Sensorstation: Exploring Simple Sensor Data in the Context of a Shared Apartment

Teresa Denefleh[1], Arne Berger[1], Albrecht Kurze[1], Andreas Bischof[1], and Christopher Frauenberger[2]

[1]Chemnitz University of Technology, Chemnitz, Germany

[2]Human Computer Interaction Group, TU Wien, Vienna, Austria

{teresa.denefleh, arne.berger, albrecht.kurze, andreas.bischof}@tu-chemnitz.de, christopher.frauenberger@tuwien.ac.at

ABSTRACT

We present *Sensorstation*, a research product to explore the effect of smart sensors and services on the communal life within a shared apartment. *Sensorstation* utilizes wireless sensors and a shared output device displaying a steady data stream of sensor based notifications. It was deployed on the kitchen table in a shared apartment for 19 days to enable communal residents to co-design and to co-speculate on smart sensors and services in the context of their shared apartment. We synthesize and interpret findings to illustrate how residents created positive connections between each other, while simultaneously exercising self-monitoring, control over others, and contemplating reward systems and penalties. Our work contributes to a nuanced understanding of smart technology for shared apartments. We argue that design has an obligation to consider smart technology that acknowledges boundaries and to provide negotiation spaces to configure agency.

Author Keywords

Smart Home; Internet of Things; IoT; Shared Apartments; Empowerment; Co-Speculation

CCS Concepts

•**Human-centered computing** → **Field studies;**

INTRODUCTION

There is much research about the use of smart technology within 'the home' [9, 22, 47, 48], contributing to a better understanding of how people use and appropriate smart objects and services in the domestic realm and informing design about the complex entanglements between smart technology and people in this context. Most research conceptualizes 'the home' as a social community of a family living together. The HCI community has gradually expanded towards more nuanced understandings of 'the home' [19, 33]. However, there is still relatively little research on the impact of smart objects and services on people living in shared apartments. This form of 'other home' is prevalent worldwide [25, 5, 27]. In Germany, in particular, almost every third student lives in a shared apartment, making it the most frequently chosen form of living among students [28].

This paper presents *Sensorstation*, a research product aimed at exploring the effects of smart sensors and services on the communal life within a shared apartment of students in Germany. *Sensorstation* utilizes customizable wireless sensors and a shared base station. The wireless sensors could be used in the whole apartment, while the shared base station was deployed in the kitchen, the central meeting point within the apartment, where it displayed a steady data stream of sensor based notifications. *Sensorstation* supports people in creating, appropriating, and practically using smart home applications based on simple sensor data like humidity, light, movement, temperature, and air pressure. *Sensorstation* was deployed for a field study of 19 days in an apartment shared by four students. At the end of the field study we conducted a group discussion, focusing on co-speculation with the residents.

Figure 1. Sensorstation input screen with Sensortags

We synthesize and interpret findings to illustrate how residents used *Sensorstation* (Figure 1) to create positive connections between each other, while simultaneously exercising self-monitoring and control over others; and how *Sensorstation* enabled residents to co-speculate about possible smart applications that implemented reward systems and penalties to structure communal living.

DIS '19, June 23–28, 2019, San Diego, CA, USA

ISBN 978-1-4503-5850-7/19/06…15.00

DOI: https://doi.org/10.1145/3322276.3322309

Our work contributes to a nuanced understanding of how smart technology in the context of shared apartments redraws and reconfigures boundaries between people and places. We then argue that design has an obligation to consider smart objects and services that acknowledge boundaries and that smart objects and services need to provide a negotiation space to configure agency within these.

The HCI community can benefit from this paper in several ways. With *Sensorstation* we developed a research product that supports researchers in gaining insights into the impact of smart applications for shared living arrangements and the values pertaining to such communities through their lived practice. With this study we contribute towards a corpus of exemplars that represent the diversity of what makes up 'the other home', in particular, shared apartments. We also contribute an appeal for design to consider smart technology that proactively empowers people to negotiate power and boundaries within shared apartments.

RELATED WORK

With *Sensorstation* we aimed at empowering people to create smart home applications based on simple sensor data. Our goal was to enable people to practically use and understand simple smart home applications of their own design within their domestic realm without interference from us researchers. To that end, our work is positioned within a growing body of prior work that is concerned with 1) design research on smart objects and services for alternative forms of housing and the peculiarities of shared apartments in Germany; 2) how appropriation of simple sensors and access to their data can empower people in designing and understanding smart home applications within their specific domestic reality.

