Understanding Artefact and Process Challenges for Designing Low-Res Lighting Displays

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ABSTRACT

Low-resolution (low-res) lighting displays are increasingly used by HCI researchers, designers, and in the industry as a versatile and aesthetic medium for deploying ambient interfaces in various contexts. These display types distinguish themselves from conventional high-res screens through: high contrasts, hi-power LED technology which allows visibility even in bright environments, and their ability to take on three-dimensional free forms. However, to date most work on low-res displays has been either of experimental nature or carried out in isolated industry contexts. This paper addresses this gap through an analysis of our own experiences from previous experimental design studies and related work, which led us to five domain challenges for designing low-res displays. We then describe how we approached these challenges in a deployment study, which involved the implementation of a prototype guided by a low-res prototyping toolkit. Based on an analysis of our design process and findings from the deployment study, we present ten design recommendations for low-res lighting displays.

Author Keywords

Information design; low resolution display, ambient lighting systems

ACM Classification Keywords

H.5.2. Information interfaces and presentation (e.g., HCI): Design.

INTRODUCTION

The advent of the light-emitting diode (LED) technology enabled the creation of visual displays that are more flexible in terms of size, shape, resolution, pixel arrangement, material, and integration into product designs, and their lighting quality distinguishes them from conventional screens [14]. These displays, which consist of only a few hundred of self-luminescent pixel units, provide a rich design space for conveying information using explicit text and image [27], iconic [15, 18], or fully abstract lighting behaviors [23, 25]. Due to the great flexibility in terms of the physical properties combined with the ability to easily manipulate the digital layer, this type of visual display – from here referred to as low-resolution (low-res) lighting display – is increasingly applied in research implementations [5, 8, 13, 26], conceptual design works [6, 10] and products, such as Internet-of-Things (IoT) devices, wearables, and even large-scale media architectures. However, to support the design of these displays from scratch requires more specialized tools and approaches.

Because the specific characteristics of low-res lighting displays differ from traditional graphical user interfaces (GUIs), existing tools cannot easily be adapted. These tools were conceived to deal with content displayed on high-res devices, which would not be recognizable when scaled down to not more than a few hundred pixels. Furthermore, such tools do not support the fast exploration of low-res lighting display's material properties (e.g. different diffuser panels) along with content. Consequently, designers are often not aware of the strategies for (1) communicating information in a very low resolution [27] and (2) designing lighting displays as an aesthetic material [11, 34], leading to poor designs that are rather driven by technical limitations instead of taking advantage of an expressive design space. Further, applying common interaction design processes, such as the active involvement of potential users during early design stages, is difficult because of the users' unfamiliarity with such rather complex design contexts.

Hence, in this paper, we focus on how designers can be supported in designing low-res lighting displays through iterative prototyping and testing by the means of purpose-built toolkits. This research is grounded on previous work from two research labs. It analyses five experimental design studies carried out across the two labs over the last four years. We briefly introduce the cases – *TetraBIN, Prototyping Urban Interfaces, Hybrid Media Display, Interchange of the Future*, and *Share Your Power* – which have motivated the need for structured design support in this context. We then report how we addressed the domain specific challenges, namely *developing content, conveying information, designing the screen as a material, involvement of stakeholders as co-designers*, and *toolkit flexibility* in the context of a follow-up design study set out as a collaboration between the two research labs and an

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industry partner. The aim of this study was to design and develop an in-home low-res lighting display to visualize real-time energy performance data of private households additionally to an existing, commercially available web service. Extending the user-centered design process, we report how we applied a prototyping toolkit as an additional means during the user research phase, the development, and testing of design concepts with experience prototypes. Following this process led to the creation of a high-fidelity prototype low-res lighting display: we first briefly describe its implementation, before discussing a deployment study involving three family households that explored its use, interpretation, and aesthetic perception. We conclude the paper by translating the findings from this deployment study, lessons learned from previous implementations, and the experiences gained during the design process into preliminary design recommendations that may guide other designers and researchers.

In summary, the contribution of this paper is three-fold:

- First, we identify challenges for the design of low-res lighting displays based on five cases we have implemented over the past four years.
- Second, we report on our approach considering these challenges in designing a low-res lighting display using an extended user-centered design process and present findings from a preliminary evaluation in three households.
- Third, we present lessons learned from our exemplary design study and derive design recommendations for in-home low-res lighting displays.

CASES AND CHALLENGES FOR PROTOTYPING LOW-RES DISPLAYS

Over the past four years, our research labs have conducted five experimental design studies, which involved the development and deployment of low-res display applications. During these projects, in which low-res displays and their content were designed in a 'straightforward' manner, we faced recurrent domain challenges, which have motivated the need for purpose-built but adaptable tools and a more systematic approach for designing such systems.

Cases

Hereinafter, we briefly introduce the low-res display cases: four used LED technology and one used a physical flip-dot display.

TetraBIN

The *TetraBIN* project emerged out of a design study addressing the issue of littering in cities [33]. It encourages people to put their rubbish into city bins by reinforcing positive behavior. This is achieved through a low-res display wrapped around city bins, essentially allowing people to play a Tetris-like game by placing rubbish into the bin. The display consisted of 900 LEDs mounted on a custom-produced layer onto the outer surface of the bin.

