Designing Low-Res Lighting Displays as Ambient Gateways to Smart Devices

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ABSTRACT
The Internet of Things (IoT) enabled through sensor-rich environments and smart devices allows us to collect and exchange vast quantities of data. The advent of new markets, such as the smart home sector, and movements, such as the quantified self, indicate the IoT's huge economic and social impact. With the increased availability of IoT services, it becomes important to enable users with intuitive mechanisms for accessing the gathered data. In this work, we present findings from an exploratory design case study, in which we deployed a low-res lighting display in three family households to visualize domestic energy performance data. Our study showed that the standalone lighting display was preferred over a commercially available web-based application. Further, we found that in two of the three households those participants, who did not use the mobile application before, became the main user of the display and actively engaged with the visualized data. The paper concludes with design implications for pervasive displays connected as ambient gateways to smart devices.

Author Keywords
Information design; low resolution display; ambient light systems.

ACM Classification Keywords
H.5.m. Information interfaces and presentation (e.g., HCI): Design.

INTRODUCTION
The advent of sensing-technology services in our lives is increasing rapidly due to widespread mobile access to high-speed internet and reduced component costs, enabling the Internet of Things (IoT) in the private domain [3]. Sensors and actuators are already being deployed at large scales in our daily environments. At the same time the wide distribution of mobile devices allows manifold interaction opportunities between data and people. However, the appropriate distribution of gathered information to users in an intuitive way remains a challenging task: communicating data to people only via mobile devices may result in information overload and/or hindrance of mutual dialogues and behavioral changes. Further, less technically skilled people may be excluded as data representations are often difficult to understand and engage with [10]. It also remains an open question how these systems can be systematically co-developed and evaluated with the intended users [8].

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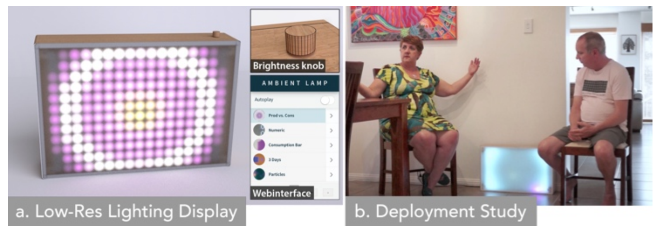

Figure 1. (a) Rendering of the low-res lighting display visualizing sensed energy performance data, (b) the display during the deployment study in a participating household.

To address these challenges we propose the concept of ambient gateways as a means for creating a more seamless and natural interplay between IoT-based data sets and the physical environment. The concept builds on early research on ambient displays and provides users with seamless access to data sets instead of relying solely on mobile devices or web platforms. In this paper, we provide a deeper reflection on how a custom built smart low-res lighting device served as an input and output medium and as ambient gateway to smart devices. Our low-res lighting device was acting as semi-public interface displaying energy related content on its outer shell while also acting as a *trigger* for deeper user engagement with the underlying service. We conducted a field study in three family households over longer time-spans (i.e. several weeks) which provided findings on the user acceptance, usefulness, ambient aesthetic qualities and on behavior changes prompted by the integration of our low-res lighting display in the family's homes.

Our contribution is two-fold: First, we present insights and findings form a field study of a low-res lighting display connected to a smart metering device, and second, based on those findings we provide design implications for ambient low-res lighting displays as a form of ambient gateway.

RELATED WORK

Ambient Displays

Ambient information systems take advantage of humans' background processing capabilities. Ishii et al. first described the vision of an architectural space that serves as an ambient interface for displaying information in the periphery of the user's attention, without distracting from primary tasks [11]. Inspired by natural phenomena, ambient media systems, such as the ambientRoom [12], use subtle changes in light, sound or movement to process information. Ambient displays were also explored in the context of persuasive technology, for example to promote energy awareness in the home [4, 13, 15]. Ambient displays feature high aesthetic qualities, support monitoring of non-critical information and can move from the periphery to the focus of attention [21]. While ambient displays have already been studied in the late nineties, the IoT paradigm provides new application areas for ambient displays as an alternative output channel. For example, Houben et al. developed Physikit [10], a toolkit that makes environmental or personal IoT data easier to grasp using physical and embedded data visualizations and allowing the end-user to program the data mapping. Our paper adds to developing a better understanding of how ambient display principles can be translated into today's IoT era.

