old ($M = 29$, $SD = 5.6$).

Interviews took from 36 minutes to 67 minutes ($M = 52.50$ minutes, $SD = 9.36$ minutes) and participants were remunerated with 10 € .

5.2 Apparatus

The interviews took place in an office environment in front of our smart window prototype described earlier. We integrated the prototype into a movable wall that we placed in front of a large window. This gave users the impression of looking through a real window instead of looking at a screen. The technical part of the window, such as wires, power supply, and controllers, was hidden from the participants. For the demonstrations we used edge lighting and pixel-wise opacity changes. All interviews were audio recorded and later transcribed verbatim.

5.3 Procedure

At the beginning of the study, we informed all participants about its aim. After the participants signed the consent form, we asked them to answer our demographic questionnaire, then gave them a short introduction to the system. Next, we demonstrated various examples for each of the three application scenarios which are described in more detail below. The order of the application scenarios was counterbalanced using a balanced Latin square design. We asked the participants to provide feedback after all examples of a single application scenario were demonstrated. The interview protocol investigated primarily whether users saw a domestic potential for smart windows and what form and features interactive windows should offer in order to be accepted at home. Questions were related to their impression of the demonstrated application scenario, possible ways for improvement and whether they would like to use such a system. We encouraged them to describe their experience of an interactive window and express how they felt when looking through an augmented window. Further, we wanted to know what they thought about how content was presented on the interactive windows and whether they felt such an application was appropriate. We aimed to explore the possible social context for interactive window usage, e.g., how they would interact with windows when family and friends were present. Finally, we queried them about what features of an interactive window would be needed for it to integrate well into their everyday life. At the end of the interview, we asked for general feedback and other application scenarios we have not covered. In the following, we provide details of the three application scenarios.

5.4 Application Scenario S1: Displaying In-Situ Information

One function of traditional windows is to connect the inside of buildings with the environment outside. When people look out of a window they perceive environmental information about the conditions outside, such as the current daytime, weather conditions, or traffic conditions in view. So far, the kinds of information people are able to perceive are limited to what they see at that specific moment and location. According to our vision, an interactive smart window can augment and alter the view outside by overlaying information beyond what is immediately visible and by removing or modifying things usually seen, for example overlaying information about the current temperature; or modifying the whole view outside.

Future smart window applications could display additional information about environmental conditions outside not provided by traditional windows today. On one hand, applications could *augment* the real view out of the window by providing additional information not visible to the human eye such as details about humidity and air pressure, or could add public traffic information such as time until the next bus arrives at a near bus stop.

On the other hand, a smart window application could *alter* the environmental conditions that people see when they look outside of their window. Instead of showing the current environmental conditions, the window may overlay information from another point in time or location; for example, it could display a weather forecast for later in the evening as or the location of the next meeting.

Besides changing what a person can see, a future application could also change how users perceive the environment outside by *amplifying* the view to display improved environmental conditions. This might influence the mood of the inhabitants positively. For example, the application could add more snowflakes on a winter day with little snow or make a summer day look even more beautiful by coloring the grass greener and the sky brighter.

(a) Snow (b) Rain (c) Sunshine

(d) Temperature (e) Initial (f) Beautified

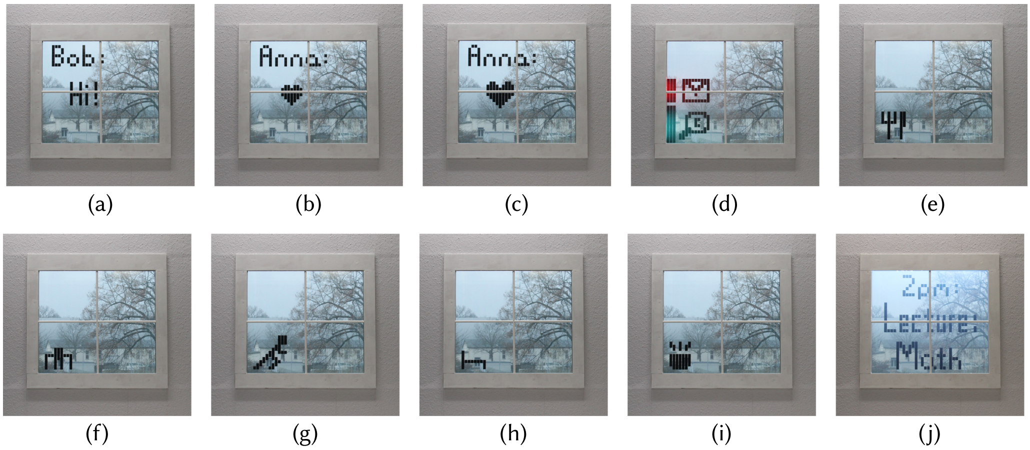
Fig. 5. Photos taken from demonstrations of in-situ information. Different weather conditions are shown as full screen animations (a and b), or static images of clouds or sunshine (c). Temperature of approx. 3°C is color coded using edge lighting (d). View is beautified from initial state (e) to a more colorful view (f).

5.4.1 Demonstration. First, we displayed weather information in a forecast scenario as an example source of in-situ information that future smart window applications could display, see Figure 5. For the representation of precipitation, we displayed animated raindrops and snowflakes on display and used the LEDs to add a blue (rain) or white (snow) tint to the window. To display clouds or sunshine, we used static icons of a cloud and the sun in the top right corner. We also added temperature information by coloring the left edge according to a color scheme used for weather maps in weather applications and TV weather forecasts. Second, we changed the view outside, amplifying the current weather by coloring the edge LEDs to increase the overall saturation of the environment and make the sky look brighter.

5.5 Application Scenario S2: Windows as Communication Display for Inside and Outside

With traditional windows, people only perceive information about the external environment when they look out their windows. Our vision of interactive smart windows enables buildings to become ubiquitous information systems. Applications could, therefore, use smart windows as communication devices for people in the interior of a building as well as those outside.

A future window application could, for example, support the people inside a building by displaying personal information such as their daily schedules or incoming messages, and inform passersby about current or upcoming events, or information about sales or products.



Bob: Hi!

Anna:

Anna:

2pm: Lecture: Math

Fig. 6. Demonstrations of the window used as an information display. Messages are shown as text (a) and animated emoticons (b and c). The number of unread messages from different channels is displayed in (d) using icons and edge lighting. Various current activities of a potential communication partner are visualized with icons (e–i). The last picture shows information as shown to passers-by in the context of a lecture hall.

The applications could display the information either as text messages or as symbols depicting the content. In addition, edge lighting could be used to highlight the displayed information or add additional information using colors.

5.5.1 Demonstration. For the information display use case, we displayed different kinds of messages on our prototype, see Figure 6. We first displayed a simple text message that could have been received from a messaging app. Then, another more abstract message was displayed showing an animated emoticon. Instead of displaying single messages, we then showed how many messages were received from a specific communication channel and used edge lighting to highlight the number. Each application was depicted with its respective icon.

In a distant relationship context, we displayed different example activities a partner could be performing at the moment, like working, eating, or sleeping. In contrast to previous examples, our last example focused on displaying information to the outside, such as passers-by.

Lastly, we showed a demonstration where information is shown to people outside of a room. We also presented a window installed in a lecture room showing what kind of lecture was about to start and at what time.

5.6 Application Scenario S3: Adaptive Shading

Ventilation and shading are currently the primary uses of windows. Shading solutions like shutters allow users to control brightness and climate in the room by covering large parts of the window and thus blocking sunlight. Shutters and blinds may also be used for glare protection. When watching TV, sunlight might be reflected on the TV-screen towards the user. With current solutions, achieving optimal brightness control and glare protection are often conflicting goals. In our vision of interactive smart windows, natural indoor lighting can be controlled precisely and interactively by shading small parts of the window. Furthermore, the window can react immediately to changes in its environment like clouds and moving users.