Designing Technology for Alternative Forms of Housing

With the promise of more comfort, safety, and efficiency, the development of the Internet of Things (IoT) starts its conquest of the home. In the last decade a series of "Smart Home" projects emerged [39, 40, 29, 48, 7]. While most research on the "Smart Home" focuses on smart objects and services in 'traditional forms of housing', often assuming a house or apartment inhabited by a single family [9, 22, 4, 33, 47, 36, 48, 20, 32] or a couple [10, 24, 23], significantly less research has been conducted on smart technology in what is considered 'alternative forms of housing' [8, 19, 26, 17, 6]. Recent studies are beginning to explore such alternative forms of housing. Notably, Oogjes et al. [33] criticize the limited view on how a home is typically seen in HCI and subsequently unfolds the values, practices, and perspectives of different types of homes, such as living in a van, on a boat, or as a nomad [33]. Focusing on one such 'other' home, Jenkins et al. [19, 18] researched co-housing, as one particular alternative form of housing more deeply. However despite some work in Europe which focuses on energy efficieny and eco-feedback [11, 6], most such inquiries have focused on the North American context.

Co-housing in shared apartments is a phenomenon that can be witnessed on every continent, e.g. "cage people" in Hong Kong [5], the temporary workers "mingong" in China [27], or college dorms in the US. However, co-housing in shared apartments is particularly widespread in northern Europe, where especially students share apartments since the 1960s. In light of tensions arising around gentrification, rising living costs, and availability of space in urban areas [33, 37, 3], this alternative form of housing has seen a steady grow in recent years [25]. Yet, the effects of smart objects and services on people and the domestic life in shared apartments have not received the attention they deserve.

Most students in Europe share housing with others. In particular in Germany, every third student lives in a shared apartment, making this the highest occurrence in Europe [12, 28]. The residential community in Germany has its origins in the student movement of the 1960s and originally pursued sociopolitical ideals. These included the abolition of private property and the classic family home as well as more sexual liberty through a liberation from "exclusive sexual mating" [35]. The residential community was considered a hierarchy-free area of independence, self-determination, and equality of women [41]. The development of residential communities was favored by legal decisions during the 1970s, most notably repealing a law, that prohibited landlords from renting apartments to unmarried people [41]. While residential communities were generally perceived as negative by the public at the time, they have now become a recognized and generally non-political form of housing [42].

Today, the residential community in shared apartments is a form of housing for a particular phase of life, for example, during the studies or at the beginning of a new job. It is a time when individuals do not yet have children and the future is mostly uncertain [42]. Students share apartments to share the costs of living [42]. Likewise, this form of housing adapts well to the needs of young adults in a transitional period of life. Residents are often within similar age brackets and share similar cultural values and dreams. Needs such as community, personal development, and safety in the group are another important focus of attention [35]. However, sharing an apartment is not without tensions.

For example, there is no tenancy law for shared apartments in Germany. Instead there are several ways a shared apartment can be rented: All residents can collectively be main tenants, or there is one main tenant and the others are subtenants [13]. In the first case every resident is fully liable to the landlord, which means that if one resident owes rent, the landlord can collect the money from any other resident. The second case can also lead to tensions, because the main tenant bears the entire economic risk and is responsible for deposit, punctual payment of the full rent, and liable for damages and compliance with the house rules. This indicates a shift in power from the hierarchy-free situation of the 1960s to several cases where one person has more power than the others. For example, one person could terminate the tenancy agreements of other residents. Or if the main tenant does not pay the rent to the landlord, or one resident behaves recklessly, everyone could loose the apartment. Privacy is another subject for tensions. People usually have one private room, but share a number of common areas, such as the hallway, bathroom, and kitchen.

They also share household equipment, such as a fridge, but also kitchenware and the letterbox. Tensions may arise around sharing spaces or placing private belongings in common areas such as the bathroom or the fridge. It is relatively easy to indicate the need for privacy in one's personal room, by opening or closing one's private room door [41]. But using shared places for private activities can be challenging. Tensions also exist around how much people want to participate in the community and around how to negotiate, distribute, and control household chores. In addition, the turnover of flatmates in shared apartments is often high, [41], which may reshuffle power dynamics between 'new' and 'old' residents.

Designing for a community in non-family relationships or partnerships offers a number of challenges for domestic design. Not only does this raise questions about overall organization of mutual tasks in daily life and social interactions (and obligations) within the group. This form of housing in particular raises questions on 'lived in' values and norms of privacy, trust, and hierarchy between residents, boundaries between common and private areas. In particular, this raises questions on the effects of smart objects and services within this realm.

Sensors For Empowerment and Co-Speculation

Commercial "Smart Home" products usually offer their users only little insight into underlying processes. Thus, collecting and processing of sensor values is usually hidden from users. In addition, the sensor data is usually interpreted and presented based on the ideas of the manufacturers of these "Smart Home" products. This development has been questioned by research, aimed at understanding how people interpret and use data in what is called "data work" [9]. One such area of this are citizen science projects in the "Smart City" that enable people to collect and interpret data about their environment using sensors [15, 2, 21, 2]. Examples include *AirQualityEgg*, for measuring air quality in a city [21] or *SafeCast* for measuring radioactive radiation [2]. If we look at the "Smart Home", we also see a range of research around data work on sensors in the home, e.g. energy advice, eco-feedback, ambient assisted living, or privacy concerns [4, 46, 44, 9, 49].