Figure 1. Three different cases in prototyping low-res lighting displays aimed for large public places: (a) Hybrid Media Display [36], (b) Urban Prototyping Festival [17], and (c) Tetra Bin [33], which served as a motivational basis for our work on establishing a more structured design process.

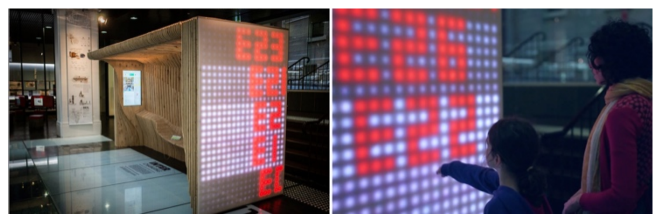

Figure 2. Low-res LED display integrated into a bus stop prototype envisioning a future public transport hub [9].

Two *TetraBIN* prototypes were deployed at a light festival running for a period of 18 days (see Figure 1c).

Urban Prototyping Festival

Creating novel urban installations together with the inhabitants of a city is the spirit of the urban prototyping movement. In our previous work, we have utilized this approach to investigate different forms of interactions with buildings and media façades and conducted an urban prototyping festival over the duration of two days in a large European city [17] (see Figure 1b). Participants had the opportunity to interact with a temporary low-res LED media façade via (1) tangible interfaces, (2) in-tangible gestural interfaces, and (3) using everyday objects as an interaction trigger.

Hybrid Media Display

To investigate the advantages and disadvantages of types of content (low-res vs. high-res) displayed on a large public media screen, we developed a hybrid media display and deployed this prototype in a public building and an urban outdoor environment in the middle of a large city over long timespans (i.e. several weeks) to conduct studies on the general acceptance of the different forms of content presentation [36] (see Figure 1a). The prototype included low-res content displayed via hi-power LEDs as well as high-res front-projected content as a second layer of information. In two scenarios, we displayed live air quality measurements and real-time public transport information via different means of display modes (low res only, high res only, and low/high res combined) in order to determine which type of presentation would be favored by the viewers.

Interchange of the Future

As part of a larger project that involved the design and prototyping of a future transport hub [9], we included a low-res large-scale LED display covering the entire side of a bus stop prototype (see Figure 2). The custom-made 19x29 pixels low-res lighting display was created by fixing LEDs onto a laser-cut Perspex sheet and adding a 2cm Polycarbonate sheet for diffusion and protection. The display was used to visually show the arrival of buses through mapping their line number to the horizontal axis. Shading was used to display how crowded each bus was. The prototype was displayed for nine days during a design festival inside the foyer of a public building.

Share Your Power

The aim of the *Share Your Power* project was to develop real-time visualizations of domestic electricity usage and to study the implications of sharing such personal information in a semi-public context [33]. Therefore, we used a so-called flip-dot display, consisting of electro-mechanically controlled discs to either show a black or white dot, and deployed it at the front yard of two households for a period of 20 days. We designed various visualizations for the low-res display, including numerical, pictorial, charts and a combination thereof (see Figure 3).

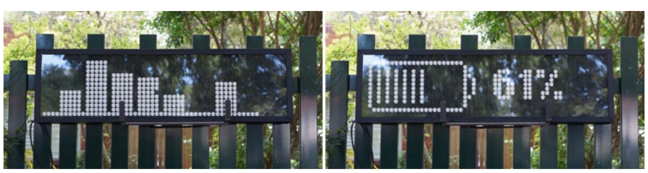

Figure 3. Exploration of various visualizations of energy usage [33]: weekly graph (left), battery pictogram (right).

Challenges

When designing the low-res displays presented above, we faced recurring difficulties that we hereafter formulate as a preliminary set of five challenges. The first three challenges are concerned with the characteristics of low-res lighting displays; we refer to those as *Artefact Challenges (AC)*. The latter two are concerned with the design, development, and evaluation of low-res lighting displays; we refer to those as *Process Challenges (PC)*. In addition to our own experiences, the challenges are based on an analysis of related work, which we also discuss in this section.

AC 1: Low-res Content & Interface

In all five cases presented, the displays differed strongly from traditional GUIs because of their low resolution, which made it difficult to develop content that works for this medium. For the *Hybrid Media Display*, an additional challenge was to imagine how content comes across the diagonally arranged pixel patterns of the LED-based screen. Consequently, tools for prototyping content should consider the display's specific qualities [14] and nature, such as its low resolution, shape, pixel configuration, pixel shape, and in the case of LED-based display technology, the lighting quality.

AC 2: Information Encoding

If the content of a low-res display application serves not only pure aesthetic and embellishment purposes, but also communicates meaningful information, another challenge is to encode explicit information sources in a low resolution. This was for example the case with *Share your Power*, *Interchange of the Future,* and *Hybrid Media Display*, which all had the purpose of making information-based content (i.e. public transport and energy performance data) comprehensible for a large audience: whereas from an aesthetic point of view participants liked the pictorial representations on the flip-dot display, they stated that from a functional perspective they preferred the numerical representations because they were easier to understand and therefore more meaningful [33]. The *Hybrid Media Display* study further revealed a trade-off between aesthetics and functionality. Showing only abstract low-res presentations failed because the relative encoding was not precise enough for time-sensitive applications as in the case of public transport [35].

