What Happened in my Home?: An End-User Development Approach for Smart Home Data Visualization

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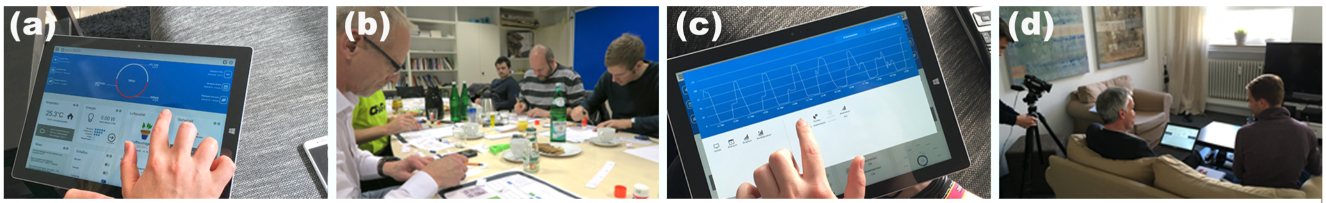

Figure 1. (a) *open.DASH* dashboard interface (b) households create paper-based smart home visualizations (design-workshop) (c) creating a new visualization with the EUD environment (d) usability test of *open.DASH* with participants

ABSTRACT
Smart home systems change the way we experience the home. While there are established research fields within HCI for visualizing specific use cases of a smart home, studies targeting user demands on visualizations spanning across multiple use cases are rare. Especially, individual data-related demands pose a challenge for usable visualizations. To investigate potentials of an end-user development (EUD) approach for flexibly supporting such demands, we developed a smart home system featuring both pre-defined visualizations and a visualization creation tool. To evaluate our concept, we installed our prototype in 12 households as part of a Living Lab study. Results are based on three interview studies, a design workshop and system log data. We identified eight overarching interests in home data and show how participants used pre-defined visualizations to get an overview and the creation tool to not only address specific use cases but also to answer questions by creating temporary visualizations.

Author Keywords
Smart Home; Qualitative Study; Data Visualization; domestic routines; Living Lab; Interface Design.

ACM Classification Keywords
H.5.2. User interfaces - User-centered design

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INTRODUCTION
Smart home systems and smart devices have become increasingly available and affordable. These smart home technologies are collecting large amounts of data (e.g. on brightness, temperature, humidity, energy consumption and movement) through a wide variety of sensors, actors and other Internet of Things (IoT) devices within the home. Data include comprehensive information about the habits and routines of people and information about the current and historical status of the personal home itself [26]. Visualizing this data appropriately enables people to discover more about themselves and their homes and allows them to satisfy data-related requirements.

There are established research fields within human computer interaction (HCI) that deal with the visualization of individual use cases for the domestic context (e.g. eco-feedback and ambient-assisted living) and that uncover highly individual information demands. However, so far, research on integrated smart home systems has focused more on enabling technologies and automation, thereby ignoring potential to make home data accountable.

To close this gap, we conducted an 18-month qualitative study with 12 Living Lab households equipped with smart home technology. Our objective was to understand what specific data-related use cases our participants were interested in. Furthermore, we developed a flexible smart home interface that allows users to build customized and personalized visualization dashboards based on their needs and to evaluate our prototype over a period of three months.

Our main contributions in this paper are:

- to provide data-related use cases and related information necessary for a user to satisfy a specific need;
- to demonstrate the concept and development of a hybrid interface that includes pre-defined

visualizations and a visualization creation tool that lets users without programming skills extend the system (end-user development);

- to provide information on using and integrating the *open.DASH* prototype and on the appropriation of our approach for visualizing smart home data.

RELATED WORK

Research into the topic of home automation or smart homes that support their inhabitants in their daily lives through the use of technology has been available for several years [3]. Smart home research addresses various issues at different levels of abstraction [46]. Since we cannot give a complete overview of all smart home and home automation research, we focus on studies related to our work and give a brief overview of enabling technology, smart home usage and visualization of domestic sensor data research.

Enabling Technology (Data and Infrastructure)

Smart home research has a long tradition that focuses on enabling technology, including smart home hardware and infrastructure to collect and transfer data and to set up a smart home.

In the last few years, new developments, especially in the field of wireless network technologies and IoT, have prompted new research. These new technologies and the increasing availability of sensors for retrofitting have also introduced new challenges, e.g. the complexity of, and technical challenges to, running a smart home network or the inflexibility of commercial systems that limit usage [22,32,48]. Thus, research has focused on ensuring that technology is in line with daily routines and habits by simplifying the installation and administration of IoT for the home and on customizing the technology to support experimentation and innovation [46]. Along with these efforts, there are an increasing number of do-it-yourself (DIY) solutions for hardware and infrastructure [48]. This trend is facilitated by advances in affordable microcontrollers, such as the Arduino and by DIY platforms such as LilyPad [12]. These advances enable users to create their own systems. Mennicken and Huang [46] state the importance of supporting these tech-savvy users, who are willing to program and create custom solutions that fit to the existing infrastructure and the needs of individual households.