There are different ways to present sensor data. Some studies incorporate 'raw' sensor data mapped over time visualized in graphs [15, 21, 38]. Thus, by looking at values measured, it is possible to draw conclusions about past events and hypothesize about future ones, and also to understand the relationship between users and sensor data [46, 9, 38]. The sensor data is accounted for in retrospective interpretation for reasoning about daily routines, events, persons, and even domestic activities [46]. However, such representations are often difficult for non-expert users to make sense of and to appropriate the collected data [14]. Co-speculation on sensor data with residents is often facilitated by experts, e.g. giving energy advice or interviews between residents and researchers [9, 46, 38].

Other previous work takes a different approach and incorporates live access to pre-interpreted sensor data [4]. The sensor data is linked to pre-defined meanings, such as event detection or counters, e.g. for door openings or detected movements of persons. These studies typically focus on the appropriation of smart home technology, usability and how such visualizations might be used for certain purposes, e.g. to save energy. In smart home applications, it is often of high interest when an event triggers. For example, people who place their sensor in the bathroom might want to monitor humidity values so that they can heat or ventilate to avoid mold growth. In order to enable users to generate and receive contextual information from sensors they need to connect the data with meaning. Some studies allow users to create own (meaningful) visualizations or even evaluation rules for their own usage [4, 14]. Here, users can create complex rules that evaluate various data source, including IoT sensor data, to trigger actions and notifications for numerous data sinks and communication channels [34]. Nevertheless, these systems are not intended nor being researched as a means of communication to other users in shared apartments, or to use others' data or to let others use data for this purpose.

This previous work has shown that access to simple sensors and matching data visualization can empower people in designing and understanding the 'inner workings' of sensor enabled smart home applications. However, significantly less research has considered designing and deploying research products that enable residents to directly create smart home applications, to use them and to subsequently reflect on.

DESIGN RATIONALE

The goal of *Sensorstation* is to enable residents to develop and test smart home applications of their own design. *Sensorstation* consists of simple sensors that can be placed anywhere in the apartment, one screen to link sensor measurements with custom notifications, and one screen to display a constant live feed of all sensor notifications.

When confronted with new technology, such as sensors for the home, people often struggle to come up with meaningful scenarios. People can not imagine what smart sensor data could possibly drive and social routines have not been established around the new technology. To account for that and to encourage people to co-speculate free from constrains, other researchers have taken probe based approaches [33]. While probes are useful to spark the everyday creativity of people, they do not empower people in exploring future technology through use. Building on the potential of sensor applications for empowerment, we wanted to leverage technology exploration through use. We speculated, that a continued exploratory use would reveal some of the tensions occurring from actual use of smart home technology.

We aimed at establishing *Sensorstation* as a finished product which could become part of the everyday life within the community instead of making the impression of an unfinished prototype. Therefore we decided to give it an aesthetically pleasing appearance. In conceiving this research product [31] we speculated, that longer use and a prominent position of the research product in a common, often frequented area, would exhibit how self-designed smart home applications would directly and indirectly influence the housing situation and would reveal routines, tensions, power relations, boundaries, and ethics of control arising around technology use in the shared home designed by the residents.

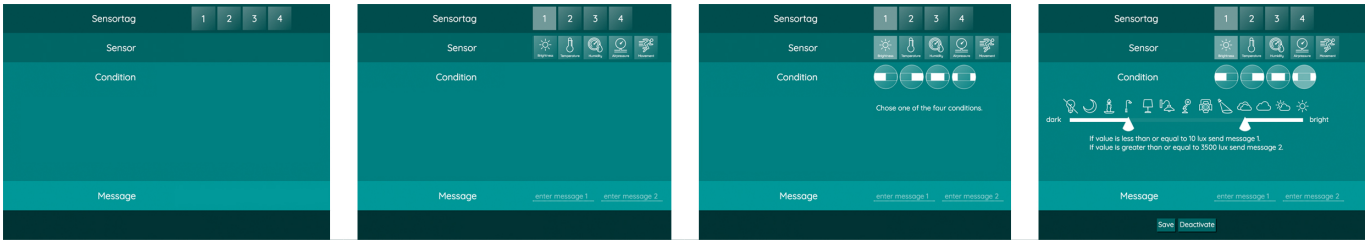

Figure 2. ***Sensorstation*** **is aimed at empowering participants to develop and explore smart home applications in their home and enables researchers to gain insights into how residents use sensor data in their home and how this affects the group living together.**

How Sensorstation Is Used

Sensorstation enables residents to create and explore smart home applications based on simple sensor data and custom notifications that are linked to the sensor data and are displayed on a shared output screen. *Sensorstation* consists of two main parts. The first part of *Sensorstation* are several color-coded *SensorTags* (Figure 1). The *SensorTags* [16] are compact and energy efficient off-the-shelf sensor platforms that hold sensors for measuring light, temperature, humidity, air pressure, and detecting movement on one circuit board. Each resident has access to one such color-coded *SensorTag*.

