A Media Architecture Approach to Designing Shared Displays for Residential Internet-of-Things Devices

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Figure 1. Low-resolution displays in two opposite residential contexts: Flip-dot displays installed at two households showing the comparison of energy consumption in the neighborhood (left), LED display deployed in the living room area of a household, displaying solar production and energy consumption (right).

ABSTRACT

Research on media architecture to date has predominately focused on the integration of digital technologies, such as low-resolution media façades, into urban environments within a public context. In this paper, we present an analysis of two case studies, which investigated the use of low-resolution display technologies within a residential context for visualizing data streams generated by Internet-of-Things devices. Each study involved the deployment of a display prototype and both studies focused on visualizing electricity data. The first study used the front yard as a deployment location to encourage friendly neighborhood competition on electricity consumption and the second study focused on visualizing the performance of residential solar panels in the home. The paper discusses how we used media architecture principles as a framework to inform the design of both prototypes. Based on an analysis of the two cases, we present seven design insights for residential low-res displays as well as a series of design recommendations for residential media architecture.

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CCS CONCEPTS

• **Human-Centered computing → Interaction design.**

KEYWORDS

Media architecture; ambient displays; urban informatics; data visualization; internet of things.

1 INTRODUCTION

With the rise of the Internet-of-Things (IoT) paradigm and its application spreading into the private domain, more and more data streams are being generated by electronic devices distributed in the residential environment. Currently, the most common approach to monitoring and observing these personal data sets is to view them via dedicated apps or websites on personal digital devices such as smartphones or tablets. This approach can be a limiting factor when it comes to deeply engaging with the data and users' ability to make behavioral decisions based on the feedback gained from these IoT devices: First, it requires users to install and then actively open a specific app or website. Second, users who are not technically skilled may experience challenges with accessing and interpreting aggregated information [27]. As a result, data sets on environmental aspects, such as for example, electricity consumption, water usage, air quality, and so on, often remain undiscovered.

The aforementioned challenges hinder the full potential of the utilization of available data sets, as they create barriers for people to engage with on-going hidden processes that may have an impact on their lives [48] or that may allow them to adopt more sustainable ways of living [42].

In this paper, we address these limitations of current IoT devices by investigating the use of embedded displays that facilitate a shared discourse and exploration of relevant data sets. We position our investigation within the context of media architecture, which has played a leading role for defining the integration and use of digital media within urban environments. As a framework, media architecture offers a unique approach, which emphasizes aesthetic [12, 19, 54] and social [1, 6, 16] concerns over technological considerations. The studies presented in this paper also build on knowledge from human-computer interaction (HCI), in particular research on pervasive displays and eco visualizations, and on situated and embedded data representations [46, 50]. It is becoming increasingly clear that future urban environments will be saturated with digital media displays [11], which creates new opportunities for displaying relevant information to people when and where it matters [3, 42, 43]. Through this paper, we suggest that in a similar way to how media architecture principles contribute to the long-term success and acceptance of such displays [10, 47], the same principles can also be applied to create shared displays in the residential domain that incorporate aesthetic and social considerations. In other words, the paper suggests that when designing displays for visualizing IoT data sets, it is equally important to carefully design the right content as well as the right physical appearance and integration of the display technology.

To date there have been only very few attempts of applying media architecture in the residential domain. Wouters et al. presented a series of situated public displays that were attached to house façades and designed to facilitate communication and interaction between households and their local neighborhood [52, 53]. The situated displays were developed through a participatory design process resulting in solutions that were specifically customized to the needs and context of each of the three households. Vande Moere et al. deployed low-fidelity displays that resembled chalkboards, which were installed at the front façade of five terrace houses [48]. The information on each display was manually updated daily to reflect the household's electricity consumption in an attempt to encourage a playful neighborhood competition and a discourse on sustainable ways of living within the local neighborhood.

The paper extends this previous work on media architecture in the residential domain by reporting on our experiences and insights from two case studies. Both case studies used media architecture technology in the form of low-resolution displays for visualizing electricity consumption data on a local scale in different residential contexts (outdoor / indoor, semi-public / private). The paper reflects on those studies with the aim of acquiring a better understanding about the use and acceptance of low-res media architectural interfaces in a residential context, which has not been extensively studied yet. Our contributions are 1) a synthesis of media architecture principles and an evaluation of their applicability in the residential domain, 2) design insights for visualizing personal data sets through shared displays in semi-public or private spaces, and 3) design recommendations for residential media architecture.

2 BACKGROUND: MEDIA ARCHITECTURE PRINCIPLES

The rapid development of efficient lighting technologies at an affordable cost, has driven the creation of new architectural designs that use digital media to dynamically transform the outer shell of a building [18]. As media façades have now become a global phenomenon [21], researchers from various disciplines have begun to explore its social, spatial and technological aspects under the umbrella term "media architecture" [4, 5, 9, 10]. While initially focusing on the design of building-scale displays integrated into the built environment, the term has expanded to include urban media applications beyond screen-based technologies [52] and such that can take on a range of scales [42]. Due to the fact that the field is still developing, there are only a few comprehensive definitions of media architecture available to date such as, for example, the following by Brynskov et al. [4] who describe media architecture as an *"overarching concept that covers the design of physical spaces at architectural scale incorporating materials with dynamic properties that allow for dynamic, reactive or interactive behavior"*. To translate knowledge from media architecture into new design contexts, such as the residential domain, it is necessary to first establish an understanding of the design principles in "traditional" media architecture. With traditional media architecture, we here refer to prestigious media architecture in predominantly urban locations. Based on a review of previous work and our own experience with working in the field, we identified five media architecture principles.