Smart Home Usage (Configuration and Processing)

Another popular smart home research agenda deals with the control and processing of smart home data e.g. by focusing on tools that enable users to configure their smart homes [46].

Brush et al. [11] observed two levels of configuration required to automate actions in the smart home. The first level is the combination of different actions that are executed when the user manually carries out one specific action (e.g. a switch for turning on all lights). The second level involves rule-based systems to define conditional rules based on contextual events. Several studies deal with tools that let users define rules and scenarios when customizing the behavior of their smart home (e.g. [19,20,37]). In this area, end-user development (EUD) is one of the most relevant research topics, letting end-users define their own rules for their smart home [39,72]. The most popular example of a rule-based system (that includes home automation) is *if-this-then-that* [38] (IFTTT). IFTTT allows users to create programs that perform actions when a certain event occurs. Another prominent example is iCAP [20], a rule-based system for smart environments, where users can build trigger-action programs.

Designing for the Smart Home Context (Visualization)

A third category deals with representing and monitoring smart home sensor data and the role of data visualization. So far, little research has been conducted in this area [9] even though informing inhabitants about the collected data and executed events play a major role in context-aware systems [5,47].

Unlike in the other two categories (enabling technology and automation), up to now, there is no EUD or DIY community dealing with visualizing smart home data. Although there are approaches, e.g. by the Information Visualization community, to support the user in creating visualizations for different applications [35] (e.g. the InfoVis Toolkit by Fekete [24], the XML Toolkit by Borner et al. [8] or Prefuse by Heer et al. [35]), they are very generic and aimed at programmers. This is also true for visualization tools such as Grafana [52], which require an understanding of databases.

Currently, commercial smart home interfaces often provide user interfaces with static elements that display raw data as numbers, text, tables or log entries [47] and focus on data that are isolated per device and not linkable to other data [68]. These deficits can lead to a loss of user trust and of acceptance of smart home systems [44] and, moreover to unused system potential [36]. Recently, more advanced smart home visualizations have been developed, e.g. by Mennicken et al. [47], who integrated smart home data into a digital calendar to improve the linking and contextualization of domestic data with everyday activities. Related work revealed that users' motivation for the smart home differs as well as their technical background, and the resulting different requirements have to be considered in the design of smart home interfaces [46,47,76]. Other work on the visualization of domestic sensor data has otherwise typically been conducted separately for two specific use cases, outlined in the following.

Eco-Feedback

There is a long tradition in HCI research looking at the effects of eco-feedback in supporting energy-efficient behavior by raising awareness of energy consumption (e.g. [7,14,18,30,58,59]). Early systems for presenting energy consumption data were simple energy monitors that displayed raw consumption data of the whole household on a Screen [40]. More sophisticated feedback systems use smart plugs to provide consumption data at a device level and therefore allow the visualization of different aggregation levels [57]. Today's feedback systems are more advanced and aesthetically pleasing as design-centric surveys (e.g. [29,55]) show. Additionally, a series of design studies have elaborated guidelines [34,45] and suggest design frameworks [7,27,56] for visualizing consumption data.

A major trend in eco-feedback design is to draw attention to user diversity, taking gender [2], age [56], motivation type [54,60,66], attitudes [31], prior knowledge [33], saving experience [17,54], and energy awareness [42,75] into account. All these factors seem to affect both the effectiveness of feedback as well as the users' preferences and needs. Kirman et al. [41] stress therefore that persuasion design could benefit from adapting to individual preferences.

Ambient Assisted Living and Aging

Ambient Assisted Living technology (AAL) is another active community dealing with technological support for a comfortable and independent life of elderly people in the home [16,65]. The overall framing for such systems is highly dependent on the user, user groups and their role, which influence the motivation for such systems. Primary users are the care recipients themselves, but the user list also includes formal care givers, remote care givers and family, neighbors and friends [49]. Furthermore, Stein et al. [63] show that, within the different user groups, there are still more finely categorized use cases that have to be considered, when designing smart home systems for elderly people, e.g. awareness, safety, health, emergency and enhancing of wellbeing.

The consideration of these factors can be seen more easily in the progress of systems that have evolved from simple telecare systems to more sophisticated ones. Takács and Hanák [67] developed an ambient facial interface (a digital human face) that used facial expressions to display emotional information about the current state of care recipients or of information on products they interacted with. Truong et al. [70] presented a more user-centered and interactive system that allowed users to write their own applications for scenarios in daily life. Mulvenna et al. [49] support this effort and suggest developing adaptive interfaces that target the specific needs of different users.

Challenges for Visualizing Smart Home Data

The known issues in the design of interfaces and the visualization of domestic sensor data call for human-centered approaches. Research in smart home enabling technologies (including hardware and infrastructure) as well as in smart home usage (including configuration and processing) tend towards customizable and DIY approaches, such as EUD, that let users adjust the smart home to their needs and ensure an inhabitant-centered design [19]. According to Newman [50], end-user configuration capability is a key factor in smart home systems. On the visualization level of smart home data, no EUD approach has yet been discussed in literature, but much work deals with static visualization elements. These studies provide best practices and design implications mostly for specific use cases (e.g. energy, security, health, etc.) or for specific users. These works highlight that visualization play a crucial role in domestic systems. Furthermore, research shows that, even in these specific use cases, the needs, interests, capabilities and goals differ between users ("one size does not fit all" [34]). These needs and interests could also change over time with the use of such systems, and they depend on the user's current situation [42]. This variety of parameters is challenging when designing smart home visualization. Users need flexible tools for customization, data comparison and annotations that make the data understandable and to support sense-making [4].