Low-Res Lighting Displays

With the small form factor and the ability of precise dynamic color control, programmable LEDs open up new design opportunities for ambient media displays [23]. Bright colored lighting can positively affect people's mood and emotions [9], and thereby convey information in the periphery of attention [18]. Lighting comes with a rich set of parameters to encode information [17], such as color hue, brightness and saturation as well as dynamic parameters, including duration and frequency of changes [9, 16]. Whereas color and movement work even on the lowest end of resolution, i.e. for single pixel lighting displays [5], text and images require a pixel matrix consisting of a slightly higher resolution [20]. Besides the issue of information encoding, recent research has investigated designing the screen as a material as it plays an integral role for the overall aesthetic appearance of low-res lighting displays [7, 8, 24].

RESEARCH AIMS & OBJECTIVES

The aim of our research was to explore ways of integrating real-time data more seamlessly into physical spaces and thereby making visualized information easier accessible for the user. Proposing the use of a low-res lighting display, we were in particular interested in how users perceive the aesthetic qualities of such a display and their ability to decode the visualized data.

Whereas possible application areas are manifold, in this research project, we chose energy performance monitoring as design context. As such, we collaborated with a small company in the smart home sector, Solar Analytics (https://www.solaranalytics.com/au/), which operates a cloud-based platform, called Solar Analytics Dashboard (SAD), offering live observations and past analysis of energy performance data sensed through a solar metering device. Solar Analytics was interested in trialing an additional physical in-home display to make the sensed data easier accessible and to provide a more seamless real-time experience in order to help users to make better use of their solar power. Therefore, we adapted a previously developed low-res lighting display to function as an ambient gateway to the solar metering device. Compared to existing single-pixel displays, such as the Ambient Orb or Phillips Hue [6, 19], our system is able to display both abstract and informational data. In other words, using a low-resolution display allowed us to encode information not only through color but using more complex encoding techniques such as movement, text and images [20], and to display multiple information sources [21].

SYSTEM DESIGN

The development process of the low-res lighting display lasted over 8 months in total. We involved experts and end users in various co-design activities, including the iterative testing of design concepts using a prototyping toolkit [7]. This section provides a brief overview of the final system design, but full account can be found in [8].

Display: The display features a discrete and continuous representational mode in order to support a wide range of visual representations and to explore the boundaries between display and luminaire design. We used a 17x12 hi-power LED grid, which can be moved back and forward behind the acrylic front plate using a linear motion system to switch between the two modes. The display case is made from wood and measures 61cm in width, 38cm in height and 12cm in depth (see Figure 1a).

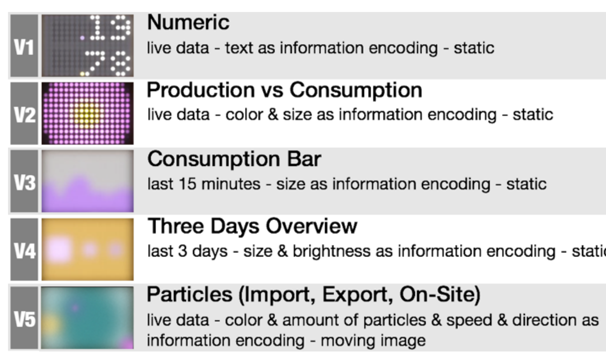

Figure 2. Overview of the visualizations, including temporal context, information encoding and lighting dynamics [8].

Visualizations: We used the Java-based programming language Processing [22] to develop five distinct visualizations, which were connected to the real-time energy data that was retrieved via an API. The software ran on a Raspberry Pi 3. Figure 2 provides an overview of the visualizations: we designed one simple numeric visualization V_1, displaying the current energy production (top) and consumption. V_2 shows the current energy consumption (purple) and production (yellow) through circular area charts. V_3 uses a bar graph to indicate the energy consumption of the last 15 minutes and V4 uses three squares for a comparison of the total consumption for the past three days encoded via brightness and size. In V5, 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.

Interaction: For controlling the brightness of the display, we attached a rotary knob to the housing. Additional settings, such as selecting a specific visualization or adapting the colors, was made accessible via a web application implemented using the Meteor framework.

STUDY SETUP

To study user acceptance, usefulness and aesthetic qualities of the low-res lighting display in a real-world context, we deployed the prototype consecutively in three family households over a period of two months in total (see Figure 1b). Adopting an exploratory study approach, we did not explain the specific goals of the study and did not instruct participants in which way or to what extent they had to make use of the display.