One important principle that has been widely discussed within the research community and that distinguishes media façades and media architecture from conventional flat and rectangular public displays, is the **physical integration** of display technology within architecture [7, 18, 19]. Based on a survey among architects that had to assess the perceived architectural quality of 24 media architecture projects, Wouters et al. found that projects aligned with the overall architectural design rationale, were more likely to be perceived positively than those that incorporated retrofitted media displays onto existing architecture [54]. Thereby the level of display integration is manifold, including: high-res screen-based displays and projections that augment existing architectural structures, low-resolution pixel units that are interwoven in the outer shell of a building [18], LED displays that can be flexibly mounted to any surface [7, 40], architectural illumination, and the embodiment of information in the landscape and architecture itself [31, 32]. Besides the integration of display technology, also the spatial layout, including viewing and interaction zones, needs to be taken into consideration for a successful architectural integration of media architecture into the urban fabric [13].

Another principle that is integral in particular to screen-based media architecture relates to the **material aesthetics** of the medium. This principle is related to the issue of physical integration, however, the emphasis here is more on the intrinsic qualities and haptic visuality [38] of the utilized medium. Based on Marshall McLuhan's work ("The medium is the message"), Ebsen introduced the concept of "material screen" and referred to media art and architecture practices, which approach the screen not only technologically as a means to frame visual content but as an aesthetic material in itself [12]. Well-known examples include the media façade works by realities:united, which often use low resolution, low-tech display technologies and unconventional pixel shapes, such as the circular fluorescent lamps in the BIX façade of the Kunsthaus in Graz (see Figure 2-1). As such, media architecture can create sublime experiences [14] that go beyond what can be conveyed through conventional screens [12, 38] and establish an atmospheric mood (see Figure 2-3), which – according Wouters et al.'s analysis – particularly relevant to indoor environments [54].

Other reoccurring questions revolve around the **communicative and informative aspects** of media architecture. Often media architecture is interpreted and used as a communication channel that is addressed to the public instead of individuals [49], such as: applications informing urban dwellers about infrastructural issues and maintenance processes in the city [28], raising awareness of environmental and social issues [34, 35, 45], enabling participatory processes and civic debates [6, 13], or transforming public spaces into augmented playful environments [22] (see Figure 2-2 and Figure 2-4). Designers have to consider not only *what* but also *how* to communicate to the public, thereby seeking for novel and creative visual representations [54]. In the same way, it is appropriate to question whether media architecture has to communicate information at all, even though information is often conveyed also through implicit modes, such as the intrinsic qualities of the architecture itself [32].

In particular, in the case of communicative and informative media architecture, the consideration of **contextual aspects** plays an important role for a successful deployment in public spaces [47]. Coining the concept of situated urban visualizations, Vande Moere and Hill stress that visualizations embedded in the form of physical displays, need to respect and respond to the characteristics of the surrounding place, providing information that relates to the local context and that offers socio-cultural relevance for the local population [46]. In the past, several real-world projects were reported to have failed, for instance, due to top-down design strategies applied by the responsible public authority [23] or changes in the societal perception of the operator [47]. In this regard, Dalsgaard et al. highlight the need to balance various stakeholders' interests as a challenge to be tackled in media architecture projects [9].

Finally, media architecture with its communicative power and placemaking capabilities is seeking to facilitate and improve **social interactions** in the urban environment [41] and to stimulate essential needs in public space, such as active and passive engagement [29]. In the past, researchers have investigated how various design dimensions, such as spatial layout, scenography and interaction technique foster specific forms of social interaction patterns and behaviors [20]. Others explored various application areas for social urban media applications, highlighting the potential that these technologies provide to enable civic participation [39], cross-municipal exchange [35] and social inclusion [15].

Figure 2. (1) Low-res media façade of the Kunsthaus Graz in Austria (top left), (2) interactive media façade installation controlled via twitter (top right), (3) indoor installation "*The Weather Project*" (bottom left), (4) full-body interactive light and sound installation. Photo credits: (1) © Norbert Eder via Flickr (CC BY-SA 2.0), (2) © Public Visualization Studio, (3) © wonderferret via Flickr (CC BY 2.0), (4) © Luke Hespanhol.

As interactive experiences are increasingly prevalent in the built environment, interactivity has also become an important aspect in media architecture research [23]. However, we do not see interactivity as a principle in itself. Rather, we suggest that for interactive media architecture to be successful, it needs to meet the aforementioned principles.