Our *open.DASH* system (see Fig. 1a) combines these two approaches: integrating pre-defined visualizations based on gained insights and experience in specific domestic areas and additionally allowing free customization based on an EUD approach [43]. Our goal is to provide tools that allow users both to explore their smart home to gain further insights into their routines, habits and the home itself and to adjust their smart home interface to fit their specific needs.

METHODOLOGY

In our study, we followed the user-driven design approach proposed by Stevens et al. [64] and Wulf et al. [73,74] to inform the design of our smart home interface. Thus, we applied a Living Lab approach to understand users and their contexts and to investigate the use of smart home systems in real-life environments [23,28]. With this approach, it is possible to bring users and technology together with different stakeholders from research and design in an open design process [28]. Living Labs support long-term cooperation, co-design and in-situ exploration and therefore the integration of users into a continuous evaluation of the designed artefacts from the very beginning [6]. They also allow early discussions of new concepts, testing not fully operative prototypes and field tests for long-term appropriation of new smart home systems. Especially for the smart home, it is important to investigate users' needs and the contexts for which systems should be designed [53].

User Sample

We focused on gaining a heterogeneous user sample to have as many different users and types of households as possible. After a multi-stage recruitment process, including newspaper ads, local radio features, etc., we made a pre-selection based on spatial proximity and conducted telephone interviews with 63 interested households (from over 100 registrations) to gather an impression regarding motivation for participation, willingness to actively participate in the project and technical and smart home related foreknowledge. Twelve households with a total of

29 inhabitants were selected, varying in terms of age, living style (rented or owned home, house or flat), rural or urban residential area as well as technical level (see Table 1).

#	household size, living style, location	tech. knowledge
H1	2-pers. household, apartment, city	Yes
H2	3-pers. household, house, rural area	Yes
H3	3-pers. household, house, rural area	Yes
H4	3-pers. household, house, rural area	Yes
H5	4-pers. household, house, rural area	Yes
H6	2-pers. household, house, rural area	Yes
H7	2-pers. household, apartment, city	No
H8	1-pers. household, house, rural area	No
H9	3-pers. household, house, rural area	No
H10	2-pers. household, apartment, city	No
H11	1-pers. household, house, city	No
H12	3-pers. household, house, rural area	No

Table 1. Overview of Living Lab user sample

Study Design and Data Collection

We conducted a two-stage qualitative empirical study, which is illustrated in Fig. 2. All interviews were audio-recorded and transcribed verbatim. In addition, the design workshop and usability evaluation were video-recorded to facilitate subsequent analysis.

Phase 1: Understanding and Requirements

We started with an explorative on-site study with a semi-structured interview (**T0**). Our main goal was to gain an understanding of the participants' homes, their daily routines and habits as well as their information needs, interests and ideas for use cases of a smart home system. Afterwards, we provided them with an "off-the-shelf" smart home solution that is currently available on the market. This Z-Wave-based (wireless communication protocol) plug'n'play smart home platform system was used as a technological probe (consisting of 6-36 components per household, selected from a wish list). Three months after the installation, we conducted a second interview study gathering experiences, demands, limitations and gained insights when using the smart home system in participants' everyday life (**T1**). After a further three month period, we conducted a design workshop with five households with the goal to validate requirements identified in T0 and T1 and to gain insights about the design needs. The gained understanding (T0), the mentioned experience and demands (T1) and the design needs from the workshop drew a first set of requirements for our *open.DASH* prototype.

Phase 2: Evaluation and System Usage

After the development, we conducted a three-stage usability evaluation to ensure that the prototype was usable during the households' everyday life (see Fig. 1d). In this evaluation, users had to perform two scenarios based on T0 and T1 with overall 12 tasks. We first conducted a heuristic usability evaluation with three usability experts from within the university, using Nielsen's usability heuristics [51]. Afterwards, we repeated our usability evaluation first with five and then again with six participants from our Living Lab. We used thinking-aloud to see how users interact with our developed interface [51]. Having addressed all problems mentioned, we rolled out the prototype in 10 out of our 12 Living Lab households (due to sickness and to technical problems, we were unable to install/run our developed interface in two households). Our system was installed as a supplement to the commercial smart home system and was connected to the same sensors and actors, thus used the same data. The participants used the *open.DASH* interface over a period of almost three months. Subsequently, we conducted a third interview study (**T2**) to gather experiences regarding the use, limits and desired extensions of our *open.DASH* interface.