H_1	Family with three kids, aged 2, 4 and 16; living in a small terraced house; mother home during the day; only husband checks the dashboard; high energy awareness.
H_2	Couple with a small child; living in a spacious single-family house; husband at work during the day; wife runs small online business from home; husband checks the SAD regularly; average energy consumption.
H_3	Couple living together with their grown-up daughter in a spacious house; wife regularly checks the SAD on a desktop PC; almost twice as high energy consumption of an average household.

Table 1. Overview of the participating households.

Setup and Participants

After explaining the functionality of the system, we installed the display in the first two households (see Table 1, H_1 and H_2) for 10 and 11 days, respectively, and in a third household (see Table 1, H_3) for 26 days to investigate varying usage behavior that might occur during a longer period of use. At the beginning of the installation setup, we asked the families to choose a preferred place for the display: H_1 placed it on a shelve in their tiny kitchen living room, H_2 put it on the floor of their spacious open plan kitchen living room and H_3 placed it on the floor of their reception room. In household H_1 and H_2, the participants accessed our web application via a smartphone, in H_3, they used their desktop PC which was located in the same room.

Data Collection and Analysis

During the field study, we collected both quantitative and qualitative data. For later analysis and with consent of the participating households, Solar Analytics authorized us to access the interaction logs with the SAD collected via Google Analytics. Further, we stored all interactions with the display locally on the Raspberry Pi. After the deployment, we conducted a semi-structured interview in each household to find out about the general experience of using the display, the preference for a visualization and the effect on using the SAD. In each of the three households, the 45-minute interview session was attended by both, husband and wife, together. We conducted the interviews next to the display's location in order to help participants to remember past events and to perform interactions with the display while retelling [1]. All interviews were video recorded for later analysis via open coding [2].

DISCUSSION OF RESULTS

The quantitative data analysis and the findings from the interviews revealed that all households were engaged with the low-res lighting display and used it during the whole time of the deployment. In this section, we first discuss the *usage* of the display versus SAD, supported by the interaction logs and interview statements. We then present five themes that emerged from the qualitative data analysis: *interpretation of meaning, audience, expectations, associations* and *judgement of user experience.*

Usage

Solar Analytics Dashboard

As we were interested how the low-res lighting display as an ambient gateway would influence the engagement with the dashboard, we counted the number of daily dashboard accesses (i.e. unique sessions tracked via Google Analytics) for each household before and during the deployment (over the same period of time), to analyze if there was a significant change in usage. For household H_1 and H_2 no correlation was found between during the deployment (H_1: M=1.6, SD=2.22; H_2: M=1.27, SD=1.42) and before the deployment (H_1: M=1.4, SD=0.84; H_2: M=1.73, SD=1.56), H_1: $Z=-0.2$, $p>0.05$ and H_2: $Z=-0.93$, $p>0.05$. For household H_3 the dashboard usage was significantly higher during the deployment (M= 1.03, SD=1.28) than before the deployment (M=0, SD=0), $Z=-3.18$, $p<0.01$, indicating that the low-res lighting display increased their awareness of the dashboard and triggered usage.

Low-Res Lighting Display

On the one hand, the in-depth interviews revealed that participants favored a visualization based on a combination of both aesthetic and functional criteria, though with different emphasis. H_2 explained that she preferred the numeric visualization because of the clear meaning. On the other hand, one participant in H_3 mentioned that she is "more a color than a numbers person" and stated the numeric visualization "didn't provide anything in addition to what the dashboard would give". Whereas these two households had a strong preference towards either the numeric or the graphical representation, the participants in H_1 confirmed a hybrid use*:*

Female Participant in H_1: Probably the number one I had on the most was the Production versus Consumption [V_1], because it's so pretty and [...] it really tells you what's going on. And then very closely followed by the numeric [V_2]. Often when something happened on the Production versus Consumption, I flick it to the numeric to see the detail.