This issue has been also pointed out in other research: for example, Offenhuber and Seitinger discussed the challenge of conveying information through low-res media architectures and presented five design strategies depending on the available resolution: information as *color*, *movement*, *text*, *image,* and *architecture* [27]. On the lowest end of resolution, Harrison et al. explored the design space of *point lights* in consumer devices, and came up with a set of *iconic* light behaviors that were evaluated according to specific information classes (e.g. 'pulse slow' for 'low-energy') [15]. Following this domain challenge Hoonhout et al. surveyed whether dynamic light sequences in luminaire design can arouse specific moods and atmospheres [18]. In the scope of ambient lighting systems, using multiple colors and LEDs, other researchers analyzed existing encoding parameters and derived design guidelines for the use of *non-iconic* lighting parameters, namely *color*, *brightness*, and *LED position* and combinations thereof [25]. While previous work in this domain introduced taxonomies and guidelines based on display resolution, encoding strategy, and the represented information class, our work investigates how to actively support the creative process when designing information-based content for low-res lighting displays. Creating a variety of concepts and testing them early in the design process might help to spot insufficient designs before the actual deployment in order to prevent failure as in the case of our previous described case study *Hybrid Media Display*.

AC 3: Screen as a Material

Low-res displays have also been repeatedly used in the field of the fine arts. In his LED works, Jim Campbell [12] explored the boundaries of human visual perception and demonstrated that the creation of meaning is not solely a matter of resolution, but will also require appropriate materials. For example, in *Church on Fifth Avenue*, he used acrylic diffuser sheets mounted with a distance in front of the low-res pixel screen, thus causing the light to blend into a continuous image increasing the perceived resolution of the displayed video sequences. However, while such artistic projects have extensively explored the screen as an aesthetic material, in current interaction design practice and HCI research, the display design is far too often limited to the purpose of framing visual content. Not equipped with the necessary knowledge and tools, in two of our own projects, *TetraBIN* and *Interchange of the Future*, we ignored the use of secondary optical elements (e.g. reflectors, diffusers, opaque pattern sheets), which resulted in glaring and non-uniform pixel shapes. Further, by using rectangular pixel shapes for the *TetraBIN*, the aesthetic of 8-bit era video games could have been additionally reinforced. However, at this early development stage, we were concerned with the digital content and were simply not fully aware of the design space. To our knowledge, only little research has been conducted to date on including physical aspects early into the design process of low-res interfaces. In the context of luminaire design, Torres et al. [34] recently presented a tool chain to create and simulate physically shaped light objects and fabricated the physical, electronic, and optical design.

PC 1: Involving Stakeholders as Co-designers

In traditional user-centered design (UCD), the design team develops a concept based on the user's needs (e.g. informed through a user research phase) and evaluates the resulting prototype. In co-designing approaches, on the contrary, the distinct roles between researcher, designer, and other stakeholders (e.g. partners or end users) blur towards collective creativity with the non-designers taking an active role in problem-solving and creating design concepts [31]. Following this mindset and transferring it to our domain, designers and researchers should provide non-designers with tools that serve as a source of inspiration and help to express themselves, which is particularly critical for complex and novel design contexts as the one presented. In the *Urban Prototyping Festival* project, for example, we facilitated co-creation processes in the context of low-res media façades; however, one shortcoming was that the provided tools still demanded programming and hardware skills, which hindered participants to implement their own design ideas. Therefore, in the here described research work we were specifically interested in lowering the technical barriers for prototyping low-res interfaces in order to stimulate co-creation sessions and discussions with various stakeholders involved.

PC 2: Design Exploration and Iterative Refinement through Flexible Tools

Another challenge that comes with the specific form factor of low-res displays, is the demand for tools that can be easily adapted to various designs. For example, in the case of *Hybrid Media Display*, different explorations of the low-res pixel density would have been helpful before deployment; however, this was not feasible due to the inflexibility of the utilized LED modules to reconfigure the pixel configurations fast and at low cost. Further, in all cases, we found that carrying out design iterations early in the design process was challenging, because existing tools in this context [17, 34, 35] were simply not appropriate for creating low-fidelity prototypes without involving lighting hardware and electronics. To address this challenge, this paper investigates an entire design process cycle, supported through a lightweight prototyping toolkit of adjustable fidelity levels that enables broad design explorations in the beginning and refinement of ideas at later stages [3].

DESIGNING LOW-RES LIGHTING DISPLAYS: A STRUCTURED APPROACH

In this section, we describe how we have systematically addressed the identified design challenges using a prototyping toolkit and an extended design process in close coordination with the intended user groups.