Data Analysis

Our analysis is based on all Living Lab research activities during the 18 months, including T0, T1, and T2 interviews, design workshop results and field notes from visiting the households. All transcripts were analyzed by two researchers independently using thematic analysis with an inductive coding process [10]. After each of these research activities, code categories were consolidated and developed iteratively. We also internally discussed gained insights with researchers not involved in the project. We recognized the need for some degree of inter-rater reliability and so enlisted other internal researchers that are not involved in the project to check our coding decisions. Additionally, for the evaluation of our developed prototype, we collected quantitative data on the number of site visits, visiting time, duration and customization activities.

In the analysis, we looked for common information needs and interests, actions related to information provided through the system and how the participants configured their smart home. Furthermore, we looked at the integration of smart home data into everyday life especially when users were interested in smart home data, and what questions they wanted to be answered. All quotes in our findings section were translated from the German by the authors.

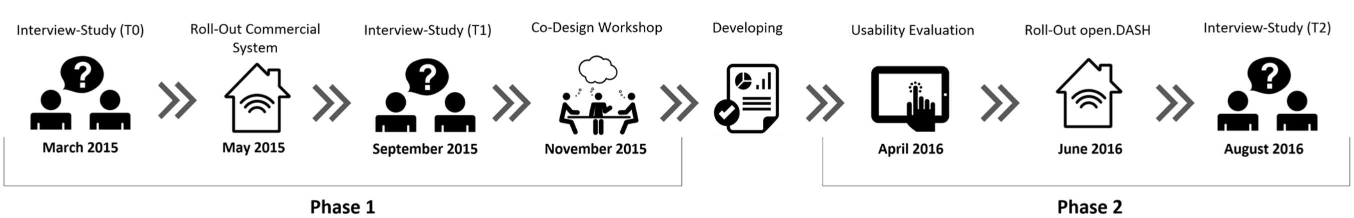

Figure 2. Methodology timeline

INFORMATION DEMANDS ON SMART HOME DATA

In this section, we present findings from the analysis of Phase 1 that resulted in requirements for the first prototype of our *open.DASH* interface.

Information Needs and Scenarios

Our analysis resulted in three overall topics for the use of smart home sensor data, which are outlined below.

Events and Home-Status

A frequent information need was about the current status of the home, especially in the "*leaving-home"* scenario. The participants wanted to know if they had forgotten something such as electric devices or radiators that were still on or open windows and doors: *"Is everything O.K. when I am not at home? Did I forget something?"* (H8, T0). Although motivation varied, nearly all participants mentioned that immediate information about the current status of the home would give them a feeling of security. Another related demand dealt with situations where the participants were *away from home for a longer time*, e.g. when on vacation. Here, the focus shifted, and it was more important for participants to get information on events that happened in the home than on the home's status: *"When we are on vacation, the events are more important, for example if there is movement or if a window or door was opened"* (H8, T0). After installing the commercial smart home system, some participants mentioned that they looked regularly at their event diary, even if they were at home, to get a feeling about what was happening in the home.

Energy and Performance

Another recurring demand of households dealt with energy efficiency and performance. Before the installation of the commercial smart home system, there was a great need to check whether the devices in the home were energy efficient or not: *"I don't know how much energy is consumed by my devices, I have no possibility to check it"* (H9, T0). *"It is interesting to track what we have to pay for energy every week"* (H7, T0). *"I want to track my standby consumption"* (H12, T0). Most participants mentioned interest in feedback on energy consumption data. With the commercial system installed, requirements towards consumption data tracking and visualization turned out to be very individual. While some participants continuously tracked their consumption, a few households would only check consumption data occasionally, i.e. when they got a *new device* or when *receiving their electricity bill*: *"[Energy] is only interesting if we have a new device"* (H6, T1).

Besides electricity, heating was a very personal topic for the participants because most participants had their own "feel-good" temperature and it sometimes was difficult to quantify this optimum temperature: "*What is the real temperature? […] How does the sun influence the inside temperature? […] What effect does an open window have?*" (H9, T0). Therefore, it was also difficult for them to define criteria for performance or efficiency of their heating routines: *"For example, when I have invested, let's say into my heating, I want to know: Does it pay off?"* (H9, T0). *"I don't know what the influence of my heating routine is"* (H8, T1). When the participants could see the real temperature in their rooms, they developed an awareness and could identify *anomalies* by looking at the current temperature. That was also true for energy consumption. After gaining an awareness of energy consumption and temperature levels, participants looked at the data to see whether everything was o.k. and, if not, they tried to find reasons: *"If the [energy] trend is negative then I want to check why"* (H6, T1).

Awareness of my Smart Home

The installation of the commercial smart home system also resulted in new requirements related to the configuration and automation of the smart home. Because the participants initially lacked trust in the system, they were concerned about false behavior of the smart home and checked the information on the smart home interface to see if their configuration and defined rules were working properly (this is also mentioned by Mennicken et al. [47]): *"I check the system to see if something has failed, like my heating control at the beginning"* (H3, T1)

Furthermore, data served as information about the right configuration, e.g. if the defined rules worked the way the user wanted them to. The information was also used to gain awareness and for participants to build their perfect configuration: Which brightness level is enough and when should the light automatically turn on? How long does it take for the rooms to heat up? Generally, the households used a trial-and-error approach to adjust the settings step-by-step until they were satisfied with the result.