In the context of shading, the smart window is a programmable shutter which allows fine-grained control over light and shadows. Combined with other sensors in the smart home, it can

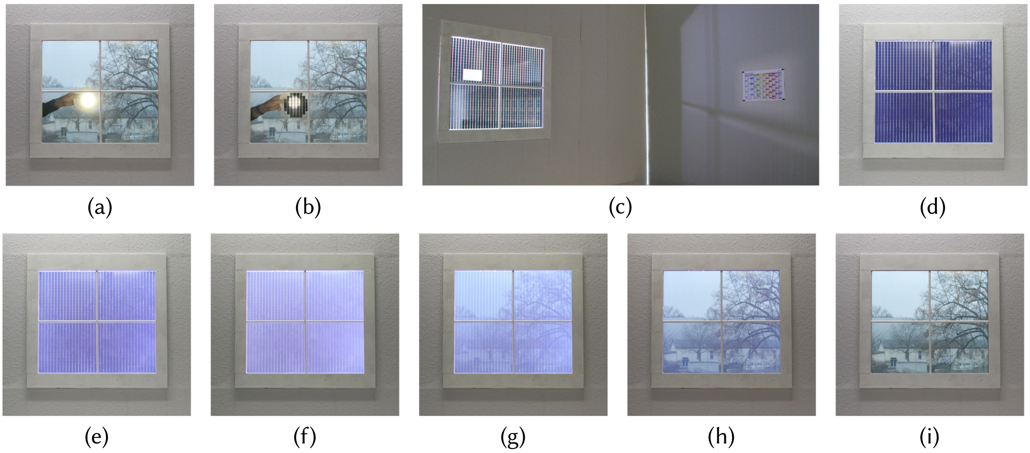

(a) (b) (c) (d)
(e) (f) (g) (h) (i)

Fig. 7. The smart window prototype demonstrating examples of the adaptive shading use case. When the sun is blinding (a) the user, direct sun light can be blocked by making a small part of the window opaque (b). The window is used to highlight a calendar on the wall as an ambient notification when everything else is dark (c). The last example shows the window as a wake-up light (d–i), the initially opaque window increases edge lighting to simulate sun rise and transitions to transparent while continuously reducing edge lighting.

dynamically and implicitly react to changes in its environment. Changes can be *external*, *internal*, or *time-dependent*.

Sensors can detect *external* changes that happen outside of the building influencing lighting conditions in the building. The window can adjust its opacity to more transparency, e.g., when clouds cover the sun, thus keeping the brightness in the room constant while preserving energy for additional lighting.

Internal changes are primarily induced by users in the building. If the user is absent, the window can adjust its opacity to optimize energy conservation. In the summer, the window would turn opaque to block sunlight, and in winter it would be transparent to let as much sunlight in as possible and use its energy to warm the interior. When a user is in the room, glare protection must be considered. The opacity of small regions of the window is controlled by tracking users' positions and the state of other devices in the room. If the user sits on the sofa and turns on the TV, for example, the window would prevent indirect sunlight from blinding him/her through the TV screen. The projection of the TV screen surface onto the respective window regions is calculated by raycasting from the user's gaze to the screen and either directly or indirectly to the sun. Glare protection may also be inverted to highlight a specific object. Sunlight directed to other objects or the room as a whole would then be blocked, thus letting the highlighted object appear brighter than its surrounding.

Changes can also be *time-dependent*, i.e., dependent on the position of the sun and time of day. In combination with edge lighting, smart windows can extend traditional wake-up lights. The window can gradually light up the room in the morning while remaining opaque to preserve privacy. It can then seamlessly blend from the opaque state to the transparent state when the sun rises while dimming the edge lighting, creating the impression of an earlier sunrise. This enables users to shift their perception of time of day according to their needs and independently of the actual sunrise or sunset. Shift workers would especially profit from this as they have to get up very early or sleep during the day.

5.6.1 Demonstration. We demonstrated adaptive shading in three different scenarios: sun glare protection, object highlighting, and wake up as shown in Figure 7.

First, we demonstrated sun glare protection. We showed how the sun was shining directly into the room and blinding the user. Adaptive shading was then activated to block direct sunlight by covering just the bulb and leaving the rest of the window transparent. To be independent of the actual weather conditions, we simulated the sun by holding a bright light bulb (LifX Color 1000) behind the window.

Second, we implemented object highlighting where only a small part of the window was transparent and projected sunlight onto a wall calendar as a reminder of a specific event. As with glare protection, we could not influence weather conditions and the location of the sun, so we used a floodlight to cast light and shadows onto a nearby wall.

Third, the window was used as a wake-up light. It was initially opaque as is common during the night; then the edge lighting was used to gradually light up the room as if the sun was rising.

When later the real sun was rising the window decreased both its opacity and the amount of edge lighting to seamlessly blend between simulated daylight and real daylight.

According to our vision, in the future all walls of a house can be made adaptive. Therefore, we additionally asked our participants after the last demonstration whether they could imagine living in such a house.

5.7 Analysis

Interview content was transcribed verbatim. We used thematic analysis [12] to build a structured understanding of the content of the interviews. Thematic analysis is a process that involves developing a structured understanding of the data through iterative coding and grouping entities. In our case, we aimed to identify patterns in the data that characterized the users' views of future interactions with interactive windows. Three coders coded two representative interviews in parallel to establish an initial coding tree. After two review meetings, an initial coding protocol was developed. Afterwards, the rest of the data was divided equally between the coders. In the next stage, another coherence meeting was held to solve final code discrepancies. We then used affinity diagramming supported by accessing data in Atlas.ti to rearrange and re-evaluate the codes and establish themes. In this process, we translated answers that were not in English. At the end of the analysis, four themes that describe the interactive window design space emerged.

5.8 Results

Next, we present four themes: FORM, SUPPORTING ROUTINES, CONTENT, and INTERACTION.

5.8.1 Form. This theme captures aspects of the smart window regarding how content may be displayed and properties the window should have. Participants were generally satisfied with the resolution of the prototype for shading purposes. However, some found that square pixels looked rough and would prefer more natural pixel shapes:

> *"The cornered pixel which you can see well at the moment are very technical and sterile. I liked how they looked, but I think they are too cold and technical for many applications." (P8, S3)*

To some participants, colors were the most important aspect:

> *"It's more about colors than details." (P3, S2)*

Providing colors through edge lighting was perceived to affect mood:

> *"You could have colored light for the ambiance in the room since it's said that some colors have a relaxing effect." (P12, S3)*

Participants also envisioned much larger smart windows which would provide more space to display information. This was especially the case as windows were regarded as a currently unused space always available to users.

> *"The biggest advantage I can think of is: It doesn't require any additional space. For [a] tablet, it requires some space and my table is already messy with more wires [. . .]. Actually, you get the sunlight when you're looking, so I think it makes you healthier." (P2, S1)*

Large smart window façades could then also be used as public displays to show information to people outside over large distances. For indoor applications some participants suggested to replacing current displays like projectors or TVs with smart windows, or to use them as a second screen:

> *"If somehow you could make the pixel colored, you could also show videos or images. [. . .] It is then a FullHD screen and a super large window at the same time which automatically dims." (P9, Further comment)*

Others suggested displaying large images on the window:

> *"I would like to, e.g., on one day project an aquarium in my bedroom, on the next day I would prefer a desert. [I] have got different moods which you could use to show on different rooms on different occasions. As well as when I have to concentrate, it should be calm. [. . .] Depending on the activity, context should adapt." (P10, S3)*

5.8.2 *Supporting Routines.* Participants reflected how interactive windows could provide contextual information that would support their daily activities. One participant requested that the traffic situation should be easily obtainable through windows:

> *"Or getting up early. When you get up, and you have scheduled that you drive early by car and will take this road, tell me if there is anywhere, e.g. an accident or black ice." (P4, S1)*

Shading was perceived as the primary use case for a smart window by many participants:

> *"I think it [Shading] is the main application I would use." (P1, S3)*

Such adaptation should be quick and with smooth transitions between states. Others suggested a combination of controlling the window manually once and then letting the system adapt automatically.