Prototyping Toolkit: Sketching-in-Light

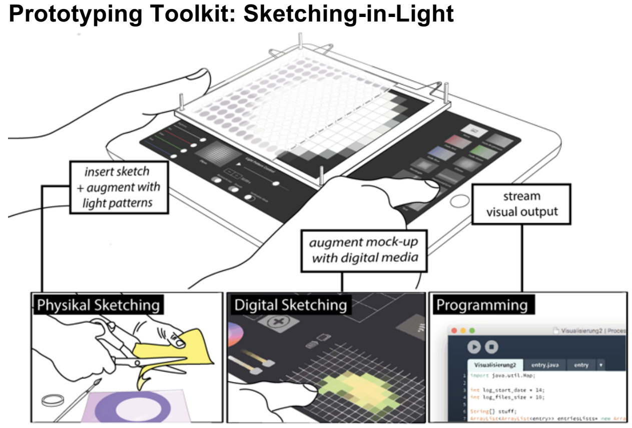

Figure 4. The low-res prototyping toolkit Sketching-in-Light [16] includes a digital tablet and a display mock-up, which can be augmented through illuminated physical sketches; digital sketches are created with the app and visualizations programmed in Processing sent to the toolkit via Wi-Fi.

Sketching-in-Light [16] is intended for building interactive mock-ups of low-res lighting displays and to create visual content using a large variety of physical and digital materials (see Figure 4). The toolkit consists of an Apple iPad Pro (12.9 inches), a custom-built app, and various lighting prototyping materials (i.e. pixel pattern sheets, spacers, diffuser foils). Sketching-in-Light enables three prototyping activities:

- *Physical sketching* with various translucent craft materials on tracing paper (e.g. using watercolor paints, water-based ink, or cellophane foil). The sketch can then be inserted into a display mock-up which is composed of modular laser-cut overlays to simulate different pixel and lighting qualities. Finally, the iPad is used as a backlight source, to augment the physical sketch with pre-defined and editable lighting patterns (see Figure 5, left).
- *Digital sketching*, using the display mock-up without the physical sketch and augmenting it with different digital means (e.g. key frame animations, text, images).
- *Programming* of visualizations in the Java-based scripting language Processing [29], which are sent via a library to the toolkit app, thus using the display mock-up as an output screen (see Figure 5, right).

The three prototyping activities of Sketching-in-Light enables users to work on various fidelity levels and move from initial sketches to fully interactive implementations without requiring the final hardware. Further, users with average skills in programming and those without any programming skills are able to use the toolkit.

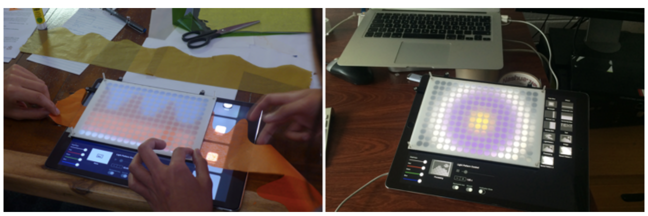

Figure 5. Two instantiations of Sketching-in-Light: physical sketch using movable paper cutouts (left), programmed visualization made in Processing (right).

Figure 6. Solar Analytics Mobile Dashboard (SAD), a cloud-based platform, which offers live observations and past analysis of energy performance data on a mobile device. Photo credits: © Solar Analytics.

Applied Context

To investigate the toolkit-supported design process of low-res lighting displays in a real-world setting, we collaborated with a small company in the smart home sector, Solar Analytics[1]. Their service comprises the aggregation, analysis, and visualization of real-time energy performance data for home solar panel owners. Their core product is a cloud-based platform, called Solar Analytics Dashboard (SAD), which offers live observations and past analysis of energy performance data (see Figure 6). The web application is optimized for desktop and mobile usage and the company's aspiration is to provide data visualizations that are easy to understand for a broad user base. However, an internally known problem with the status quo output channel is that most customers are not regularly (i.e. less than once a week) accessing the information via the online platform and especially less technically skilled people find it difficult to engage with the online representations. Therefore, Solar Analytics was interested to trial an in-home physical display to make the energy performance data easier accessible also for non-expert users.

For the following reasons, Solar Analytics was particularly suitable for our research context: (a) They initially considered commercially available lighting systems and partnering with an IoT service provider due to not having the required engineering skills in-house. Hence, with our tools, we aimed to empower design studios and start-ups to develop early prototypes of low-res lighting displays on their own. Otherwise, these firms would need to fall back on commercially available products and services that can restrict ideation and creativity due to limited flexibility, or have to hand rapid prototyping over to experts from other domains resulting in increased time and cost. (b) Having the skillset of interaction design in their team, but not being familiar with the domain design challenges, their interdisciplinary teams benefited from our tools. (c) As Solar Analytics operates in the market for domestic digital products, we were able to apply our methods and tools in a relevant design context. Further, ambient energy and resource monitoring [13, 20, 21, 32] has been thoroughly studied in the context of persuasive technology with a large body of literature available to build on, however, to our knowledge none of the previous work focused on providing guidance for designing low-res lighting displays in this context.

The engagement with Solar Analytics lasted 8 months in total. During the design process investigation, 17 adults (average age 36 years) and 4 children (average age 7 years) were involved in design activities or encountered the final prototype in the deployment study.

Involving Stakeholders as Co-designers

In this section, we report how we addressed the process-related challenge of *involving stakeholders as co-designers (PC1)* thereby considering the development of *low-res content (AC1)* and *encoding of information (AC2).*

Participants and Setup

In the beginning of the collaboration, we conducted an expert workshop with six employees (three female) of Solar Analytics: three renewable energy engineers, two interaction designers, one software developer, and the leading art director who was responsible for the design of the SAD. The workshop was structured in two parts: a focus group discussion on (a) customer value, (b) strengths

[1] https://www.solaranalytics.com/au/

and weaknesses of the product, in particular with focus on the SAD, and (c) potential benefits of launching a low-res lighting display. In a subsequent co-design session, initial ideas for visualization concepts were created by the participants. In groups of two, the participants were instructed to brainstorm which data might be interesting to present on a low-res lighting display, before working out concrete visualizations using Sketching-in-Light as a supportive tool. Both parts of the workshop lasted 45 minutes each.