Implications

The findings so far have shown numerous overlaps of needs and interests between participants, but also some opposing opinions. Overall, we identified eight questions that our participants had for smart home data visualization:

- What (has) happened in my home?
- Did I forget something?
- Are my devices energy efficient?
- Am I energy efficient?
- Is everything o.k.?
- What is the current status of my home?
- Does my smart home work as expected?
- Is my configuration appropriate?

Although, these questions were not always applicable, they were a good starting point to categorize use cases for home data. Not all participants were interested in all of this information, and the information needs could change over time. Besides personal interest, there were multiple other factors that influenced the information needs such as when the participants were on vacation or by seasonal effects: *"[interests in] brightness in winter [its getting dark earlier] and the window status in summer [for fresh air]"* (H1, T1).

Therefore we can further divide information needs into *long-term information needs* and *temporary (short-term) information needs*. Long-term information needs are interesting for participants over a longer period of time, e.g. for the routine to check if something was forgotten in the leaving-home scenario. Temporary information needs are irregular needs that only come up at specific times, e.g. when getting the electricity bill to check what devices are responsible for the consumption.

Especially after installing the commercial smart home, new requirements for smart home data monitoring were identified. The ability to collect data raised interest e.g. in long-term analysis of energy consumption or the combination of multiple devices for comparison or identification of relations between them (which was not fully supported by the commercial smart home system): *"For me, smart home is the connection of multiple devices […] I don't want a single view, but to see things together, combine things and to visualize them."* (H8, T1).

In general, we can confirm findings from the literature insofar as our participants had individual and personally-motivated information needs [34,56,63]. But we could further see that our participants had also overlapping data-related interests and use-cases. To validate our findings and to identify these mutual information needs, we conducted a creative design workshop, where participants could develop their own paper-based smart home interfaces (see Fig. 1b). In the workshop, we could see that the participants were generally interested in overviews on the topics of energy, temperature and security. Furthermore, we found that people also wanted further, external information implemented into their smart home interface, such as information about the weather or a news feed. Additionally, the workshop revealed preliminary insights into exchange of experience between participants and participant interested in use cases from other participants, to develop new ideas. The concurrency of mutual interest in information, as well as the individual interest in specific information, suggest a hybrid system that includes (1) pre-defined visualizations that can be configured by users and (2) a custom tool for building custom visualizations, fitting needs and interests and allowing a detailed view of the collected data.

DESIGN AND IMPLEMENTATION OF *OPEN.DASH*

Based on these findings and on relevant literature, we designed a flexible and highly customizable prototype to gain insights about how people use smart home data with our system in real scenarios (Fig. 3).

The system is based on a dashboard concept, allowing us to realize our general idea of multiple visualizations for the participants' needs and use cases as single web components that could easily be exchanged or configured during runtime. The header section allows direct access to the menu and customization settings. The blue-colored area shows real-time information on room level. We chose rooms as a structure because studies show that rooms build an appropriate ordering of the home [15]. A single click allows the navigation between rooms. Overall, this header section allows values in different rooms to be compared and provides an overview of the *current status*, *if everything is o.k.* or *if something was forgotten.* The customizable widget section begins under this blue-colored area. Widgets can be dynamically added, rearranged, changed in size or deleted.

Pre-Defined Visualizations

Pre-defined widgets can be dynamically added through a widget-chooser in the side-menu. In the first draft, we included five pre-defined widgets that were inspired by the design workshop, including a news widget where an RSS-feed can be included to get current news of the preferred news portal. The development of the pre-defined visualizations was steered by the Visual Information Seeking Mantra by Shneiderman [61] to first provide an overview of the related topics and filtering and details on demand.

The energy widget provides information about the current consumption level of all devices, the current amount of money for this week's energy consumption, a trend indicator that shows if the consumption of this week has a positive or negative trend in contrast to an average weekly consumption and abstract indicators that showing the consumption for up to five single devices. Thus, this widget provides quick information about devices that are currently consuming energy (*Did I forget something?)*, about the relation of consumption between devices (*Are my devices energy efficient?*) and about the usage of devices (*Am I energy efficient?).*

The temperature widget indicates the current average temperature of the home. The user can individually configure which sensors should be included in this calculation (e.g. to exclude sensors in the basement).

Figure 3. *open.DASH* - interface.

Additionally, the outside weather and the forecast of tomorrow's weather is shown. The close link between inside and outside temperature allows a quick comparison and an overview of the *current status*. Furthermore, the user can see whether the minimum temperature is maintained (*Does my smart home work as expected? Is my configuration appropriate?*).

The security widgets provide an overview of the last (security-related) event and the time it occurred. As participants mentioned that events are more important when not at home, especially movement and door/window status, this widget shows only the last movement or door/window status event, including whether it was an opening or closing event (*What (has) happened in my home?).*

The diary widget shows information about every single event that has occurred in the home, without any historical limitation. The events are placed on a time-series of one day (00:00 to 23:59), and the user can click through each day. To improve readability, the events are aggregated on an hourly level and the number of times an event has occurred is mapped through the height of the bar (*What (has) happened in my home?*). Additionally, events from configured rules or time control are visible, allowing users to check whether the smart home works properly (*Does my smart home work as expected?*).