3 TWO CASES: DESIGNING RESIDENTIAL LOW-RES ELECTRICITY FEEDBACK DISPLAYS

This paper draws on two case studies that we conducted in Sydney (Australia) between 2013 and 2016. As one of the authors was involved in both studies, the latter study built on the insights developed in the first study. However, the studies each had their own unique objectives, which have been reported on in other publications [24, 25, 43, 44]. Both studies had in common the use of low-resolution displays in urban residential areas to make locally relevant data sets easier accessible and to create shared experiences when reading, interpreting and interacting with those data sets. Electricity feedback as a form of eco feedback [26, 33] was chosen since 1) it has been studied in depth, meaning there was a large foundation we were able to build upon [2, 3, 36, 45], 2) electricity usage represents implicit information that is easy to collect, and 3) as it is a topic of social relevance, making it easier for our study participants to relate to

		Case Study	
		Flip-Dot Display	**Light-Shifting Display**
Display	**Technology**	electro-mechanical display	LED-Display
	Color depth	1-bit monochrome	true color (24-bit)
	Resolution	56 x 14 pixels	17 x 12 pixels
	Max. Frame rate	up to 10 fps	up to 60 fps
	Outer dimensions	90x26x9cm	61x39x12cm
Content	**Displayed information**	household energy consumption	household energy consumption & solar production
	Number of visualizations	8	5
	Temporal context	live data (1), trends and past data (7)	live data (3), trends and past data (2)
	Measurement scale	relative	absolute (2), relative (3)
	Visual representation	numeric (2), pictorial (6)	numeric (1), pictorial (4)
Interaction	**Remote Interface**	app to control content; running on a dedicated, stationary tablet	responsive web app to control content and customize representations accessible on any device in local network
	Physical Interface	button to trigger short animations	rotary knob to control brightness

Table 1. Comparison of the two low-res display cases.

the aims of the study. While we are building on previous HCI research on eco feedback systems, we were less interested in the behavior change aspects or proving actual energy savings, but rather in how display owners and their social environment (e.g. family members, friends, neighbors and passers-by) react when presented with personal information in a semi-public/private context. To obtain a holistic view of the residential context, thereby taking into account the diversity of situations and places, in which ambient personal information can be staged, we investigated two distinctive design situations (Table 1). We describe each of the cases briefly below.

3.1 Case 1: The Flip-Dot Display

In the first case (Figure 1, left), we designed a low-res display for the semi-public context, displaying domestic electricity consumption at the street. The Flip-Dot display, therefore, enabled sharing of data with and between neighbors and with passers-by.

3.1.1 The Display. We aimed for a display technology that would fit the built topology and character of the residential domain while supporting the cultural form that might be attributed to it [51] and conveying a sense of playfulness [17]. We consequently reviewed a large number of display technologies, including electronic paper, LED matrices, LED sculptures and mechanical systems. Each technology was evaluated against the metrics of electricity consumption, modularity, resolution, physical size, artistic character, aesthetic quality and costs. Based on this initial evaluation we decided on using flip-dot panels, a relatively little used mechanical display technology that is based on a grid of small circular discs. Each disc represents a pixel that can be individually flipped by electromagnets to show either a black or a white dot. It is therefore clearly visible in bright daylight and is highly energy-efficient compared to light-based displays. Apart from these practical advantages, flip-dot displays are generally not associated with commercial applications and offer a visual low-key appeal that we considered suitable for a residential context. We deliberately chose a narrow and wide ratio to reduce any potential resemblance with conventional computer displays or TV screens, while also adding to the system's ludic qualities. A push-button was located on the side of the display to allow passers-by to interact with its content (see Figure 3 – top).

3.1.2 The Data Visualizations. We designed eight distinct visualizations of the household's electricity usage. The visualizations were chosen to work with the low resolution of the public display and to include a wide range of alternative representations of electricity data. This included different types of visualizations, such as numerical, pictorial (see Figure 5) and charts, as well as aggregations of data over various time periods. Two of the visualizations represented a direct comparison of the household's data to their neighbor's data (see Figure 1, left).

Each visualization consisted of a main view (e.g. "42% less"), followed by one to two views to provide further information (e.g. "electricity" and "than one day ago"). The display continuously cycled through these views, showing an invitation to push the button at the end of each cycle (seen in Figure 3 – top). The low resolution of the public display required us to drastically simplify the visualizations. The general purpose of the display was clearly communicated using words like "electricity" or "usage" in one of the display views, however the exact interpretation of some of the representations remained ambiguous. We chose to include this level of uncertainty in our design to encourage subjective interpretation and enable people to reflect upon their experiences and aspirations [37].

To include a more playful visualization of the rather factual electricity data, we developed three short animations that were driven by the consumption behavior of all participating houses. For example, in one of the animations, a flock of birds would congregate at the house using the least amount of electricity. The animations were played back in random order in response to activating the push-button at the display.

3.1.3 The Control Interface. To control the content shown on the public display, we built an app, which ran on a dedicated tablet device (a 7-inch Blackberry Playbook, Figure 3 – bottom). The tablet was configured to be always on, providing energy feedback at a glance through two different dashboard views, each containing four distinct visualizations. Users were able to share a particular visualization on their own and their neighbor's Flip-Dot displays through activating the according panel. Taping an already active panel would turn the Flip-Dot display into an idle mode, in which it showed subtly animated flowers. Having both the semi-public Flip-Dot display and the tablet app showing the same data, enabled us to be more playful in the visual representation on the Flip-Dot display, while conveying a sense of trust through the more utilitarian tablet device.