Together, all households made 176 actual changes to the low-res lighting display ($\bar{x}$ = 58.67, min = 16, max = 84), thereof 108 changes of brightness with the physical knob ($\bar{x}$ = 36, min = 3, max = 60) and 68 total changes with the web application ($\bar{x}$ = 22.67, min = 13, max = 24). H_2 stopped interacting with the display after half of the deployment, whereas H_1 and H_3 interacted with it throughout the entire deployment period. The pattern for those two households resemble one another, with the physical brightness knob used most consistently and the occurrence of peak levels for visualization changes (peak at day 6 with 13 changes in H_1, and peak at day 9 and day 15 with 7 changes each in H_3).

Overall, the data shows that all households ran the display throughout the entire deployment, however the interaction patterns varied widely. Based on the overview of the displayed visualizations and the interactions with the display, we identified different types of usage behavior:

- **24/7 background operation:** the display was running throughout the entire deployment with only few interactions performed (H_2).
- **Daytime operation:** the display was running throughout the day with a medium level of interactions, primary for turning on and off the display (H_3).
- **On demand:** varying times of use throughout the day with the highest rate of performed interactions per day (H_1).
- **Interaction peaks:** sharp interaction peaks for particular days. The peaks did not occur at the beginning of the deployment (as might be expected due to the novelty effect), but rather halfway of the deployment (H_1, H_3).

Interpretation of Meaning

The interviews revealed that all participants were using the display, in the first place, as an information carrier, which implies that they successfully interpreted the meaning of the visualizations. Not surprisingly, the numeric visualization was the easiest to interpret: H_2 mentioned that they were able to make use of the information instantly after the display was deployed. Whereas H_2 ended up solely using the numeric visualization, the two other families relied on different approaches to interpret the information of the graphical visualizations: the participants in H_1 combined the various pieces of information provided by the different visualizations (e.g. switching to "see the finer detail"). The participants in H_3 used a multitude of external sources of annotations for understanding the meaning. Besides "calibrating" the light patterns with the information on the dashboard, they mention that also the daily course of the sun and comparing appliances to their baseline consumption reinforced their understanding of the underlying data. One of them compared the learning curve for interpreting the particle speed of visualization V_5 with the following phenomena:

Female Participant in H_3: It's like when you are an experienced driver here in Australia – [on] the main roads, everything is 60 [kph] and you know when the cars moving at 60 [kph], you don't need the velocimetry because you know what it visually looks like.

Sometimes, however, when participants were not able to interpret the data correctly, such as in the case of the three-day overview visualization V_4,, it also led to frustration. The participants in H_1 tried to relate the patterns to their activities of the past days, e.g. remembering when they've been home all day or the cleaner came in, which both resulted in a higher energy consumption, however one of them concluded:

Male Participant in H_1: Personally, I don't think that it's accurate. For me it just looks wrong and gives me no information. I never looked at it and saying that's telling me something.

We relate this to the fact that slow and subtle feedback loops can lead to the assumption that the underlying data is not *accurate* or mapped *wrong*, which then can provoke denial. Whereas the interpretation of the real-time data was backed by immediate contextual changes (e.g. cloud cover, course of the sun) and active exploration (e.g. turning devices on and off), past values seems to be more difficult to interpret when represented purely visual.

Audience

The interviews that we conducted with the families prior to the deployment, in the context of the co-design activities, revealed that in each household only one member was primarily accessing the SAD: in H_1 and H_2 the husband was responsible for checking the dashboard, whereas in H_3 the wife was in charge for managing any energy related issues. Contrary to our expectations, in two of the three cases the person who usually never checked the dashboard at all became the primary user of the display:

Female Participant in H_1: I probably used it more, because I'm home during the day – a lot more – and I absolutely loved it. I was surprised how much I was into it. [...] And it really engaged me how I used energy - [because] I wouldn't have been looking at my Solar Analytics webpage. But because of this, it was directing me towards it and I was engaging with it a lot more.

The interviews revealed that in two households (H_1, H_2) the reason why the wife never checked the SAD was not because they were not interested in the data, but simply because the medium – a web application – was not an appropriate medium for their requirements. This points towards a contradiction in terms of who is using the dashboard and who the end user is that could make use of the provided information. In both households, the wife was primarily at home during the day and therefore the "consumer of energy in the household", however, solely informed about the energy balance by their husband:

Male Participant in H_2: When I'm at work, I'm 50 kilometers away looking at it [the Solar Analytics Dashboard] – and it doesn't really make any difference. The end user is her at home, so it's more practical for her than someone else looking.