End-User-Development Visualization Tool

To allow a very personal customization and a detailed exploration of smart home data on demand [61], we developed an EUD environment to create custom visualizations of smart home data. As EUD for the smart home is currently a highly topical theme, we developed our environment with consideration of best practices from the literature. Therefore, we developed a guided step-by-step creation mechanism that supports the users. Furthermore, we provide simple click/touch interactions instead of more complex operations such as drag & drop [19].

Our visualization creation process consists of five-steps (see Fig. 1c,4), following the visualization pipeline by Card [13]: selecting data (Data Analysis), selecting time (Filtering), selecting chart, configuration (Mapping) and adaption (Rendering). The first step is to choose which data should be visualized. The user can choose one or many devices and sensors from the list, which contains all of the installed sensors in the home. The second step is about when the data is aggregated. The user can choose between an absolute timespan (e.g. for the exploration of a specific billing period) or a relative timespan (e.g. the last four months). After these two steps, the user can select how the data should be visualized. We implemented an algorithm that analyzes the selected data source and timespan to automatically suggest appropriate chart types. The algorithm is based on Aigner et al.'s [1] characterization of time-oriented data, and checks whether the data are univariate or multivariate, interval or point-based and whether cyclic time domains exist (e.g. for univariate data

Figure 4. Five-step process for creating an own visualization.

the system would not suggest a pie chart). Additionally, it checks whether data could be easily summed up (energy consumption could be aggregated to hour values by summing minute-based values). The fourth step contains the special configuration for the selected chart type, e.g. whether data should be mapped on lines, points etc. on a timeline chart. After these four steps, the user gets a preview of the chart, where interaction such as zooming or selecting or hovering over points to get a tooltip with information is possible. This step mainly supports task-driven adjustments, e.g. for localizing or identifying data [69]. From this step, the user can go back to the four previous steps to change the settings or can configure the interaction or layout of the chart (e.g. changing animation settings, allow/disallow zoom). The user can decide whether the chart should be added to a dashboard as a widget or discarded. If the user wants to add it to a dashboard, a title can be added and the size defined.

By using the flexible tool, participants were able to get detailed information on questions concerning *are my devices and I energy efficient, what has happened in the home*, *does my smart home work as expected and is the configuration appropriate or not*.

RESULTS

In this section, we present the results of our Phase 2 studies. Before we installed our *open.DASH* interface in the Living Lab households, we conducted a three-step usability test to minimize system usability or acceptance issues that could have influenced its usage. The heuristic usability evaluation showed some issues regarding the navigation inside the page, the wording of some features and labels, the font-size and the choice of symbols. Additionally, some parts of the EUD assistant were too complex and not clearly understandable. To overcome these issues, we implemented more filters to the interface elements to automatically hide unnecessary items. Overall, we reduced the number of symbols and text, ensuring a clearer interaction design.

User Experience, Appropriation and Use

After three months of use, we had a total of 1,394 page visits of the *open.DASH* interface, with 70.09% from a desktop computer, 24.10% from smartphones and 5.81% from tablet PCs. In the first two weeks, the average visit duration was significantly longer than in the remaining time, which could be explained by the novelty factor and the testing of all functions. Overall, 60.47% of the visit duration was under 10 seconds and 28.43% were over three minutes.

From the T2 interviews, we found that the first impression of *open.DASH* was consistently positive. The participants liked the design and its simplicity: *"The design is very good, very clear […] I can also customize and set up many different things […] Here you can do that intuitively and very quickly"* (H10, T2).

Participants reported that they liked the room-based overview, allowing them to look into every room and get aggregated information about its current status. We found that aggregation of data (to the total amount or into smaller units such as rooms) was perceived as useful (in the commercial system, the devices are isolated and participants had up to ten sensors measuring temperature and 20 sockets that measured energy consumption). This aggregation improved the ability to quickly "*get an overview*". Additionally, it reduced the amount of information displayed to the user: *"I had no total consumption with the [commercial] system, I had to sum up the single values manually"* (H3, T2).

The graphical visualization of sensor events in the diary widget not only made patterns and regular times of action visible but was also used to clarify the information value of smart home data, thus, letting people think about the effect of the digitalization: *"After looking at the diary widget, I realized what information the smart home collected. Especially, in terms of motion profiles, because this is safety-critical information"* (H7, T2).

The hourly aggregation of event data within our diary widget was experienced as an obstacle for some participants, as it allowed neither a fine-grained retrospective of action nor, especially, whether the configured rules were working properly. Another drawback to our system was the missing ability to switch devices directly from the interface, which meant that if a participant recognized some energy wastage, he or she could not act directly.

How People Customize Their *open.DASH*

As He et al. [34] mention, there is no system that fits to the needs of all users. We thus were interested in how people customized their *open.DASH* to fit their needs and to get (only) the information they were interested in.