> *"At the beginning, I think I will specify the region and then when the sun moves around, it can adapt." (P2, S3)*

Further, participants identified opportunities for helping maintain sleep patterns or accommodate cases where alterations to a routine were necessary. Simulating sunlight for a better wake-up experience was mentioned:

> *"I have a wake-up light, and I find it brilliant, I can more likely imagine that. Maybe not in every room but in the bedroom." (P3, S3)*

Displaying reminders and to-do lists were also an often-mentioned functionality with users requesting easy tools to add and erase information from a window:

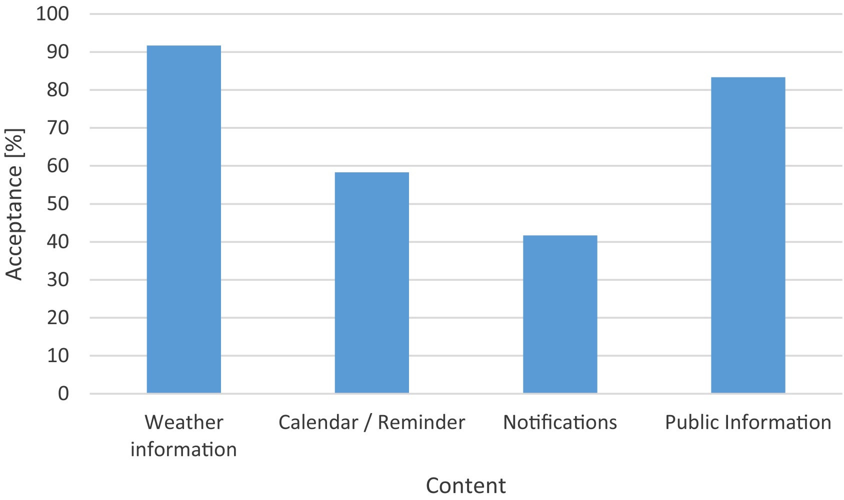


Fig. 8. Agreement for different contents for smart windows as ubiquitous displays.

> *"For everything else [except weather] I can think of it being integrated into a wall, like a whiteboard." (P7, S1)*

Some users requested specific functionalities connected to their usual leisure activities. For example, one user requested functions for facilitating her long-distance relationship:

> *"Maybe it could make my window view look like their [boyfriend and parents] window view." (P6, S2)*

Another participant reflected on the possible role of a smart window in the daily life of small children:

> *"[a surface] Where kids can paint simply with their hand, through touch input." (P11, Further comment)*

Finally, some participants remarked that adaptive shading could change their perception of a day altogether, adapting to special life circumstances:

> *"[When] I was partying at night I know I want to sleep in, I definitively don't want it to wake me up." (P6, S3)*

The participants also stated that a smart window system was able to support the user's routines and privacy issues by controlling the transparency of the window.

5.8.3 CONTENT. The participants reflected about personal contents for smart windows systems such as notifications. Possible contents for smart windows as ubiquitous displays are displayed in Figure 8. Some participants suggested that the system should support different privacy settings for different rooms. Thus, private information should not be displayed in more public environments such as the living room:

> *"[I would not have privacy issues] if it were in my bedroom [...]. If someone comes in the bedroom, it's already intimate." (P6, S2)*

Also, one participant stated that the system should support an option to turn the system off if visitors are around. However, most of our participants disliked the idea of displaying all incoming mobile notifications as messages from the smartphone on the window itself:

> *"If I had them [messages] on a glass like here, for example, glass walls and doors, then I don't use it to relax like [I do now]." (P1, S2)*

In contrast to displaying all incoming messages, some participants imagined that special persons such as close friends or family members would be allowed to push messages directly to the window:

> *"Or when you write a WhatsApp message, and he does not react, that you can project it directly to the window. A question like: Are you at home? And it appears in his apartment." (P9, S2)*

In terms of social messages, some participants stated that they like the idea of displaying appointments on smart windows:

> *"Events that you can synchronize your appointment calendar with the window so you get up and can, in any case, check your day: I've got the following appointments saved, and I have to be there at twelve." (P9, S1)*

Other participants liked the idea of highlighting objects such as calendars in the environment using adaptive shading:

> *"[…] wallet, keys, and smartphone and the window […] highlights these three things which I should always carry with me and which I often forget." (P7, S3)*

Participants reflected about general information such as weather information, information for organizations and workspaces as well as public information that could be displayed on smart window systems. Some stated that they would expect weather forecasts to be displayed on smart windows, but only in appropriate situations:

> *"The overlay should be relatively intelligent maybe that it recognizes whether I have looked at it sometime." (P9, S1)*

They reflected on which kind of information can be displayed on smart windows in public environments: Most participants liked the idea of displaying information on smart windows for public environments; for example, many spoke of displaying information regarding an occurring lecture outside of the lecture room:

> *"I liked the lecture use case. That creates transparency or walls like here [in the office]: What are people doing at the moment?" (P8, S2)*

5.8.4 INTERACTION. While our interview was not focused on interaction modalities, participants still made various suggestions for how they would like to interact with a smart window explicitly, such as that multiple modalities should be used depending on the specific use case:

> *"In the first place messages have to get onto it, and they have to be able to disappear." (P8, S2)*

> *"It would be cool if it were interactive. Touch sensitive in some form no matter if resistive or capacitive as long as I could interact with it and do something." (P7, S1)*

For basic interactions like turning the window on and off, some participants mentioned speech input or hardware switches like those currently used for lighting:

> *"Maybe it makes sense that you can turn it on and off with voice commands." (P1, S1)*

> *"I don't care how it [adaptive shading] is controlled. A manual switch on the wall would probably be the easiest." (P4, S3)*

Several participants also thought of the window as a large canvas and preferred to use direct touch and pen interaction for drawing and writing:

> *"I would like to write on it if I wanted to memorize something very quickly. And I can erase again, so I would like to play with it." (P10, Further comment)*

5.9 Summary and Discussion

Our interview study showed that users were generally interested in interactive windows and they welcomed the possibility of having one at home. However, the study also showed that there are many constraints and design dimensions to be explored before interactive windows can enter widespread usage.

Our study, especially in the form and context themes, indicates that users have a specific expectation as to how an interactive window should look. This, in turn, imposes certain technical requirements. As we observed in the form theme, users expect high resolution from windows and color support to make them look more like regular walls, which poses a challenge both on the display technology and the computers that would drive such displays. Further, with the supporting routines theme, we observed that users had a strong preference for context-awareness. This finding is in line with past research on context in ubiquitous computing environments [28]. However, in order to enable the desired context-aware interactions, extensive activity sensing that goes beyond the current state of the art is needed. Consequently, future research in computing can be stimulated by the challenges posed by interactive windows.

Moreover, we observed that participants were eager to speculate how interactive windows could have a profound impact on their routines. In the supporting routines theme, we saw how users wanted interactive windows to change roles and adapt to the current domestic activity dynamically. This suggests that there are several important design dimensions to be considered when designing interactive windows for the home. First, we saw the need to offer a variety of interaction techniques. The interaction theme showed that users expected a change in interaction modality when interactive windows changed their functionalities. Further, the content theme has shown that adaptive viewing is needed based on user preferences and who is viewing the window. As a consequence, defining privacy rules for interaction windows based, inter alia, on location information and the social context emerges as a key challenge for realizing our vision. As we observed large differences in what content the users desired to be displayed on interactive windows, customization methods need to be developed. It is a challenge for interaction design to find how to not only set one's preferences in a building full of interactive windows but also how those preferences could be communicated. For example, if content disappeared when a new visitor entered the house, possible negative social consequences could surface.

Finally, our results indicate that interactive windows may have a profound impact on a person's experience of an entire building. In the content theme, we observed how interactive windows can change how space is navigated and consequently affect the flow of people in a location. This suggests that interactive window design could borrow from current developments in dynamic signage and further enhance the user experience of buildings through dynamic information. Additionally, we observed in the form and content themes that participants were eager to use interactive windows to aid in mundane tasks or deal with everyday randomness (e.g., traffic or weather). As we see that interactive windows can be deeply embedded in everyday interaction, the question of their effect on wellbeing must be raised. Windows with adaptive shading can permanently alter the perception of spaces, and may have an impact on physiological and psychological health. Windows that display notifications may possibly carry the risk of causing (or increasing) information overload. Thus, a key design dimension for a future building full of interactive windows is finding the intricate balance between the additional features and aids interactive windows can offer and possible distractions and disruptions they can produce. We believe that a close cooperation between architects, interior designers, and interaction designers is needed to understand the details of how to design for positive impact for interactive windows. The spatial distribution of windows as well as deciding on where and when interactive features would be available merge as the key challenges to be addressed to build successful adaptive walls with interactive windows.