In the next step, we conducted user research sessions with actual customers of Solar Analytics 'in the wild', visiting them at their home to gain a better understanding of the context and identify user's needs and desires [2], thereby collecting further ideas for visualization concepts through a co-design activity. In total, three family households with three to five members each, all living in the Inner or Greater Sydney area, were involved in the user research sessions. All households were operating a solar system and using the solar monitoring service for at least six months. In one case, both adults (husband and wife) took part in the session, in one case only the wife with her minor daughter, and in one case only the husband. The interviews and the subsequent co-design sessions lasted one and a half hours per household. The participating households were recruited with the help of Solar Analytics; each of them received 150 AUD as a reimbursement for their time.

Data and Analysis

The interviews and the subsequent co-design activities of all sessions were video recorded for analysis and photographs of sketches were taken for documentation purposes. We then transcribed the recordings on Post-It notes to sort the data into groups of similar ideas (clusters) and design requirements using affinity diagramming [22].

Findings from the Expert Review

Overall, all employees were positive about the introduction of an 'in-situ' display to improve the customer's experience with Solar Analytics. They stated that the display should provide only a low amount of information sources at the same time, thus *not* replacing the dashboard, but rather engaging users to *come back to it* more often. Participants also critically reflected on the use of colored light as sole information carrier, as expressed by art director:

"It's specific to solar a funny paradox as well, because mostly the really informative time is during the day, when the sun is out. So if you have a really sunny room, you cannot see [the lighting display] if [the visualization] is to subtle."

Another participant then raised the question which 'features' a low-res lighting display could offer compared to a normal lamp, on the one hand, and compared to a conventional high-res in-home display on the other, highlighting the challenge of finding the sweet spot between functional and decorative lighting and the amount of information capacity.

In the focus group discussion, the participants expressed their concerns about how to convey information in a very low resolution. However, sketching sparked their imagination, and the participants were able to generate various promising ideas during the co-design session, some of which are presented in Figure 7. Apart from repurposing established infographic techniques, participants also created more context-specific visualizations, for example, proposing a (constantly) moving wave with its speed visualizing the current solar performance. Besides fostering creativity, the toolkit also communicated the boundaries of low-resolution designs. For example, the hand-sketched design proposal for an energy map of Australia was rejected when the pixel pattern was applied and the intended information was not recognizable in the discrete 17x12 low-res representation, which was one given design requirement at this early process stage as we considered it as the lower bound for displaying double-spaced text.

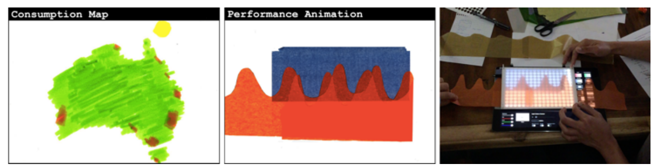

Figure 7. Documentation of the co-design session with the employees: (1) energy production (or consumption) map of Australia, (2) silk paper cutouts to visualize the solar performance over time, and (3) moving the paper cutouts back and forth to express dynamic content through the physical means of Sketching-in-Light.

Findings from the User Research

All participants acknowledged that they used the SAD rather as a tool to analyze energy usage over longer past time periods than to make decisions at short notice. In this vein, one participant complained about the effort to *"go, find the computer and login"* before starting an appliance. In summary, the interviews revealed that checking the SAD is rather perceived as a duty than an activity that brings joy. As a consequence, in all households primarily one person was responsible for accessing the dashboard.

All participants mentioned that they would prefer a graphical representation over a numeric representation and considered the live feed as the most promising data set to visualize with a low-res lighting display. One participant mentioned that, in case of being able to interact with the display through a smartphone, it might be useful to change between daily, weekly, or monthly views. Another participant mentioned that it would be important for her to be able to change the colors of the visualization in order to match with her interior.

In the co-design sessions, participants applied diverse approaches using the toolkit: one of the participants came up with sketches of established infographic techniques, such as area charts and bar graphs, using the physical sketching tools together with the pixel pattern sheet as a template. In contrast, other participants stated that they *"don't like having [the visualizations] in really strong sections, because it's just looking like a graph"*, associating a discrete bar graph visualization with *"something boring"*.

Design Concepts

In this section, we discuss the design of a low-res lighting display, which is based on insights gained through the co-design sessions and evolved from further prototyping and testing *(PC2: Iterative refinement).* In doing so, we particularly focused on the display characteristics *(AC3: Screen as a material)*, the data visualizations *(AC1: Low-res content, AC2: Information encoding),* and the interaction with the display *(AC1: Low-res interface)*.