The second part of the product is a base station consisting of two screens in a cork housing of our own design. The input screen allows residents to choose and configure sensors, select thresholds for sensor readings, and linking them to custom notifications. The output screen continuously displays a live feed of all configured sensor notifications.

Figure 3. Sensorstation input and output screen

In order to set up a smart home application, a resident needs to follow a simple routine (Figure 2). First, the resident attends to the input screen and selects their *SensorTag* and the sensor on the *SensorTag* that should be used to measure a certain value. Second, the resident sets conditions and thresholds for this sensor. Third, the resident inputs a custom notification to be triggered based on the sensor measurements, conditions and thresholds. Lastly, the resident places the *SensorTag* where they want the measurement to take place. This smart home application is immediately active and available on the output screen of the base station.

The output screen is on the backside of the input screen and shows a constant live feed of all custom notifications (Figure 3), which are color-coded to match the accompanying *SensorTag*. Once a condition is met, the corresponding notification is shown chronologically on the output screen. Each *SensorTag* sends its text in a different color (blue, red, yellow, green), which allows a quick assignment of the sending sensor at a glance. Further metadata such as the day when the notification was sent, the sensor and the *SensorTag* are added. This live stream is refreshed in constant intervals and shows the last five notifications at a glance on the display. All other notifications and can be viewed by scrolling down the list of notifications below.

For example a resident could set up a smart home application for the temperature sensor, by placing the *SensorTag* outside a window and setting up condition and threshold to ‘below 15 degree centigrade’ and a notification that says “it is chilly outside, you might need a sweater”. Another residents might place their *SensorTag* at the apartment door and set up a condition and threshold, so that a notification says “someone is at the door” every time the door is moved. Whenever one of the conditions is met, its notification is displayed on the output screen. Residents can change their smart home application anytime they wish.

All data collected by the sensors are sent via Bluetooth Low Energy to a Raspberry Pi 3 which preprocesses the incoming data and checks if conditions were met before sending a notification to the output screen. There they are saved and processed in the programming tool Node-RED [30]. A preconfigured router connected to the Raspberry Pi enables a quick and easy use in the field and lets the *Sensorstation* communicate via WiFi with the Raspberry Pi. Once the system is attached to the residents’ router it additionally opens up the opportunity to receive sensor notifications outside the home network.

In addition to the notifications shown on the output screen we integrated the option to receive notifications on the individual smartphones of the residents via the short message service *Telegram*[45]. In this way we provide the possibility for residents to receive and check notifications on their personal smartphones.

Next, we will detail our field study with *Sensorstation* and discuss exactly how the deployment of *Sensorstation* allowed communal residents to design and use their own smart home applications, and how this enabled them to co-speculate on future use.

FIELD STUDY

We recruited a group of students living in a shared apartment in a middle-sized city in Saxony, Germany, via social media. The participants, a group of four students (age: 22–33) from different study courses were given *Sensorstation* ready to

use. Names of participants are used for readability and better allocation but have been changed in order to protect the participants' privacy. They are named Patrick, Martin, Marie and Sahra. While Patrick (automobile construction student), Sahra (management and organization studies student), and Marie (sports engineering student) were still studying at the time of the field study, Martin (economics graduate) had already completed his studies. Striking is the big age difference of 11 years between the group members. Marie, the youngest member of the residential community, is 22 years old. Sahra and Patrick are age 26 and 27. Martin, who has completed his studies, is the oldest member of the group at the age of 33. While Sahra and Marie lived in the shared apartment for only two months at the time of the field study, Martin and Patrick lived together in the apartment for one and a half years. With a total length of four years, including two and a half years with other flat mates, Martin lived the longest time in the apartment.

Sensorstation was deployed in the residents' kitchen for a period of 19 days, a common space within the apartment where every member of the residential community could make changes and view the output at anytime. Each participant chose a color-coded *SensorTag* for their personal use. This enabled participants to design their own custom smart home applications and also helped us to assign and better analyze these applications afterwards.

At the end of the field study, we conducted a 90-minute group discussion, that was moderated by two researchers. The stored sensor settings were digitally documented in the form of a list (*SensorTag*, sensor, notification as well as date and time when they where saved and sent) and served as the basis for the group discussion. Here, residents informed us on the deployment and the smart home applications they developed. They also reflected on the effects using *Sensorstation* had on them and co-speculated on future smart home applications. This group discussion was audio recorded, transcribed, and analyzed by using the Grounded Theory method [43]. Quotes and vignettes have been translated by the authors from German to English.