6 INTERACTING WITH SMART WINDOWS AS UBIQUITOUS DISPLAYS

So far, we have presented our vision of future adaptive buildings using interactive smart windows as ubiquitous displays to change the shape and look of the windows dynamically and to use them as integrated ambient information displays. Also, we have shown that interactive smart windows can be built with currently established technologies. Furthermore, we conducted interviews to prove our vision by investigating possible benefits of interactive smart windows in domestic environments. The results of the interviews show that our participants welcomed the possibility of having smart windows in their homes.

According to our vision, adaptive buildings using interactive smart windows as ubiquitous displays will allow new ways of interacting with buildings in the future, noting that traditional direct touch input modalities and physical switches will be insufficient to utilize the full potential of smart windows.

Regarding future interactions, participants suggested various kinds of interaction modalities in the interviews. Also, they recommended using different modalities depending on the used feature and the user's current context. We explore the interaction space of smart windows with different interaction modalities. First, we investigate how the different interaction modalities are related to each other, and then we investigate mid-air gestures and a smartphone interface as two complementary explicit interaction modalities in more detail.

Using mid-air gestures, users can interact spontaneously with smart windows in their physical environment if the window is located directly in front of them. They do not need to use an additional device to perform mid-air gestures. In addition, users can also interact with smart windows in their physical environment using a smartphone app; thus, they can interact with a smart window without being directly in front of it. We investigate both interaction modalities in a gesture elicitation study. Gesture elicitation studies are a methodology to derive intuitive gestures from the participants [88]. Wittorf et al. [87] conducted a gesture elicitation study to investigate gestures for wall displays. They found that gestures to control wall displays tend to be more physically-based and larger than usual gestures.

According to our vision, smart windows will become ubiquitous displays in the future. Traditional windows have already been an essential part of buildings for hundreds of years and are omnipresent in the physical environment. Therefore, users will interact with their windows in their daily lives more frequently than with other devices such as large displays. Also, smart windows provide the opportunity to change the transparency of the window. The differences between smart windows and other devices, such as large displays, might influence the way users interact with them. We conduct a gesture elicitation study for mid-air gestures as well as gestures on the smartphone to derive intuitive gestures regarding smart windows.

6.1 Interaction Modalities

We envision that future smart windows as ubiquitous displays have to support multimodal interactions. The interaction modalities are chosen based on the controlled functions of the window as well as the specific context of the user. In smart environments, the user will interact implicitly with the smart windows most of the time. However, smart windows should also support explicit input to put the user control over it in situations where the system cannot foresee the user's actions.

6.1.1 *Implicit Interaction.*

Most interactions with smart windows will occur implicitly in the future. The system will gather information from the environment through the use of external sensors such as temperature and light sensors, depth sensors and cameras, as well as tracking devices to capture users' locations and context. In addition to physical sensors in the user's home environment, the system could also have access to their other sensors such as their digital calendars. Intelligent algorithms can transform the incoming sensor data to concrete actions reliably and predictably. If the system has access to Bob's digital calendar, for example, public transport information can be shown automatically on a smart window before Bob leaves for the train station in the morning.

6.1.2 *Explicit Interaction.*

From time to time, users will have to interact with the building infrastructure explicitly. Interaction can be as simple as making a window completely transparent, which can be done with a short voice command or by using a wall-mounted switch. However, more complex interaction would often be needed to adjust parts of the building, e.g., to set up initial regions for glare protection, which will be adjusted implicitly based on the location of the sun automatically afterward. This is more easily achieved by using other modalities than voice input or wall-mounted switches. Useful for more complex interactions are direct touch input, gestures, or interactions with a smartphone app.

We envision that interaction modalities can be arbitrarily chosen and combined so users can use the interaction modalities that match their particular situation best. If Alice is at home and likes to make the lower part of a window opaque to have some privacy and she is not carrying her smartphone with her, she would use mid-air gestures or speech input instead of picking up her smartphone. For example, she could activate the interaction using speech or a mid-air gesture to create a privacy region, then use mid-air gestures to define location and size of the privacy region quickly.

6.2 Eliciting User Interfaces

As a first step towards multimodal interaction with smart windows, we conducted an elicitation study to investigate basic manipulation tasks. We reported parts of this study in a poster published at CHI 2017 [7]. Our tasks are in the context of defining and manipulating rectangular regions relevant for selecting areas on a smart window, for example to initially set up the glare protection. We chose gestures and a smartphone interface as two complementary explicit interaction modalities. We did not include direct touch because of reachability issues with large windows. Also, we found in our conducted interviews that our participants do not want to leave fingerprints on their windows through touch-interaction.

In the elicitation study, we investigated mid-air gestures as well as a smartphone interface. We decided to use mid-air gestures for spontaneous interactions so users do not have to use an additional device when they are located directly in front of a smart window. Also, we investigated smartphone interfaces because users carry their smartphones with them most of the time, which means they do not have to be located directly next to the window to interact with it.

6.2.1 Participants. In total, 16 participants (14 males, 1 female, and 1 unspecified) took part in our study. Our participants were students aged between 21 and 33 years old (M = 26, SD = 2.5). One participant was left handed. We obtained informed consent from each participant.

6.2.2 Apparatus. We used a façade test facility; a two-story timber building at our local university. The facility consists of four test rooms with a glazed south façade. The study took part in a room with a $1.6 \times 2.6\text{m}^2$ LCD-based smart window prototype. Further details according to the used prototype are described in Section 4.4.

We showed the respective window state for the displayed referents,[5] so users were able to look through a real smart window during the study (see Figure 2(d)). We placed a Kinect v2 depth sensor in front of the window and recorded the users' gestures with 30 frames per second.

6.2.3 Referents. We defined 21 distinct actions which users can perform to manipulate sunlight blocking regions on the window. These represent basic actions in four categories and are related to region *creation*, changes in *size* or *transparency* or serve as a *gesture delimiter*. The *gesture delimiter* category only applies to the gesture interface and is for preventing unintended input by starting and stopping the gesture recognition. Actions for each category are as follows:

Creation: Create, delete, select, deselect, move.
Size: Enlarge top, shrink top, enlarge bottom, shrink bottom, enlarge left, shrink left, enlarge right, shrink right, scale up, scale down.
Transparency: Increase transparency, decrease transparency, window opaque, window transparent.
Gesture delimiter: Start detection, stop detection.

6.2.4 Design and Procedure. We used a within-subjects design and asked participants to perform gestures and make suggestions for the smartphone interface. The study took 45 minutes on average, and participants received some sweets as recompense. First, we briefed participants on the topic and the procedure and demonstrated the basic operation of the smart window. Then, participants filled out a consent form and a background questionnaire.

We counterbalanced the order of the interface that the participants used first. We displayed the referents in a randomized order; however, the referents in the *gesture delimiter* category were always the last displayed referents and only shown for the gesture interface. This eliminated priming participants on technical limitations for the other gestures.

For each referent, we displayed the initial state of the system. We told the participants which action the system would perform and then displayed the resulting state. We decided against showing transitions between the states to remove bias towards gestures that try to mimic specific transitions. For the gesture interface, participants were asked to perform the actual gesture. In case of the graphical smartphone interface, we asked the participants how they would perform each action. We also provided an overview of typical smartphone user interface elements for our participants. We audio-recorded participants' answers, and they could also draw sketches on paper. The study closed with a questionnaire about their overall opinion on such systems.

6.3 Results

Participants performed in total 104 distinct gestures for the gesture interface. For the smartphone interface, the participants described 72 distinct interactions. We report on the agreement between participants and present a taxonomy for both interfaces.

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[5] Individual actions are called *referent* in gesture elicitation studies.