3.1.4 System Implementation. We built two custom-made waterproof cases housing the flip-dot panels, which could be either hung onto a fence with a planter box hook or simply placed on a flat surface, such as a brick wall (Figure 1, left). The two displays were connected with two cables for power (24 volts) and data, and one of the displays was connected to a central control unit located inside one of the houses. The electricity measurement was based on OpenEnergyMonitor[1], an open-source platform providing wireless sensors, a base receiver, and server software for statistical calculations. Using a local area network ensured the privacy of the recorded data.

Figure 3. The Flip-Dot display with the push-button located on its side for triggering a data-driven short animation (top), and the tablet app to control the content on the low-res display (bottom).

3.1.5 Deployment Study. The Flip-Dot display system was deployed in two locations to incrementally improve its components. In the first location, the display was installed for one week in a semi-house with a single mother and her three children (between 3 and 7 years), from hereafter referred to as C_1-H_1 (for case study 1, household 1). In the second location, two connected Flip-Dot displays were installed for a period of 20 days at two family houses that were located next to each other (see Figure 5) and offered similar characteristics: a couple and their two children, 5 and 8 years (C_1-H_2), and another couple and their two children, 10 and 12 years (C_1-H_3). The Flip-Dot displays were attached to the fences of each house, in order to make them visible for neighbors and passers-by. The tablets were installed inside the house, in a place chosen by the participants. Participants received a brief explanation of the system and were encouraged to explore the system's use in their domestic everyday lives. We conducted an interview with C_1-H_2 and C_1-H_3 half-way into the study at which point we deployed some updates based on the interview and again after the study.

3.2 Case 2: The Light-Shifting Display

In the second case, we collaborated with a green-tech company, Solar Analytics, to design a low-res display that was used to visualize the performance of solar panels in a private domestic context (Figure 1, right). The display served as an alternative output channel to the existing web-based online dashboard. Its ambient character allowed for sharing data amongst people living in the same household as well as visitors.

3.2.1 The Display. As the display was intended for indoor-use, we aimed for a display technology that would create a pleasant lighting atmosphere. Falling back on LED technology, we designed a display concept that could dynamically change from *discrete* (showing individual pixels, see Figure 1, right) to *continuous* representations (showing a diffused layer of light, see Figure 6). Being able to dynamically switch between two representations expanded the design space in the following ways: (1) wider support of visual content that can be displayed, and (2) exploring a cross-functional product that can transform its appearance and function from a standard pixel-based display, suitable for daylight use, into a luminaire, suitable as ambient background lighting source during evening times.

3.2.2 The Data Visualizations. We created two visualizations for the discrete mode: one simple numeric visualization displaying the current energy production and consumption (see Figure 1, right), and a second visualization showing the current energy consumption and production through circular area charts, providing information about the energy balance just by glancing at it. We further created three visualizations for the continuous display mode: a bargraph to indicate the energy consumption of the last 15 minutes, a graph consisting of three squares to encode the total consumption of each of the last three days via brightness and size (see Figure 6), and a visualization that displayed current electricity balance through speed and amount of randomly occurring particles.

3.2.3 The Control Interface. For important functions such as turning the display on and off and dimming the brightness we attached a rotary knob at the top of the display's housing (see Figure 4, right). For controlling all other features, we created a web interface that could be accessed on any device that could run a web browser (see Figure 4, left). For each visualization, customized settings could be made, such as changing its predominant color. Additionally, the mobile interface provided short descriptions for each visualization to support users to learn the meaning of the ambient information encodings.

3.2.4 System Implementation. All hardware components were built into a single-piece wooden housing with an acrylic resin plate as a front featuring an even light distribution. To create round pixel dots in the discrete mode, we attached 3D-printed reflectors to each individual LED. For a planar light distribution in the continuous mode, the distance between the diffuser front

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[1] https://openenergymonitor.org/

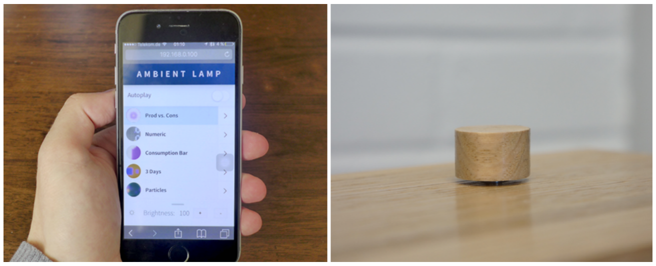

Figure 4. The web app to control content and representations of the Light-Shifting display (left), physical knob to control the brightness (right).

panel and the light source was increased to approx. 4cm using stepper motors that moved the LEDs behind the front panel forward and backward. We used 17 high-power RGB LED strips with 12 single controllable LEDs, which were controlled via an ArtNet DMX Ethernet controller.

The software running on a Raspberry Pi 3 consisted of two modules: (1) a Java program for retrieving the real-time data from the Solar Analytics API, creating the visualizations using the Processing's core library and controlling the involved hardware components, and (2) a web application using the JavaScript and Node.js based Meteor web framework, which allowed cross-platform access to the web app.