Customize the Pre-defined Visualizations

Nearly all (9/10) households adjusted their starting dashboard in some way. This also included configuring pre-defined widgets and deleting or moving existing widgets. Households deselected devices for the average temperature calculation to only include "*important rooms*" (H2, T2) and entered their city details to get weather information for their location. Three participants also reconfigured the news-feed to get news from their preferred news portal (the initial news feed was the one from the project itself). The households also rearranged widgets to see their most important information first. Some households also deleted pre-defined widgets because they were not interested in that kind of information or because they did not have enough sensors in their home to get an added value from the generated information: *"Temperature is not interesting for me neither is the news-feed."* (H6, T2). *"I've deleted the security-widget, because I have too few sensors for this widget"* (H3, T2). *"There is information about energy consumption and a diary of smart home events, I don't need more for this household"* (H1, T2).

Overall, the participants liked the idea of the temperature widget and excluding specific sensors for the calculation of the average temperature, but they also would have liked to see this configuration ability in all other pre-defined widgets. For example, two participants used a motion sensor at their television that detects whether a person was sitting in front of it. As long as a person is in front of the television the system kept the lights on. In this example, the motion detector was partly triggered over 200 times in one hour, which had a negative influence on the diary visualization. Thus, the households in question wanted to exclude this sensor from their diary widget.

Making Own Visualizations

During the three months with *open.DASH* the participants created 203 charts with the EUD environment. 55 of these created visualizations were added to the dashboard. Most of the visualizations were created at the beginning and the end of the study.

Participants mentioned that they first used the EUD environment to play around with the data. They created charts, e.g. for temperature data, consumption data, etc., to get a feeling for smart home data and to explore possibilities for useful extensions for their dashboard. *"[At the beginning] I created some graphs, e.g. with the temperature curve, but they were not yet useful enough for us"* (H1, T2). After getting a feeling about the tool and its possibilities, the tool was used explicitly for individual use cases, e.g. for verification of configuration: *"I have created some [new widgets – saved to dashboard] […] to check if rules work properly"* (H3, T2), the monitoring of specific devices in terms of energy consumption and temperature profiles: *"During a vacation, we could check if it was too hot for the cats at home."* (H1, T2). The visualizations of energy consumption data, especially, changed over the three-month usage. In most cases, the energy consumption visualization became more specific by displaying fewer devices in a chart, or it was removed completely after the first weeks. Another interesting usage scenario was that, for specific rooms participants sometimes created charts where they combined consumption data, temperature data, brightness data and event data to learn about what was going on in the room.

Additionally, participants used the creation tool to temporarily create visualizations to satisfy urgent questions and requirements or simply for "*looking into the data*". These visualizations were typically not added to the dashboard; only the preview was used to get the needed insights from the data. For example in the situation where something was considered as abnormal, participants looked into multiple data for the current day to find reasons. Another example was looking for changes in consumption behavior. If participants bought a new device or changed something in their smart home settings (e.g. cutting standby consumption off at night automatically) or their behavior, they created a time chart to compare current consumption levels with past consumption levels.

Overall, the participants stated that they liked being able to check and analyze their data spontaneously and flexibly. It allowed them to learn from the data and to continuously adjust their smart home. Yet, for some participants it was difficult for them to find any use cases themselves and especially for their set of sensors: "*I could not create any useful visualizations because we have not enough devices [sensors] installed.*" (H4, T2). The lack of ideas was also identified as a barrier for using the tool to explore data. The same household mentioned that "[…] *a source for ideas would be interesting*" (H4, T2).

Limitations

For the evaluation of our *open.DASH* interface, we used the sensors available in the households from the commercial system (see methodology section), which lead to a few limitations. The main use cases for these sensors are: energy consumption, temperature, brightness, motion, door/window status. The evaluation of our *open.DASH* interface was conducted during the summer months, where households mentioned that temperature and brightness are not that relevant when dealing with a smart home system. Therefore, we could not investigate all usage areas for our developed system. Additionally, some households had only a few sensors installed and, as a result, little data were collected. The households mentioned use cases that they would like to uncover but, because of the limited number of sensors available, the participants were unable to realize them in an appropriate and sense-giving manner.

DISCUSSION AND IMPLICATIONS

In this section, we discuss our results and provide implications that aim to support the design of future systems dealing with the visualization of smart home data.

Pre-Defined Visualizations vs. Visualization Creation Tool

We could see that pre-defined visualizations are important in allowing the participants to have a starting point in dealing with smart home data. The participants configured and used these pre-defined visualizations to gain awareness of the data and to get an overview of the current status of their (smart) home. Topic-based widgets with aggregated data, which can be selected and (re-)arranged on the dashboard freely, seem promising in this regard [25]. Additionally, when aggregating data, it is important to empower the user to select which sensors should be included in the calculation/aggregation process to exclude data from specific sensors that are (not) relevant for specific use cases.

The EUD environment enabled participants to get more detailed information about their smart home in a flexible manner. Particularly with regard to very individual requirements and use cases, the creation tool was helpful for the households as it allows non-programming users to query their data in an understandable way. Participants explored the tool and their data to get inspiration for new use cases or information within the data. The deployment of *open.DASH* in the Living Labs showed that the *combination of customizable pre-defined visualizations and creation tools for individual visualizations* could address different information needs and interests.