Table 2. Taxonomy of Interaction Based on 104 Mid-Air Gestures and 72 Smartphone Actions

Taxonomy of Interaction		
General		
Nature	Physical	Gesture acts physically on objects.
	Symbolic	Gesture visually depicts a symbol.
	Metaphorical	Gesture is metaphorical.
	Abstract	Gesture mapping is arbitrary.
Flow	Continuous	Response occurs after the user acts.
	Discrete	Response occurs while the user acts.
Binding	Absolute	Hand motion causes an absolute change.
	Relative	Hand motion causes a relative change.
	Arbitrary	Hand motion does not directly cause a change.
Axes of Motion	Stationary	User does not move hand during the gesture.
	Horizontal	User moves hand left or right.
	Longitudinal	User moves hand up or down.
	Saggital	User moves hand forward or backward.
	Compound	User moves hand in multiple directions.
Mid-Air Gestures		
Hands	Single	Gesture is performed with one hand.
	Both	Gesture is performed with both hands.
Smartphone Actions		
Fingers	Single	Action is performed with one finger.
	Multiple	Action is performed with two or more fingers.
Target	Preview	Action is performed on the window preview.
	UI-Component	Action is performed on a default UI-component.

Note: General categories apply to both interfaces.

6.3.1 Taxonomy. We categorized distinct actions performed with both interfaces using a unified taxonomy as shown in Table 2. This taxonomy combines and extends two taxonomies from previous work on surface computing [88] and mid-air gestures for blind people [25]. It defines four dimensions that apply to both interfaces and three dimensions which apply to either interface. We directly applied the dimensions *nature*, *flow* [88], and *axes of motion* [25] from previous work.

We redefined the *binding* category which describes how a gesture or action relates to its referent. If the *binding* is *absolute*, changes in hand/finger position during the action directly map to changes on the window. For example, the user grabs the right edge of a region with one hand and moves the hand to the right, and the edge will move in the same direction as if the user were holding the edge at the moment. In contrast, if the *binding* is *relative*, changes in hand/finger position only indirectly map to changes on the window, for example, a user can increase transparency by performing a clockwise rotation with her hand. Actions that do not relate hand/finger motion to changes in the window are categorized as *arbitrary* actions. An example of an arbitrary action is when a user deletes a region by waving his hand.

We added two similar dimensions for the mid-air gestures and smartphone actions regarding number of *hands* or *fingers* used. One-handed gestures may be performed in encumbered situations and may also allow the combinations of two gestures at the same time. For the smartphone actions, single finger interactions are easier to perform when holding the phone one-handed.

For the smartphone action set, we included another dimension regarding the *target* on the touchscreen. Actions can be performed on a *preview* of the window on the smartphone display. These

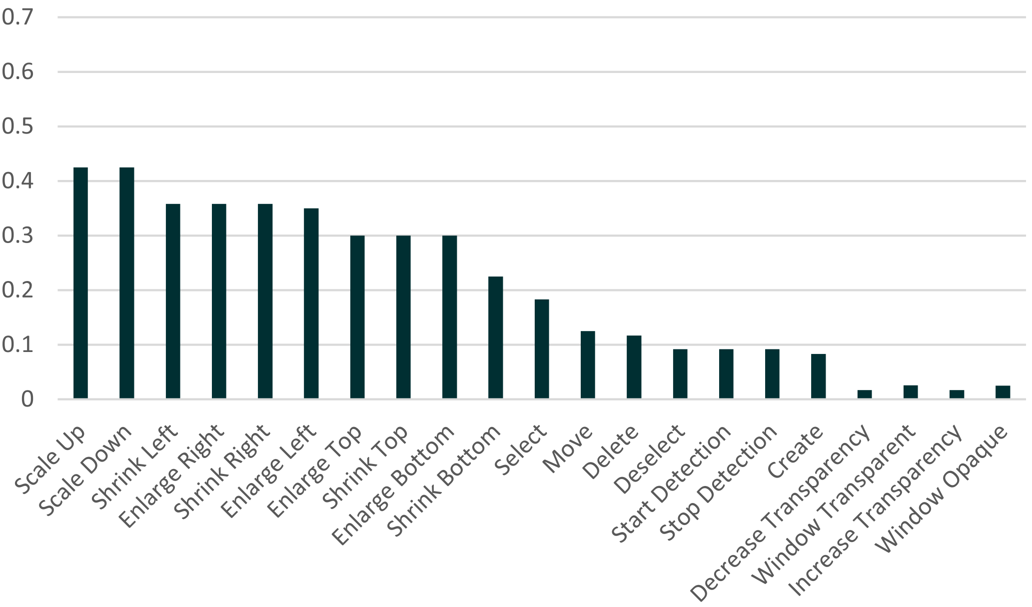

Fig. 9. Agreement rates for mid-air gestures.

actions are typically surface gestures. Alternatively, users can use a default *UI-component*, like a button or slider to perform a specific action.

6.3.2 Categorization of Mid-Air Gestures. Mid-air gestures were mostly performed with *both hands* (57.7%) and *flow* was continuous (67.3%). The *nature* of the majority of all gestures was *physical* (65.4%) especially for the size related referents (93.8%). *Symbolic* gestures were only used to *start* or *stop detection* (21.4%). Other gestures for *delimiter* were either *abstract* (50.0%) or *metaphorical* (28.6%). Number of hands used was highly related to whether the binding was *relative* and *absolute* ($\chi^2(2, N = 82) = 30.03, p < .001$). Gestures with relative binding were primarily performed with both hands (86.7%) whereas gestures with absolute binding were performed with one hand (73.0%).

6.3.3 Categorization of Smartphone Interaction. In contrast to the number of hands used for mid-air gestures, most actions for the smartphone interface were performed with a *single* finger (70.8%) and their binding was mostly *absolute* (58.3%). There was no clear preference in the *nature* between physical (29.2%), symbolic (22.2%), metaphoric (33.3%), and abstract (15.3%). However, *flow* of actions was primarily *continuous* (70.8%). We found statistically significant relations between *target* and *flow* ($\chi^2(2, N = 72) = 27.45, p < .001$). Participants used *UI-components* (66.7%) primarily for *discrete* actions and the *preview* (92.2%) for *continuous* actions.

6.3.4 Agreement Analysis. We analyzed agreement based on the *agreement rate* $\mathcal{AR}$ introduced by Vatavu et al. [78]. The overall agreement was $\mathcal{AR} = .203$ for mid-air gestures and $\mathcal{AR} = .439$ for the smartphone interface. Individual agreement rates for mid-air gestures are shown in Figures 9 and 10 show actions for the smartphone interface. Referents that were *size* related achieved comparatively high agreement rates for the gesture $\mathcal{AR} = .340$ and smartphone interface $\mathcal{AR} = .535$. Participants had difficulties to come up with *transparency* related gestures; therefore, agreement was low.

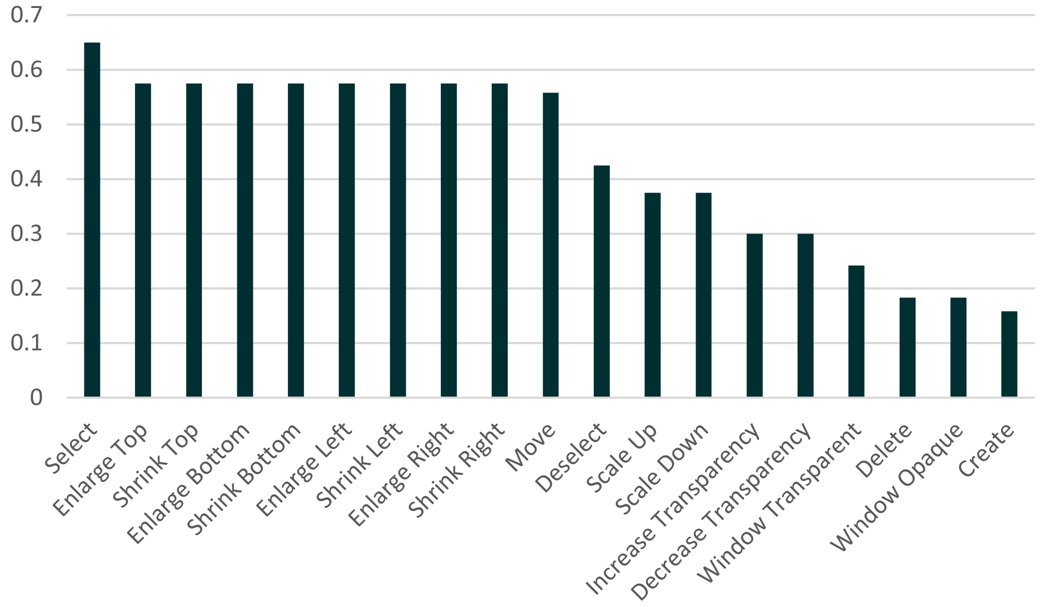

Fig. 10. Agreement rates for smartphone actions.