Display Characteristics

Experimenting with the different overlays of the modular display mock-up, not only the content in itself was part of the discussions with the user research participants, but also the characteristics and affordances of the display. Upon reviewing the findings from the co-design sessions, we explored a display concept that would dynamically change from *discrete* (showing individual pixels) to *continuous* representations (showing a diffused layer of light). Whereas previous research explored shape-changing light as a visual clue to encode ambient information sources [4, 37], our aim was to design a prototype that could switch dynamically between two representations. A low-res lighting display that unifies discrete and continuous representational modes expands the design space in the following ways: (1) Wider support of visual content that can be displayed. (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 during evening times.

Data Visualizations

We developed five distinct visualizations that cover a variety of information encodings and temporal contexts. The design of the visualizations was informed by reference literature and the deliverables from the co-design sessions. At this stage of the design process, we used the programming interface of Sketching-in-Light to perform next design iterations and the physical overlays to simulate the discrete and continuous display mode.

Figure 8 provides an overview of the created visualizations, that are also shown in the accompanying video. We created two visualizations for the discrete mode: we designed one simple numeric visualization V_1, displaying the current energy production and consumption, for the purpose to find out if the users' opinions would shift in an actual usage scenario. The second visualization V_2 shows 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: V_3 uses a bargraph to indicate the energy consumption of the last 15 minutes and V_4 uses three squares to encode the total consumption of each of the last three days via brightness and size. For both visualizations, the continuous display mode was considered as an interesting stylistic means to provide these simple visual elements with a more *vivid* look and feel by blurring the regular pixel grid. In V_5, the current energy balance was encoded through speed and amount of randomly occurring particles. The energy imported from the grid and that consumed on-site is represented through particles that move from the outside to the center of the screen, whereas exported energy is represented through particles moving the opposite direction, thereby all three types of particles are clearly distinguishable by color. Through *the continuous representation mode* the lighting effects are smoother and the perceived resolution of the particle movement is increased.

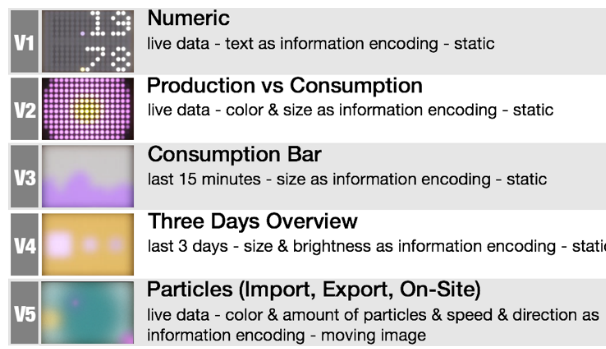

Figure 8. Overview of the five visualizations, including the temporal context, the information encoding, and the lighting dynamics (i.e. static or moving image).

Interaction with the Display

For turning the display on and off and dimming the brightness – operations that were both considered important by the participants – we decided for a rotary knob that was attached to the display. For controlling all other features, we created a web interface that could be accessed on any device that could run a web browser. The interface consisted of a list showing the five available visualizations that could be selected by the user. Further, for each visualization customized settings could be made: for example, changing the predominant colors of each visualization using a hue, saturation, and brightness (HSB) color wheel. Additionally, the mobile interface provides short descriptions for each visualization to support users to learn the meaning of the ambient information encodings. At this design process stage, most of the interactive features were implemented, however, the final hardware prototype was not finished yet. Using Sketching-in-Light as a low-fidelity representation, which simulated a realistic experience of interacting with a low-res lighting display with respect to pixel and light quality, we were able to test the usability of the visualizations in conjunction with the interface components. Further, the setup allowed us to test the robustness of the interplay of all hitherto available technical components (i.e. hardware platform Raspberry Pi running the software, smartphone accessing the web interface, Wi-Fi router).

Implementation

After several iterations with the prototyping toolkit, we were ready to build the final display prototype using actual lighting components and deploying the software to the actual hardware platform. Hereafter, we briefly describe the implementation and components of the resulting high-fidelity prototype.

Housing and Lighting Materials

All hardware components were built into a single piece housing made from wood, measuring 61cm in width, 38cm in height and 12cm in depth (see Figure 9). As a front panel, we used a 2mm acrylic resin plate[2], which featured an even light distribution with a high light transmittance rate (85%). 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 panel and the light source needed to be increased to approximately 4cm. To reduce the *pixilation effect* in the continuous mode, we attached a thin diffuser sheet[3] with a distance of 1mm in front of the reflectors.

Hardware

The core unit running all software components was a Raspberry Pi 3. We used 17 hi-power RGB LED strips with 12 single controllable LEDs, which were connected with the core unit via an ArtNet DMX Ethernet controller. For switching between discrete and continuous modes, we developed linear motion system using a stepper motor that moved the LEDs behind the front panel forward and backward.

Software

The software 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. (2) A web application using the JavaScript and Node.js based Meteor web framework, which allowed cross-platform access to the web interface in order to control the display and make changes to the visualizations.

Experiences Deploying the Display *in the Wild*

To study how people would use and perceive the resulting prototype in an actual usage scenario, we deployed it in three family households (referring as H_1, H_2 and H_3) over a period of two months in total (see Figure 10). The collected data comprised interaction logs and qualitative interviews that were conducted after the deployment in each household with both adult family members attending. In this last design process investigation cycle, we were in particular interested to retrospectively assess the above described design process steps and the decisions made in terms of content type, information encoding and display aesthetics.