The reason why these participants felt more engaged with the display than the SAD was varying: the wife in H_1 stated that some of the graphs from Solar Analytics are not "easy to just glance at and understand what's going on", whereas with our low-res lighting display she highlighted the "[…] convenience, the attractiveness and the ease of interpretation". It is apparent that she preferred the display because she perceived it as less technical and more intuitive to use than the dashboard. The same participant also told us a small anecdote when friends came over for a visit and she was the one explaining the display:

> **Female Participant in H_1:** Anything technical I let just [my husband] S. do or talking. If, we would have talked about Solar Analytics, I would not have said anything. But with this, I was so confident, I got out my phone [...] and I was changing stuff for them, was explaining what all meant, how to interpret – because it's so straightforward, it's so easy.

On the other hand, the wife in H_2 stated that she is "tech-savvy", but was never interested to spent time on checking the SAD. She mentioned that looking at the display "was like an obsession", however, she would not begin to use the SAD after the research prototype will be removed:

> **Female Participant in H_2:** It's too much work. […] I get on my phone so much already. I'm a mum and I want to be more present in my world. The less things I have to do on my phone the happier I am. […] I would like, where [the display] is on the wall or somewhere accessible, just walk pass it – so I don't necessarily have to disconnect with another human being to get the information – that's important to me.

Expectations

Overall, two of the three participating households explicitly mentioned that they were surprised about their reaction towards the display. In particular, both of the female participants in H_1 and H_2 who became the primary user of the display stated that they were surprised "how much [they were] into it". One of them highlighted the importance of really experiencing the display in their day-to-day life:

> **Female Participant in H_2:** I was really paying attention to this, the whole 10 days. […] But if I hadn't had this experience, I wouldn't know. I didn't foresee what this would do for our lives, for our usage habits. But when I used it – I was like 'fantastic'.

Associations

The analysis of the interviews revealed that our prototype suggested strong associations with existing media and items from a domestic environment, due to both visual and conceptual similarities. The statements of H_2 regarding the prototype often revolved around the concept of a clock ("It's like having a clock in the background."). This perception might have stemmed from the digits of the numeric visualization, however it is also closely linked to their usage behavior: they preferred to have the display "always visible", but having the information rather in the background and limited to the display's frame instead of illuminating the surrounding space ("I like the functionality of it more than the lighting feature."). On the other hand, the participants from household H_3 stated that, besides of the informational purposes, they also made use of the display as an ambient light source. With regard to the look and feel, the same participant highlighted the resemblance to a decorative novelty item:

> **Female Participant in H_3:** There is some of a reminiscence of the 60s lava lamp – so it resonates well with people who either had parents, who were young adults or who were born in the 60s. Though lava lamps like any fashion items had that resurgence. So, a lot of people in Australia understand that oil water and color concept – and that reminds me.

The interaction with the prototype was also influenced by the internalization of interaction forms from existing media. For example, one participant stated that controlling the display with her smartphone "was like [using a] remote control". In this vein, she also described her interaction with the display as "flicking between the [visualizations]" and added that "[she] changed the visualizations all the time depending on what [she] wanted to see."

Judgement of User Experiences

To provide a clearer picture about what aspects of our low-res lighting display led to positive or negative perception, we analyzed the data using the user experience (UX) framework by Kort et al. [14]. Therefore, we searched for categories that can be ranked according to three proposed aspects of UX: *compositional aspects* referring to a product's pragmatic characteristics, such as utility, ease of use and efficiency, *aesthetic aspects* addressing the look and feel of the product, and *aspects of meaning* relating to the user's higher goals, including needs and desires.

Compositional Aspects

All participants – regardless whether they were using the dashboard more or less during the deployment – mentioned that they prefer the display because of the constant physical presence of information. One participant in H_1 stated that "the whole effort it takes [...] to understand what's going on in the household" is to "be in the kitchen and glance at it". In contrast, when referring to the dashboard, participants complained about the physical effort (e.g. get out the phone, go on the computer) and the mental effort (e.g. start the right app, execute a login) that it takes to access the information. When accessing the information on a smartphone or tablet, participants also highlighted that the dashboard concurs with other applications. For example, H_2 stated that they would not mind an iPad from an aesthetic point of view, however, it has to be fixed and standalone as otherwise they "might tend to run other stuff." Even though the dashboard provides the same data accuracy, the participants perceived an enhanced real-time experience through the display: "The dashboard is more like looking at a report, the display is live action".