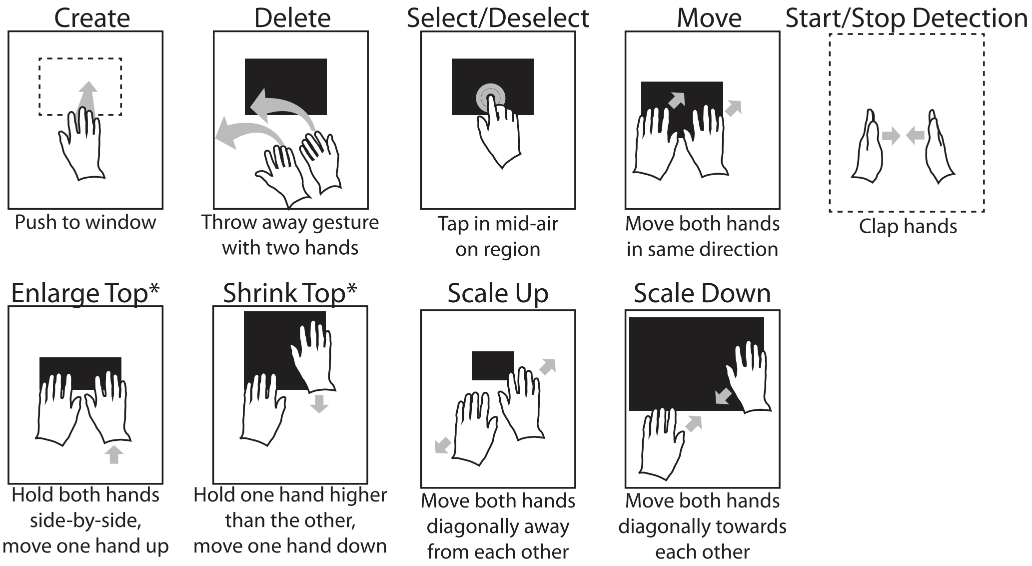

Fig. 11. Gesture set derived from elicitation study. Gestures marked with * are performed accordingly for top, bottom, left, and right.

6.3.5 *A Mid-Air Gesture Set for Smart Windows.* We derived a gesture set based on users' agreements, see Figure 11. We selected the gestures with the highest agreement for each referent. All but three gestures (*create*, *select*, *deselect*) were performed with two hands and participants held their hands open while performing gestures. Participants "pushed" towards the window (2%) to

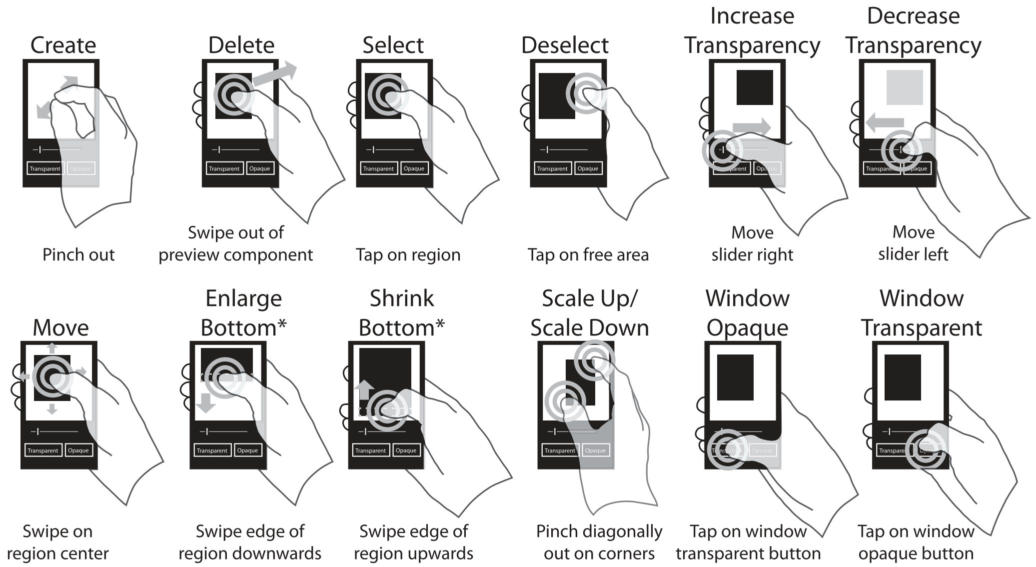

Fig. 12. Smartphone interface derived from elicitation study. Gestures marked with * are performed accordingly for top, bottom, left, and right.

create new regions and "threw the region away" (25%) to *delete* it. Most participants (63%) moved both hands diagonally apart or towards each other to *scale* regions *up* and *down*.

To enlarge a region in one direction, participants held both hands in front of them and moved one hand away from the other. Participants performed inverse gestures to shrink regions, starting with both hands apart and moving one towards the other. We illustrate only the enlarge and shrink gestures for the top edge of a region in Figure 11. Gestures in other directions were performed analogously.

Most agreement (31%) for *start* and *stop detection* was achieved with the clap gesture. Referents in the *transparency* category did not have a statistically significant agreement and were thus excluded from the gesture set.

6.3.6 A Smartphone Interface for Smart Windows. We derived a set of actions for a graphical smartphone interface also based on maximum agreement per referent. The action set is depicted in Figure 12. Five participants chose a pinch out gesture to *create* new regions and most participants (75%) dragged a region out of the preview to *delete* it. Similar to the gesture set, *selection* was done by tapping on a region (81%). However, *deselecting* a region occurred by tapping on a free area (63%).

Most participants (75%) swiped to either *move* a region or *enlarge*/*shrink* the respective edge of a region. Only *enlarging* and *shrinking* a region at the bottom is depicted in Figure 12, other directions were changed analogously. To *scale up* or *down* uniformly, participants (63%) pinched opposite corners with two fingers. *Create* and *scale up*/*down* were the only actions which were performed with two fingers simultaneously. Participants chose *UI-components* for all *transparency* related referents.

6.4 Summary and Discussion

We investigated possible interactions with smart windows and explored two interaction modalities suitable for home environments. In contrast to the interaction with large displays [87] or gaming consoles which require the user's full focus while located at designated locations, we envision the interaction with smart windows to often be a secondary task during activities such as house-holding, cooking, or conversations at any location. Since previous results cannot be transferred to smart windows, we conducted a gesture elicitation study for a mid-air gesture interface that enables spontaneous interactions. Participants further suggested a smartphone interface that enables interaction at any location. This especially supports scenarios in which the user is occupied with other tasks. We followed the methodology proposed by Wobbrock et al. [88] and used the AGATe toolkit [78, 79] for the data analysis. The resulting gesture sets are shown in Figures 11 and 12.

With an agreement rate of $\mathcal{AR} = .439$, the smartphone interface achieved an overall high agreement rate compared to mid-air gestures and various domains presented in previous work [9, 63, 77]. There are two reasons for this: On the one hand, established operating systems (e.g., Android and iOS) have clear and consistent design guidelines for mobile applications to which users get accustomed in their daily usages. These designs make it easier for users to get familiar with new applications, and more importantly, leads to more consistent user interfaces across designers (such as the participants in this study). On the other hand, the touch input vocabulary on recent smartphones is limited to 2D touch positions and thus is more constrained than a mid-air gesture interface.