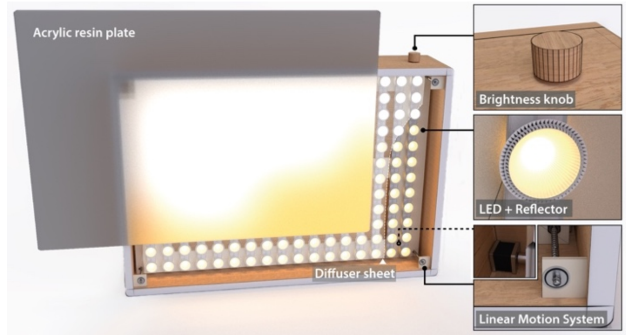

Figure 9. Exploded view of the final display prototype.

The interviews lasted 45 minutes each and were video-recorded for later analysis. We transcribed the interviews and analyzed the data using "a priori coding" [7] towards the artefact-related design challenges of low-res lighting displays, and synthesized the findings into a preliminary collection of design recommendations.

DESIGN RECOMMENDATIONS

Based on our previous work over the past four years and the findings from the deployment study we propose ten design recommendations for low-res lighting displays. These recommendations are not 'set in stone' and based on our own experiences developed across two labs, hence, they may require adaptation to fit other design contexts and circumstances. As such, they are presented to provide a starting point for designing low-res lighting displays.

Low-Res Display Aesthetics

Visual Composition

In the actual usage, the visual composition played a key role in terms of aesthetic aspects, with different visual elements contributing to a positive or negative perception. If the visualization was dominated by a round shape, as in the case of V_2 and V_5, this characteristic was explicitly mentioned as being aesthetically pleasing. On the other hand, if large parts of the screen were too dark or not being part of the composition, it was perceived as unpleasant:

Figure 10. The display placed on the floor in the living room area of one of the three households that took part in the last design process investigation cycle.

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[2] https://www.australiansheettraders.com.au/lighting-diffusers/led-diffusers

[3] https://www.tech-films.de/produkte/polycarbonatfolien-pc/makrofolr-lm-diffusion/

"If I wasn't consuming any energy, like at night, and the particles were not moving it was not attractive." (H_1, f)

Interestingly, the participants did not feel disturbed by constant visual movement, but rather criticized, in case of V_5, the low amount and predictability of particles:

"If we are at our peek there should be so many particles, it's like insane amount of particles. [...] and have them maybe going in random different directions, not all just into the center. So that's much more artistic." (H_1, m)

To sum up, our previous research on the topic also confirmed some of the few available guidelines on the aesthetics of ambient and dynamic lighting [18, 25, 28], indicating that these may be transferable to low-res lighting visualizations:

DR1 – Using spherical lighting compositions: In line with other studies on aesthetic psychology [1], our study participants preferred round visual elements for low-res lighting displays (see V_2, V_5) over rectangular shapes such as, for example, bar chart visualizations (see V_3).

DR2 – Utilization of the whole display space: Previous research on 3D luminaire design stated that lighting animations using the whole display space are perceived as being more pleasant [18]. Our experiences indicate that this is also the case for low-res lighting displays. Therefore, we propose to use (dimmed) background lighting if large parts of the screen are not used for information purposes (see V_5).

DR3 – Using randomized visual elements: Our previous research investigations confirmed that random parameters (see V_5: random colors within a defined color range; random spawn points of moving visual elements) can increase the aesthetic perception of dynamic lights. However, in the context of information design, this should be used carefully in accordance with the overall visualization concept and while ensuring that it does not affect the readability of information.

The Screen as a Material

Through our physical prototyping toolkit, we were able to address the materiality of the screen already early in the design process, focusing on the exploration of a discrete vs. continuous screen characteristic and its implication on the overall visual experience. However, when it comes to the final implementation (re PC2: Iterative refinement), the hybrid simulation approach also revealed limitations in that we could not transfer previous material choices and specifications (e.g. reflector and diffuser material, optimum distance) to the actual high-fidelity prototype due to the miniaturization and lower light intensity of the iPad compared to actual lighting hardware. Building on previous experimental art projects [12] and our specific context investigated through the deployment of a transformable low-res lighting display, we propose the following recommendations:

DR4 – Continuous representations increase the perceived resolution: Attaching a diffuser sheet at a distance to the light source increases the perceived resolution. Thus, the pixel's brightness can serve as another parameter to increase or decrease the resulting area of a particular visual element. We advise to use continuous screens for moving images (see V_5) and indexical content that is expected to be displayed in high-resolution (e.g. photographs).

DR5 – Using discrete screens for text: For readability of text, a discrete screen is advised (see V_1). Also for some iconic content (e.g. Pixel Art [6]), the discrete representation style can be an important part of the overall aesthetic.

DR6 – Using continuous screens for abstraction: The continuous representation transforms established infographic techniques, such as bar graph visualizations or area charts, into a more organic and vivid appearance (see V_3, V_4).

Form Factor and Style of the Display

Based on our understanding, we consider the rationale of form factor and style as another challenge that requires more careful consideration throughout the design process. Future toolkits, therefore, need to address this challenge to allow for prototyping various physical dimensions and styles along with content.