FINDINGS

Within the 19-day field study the group developed and tested a series of different smart home applications for their apartment. The group placed the sensors in the apartment and attached them to objects, set thresholds and notification which they received through the output screen as well as the messenger *Telegram* on their smartphones. We clustered them into four motives for sensor usage: 1) Creating Positive Connections Between Residents; 2) Self-Monitoring; 3) Control Over Others; as well as 4) Reward Systems And Penalties. Especially at the beginning of the study, the sensors were primarily used for creating a positive connection within the community by creating smart home applications which aimed at making members of the group happy. Apart from this, the group developed and proposed several monitoring scenarios and reward systems with the desire to change their own behavior or that of others. While some of them have been tested by the residential community under real-life conditions in the apartment, others were fictitiously thought of as future applications and discussed controversially in the group discussion.

Creating Positive Connections Between Residents

The residential community focused intensively on the exploration of the sensors and the development of group-related smart home applications in the shared apartment. During the first days they explored the modes of operation of the sensors by trying out different settings of the *SensorTags* at short intervals. These measurements, which were aimed at receiving immediate notifications, were jointly explored by the members within the first three days, in places freely accessible to all members in the home such as the bathroom, the kitchen and the hallway. The focus was on the correct measurement of the sensors, like detection of movement or light, as well as on the prompt output of the text notification on the output screen.

After this initial learning phase, some participants developed sensor applications for technology-based interaction with other members of the residential community. This form of sensor usage was initiated by Martin. He attached his *SensorTag* to the kitchen window on the first evening (Figure 4). At sunrise he wished all members of the shared apartment a "*good morning*". His interest was less the precise measurement of time at sunrise, but rather the use of *Sensorstation* as a contribution to a positive coexistence in the residential community.

Marie also developed a smart home application in order to make life in the community more positive. To do this, she chose the accelerometer and placed her *SensorTag* at the kitchen door (Figure 4). Every time the door was moved, the *SensorTag* sent a notification to welcome or say goodbye to the people entering or leaving the kitchen. While Martin's application, which he programmed to send a "*good morning*" to his flatmates, only sent once, Marie's *SensorTag* sent the notification "*Welcome/Goodbye*" every time the kitchen door was moved, for a period of eleven days. This was perceived positively at the beginning of the study, but annoying after a few days due to its frequency. Therefore, the group often perceived the repetitive notifications as "*noise*" and thus payed no longer attention to those notifications.

Patrick also devoted himself to the development of sensor applications for making life in the shared apartment more fun and engaging. By attaching his *SensorTag* to the mascot of the shared apartment, a cardboard display stand called "*Gary*", he playfully explored the use of the motion sensor (Figure 4). When someone entered the kitchen, it caused a vibration in the floor, which triggered the motion sensor. The notification then sent, "*Who maltreats my pet?*", made reference between the person who configured the sensor, in this case Patrick, his mascot "*Gary*", the *SensorTag*, and the person which triggered the sensor. Out of the common story the members of the apartment share, Patrick got his nickname "*SpongeBob*", whose pet is a snail named "*Gary*". This cardboard display is thus closely linked to the shared history of residential community and is humorously referred to by the group as a member of the shared apartment: "*[...] we are four. Five people, even Gary has participated*". In terms of form, the question of who maltreats Patrick's pet implies less an interest in the outcome