In the interviews, the form factor of our low-res lighting was frequently discussed. One participant remarked that keeping the display on the floor worked well for their spacious house, however, it would be preferable if the display would also fit on a table or countertop. She further mentioned that the wooden style of the display fitted with the "rustic feel" of their interior decoration, however, it might not with others. Therefore, she considered the size of the display being "key" in relation to the style.

Aesthetic Aspects

As expected, the visualizations played a key role in terms of the aesthetic appearance, with different visual elements contributing to a positive or negative perception. Besides colors, which were judged based on individual preferences, a series of other properties were given a similarly assessment: if the visualization was dominated by a round shape, this characteristic was explicitly mentioned as being aesthetically beautiful. On the other hand, if large parts of the display surface were too dark or not being part of the composition, it was perceived as aesthetically unpleasant. Interestingly, the participants mentioned that they did not feel disturbed by the constant visual movement, but rather the lighting dynamics were perceived as aesthetically beautiful that "your eyes get drawn to". In this context, the randomness or unpredictability of the particle visualization was perceived as aesthetically pleasant and being "artistic".

Aspects of Meaning

Besides looking at the display in regard to the aspect of usefulness, we noticed that participants often described the display as enjoyable. One participant mentioned that the need for sustainability and enjoyment is equally satisfied through the display and made the following distinction between the display and the dashboard:

> **Female Participant in H_3:** They both have a similar use but you experience them in different ways. [...] You don't ever go to the dashboard and look for enjoyment whereas when we could see in the middle of the day how much we were exporting back to the grid - even though all the energy we export back to the grid we make a loss on – there was a feeling of that we are doing something good for our environment – it was a positive emotional response that you don't have to the dashboard.

Further, a series of statements could be mapped to the need of (self-)confidence, in particular the two participants who never interacted with the dashboard but through the display became the primary users of Solar Analytics were talking about feeling "confident" caused by the ease of use, indicating that they felt empowered about being able to make full use of the smart solar metering device.

DISCUSSION AND CONCLUSION

Our field exploration revealed that our ambient low-res lighting display raised awareness of the connected IoT service and triggered active data exploration. The constant availability, ease of use and aesthetic appeal resulted in more household members being engaged with the data, in some cases triggering additional use of the online platform. We therefore recommend a hybrid approach, using physical low-res lighting displays and mobile multi-purpose devices (e.g. smartphones). This provides mutual benefit as the ambient lighting visualization promotes the online platform, which in turn extends the omitted information.

It turns out that even though our low-res lighting display differed from conventional high-res screens, among other things because of the low resolution and the lighting quality, other characteristics (e.g. interactive options, nature of use) can provide connotations with existing media. Bearing in mind Marshall McLuhan's famous saying that "a new medium is never an addition to an old one, nor does it leave the old one in peace" [18], one should carefully consider, which connotations are desired and which not when designing implicit information displays.

In line with previous research on physical ambient displays, it seems to apply also to low-res lighting displays that live data is more likely to gain acceptance by users than historical data. However, our findings also indicate that more research is needed to explore how existing encoding techniques can be successfully applied to datasets with arbitrary temporal contexts. Since the number of connected devices will further increase, one challenge will be to design ambient gateways that can be linked to multiple information sources, however, without giving up their original intention, which is to unburden the user from cognitive load.

We acknowledge that our findings are limited in their generalizability as our study only involved three households. Longitudinal studies with more households and in various cultural contexts may lead to alternative or completely unexpected usage patterns, which could be investigated in future studies. As we found that all participants had different ideas on how to integrate the display into their homes it would be beneficial to provide flexible form factors to have an even closer *coupling* of ambient media and physical space. As the value and benefit of ambient gateways seems difficult for users to grasp without really having experienced them, we consider aesthetic qualities, flexibility and seamless physical and technical integration even more important to leverage wider dissemination within the IoT ecosystem.

Over the course of this work we have reflected on our experiences exposing a custom built IoT prototype, we referred to as low-res lighting display, in different household over extended periods of time. We conclude that this study points towards an alternative use of smart home data by: (a) having smart-home data content directly displayed in the context instead of relying solely on personal devices to make it accessible also to less technically skilled users and (b) proposing a *hybrid* usage of pervasive home displays that serve as an ambient gate-way to smart home devices.

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