3.1.5 Deployment Study. The Light-Shifting Display was deployed in three family households for a period of two months in total, thereof for 10 days in household C_2-H_1 (a couple with three children, aged 2, 4 and 16), for 11 days in C_2-H_2 (a couple with a small child), for a duration of 26 days in C_2-H_3 (a couple with grown-up daughter). The families operated a solar panel system in their houses and previously used the commercial solar monitoring platform. We let the families choose the preferred place for the display and set up the link for the web interface as a favorite on their private mobile phones. H_1 and H_2 located the display in their open kitchen living room, H_3 in their reception and dining room. Similar to case 1, participants received a brief explanation of the system and were encouraged to explore the system's use in their domestic everyday lives. We conducted an interview with each of the families at the end of the evaluation. We also collected quantitative data, which formed the basis for a separate analysis of the display usage and its influence on the existing online dashboard [25].

4 FINDINGS: DESIGN INSIGHTS FOR SHARING PERSONAL INFORMATION ON LOW-RES DISPLAYS

In this section, we present and discuss the findings from both case studies in relation to the aims of this paper, which are: 1) the acceptance of low-resolution display technologies within a residential context, 2) control mechanisms for low-res displays via handhelds and/or physical control interfaces, and 3) the social interactions occurring around shared displays in a semi-public/private space.

4.1 Acceptance of Low-Res Displays within Domestic Space

4.1.1 Acceptance of the Flip-Dot Display. In the case of the Flip-Dot display, the low-tech character of the display, and the resulting limited information capacity was an important aspect for its acceptance. Not just as it ensured a level of privacy, but also, as one participant stated, since displaying more detailed information might *"[...] have looked like we are showing off"*. The participant attributed this abstractness to the low resolution and mechanical properties of the display, stating that she would not have liked to have an LED display with *"[...] bright flashing lights"* in her front yard. The participant from C_1-H_1 stated that she would have preferred a display that would have attracted more attention, as she found that *"[...] no one looked at it"*. She stated that she was keen for people to notice the display, since she considered it as a mechanism for publicly expressing her opinion on a certain topic, in this case energy consumption and the topic of sustainability at large. One of the participants from C_1-H_2 stated that she liked the fact that it looked *"so low tech"*, making it *"more interesting"* and like *"someone has made an effort"* in designing it. Echoing these comments, one of the participants from C_1-H_3 in the first interview described the display as *"unobtrusive enough"*. However, during the second interview at the end of the study, the same participant expressed concerns about the large size of the display. This was surprising since we considered the display to be rather small and inconspicuous in particular due to its long and narrow ratio. Both participants from C_1-H_3 found the tablet device useful for monitoring their electricity consumption, but were uncertain about the value of the shared public display, which suggests that the acceptance of a low-res display within the semi-public boundary of domestic space is strongly linked to its perceived value.

4.1.2 Acceptance of the Light-Shifting Display. The real-time experience and the high visibility of the displayed information, in terms of its physical integration and accessibility were the key factors for the high acceptance of the Light-Shifting Display. One participant mentioned that compared to the online dashboard, the display offers *"live action"*, and argued that *"[...] the dashboard just changes a little bit, whereas the visualization on the display really starts to kick off when your consumption goes up"*.

For the participants from C_2-H_1 and C_2-H_3 – both liked the abstract visualizations – the visual representation and composition of the content played a key role in terms of the overall aesthetic perception. For example, if large parts of the display space were just dark, they perceived the visualization as aesthetically less pleasant. This can be also tied back to the fact, that these participants used the Light-Shifting Display not simply as an information display, but in particular in the evening as ambient lighting source with the purpose to illuminate the surrounding space (see Figure 6). In terms of the colors, family C_2-H_3 also mentioned that friends of them liked the idea to *"personalize the display"*. Family C_2-H_3 further stated that they would prefer a *"bigger and wall-mounted"* display in order to

Figure 5. The Flip-Dot displays using pictorial representations to show the last four days consumption.

"[...] make use of it as a piece of light art". On the other hand, family C_2-H_2 who preferred the numeric representation and used the display similar to a *"clock"* in the background, stated that they would prefer if the display was smaller.

Besides the size, participants also frequently commented on the style of the display. Friends from family C_2-H_1 were *"impressed by the wooden finish"* of the display. Family C_2-H_3 explained their positive attitude towards wood as an aesthetic material, and from an intellectual point of view highlighted *"[...] the CO2 capture of wood and the power to reduce CO2 in the atmosphere"*. Besides the low resolution also the finishing of the display housing obviously influenced the participant's perception of the display. Being asked if displaying the information on a standard TV screen would be the same experience, triggered an interesting conversation between the couple in C_2-H_1: the wife clearly rejected this suggestion and argued that they were *"[...] very non-television people, and not interested in having a TV screen"*. Further, she pointed to the *"diffusing properties"* of the Light-Shifting Display. Her husband argued that *"one could make it look exactly like this"*, referring to the fact that one can simulate the diffused material in 3D-renderings. He added though that *"[their] interaction would be totally different"* if the visualizations were displayed on a TV screen. In this context, they also pointed out the potential interference of the low-res lighting display with other screen-based media use, therefore suggesting to *"put it in a room other than where the TV is"*.