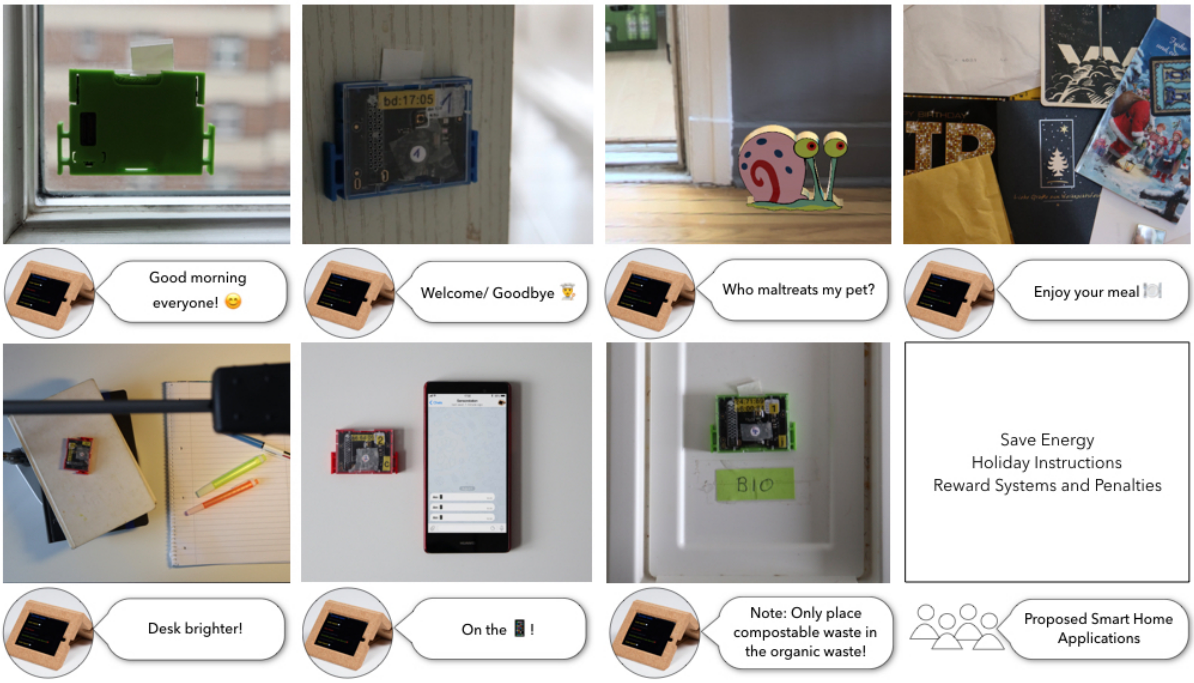

Figure 4. Developed and proposed smart home applications. Top and Bottom (L to R): Top: smart home applications for creating a positive connection between residents. T1. Attachment of a *SensorTag* to the window to measure the sunrise and send notification when the light exceeds a set value; T2. Placement of a *SensorTag* on the desk below the lamp to measure when brightness falls below a set value; T3. Attachment of a *SensorTag* to the mascot. Notification was sent when it sensed movement; B1. Hidden attachment of a *SensorTag* to the fridge. Notification was sent when the door was opened; T4. Attachment of a *SensorTag* to the kitchen door. Notification was sent when the door was moved; Bottom Left (B1, B2): smart home applications for self-monitoring. B1. Placement of a *SensorTag* on the desk next to the smartphone. Notification was sent when the phone was picked up; B2. Placement of a *SensorTag* on the desk below the reading light. Notification was sent when the measured light fell below a set value; Bottom Right (B3, B4): smart home applications for Control over others. B3. Attachment of a *SensorTag* to the bio waste flap. Notification was sent when the flap was opened; B4. Not developed but proposed smart home applications during the group discussion.

of the measurement than a type of communication and interaction between Patrick and the other members of the community which they found entertaining. While the wording "*maltreat*" has a very negative connotation and could be understood as an accusation or a request for omission, Patrick explained it as a provocative statement in the context of shared housing in which the cardboard figure is equated with a living being. Sahra commented positively on the integration of the mascot and suggested extensions in which the mascot "*meows if you pass by*", which she considered "*very cool*" and "*pretty funny*".

As another form of sensor-based interaction, Patrick developed with the goal of "*hiding the SensorTag a little, that it is not so easy to find*". For this, he hid his *SensorTag* unobtrusively between magnets on the refrigerator door. When the door was opened he wished his flatmates, with the help of the sensor, to "*enjoy their meal*" (Figure 4). Patrick used the motion sensor as a communication medium to give his flatmates pleasure and communicate with them regardless of his presence. The group received the notification when they opened the refrigerator but could not spatially allocate it due to the hidden positioning of the *SensorTag*. They took that to the occasion to play "*hide and seek*" with the *SensorTag*. While in the course of the field study, the members of the residential community mainly dealt with their personal *SensorTags* independently of each other, the playful search for a *SensorTag* created a situation which all participants liked and in which all collaborated.

This interactive and playful use of sensors was perceived positively by the group. While Sahra and Patrick were especially happy about attaching a *SensorTag* to the mascot, Marie was pleased to hear about the unexpected morning welcome, in which Martin wished the community members a "*good morning*" with the help of his *SensorTag*. In summary, the smart home applications not only delighted the participants through sending and receiving positive notifications, but also promoted community life in the group by playing hide and seek with the *SensorTags*.

Self-Monitoring

After a particularly pronounced collaborative exploration of the sensors, especially at the beginning of the field study, the group pursued different application goals. In addition to the development of smart home applications in the group, the development of personal applications was another focus of sensor usage. We wanted to give the residents the possibility to freely explore smart home applications in their apartment. Therefore we integrated the messenger service *Telegram*, which enabled the residents to receive the sensor notifications from anywhere and not restrict them to the output screen placed in the kitchen. While most smart home applications were aimed

at providing "*information for all*", other applications were used by individuals for self-monitoring. Unlike the implementation of smart home applications for the group, which were placed in freely accessible places such as the kitchen, the bathroom or the hallway for all members of the residential community, personal applications were deployed exclusively in private rooms of the residential community members. For this purpose, Sahra and Marie each used their *SensorTag* in their private rooms to monitor their health and to promote their own "*self-monitoring*". These motivations relate exclusively to the participants themselves and are therefore referred to as an interest in self-monitoring.