The majority (70.8%) of the smartphone interface referents can be performed one-handed, which benefits the user especially in encumbered situations such as while performing house-holding tasks. As expected, participants used UI-components such as buttons for discrete actions while the preview was mainly considered to provide feedback in continuous actions. Regions were treated similarly to images on a touch interface so that participants suggested established touch gestures such as swipes and pinches for moving and resizing regions. These scaling operations yielded a lower agreement rate, which could be due to two different methods to scale images: pinching mostly for two-handed use, and double-tap combined with swiping up/down for one-handed use.

Compared to the smartphone interface, the mid-air interface achieved a lower agreement rate of $\mathcal{AR} = .203$. Mid-air gestures comprise more degrees of freedom and, further, are not widely adopted yet. The lack of experience and the higher complexity leads to a lower agreement for all referents across participants. Conforming with findings from Knudsen et al. [44], we noticed that the size of gestures is spatially related to the display space. Also, we observed that our participants tend to use both hands for the mid-air gestures for smart windows whereas they prefer interacting with the smartphone interface with one finger only. This confirms the results of previous research that the size of a device moderates the performed gestures [61, 87] and interactions larger devices are more likely to promote whole-body gestures [87]. However, Wittorf et al. [87] found that public display gestures (for operands other than "resize") were primarily one-handed, while in our study the suggested mid-air gestures for manipulating a region were always executed with both hands. This constitutes a difference between smart windows and wall displays. Size-related gestures achieved above-average agreement rates both for the mid-air gesture interface ($\mathcal{AR} = .340$) and for the smartphone interface ($\mathcal{AR} = .535$). Participants also did not focus on specific hand postures while performing these gestures. Thus, an implementation can neglect the hand posture for the majority of gestures. Not only does this simplify the implementation, but it also allows the user to perform gestures when holding objects.

We had to remove all transparency related referents from the gesture set due to insufficient agreement among participants. One reason for this could be that transparency is a more abstract concept than physically moving objects and users have no clear mental model for it. Furthermore, users typically do not adjust transparency outside of graphics software. Results from the smartphone interface support this assumption as all transparency related actions are represented via abstract UI-components like sliders and buttons. To address this challenge, the users' expectation of this abstract concept needs to be thoroughly investigated in a future study to gain an understanding of user mental models. Results of such a study could then be used to derive more intuitive and consistent interactions for manipulating transparency.

We also recognize that in order to execute the study, we needed to make choices that may have affected its outcome. First, the study was the participants' first encounter with an interactive window. Consequently, we recognize that the results may have been influenced by the novelty effect. However, we see our gesture set as primarily an indication that gestural interaction for interactive windows is desirable and envision that future studies will refine our results. Second, our study was limited to the tasks for which we elicited gestures. We chose the referents based on user expectations reported in the interview study. Again, novelty effects may have affected this choice, and thus more gestures may be required as interactive windows become more readily available. Finally, we chose to not account for legacy bias in the study. While some studies show that legacy technologies may influence the interaction techniques suggested to users [55], other studies have failed to confirm this [37]. As we wanted to address many tasks (given the explorative nature of this work), we elected to reduce the burden to participants by not introducing techniques that possibly reduce legacy bias.

In summary, we explored two complementary modalities for interactions with smart windows. The elicited gesture sets are a first step towards interaction with houses where architecture, especially window locations and shape, may be defined interactively by inhabitants and not statically by an architect. In future work, we plan to perform long-term studies in such buildings to evaluate our gesture set and to receive feedback on users' perception and usability.

7 DISCUSSION

Here, we take a holistic look at our vision and put it in the perspective of the results of the two studies. To that end, we first present design dimensions for interactive windows elicited in our work, then we discuss emergent research challenges that stem from this research.

7.1 Design Dimensions for Interactive Windows

Our work points to certain aspects that designers of future interactive windows and buildings that house them should consider. These design dimensions are intended to work as a "checklist" that helps to ensure that key facets of the future design are addressed in the design process.

7.1.1 Architectural Integration. In both of our studies, we observed that participants often considered and referred to the architectural context of an interactive window. To build interactive windows that fit well in everyday environments and become meaningful situated artifacts, considering the location of the window is key. What is important is that location is not understood here in the classical computing context, i.e., the geographical position of the object. Instead, it becomes a more complex, partly qualitative concept. Designers should not only consider where a window is situated, but also a number of additional aspects such as: what side of the house is the window exposed to and thus what sun conditions are to be expected, what is the regular view outside of the window (e.g., busy street or forest), what floor is the window located on, is the window perpendicular to the floor or at angle. Similarly, past work in media architecture has shown that dynamic architectural elements must seamlessly coexist with static elements [89]. As a consequence, we suggest that future designs include an enhanced understanding of the architectural context of an interactive window.

7.1.2 Content Curation. Our studies illustrate that a key question that will determine if interactive windows can be integrated into everyday environments is how users can be empowered to curate content for their interactive windows effectively. Both private and public spaces can benefit from content selection, and every interactive window system should address how this is to be achieved. We also observed that participants preferred to show only a single kind of content at the same time and only when necessary. This implies that content switching and the means to deliver content on demand are other key considerations. Also, participants preferred to display pragmatic content, like weather information, pollution, and information about public transport. This in line with the results of a study by Ventä-Olkkonen et al. [80]. Consequently, future interactive window systems should explicitly address how content for the window is to be selected, switched, delivered, and curated in order to foster the possibilities for domestication.

7.1.3 Context Awareness. Our work shows that high context awareness is a highly desired and almost necessary feature of smart window systems. The participants in our study assumed that interactive windows would be an effective extension to their growing device ecologies [41]. Given that an ever increasing number of assistive technologies is expected both at home and in public places, the interactive window must be designed to integrate into the existing automation landscape of a location. As a window is expected to assume many roles, from a transparent sheet of glass to an interactive whiteboard, its perception needs to change from a static architectural object to a versatile media space. This can only be achieved through context-based adaptation. In public spaces, interactive windows are expected to help navigate spaces, e.g., by showing room availability. This implies that future windows will be expected to sense who is looking at them and what that person's needs are. Designers of interactive windows should consider how their systems can benefit from existing sensing, fit into existing Internet-of-Things ecologies and, consequently, deliver context-aware experiences. In this dimension, our work shows that the insights for wall-sized objects presented by Wouters et al. [89] are also valid for smaller, window-sized interactive artifacts.

7.1.4 Implicit and Explicit Interaction. While exploring interaction modalities for smart windows, we found that participants had no preference for a specific input modality or thought of defining glare protection via touch, gestures or a smartphone app. As interactive windows are expected to switch roles and offer multiple functionalities based on context and current needs, we see a need to develop alternative simultaneous input methods. We believe that legacy bias may play a role in the interaction modalities requested by the users. Further, as interactive windows may represent large interactive surfaces, users will be drawn to use the vast interaction space. Expressing the desire to use windows as whiteboards-on-demand suggests that interactive windows may possess what Dillenbourg dubbed a "socio-constructivist flavor" [24]—their large surface may provoke creativity and building things. It remains a question of if and how designers of interactive windows can borrow interaction techniques from other devices that possess similar qualities, such as tabletops [24] or Large High-Resolution Displays (LHRDs, [57]). Future interactive windows should offer a multitude of interaction techniques and design input tailored to their many functionalities. Our work explored two modalities and offers clear starting points for using gestural input and remote smartphone application control, but further research is needed to explore how different control modalities can intertwine to produce efficient and engaging experiences with smart windows.

7.1.5 Social Aspects. Social dynamics and who was present around an interactive window were often addressed in our results. Content appearing on smart windows is likely to have social consequences both in private and public settings. One consideration that emerges is how windows can adjust to the social dynamics around them. Desired actions may range from simple privacy issues, e.g., not displaying private content while there are guests in the house, to complex features such as shading conference rooms to moderate heated arguments. Further, as mentioned before, interactive windows that help navigate buildings and determine how shared space is used can impact the well-being of groups, the way work is performed and how communities are organized. These examples show that interactive windows may possibly have a profound impact on social behavior. As a consequence, smart windows should not only offer social features but also actively empower users to develop content, as was suggested by Wouters et al. [89]. Thus, when considering designing an interactive window system, designers should analyze the windows' possible social context in detail, consider the social impact the window can have on users and groups of users, and make sure that the user groups are provided with appropriate tools to curate the social content displayed.