Based on our results, pre-defined visualizations therefore could be informed by existing research in special topics such as eco-feedback or AAL to extend the possible fields of application. As they are a good entry point, they should be designed to provide an overview on a specific topic, letting users check on the current status and whether further details are needed [61]. However, future systems should also enable users to create complementary visualizations that go beyond universal visualizations. These could take their individual interests more into account.

Supporting Short-Term and Long-Term Needs

We were able to identify that participants used *open.DASH* differently according to their changing interests over time. Users addressed specific long-term interests that occurred or were monitored regularly by creating new visualizations with the creation tool and afterwards saving them on the dashboard. In contrast, short-term interests were mainly realized by creating new mappings of data, but without saving them, and therefore allowing "on-demand" requests for temporal requirements.

Our findings suggest that smart home systems should allow users to quickly and easily map data to different kind of charts, text and symbols, thus fitting to users' different needs [62] and furthermore, enabling the user to create on demand visualization that are not permanently displayed on the dashboard. This separation in regard to the design of the dashboard also simplifies the overview page by reducing the risk of information overload on the first view.

It will be interesting to see how users deal with recurring short-term needs, e.g. checking energy consumption when a new bill arrives, and whether the creation tool is used in the same way every time. So far the system does not allow the history of self-created visualization to be stored, and users have to build the visualization from scratch every time.

Community and Sharing

Our participants had different knowledge about the potential of data. Some participants reported that they had several specific use cases at hand; others found it difficult to find new use cases or even one use case. During the workshops (where participants came together), we could see that there was considerable interest in finding out how other participants used their smart home. In the interviews (T2), the participants mentioned that it would be interesting to see what other households did with the visualization creation tool.

For the working context there is growing body of work that deals with the socially based tailoring of a flexible software systems to enable users to adapt the tools to achieve a specific work task [21,71]. For private flexible smart home systems therefore, we argue for allowing creation tool configurations (e.g. for a visualization that showing the correlation of outside and inside temperature) to be shared, thus addressing both the inspiring of other participants and sharing the “how to” for creation of visualizations for specific use cases with an “over-the-shoulder-learning” approach [71]. Following the IFTTT approach could make it possible to share configurations for specific use cases on a platform that other users can configure and integrate into their interface.

(Flexible) Smart Home Data and Visualization Matters?

From our study, we learned that the participants had varying requirements regarding smart home data. Some requirements are superficial, some are very detailed, some demands overlap between participants, some are very specific and some participants are not very interested in smart home data. However, *open.DASH* gave us first insights of participants’ usage and how they customize their dashboard.

Dynamic visualization tools allow people to create different views on domestic data which allow them to gain further insights into their (smart) home: “[Only after looking at the data did I] *realize what information the smart home collected”* (H7, T2). Especially, the flexibility enables the user to adapt the system according to changing needs. This is further supported by three participants who used a wall-mounted tablet as a public display where they used our *open.DASH* or other sites that were relevant for them. We agree with Mennicken et al. [47] that it would be promising to integrate smart home data into already used tools. But we could also identify that participants wanted to integrate other data into their smart home dashboard, for instance information from social media, timetable inquiries, activity and health data or the TV program. The design workshop, where some participants asked for a newsfeed to be integrated, showed that participants are interested in making the smart home interface a place where all interesting information is shown at a look.

In this vein, especially when dealing with multiple smart components and systems we argue that future private information systems should provide a single unified interface, similar to what Few [25] description for business dashboards. Scattered access points with their own login-mechanism and incoherence in styling and control present obstacles for current smart systems. On a middleware-level open source projects, such as openHAB [77], already enable unified control from different smart components. Currently, advanced approaches for visualization and monitoring are still largely neglected. As we have shown, however, the combination of smart home data enables new applications of smart home systems and additionally offers opportunities to tap into the full potential of exploring the own home. Going a step further, we believe that creating a user-centered information portal that combines all smart home data with other relevant information could be an interesting topic for future research.

CONCLUSION

While smart home enabling technology is continually developing and smart home configuration research is increasingly integrating the end-user with EUD rule editors or DIY hardware, research dealing with visualizing integrated smart home data is rare. As specific smart home use cases, eco-feedback and AAL research have shown that the user needs for, and interests in, domestic data differ, thus demanding more flexible tools to display sensor data. Our study shows that this view is also true for the integrated smart home case. We identified eight requirement categories that include overlapping and individual data-related use cases. To address these individuality of data demands, we developed a flexible dashboard system, including configurable pre-defined widgets and an EUD environment, allowing users to create data visualizations themselves. We tested our interface in 12 Living Lab households for three months to examine the usage and appropriation of such a flexible system. We found that participants configured and used the pre-defined widgets to get an overview of interesting topics (energy, comfort, safety, etc.). The EUD environment was used to create charts for specific use cases (e.g. temperature curve, consumption baseline) to extend dashboards individually. We also found that the EUD environment was used for urgent demands e.g. to obtain detailed information on anomalies. We think that such hybrid interfaces for smart home data visualizations are a promising approach to addressing the users’ varying information demands and to supporting the development of consciousness through data exploration.

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