In order to protect their eyes, the participants placed their *SensorTag* on their desks under their reading lights. When the measured brightness value dropped below a set threshold, they received a notification to turn on their lamp (Figure 4). Another form of environmental control was expressed in the measurement of the temperature values in Marie's room. Measuring the temperature in the room should give an indication of when the room has reached the desired room temperature, so that then the heating could be turned off. The application overlaps in its own way with classic *Smart Home* applications for measuring environmental data with the aim of saving energy or gaining comfort. Unlike Marie, Sahra controlled not only her environmental data but also herself. In order to monitor and eventually reduce the frequency she spends on her mobile phone, she placed her *SensorTag* on her desk next to her smartphone (Figure 4). When picking up her smartphone, this caused vibrations on the tabletop, causing the motion sensor to trigger. By monitoring the frequency of her smartphone usage, Sahra became more aware of her smartphone usage behavior.

Control Over Others

In addition to self-monitoring, control over others played an important role in the use of smart home technology for the community. To this end, the participants developed and proposed a series of applications for the use of sensor technology in order to instruct and nudge residents to change certain behaviors. The implementation was carried out by attaching the *SensorTags* in, for the members of the residential community, freely accessible premises of their apartment, such as the bathroom, kitchen and hallway. In many cases, the explicit wish to show and promote "*compliant*" behavior was expressed. The group discussed the topics of control and behavior change with the help of sensors and took different views. The subject of instructing and nudging was first mentioned by Martin in the group discussion and named as such. In the course of the field study, he developed and tested an application for using a *SensorTag* to instruct flatmates about correct waste separation. Waste separation is an important topic in Germany as garbage is generally sorted by the consumer. For this purpose, when opening the organic waste bin, the motion sensor triggered and the following notification appeared: "*Note: Only place compostable waste in the organic waste bin!*"(Figure 4).

Although there was no resistance within the group to monitor proper waste separation, Sahra expressed initial concerns in the group discussion regarding applications for control in the living area. With her concerns she did not meet the prevailing opinion in the group, so that she initially expressed this hesitantly. In addition to the developed applications by the residential community during the field study, the group further co-speculated in the final group discussion a variety of other applications of sensors in domestic spaces. The following smart home applications concerning energy savings, holiday instructions and reward systems and penalties, were not developed and explored during the field study but co-speculated and discussed during the final group discussion.

Save Energy

As an example for self-driven behavior change, the group co-speculated a smart home application for saving electricity. For this, the group proposed a business model in which sensors are temporarily distributed in the home "*for one to two weeks*" and measure the power consumption. If for example users have "*three or four devices at the same time*" in operation they would receive a notification to reduce power consumption. The purpose of this application is to make the residents aware of their behavior, so that they can change it and reduce unnecessary power consumption.

Holiday instructions

While sharing of data within the residential community was not perceived to be problematic, the monitoring *by others* was controversial. The group repeatedly spoke of "*instructions*" and "*hints*" that should help others to behave appropriately. One such use case is a sensor application in a hotel that was conceived during the group discussion. Sahra proposed the idea to give guests of a hotel, with the help of sensors, behavioral advice. Martin agreed and adapted the waste separation application he developed, for hotels. On Martin's suggestion, however, Sahra criticized him on the grounds that a guest of a hotel, who pays for a service should not be encouraged to worry about such matters. Furthermore, she stated that the guest must "*want it*" and that, if she were a guest in a hotel, she would find it problematic if someone would dictate her behavior. Martin then intervened and agreed by criticizing that "*you pay for the hotel*" and then "*a computer tells you what to do*". In order to achieve behavior change, the group agreed that the user would need to be intrinsically motivated.

Reward Systems And Penalties

Another example of sensor-based monitoring is an application proposed by Martin, in which the landlord would get insight into the humidity values in the bathroom of the shared apartment. Such control by the landlord should encourage "*compliant*" behavior and reduce disputes. As an advantage, Martin stated that "compliant" behavior would be directly detectable, so that allegations of misconduct could be disproved. Although he did not rule out that "*interesting things*" could be deduced from this, Martin considered air humidity monitoring as rather unproblematic. For Martin, the desire to "*demonstrate compliant*" behavior outweighed privacy concerns. Expediency and comfort, that he could prove his "*compliant*" behavior, and thus save himself from arguing over the responsibility of mold, were for him in the foreground. Even though Martins idea was initially rejected by the entire group, he managed to convince most of the group of his opinion. While Patrick was initially referring to possible "*privacy*

issues" and talking about "*surveillance*", Martin countered this with the argument, "*I do not think that's private. It is his apartment*". He convinced Marie that the landlords' ability to monitor humidity values was beneficial and control is positive by comparing it to "*a dentist's bonus book*" [1]. Only Sahra was constantly critical of such a form of surveillance. Again, she insisted on a "*voluntary*" part of the supervised and the need to be informed about a possible monitoring, so that a potential acceptance of the tenant could be achieved. For her, the feeling of being controlled, which she found unpleasant, prevailed. She therefore questioned the signing of a tenancy agreement under these conditions.