4.1.3 Similarities and Differences in the Acceptance. The findings across both case studies suggest that it is difficult to make a conclusive statement about the acceptance of low-res displays within domestic space. However, they do point towards a number of aspects that seem to affect their acceptance and that even apply to distinctive design situations and regardless of the choice of display technology. Thus, based on both cases, we consider placement and size as important factors that the display owners need to be able to determine. Similarly, user preferences in terms of the aesthetic quality of the display – which to some extent can be controlled through the content design – vary from user to user. For indoor situations, the style of the display, including the display's frame, seems to be more critical than for outdoor displays. This might be explained by the fact that the interior of a house is commonly influenced by the personal taste of its inhabitants (e.g. through choice of furniture, etc.), while the outside is much less frequently modified and often determined by the architect or building owner. In both cases, participants appreciated the "low-tech" aesthetics and supported a clear demarcation from conventional media, such as LED advertising displays or TV screens.

Design Insight #1 – Size, placement and style of the display impact the level of physical integration: Size and orientation of shared displays are important factors in regard to practical concerns, such as visibility and audience interaction. In designing the shared displays for our case studies, we were conscious about the aesthetic effect of each display's size, orientation and ratio. Considering that the medium is both technology and cultural form [51], we aimed for an aesthetic that fitted with the architectural topology and character of the residential built environment. The uniqueness of the utilized displays and chosen materiality stood out intentionally form conventional display sizes and screens.

Design Insight #2 – The location (outdoors / indoors) drives the levels of abstractness, playfulness and explanatory detail: Content on low-res displays should be informative, captivating and aesthetically pleasing to support long-term engagement [24]. In our cases, designing content for the outdoor Flip-Dot display had to be both easy to understand (e.g. using percentages, tendencies) to make the data accessible to passers-by and sufficiently abstract to protect the residents' privacy (e.g. not giving away when the residents were away for a few days). The aesthetics of the Flip-Dot display were kept minimalistic to avoid conflict with the existing front yard environment and playful to encourage engagement. In comparison, the ambient indoor Light-Shifting display used more colorful and dynamic visualizations to complement participants' interior environment, and provided fewer to no explanatory details as residents were able to learn how to decode the visualization over time with cues being provided through the web app.

Design Insight #3 – Personalization is more than choosing a representation: Participants were concerned about what the display looked like aesthetically and how it was perceived holistically by visitors/passers-by. Similar to observations made by Wouters et al. [52], who found that their participatory design process with the members of three households led to three very different display concepts, our findings point towards the need to offer personalization, not just regarding the display content, such as color and typeface but also the physical appearance and conspicuousness of the display.

4.2 Controlling the Low-Res Displays

4.2.1 Controlling the Flip-Dot Display. Both families reported to mainly have interacted with the tablet app to investigate the electricity usage in their home. In retrospect, the tablet app worked too well as a diagnostic tool, while failing to establish a link to the public display. The fact that the visualizations looked significantly different on the high-resolution tablet interface might have impacted the mental model of the two displays being connected. None of the participants reported to have taken the tablet app outside to the public display to control the content and directly observe the changes in the display.

Furthermore, none of the participants reported noticing the other family changing the active visualization. This was surprising, since we expected that participants would try to override their neighbor's selection in order to share their own achievements. Similarly, the feature to turn the display into idle mode was not used at all, even though C_1-H_3 seemed to feel uncomfortable about having their electricity usage displayed towards the end of the study. The feature was likely not visible enough, and even if activated, it was possible for the neighbors to overwrite it again. In hindsight, it would be important that such opt-out features are firstly clearly indicated and immediately available, and secondly cannot be overwritten by others.

Although, the push-button at the display was popular with the children, neither of the families reported during the first interview to have seen passers-by using the button. We consequently included a message ("Push me") with arrows pointing towards the button that was displayed at the end of each visualization cycle. C_1-H_2 later reported having seen some passers-by using the button, although from our own observations while being on site we suspect that the feature was not an effective way of engaging passers-by. This can likely be linked to a dilemma of perceived ownership [8]: While our participants clearly considered the button as something for passers-by (*"I didn't feel like that was really for us, I feel that it was for passers-by to play with."*), passers-by likely thought the display and the button to denote something private. One of the participants from C_1-H_2 stated that she observed several people walking past that seemed to make an effort not to look at the display which she explained with the fact that "*[...] because it was on [her] private fence people thought they shouldn't look at it, since it was private.*"

4.2.2 Controlling the Light-Shifting Display. Both families C_2-H_1 and C_2-H_3 who had a clear preference towards a specific visualization stopped using the web interface after half of the deployment time, instead they kept the display running throughout the day and adjusted the brightness via the physical knob. One participant in C_2-H_3 stated that after a while they found their preferred setting and therefore *"[...] not really touched [the web interface] a lot for couple of weeks – except when people came in"*. In contrast, C_2-H_1 used the web interface throughout the whole deployment duration, primarily to change the visualizations. One of the participants from C_2-H_1 stated that she was often changing the visualizations from a distance, but still in view to the display. She added further that the interaction via smartphone was easy to handle and convenient *"[...] like having your remote control and not having to walk over there"*. Her husband, on the contrary, opposed that he didn't always carry his phone while being home. He expressed a preference for being able to *"cycle through"* the visualizations with an additional rotary knob, similar to selecting *"favorite radio stations"*. He justified this with the pleasant tactile sensation of the physical button: *"I know you can do the brightness from the smartphone. It felt so much better doing the brightness from [the display]"*. We also found in the logs that several times when the participants from C_2-H_1 changed the visualization with the web interface, they simultaneously or shortly afterwards adjusted the brightness with the physical knob. This usage pattern indicates a hybrid use of the web interface and the physical control interface in this household.