7.2 Emerging Challenges for HCI

So far, we have considered aspects in designing interactive windows that can be addressed by conducting further design studies and designing new systems using means that are already available, as illustrated by our proof-of-concept prototype. Next, we identify key challenges for HCI posed by our vision of adaptive buildings and confirmed by the studies conducted in this article. The challenges we present here are specific to interactive windows and stem from a system-centric perspective as they are primarily informed by our prototype. Yet we believe that many parallels can be drawn with previous work, particularly with media façades [22]. Thus, we believe these challenges are applicable to a range of dynamic large-scale interactive systems that can transform static architectural artifacts into dynamic spaces.

7.2.1 Towards In-Situ Prototypes. In our work, we have shown that building an interactive window is possible and can be done at a fidelity that enables conducting controlled studies with prospective users. However, as our work has revealed that the physical and social context of interactive windows is a key consideration for users, moving on to studies with increased ecological validity is a logical next step. This, in turn, poses several challenges. First, there is the pragmatic question of how many prototypes need to be built and deployed to consider a space transformed into an adaptive building. While initial studies may use single displays, our work suggests that deployments that change architectural spaces show much promise. Future research will have to answer when space can be considered an adaptive space that could lead to insights about adaptive buildings. Second, as deployed prototypes are likely to transform spaces where users live or work profoundly, legacy and novelty bias will be of particular concern. It remains a challenge to create methods that would slowly introduce users to interactive windows in order to avoid rapid changes likely to produce a negative response and negative user experience. Finally, the field of HCI will need to investigate if methods known from studying other interactive surfaces in the wild [17, 70] can be applied to understanding interactive windows.

7.2.2 Engaging in an Architectural Dialogue. Our work has shown that a transitional architecture with windows possibly changing to walls enables new opportunities for an architecture shaped dynamically according to user needs. As interactive artifacts begin changing how physical spaces are organized and shape the experience of entire buildings, interaction design is crossing into space traditionally addressed by architecture. While there is some crossover between research in HCI and Architecture, interactive windows appear to require specific cross-disciplinary understanding. That is why we believe that engaging in a deeper dialogue with the architecture community about interactive windows is necessary. On a knowledge generation level, HCI needs insights from architecture to build an understanding of the contextual factors in designing interaction techniques for interactive windows. On the practitioner level, we should address how to communicate insights so that architects are aware of the opportunities offered by interactive windows.

Simultaneously, interaction designers should find the means to emphasis with the architectural setting to design engaging interactive experiences.

We believe that our work offers a generative contribution that can be utilized as a starting point for a discussion about new architectural designs. We recognize that this article emphasizes a practical approach based on a proof-of-concept prototype. As the interplay between visual, architectural and interaction design is yet to be fully explored [1], we hope that through contributing a working, replicable interactive window, we offer an example of an interactive artifact that can stir cross-disciplinary discussions. We hope that our work can inspire the development of more systems that challenge our thinking about architecture thus, ultimately, inspiring programmatic thinking in human–building interaction [66]. Our results show that further research in the intersection of architectural design, interaction design, and interaction technologies is required to realized the potential behind wall displays.

7.2.3 Readdressing Privacy, Sharing, and Usage Models. In this work, we consider interactive windows to be a form of a ubiquitous display. If interactive windows are deployed in a building, display space will become abundant, and the amount of content that can be displayed will increase. This, in turn, will lead to content appearing in new spaces and new context. As information will be possible to display in almost any place in the building and visible to anyone in that space, developing a new understanding of privacy and sharing with regard to ubiquitous displays is needed. We observed how multiple factors such as time of day, group composition or weather contribute to what data can be possibly displayed on an interactive window. Combined with enhanced activity sensing and other contextual input, HCI needs to build an understanding of how users can effectively define privacy rules for ubiquitous displays. Interactive windows provide privacy and share an added spatial dimension, which may offer benefits to interaction, but also calls for more refined controls.

Ubiquitous displays at home will also pose challenges to research in user modeling. New models of usage will need to be developed to account for the prolonged exposure to interactive windows. These models will need to embrace the central notion of a window being primarily an architectural element. Thus, current models that are known from the pervasive display research field [23] will need to be redesigned for the smart home scenario. Furthermore, the notion of presence in front of the display will also change and call for new models. Future designs should explore new presence patterns, typical of what happens at home, such as ludic interaction [27] or the importance of festive occasions [43]. Reflecting the changing dynamics of what happens inside a home will pose new challenges in the temporal aspects of smart window content. Here, designers of smart windows can be inspired by arbitrary start time, and duration scheduling approaches, as previously proposed in the public display field [26].

7.2.4 Revisiting the Notion of "Home" in HCI. Our work also casts a new shade on understanding interaction design for everyday artifacts for home spaces. Designing situated artifacts has a long tradition in the HCI field. Research contributed a large number of artifacts designed to inhabit home spaces to provoke reflection [72], support relationships [45], or help in home coordination [53]. When walls and windows become displays, the contextual factors involved in designing artefacts for the home will be altered. Thus, the HCI field will need to readdress the design qualities an artifact for everyday interaction at home should possess. Gram-Hansen and Darby [29] suggested four dimensions for understanding a smart home, which can be used to inspire future designs that use interactive windows. First, they postulate that smart homes should emphasize security and control, which is confirmed by our work. Further, home as a place for activity is to be reflected in the design of artifacts for the home, which relates to our consideration about context. Our work also emphasizes the social context of interactive windows, which fits into

Gram-Hansen and Darby's notion of "relationships and community." Moreover, interactive windows and all smart home artifacts should reflect the values and identities of the homeowners. We believe that smart windows can play an active role in that process as media for creative expression and making the home a personalized space. For instance, interactive windows can be used to introduce liveliness [85] to home spaces and augment the experience of bringing cherished places to the home.

Finally, introducing interactive windows to a smart home will affect the role of what is now the primary display in most homes—the TV. Research in interaction design for television indicates a growing trend for spatially distributing video content [68]. Interactive windows will enable further alternative views. Displaying content on windows in spaces where it was not possible before will enable watching with less attention, which was reported as a desired feature [54]. Further, interactive windows can deliver imagery at low brightness levels and in a less obtrusive way. This will enable using TV content for relaxation and sleep help [54], without the drawbacks of traditional screens such as the bright light involved.

8 CONCLUSION

In this work, we presented WindowWall; our vision of adaptive buildings that use self-contained smart windows as ubiquitous displays. We envision that adaptive walls will introduce entirely new user experiences in the home and office of the future. Adaptive buildings use smart windows as walls and support changing architectures, for example, by interactively controlling the natural indoor lighting on a fine-grained level or by making the window layout dynamic. Furthermore, interactive smart windows in adaptive buildings can be used as ubiquitous ambient displays to provide information to the inhabitants or to communicate public information to people passing by.

We built a smart window prototype that showcased our vision using currently available technologies. For the prototype, we used passive matrix LCD panels with TN-LC technology. In addition, we installed LEDs around the edges of our smart window to display colors through edge-lighting. Our prototype can control the sunlight transmittance on a fine-grained level and enables using the window as an information system.

We used the smart window prototype to investigate different application scenarios in domestic environments with an interview study with 12 participants. Our results show that our participants welcomed the vision of having smart windows to adapt their homes and use them as ubiquitous displays. Users reported that they anticipated smart windows to support their daily routines extensively. We provide specific insights about the form and content to be displayed on smart windows. We also chart the contextual factors involved in designing for smart windows. Furthermore, we investigated interactions with smart windows through a gesture elicitation study. We derived a set of mid-air gestures and built a graphical smartphone interface for fundamental smart window interactions. In contrast to gesture elicitation studies in other domains (e.g., large displays), we found that the mental model for interacting with windows are leaned more towards physicality. Finally, we identified design dimensions as well as challenges that have to be explored before smart windows can become ubiquitous.

Our work constitutes the first step towards adaptive walls that use interactive smart windows as ubiquitous displays for adaptive buildings. We hope that our research can stimulate further interdisciplinary exploration of spaces augmented by interactive windows and help build a better understanding of future ubiquitous display environments.

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