Content and Interpretation of Meaning

Explicit vs. Implicit Visual Representations

Looking back to the co-design sessions, we observed that none of the participants made design proposals featuring numeric representations. However, in the actual use during the field investigation they turned out to be one of the most frequently used visualizations.

The rationale behind displaying the numeric visualization was often that it offered *"precise and unambiguous information*". In this vein, H_2 mentioned that they were able to make use of the information instantly after the display was deployed. On the other hand, H_3 who was constantly using the particle visualization described the interpretation of meaning as a process over several days *"to get a sense of the information"*. In terms of our toolkit and the involvement of customers as co-designers (re PC1), it fostered creativity and enabled participants to create unconventional design solutions. However, it also calls for the involvement of information design experts, instead of overemphasizing design proposals by users without evaluating them in an actual usage scenario. Whether choosing visualizations allowing for explicit or implicit meaning [27], we suggest the following recommendation:

DR7 – Using letters and numbers for immediate understanding, and abstract visualizations to foster data exploration: Designers should carefully reflect on the context and intended use, and not solely rely on individual feedback from participatory sessions to define user requirements in terms of information design.

Information through Particle Movement

Considering only the non-numeric representations, the deliverables of the previous co-design sessions are in line with the findings from the deployment study, in the sense that particle movement seems a promising visualization technique in the specific context of real-time visualizations.

The participants in H_3 endorsed that the intrinsic qualities of the particle movement would reflect well on the *"flow of energy"* and *"the fact that the information is constantly changing"*.

DR8 – Using particle systems to encode (live) quantitative data: Amount and speed of particles are suitable to encode quantitative data, and additionally using distinct colors and direction of movement enable the encoding of multiple information elements (see V_5). Moving particles proved to be valuable for low-res lighting displays because (a) they allow using the entire screen real estate through moving across different positions (re DR2) and (b) particle systems are suitable for randomization (re DR3).

Personalization to Ease Interpretation

The color changing function was mentioned to be useful to reinforce the process of interpretation. In H_3, the participants changed the colors based on aesthetic judgment *("purple is one of my favorites")*, but also to establish an intellectual connection with the data, therefore changing the exporting power *("green energy")* to a green color value.

DR9 – Color individualization enhances the interpretation of meaning: For visualizations that use color as an information encoding, the individualization of color schemes can ease the process of understanding the underlying data. Further, visualization individualization seems in particular desired for private environments to match with the existing interior.

In the case of personal energy monitoring, the peak in each household differed resulting in inappropriate mappings, which then led to frustration due to poor readability of information and unaesthetic visual compositions (re DR2).

DR10 – Enable adaptation of parameters: Remote devices (e.g. mobile phones) can extend the limited functionalities of low-res displays and enable users to change parameters and settings. End user programming interfaces [19] might be useful for more complex adjustments, such as mapping other data sources to arbitrary visual content.

DISCUSSION

Over the course of this paper we have reflected on our previous experiences with designing and implementing low-res displays and the interconnected challenges that are persistent in this domain. We consider it critical to gain a deeper understanding of this expressive and challenging design space in order to create design solutions that are both desirable and enjoyable [24]. Considering the presented body of work and proposed recommendations we believe that our insights could be of high value for practitioners and designers facing similar domain-specific challenges. For example, by applying a low-cost and easy to use toolkit, as presented in the above sections, we aimed at demonstrating how the 'material turn' [30] can be practically explored in a design domain, in which the appropriate choice of materials plays an important role for the overall aesthetic [34].

However, in this work, we did not fully and in-depth address all artefact and process related challenges that this domain may provide. Hence, we refer to the summarized findings merely as 'recommendations' based on our own experiences in the field rather than formal 'guidelines'. For example, in the deployment study we only applied *particle movement* to represent live data; future investigations could consider other information sources and temporal contexts. Another aspect, we did not tackle at all in our work and which may also be of high relevance is the design of non-planar and three-dimensional displays, including low-res display types which might provide additional challenges. As a consequence, we cannot adequately judge the transferability of the design recommendations to other design fields (i.e. using a toolkit for non-planar display surfaces) which would be a further valuable contribution to this emerging field.

Another limitation of this work includes that we applied our toolkit to only one specific context, the design of an energy low-res display for the home. However, since low-res displays are designed for a wide range of usage scenarios, our toolkit and the design process may require adaptations. Designing for low-res displays in public space, for example, may require a wider range of experts and stakeholders involved, a circumstance we have experienced in our *Urban Prototyping Festival* and *Interchange of the Future* case studies.

In summary, the scope of our here presented work was to investigate a structured design process in the domain of low-res lighting displays and the direct addressing of the previously identified challenges. The gaps and shortcomings discussed in this section offer opportunities for future research in this domain.

CONCLUSION

As displays become more versatile and embedded into objects and environments around us, we will be consuming more and more information via low-res lighting displays. In this paper, we have shown artefact and process related domain challenges when envisioning, designing, pre-testing, and deploying low-res displays. Our contribution to this emerging field can therefore be summarized as: (1) a presentation of design recommendations for low-res lighting displays in the home context, and (2) how the challenges that we derived from various design studies and cases can be addressed in other design contexts by following our toolkit-supported user-centered design process. Practitioners and designers can refer to these recommendations as starting points to scaffold their own process of designing low-res lighting displays.

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