Figure 6. The Light-Shifting Display in the ambient mode, displaying the last three days' consumption.

4.2.3 Similarities and Differences regarding the Control Interface. In the Flip-Dot display study, the tablet app provided the same information that was shown on the shared display, and therefore was repeatedly used as a standalone information source. On the contrary, in the Light-Shifting display study, the web interface functioned as an extension to control the display and annotate the meaning of the low-res visualizations. In retrospect, the approach in the second case was more successful because the web interface complemented the low-res display instead of replicating the same visualizations. In the Flip-Dot display study it might have been better to apply the visual design aesthetic from the public display in the control app to provide a clearer connection. The connection between the control app and the low-res display could have been further strengthened by more clearly displaying that (and which) information was shared publicly, e.g. through a short animated notification temporarily taking over the entire tablet screen. Providing a phone-based control app would have been also appropriate for the Flip-Dot display, because it might have supported using the phone as a remote control while being outside in front of the display.

Design Insight #4 – External devices complement *but* compete: Our findings suggest that mobile interfaces are suitable as an input device and to provide additional information [32] for low-res displays in the residential context. However, the outcome of our studies indicate that it needs to be carefully considered whether displaying redundant information, and, if so, we suggest to apply the visual design aesthetic from the low-res display to provide a clearer connection.

Design Insight #5 – Immediate interaction and feedback enhances the user experience: We noticed that a decoupling of the interactive elements (e.g. a remote stationary tablet) leads to decreased interest in the displayed low-res content, while real-time and tactile feedback acted as an additional motivator. Further, in our case studies we observed long pauses between the interaction periods, especially for the usage of the web interface. Therefore, the temporal dimensions of residential media architecture should be considered in future investigations, making a link to "slow technology"-design principles [30].

Design Insight #6 – Perceived ownership affects interaction. The Flip-Dot case illustrates that deployments in semi-public contexts are prone to the dilemma of perceived ownership [8]. In retrospect, the fact that we used the principle of a doorbell as design inspiration for the push-button may have made it too daunting for passers-by to actually push it. These findings suggest that to successfully engage passers-by, aspects such as instructions, location, visibility, tangibility and ambiguity need to be taken into consideration and addressed.

4.3 Social Interactions around the Low-Res Displays

4.3.1 Social Interactions around the Flip-Dot Display. Both families in C_1-H_2 and C_1-H_3 reported observing their children congregating at the display to interact with the push-button and discuss the animations. In that sense, the push-button provided a reason for the children to repeatedly 'visit' the public display, which in one case also led to social interactions with some of the other neighbors, who did not participate in the study. While being on-site, we observed that members of both families would talk about their electricity consumption in passing, joking about competing as well as analytically reasoning to explain the visualization shown on the display.

4.3.2 Social Interactions around the Light-Shifting Display. The Light-Shifting display was reported to have triggered on-going discussions on energy consumption among the family members in all households. Though the display was embedded in a private and closed indoor space, the participants repeatedly reported on social interactions around the display beyond the household members. C_2-H_2 remembered that, on one day, when friends came over for a barbecue party, *"[...] the display was the first thing they noticed"*. She then explained all functionalities to them and turned on different devices to *"[...] show them how the visualizations were changing"*. She mentioned that she and her friends *"spend quite a lot time talking about it"* and complemented that she felt comfortable and self-confident while talking about a topic that she is rather unfamiliar with.

4.3.3 Similarities and Differences in Social Interactions. We found that the displays provided a place and a trigger for social interactions. In the case of the Flip-Dot display study, this included interactions with the neighborhood and local community, which was likely supported by the placement of the displays – in close proximity to each other and at the fence or wall bordering the public footpath. In case of the Light-Shifting display – due to the private context – social interactions were restricted to the immediate environment, including family and friends. It seems that because of their prominent nature while also being clearly associated with the "owners" of the display, people considered it as a form of self-expression and were pleased by a positive response from others.

Design Insight #7 – Sharing personal information encourages social interaction: The public visualization of user-specific environmental data can be considered as a "potential mediator for social communication" on related civic issues [16, 39]. For example, the comparative percentage-based visualization of the outdoor Flip-Dot display was more successful than household-specific representations. The push-button-triggered animations turned out to be an effective way to encourage children to gather at the display and to draw neighbors into conversations around the display.

5 REFLECTIONS ON MEDIA ARCHITECTURE PRINCIPLES

In this work, we sought to investigate the question how media architecture as a framework can be transferred to the residential context. We began this paper with an introduction of traditional media architecture and identified five common principles: physical integration, material aesthetics, communicative and informative aspects, contextual aspects, and social interaction. We then "zoomed in" on the details of designing residential media architecture by analyzing two cases where we integrated shared low-res displays for visualizing personal data collected from IoT devices in distinct domestic situations and presented a collection of design insights that emerged from the evaluation of the study results. In this section, we return to the media architecture principles and reflect on how they apply to the residential context. Based on a mapping between the principles and our findings, we present a set of design recommendations to serve as a starting point when designing (low-res) media architecture for the residential context (see Table 2).

Previous research suggests that for a widespread acceptance of media architecture, it has to facilitate high aesthetic architectural qualities, which can be achieved through a seamless physical integration of (digital) media, supporting architectural forms instead of competing [10, 19]. We found that the integration of media architecture into existing structures (re Principle 1: Physical Integration) is also important for the residential context, however different approaches and measures

	Physical Integration	Material Aesthetics	Communicative & Informative Aspects	Contextual Aspects	Social Interactions
(1) Residential media architecture should fit local architectural topology and character.	✪	✪		✪	
(2) The low-res display system should be modular in size and dimensions, and flexible in placement.	✪				
(3) Content *and* physical appearance should be customizable.	✪	✪		✪	
(4) Avoiding interference with existing screen-based media.	✪	✪		✪	
(5) Offering physical controls for the most frequently used functionalities.	✪	✪			
(6) Complementing low-res content through external mobile devices.			✪		
(7) Designing content that is relevant for the permanent occupants.			✪	✪	
(8) Using situated micro-interactions to enhance user engagement and involve a wider audience.					✪
(9) Encouraging a "caretaker" role to increase acceptance of residential media architetcure.					✪

Table 2. Preliminary design recommendations for residential media architecture facilitated through low-res displays (left), with addressed media architecture principle (top).

are required: while for traditional media architecture, the synergy of media and architecture, in the best case, is part of the considerations of the architect in the planning phase of a building [54], residential media architecture needs to offer design options for a more flexible integration. Therefore, we propose a modular design for media architecture interfaces in the residential domain, affecting their size and dimensions, and to enable flexible placement (see Design Recommendation 2). Further, we suggest that content and physical appearance of the display, such as style and material properties, should be customizable (see DR 3), which also enables everyday users to adapt residential media architecture according to personal preferences and to quickly respond to changes in the surrounding space. This demand can be also attributed to the spatio-temporal context (re Principle 4: Contextual Aspects), which in the domestic area is more frequently affected by redesign and changes than in urban space.

The thoughtful consideration of material aesthetics (re Principle 2) seems to be crucial to create *unique* experiences and to avoid resemblance and interference with existing displays, such as those of televisions and personal computers, which is in particular relevant to indoor situations (see DR 4). Further, since residential areas are primarily used for living and leisure purposes, they are more sensitive to eye-catching and “loud” display concepts than it is for example the case with storefronts in a busy city centre (see DR 1).

While urban locations see people with a wide range of demographics and cultural backgrounds passing through, the audience in residential areas is usually more homogenous. In terms of communicative and informative aspects (re Principle 3), it is important that residential media architecture provides information that is relevant, in the first place, for the permanent occupants of the location where the display is situated in (see DR 7). For example, in semi-public settings, such as the Flip-Dot case, comparative visualisations that relate to the whole streets rather than a single household are more successful in terms of encouraging social debates. In addition, playful elements, for example in the form of entertaining content or micro-interactions (see DR 8), which do not require a deeper understanding of the displayed information, can be used to drive curiosity and engagement also among temporal non-local audiences.

In our cases, we repeatedly observed the concept of “taking ownership” of the shared display, which influenced the overall acceptance and in particular the social interaction around the display (re Principle 5): in households, where *one* person in particular engaged with the display prototype and took on the role of a “caretaker”, the general appreciation for the display and its acceptance across the household was high. Therefore, we suggest the use of design elements, which encourage the role of a “caretaker” (DR 9). This can be, for example, through control elements and interactions that offer a pleasant tactile sensation (DR 5), creating a moment of delight, and thus becoming part of a user’s daily routine. Another possibility is to apply local co-design approaches [52] which may establish a closer connection between the final product and people around the display.

In the semi-public context, we observed that the strong sense of perceived ownership obviously created barriers in regard to actively engaging passers-by through residential displays that are attached to the front yard of private properties. In this regard, collaborations with community bodies and local shops, which could serve as hubs for residential media architecture, may prevent aforementioned interaction barriers from occurring. However, such collaborations may also cause conflicts of interests [8], pointing to avenues for further research around issues of perceived ownership through design.

6 CONCLUSION

In this paper, we discussed the design of two low-res displays and their evaluation in a semi-public and private context respectively. Based on an analysis of the findings in relation to user acceptance, social interactions and control mechanisms we exemplified a number of design insights for the design of low-res displays in the domestic space.

Reflecting on the media architecture principles, we found that media architecture technologies (e.g. the use of LEDs and unusual display dimensions) and media architecture as a framework (e.g. carefully designing the physical integration and facilitating social interactions) can indeed bring new perspectives to the design of shared displays for IoT devices and personal data. However, different from traditional media architecture, we found that our participants expressed a strong sense of *ownership* of the shared display, which clearly affected their interactions with and acceptance of the display. In other words, as a product, residential media architecture needs to offer personalization beyond the display content and allow for a more **flexible und customizable integration**. As a process, residential media architecture needs to consider not only the specific physical context but also the characteristics and opinions of the perceived owners, for example through adopting a participatory design methodology.

To that end, our study also points out avenues for future research to further investigate the use of media architecture as an interface between the private and public domain. For example, residential media architecture in a semi-public context might benefit from considering not only the perceived owners but also representatives from the local community in the design process, leading to more inclusive and meaningful shared media architecture interfaces in the residential domain.

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