A sensor application in which the group members are not controlled by a person outside the residential community, as in the hotel or tenant scenario, but control themselves or one another, was proposed by Martin at the end of the group discussion. This is based on a playful application concept with a "*reward system*" that aims at assisting people to achieve a previously set goal, such as saving energy costs. Primarily, he proposed this to counteract a habituation effect, which the group called the "*immunization effect*". Rewards are intended to motivate users to engage with the sensors for a longer time. The game lets the user "*level up*" and "*earn points*" as well as "*rewards*", according to the principle "the better one gets, the more points one earns". In doing so, the user should be kept constantly aware of his goal, in order to motivate him to maintain his behavior or to change it accordingly. Marie affirmed Martin's idea by stating that "*such a kind of competition*" is "*always good*" at any age. She described this as a "*playful measure*", which she considered to be "*funny*". Also this application split the group in their attitude towards sensors. For example, Patrick expressed the concern that this could be used as a penalty in the sense of "*who has collected the fewest points must wash up everything next week*". Sahra also critically commented that it would be problematic if one did not participate. Martin countered that you do not have to participate and then receive "*just zero points*".

DISCUSSION

It is challenging to design new technology for heterogeneous contexts such as 'the home'. The notion, that one "Smart Home" solution will fit all homes is unsustainable, given the diversity of tensions, needs, and values arising from the diversity of existing living situations [33]. With the design and subsequent field study of *Sensorstation*, we have shed some light on what smart technology can mean in the context of shared apartments. By doing so, we expand on the domain of co-housing [19, 18]. *Sensorstation* certainly inspired some new forms of smart applications for the shared apartment, and further demonstrates that 'other homes' also demand other genres of smart objects and services. Still, the findings reveal a number of issues and tensions arising around smart home applications within the shared apartment, that we aim to foreground in our discussion.

[1] A bonus book is a system in Germany, where patients have to prove that they regularly visit their dentist in order to receive insurance subsidies for major interventions.

As this is an explorative study, we do not seek to generalize any findings, however, below we focus on three key takeaways how the residents used *Sensorstation* and will suggest implications, opportunities, and obligations for future design in this research space. In particular, we look at how the smart technology of *Sensorstation* is 1) Redrawing Boundaries; 2) Reconfiguring the Information Dimension ; 3) Reconfiguring Power Structures. In each of these three sections we i) connect the findings of our study to prior work; ii) discuss frictions emerging from the practices we have observed in our findings; iii) interpret these findings to sketch out future research directions for the design space of smart objects in shared apartments.

Redrawing Boundaries

Previous work indicates, that in shared apartments such as the one from our study, the kitchen is often the central place of attention. Here, people gather to socialize, to share meals, and also to make decisions that concern all residents [41]. Based on this notion, it came naturally, that the base station of *Sensorstation* was positioned in the shared kitchen. Through the placement of the base station, we reasoned, that *Sensorstation* would have been considered a shared device as well. Yet, by design, *Sensorstation* also allowed for distributed notifications through personal smartphones.

Our findings reveal that this setup made it difficult for residents to see, how using *Sensorstation* severely redrew the boundaries between private and shared rooms. The design of *Sensorstation* was set up to broadcast all data accrued to the base station in the kitchen and to personal devices simultaneously. Both Sahra and Marie used *Sensorstation* to perform self-monitoring within their respective private rooms. Certainly, both use cases were rather benign: Sahra checked the lightning conditions in her room, and Marie tried to tackle her smartphone usage. Even though this can be considered more private than sharing when someone entered the kitchen, in the group discussion phase both women did not express concerns about others checking those personal measurements. One could argue that it was due to the close relationship within the group, that they were comfortable with sharing that data, because it was data from within the shared apartment. This could be read that both women did not have any concerns in sharing private massages in a shared apartment. But, we strongly argue otherwise. Both women only considered this form of self-monitoring as unproblematic, because there was nothing at stake. It is easy to imagine a situation when something is at stake.

Implications: If the nature or origin of data changes, the presented behavior would certainly change as well. This raises the question, who should decide, which new boundaries demarcated by smart home technology within shared apartments are to be accepted by all residents? This is a point of power structures between residents but also a question of how smart technology interacts with and changes these structures. A flowmeter within a smart shower [1] might nudge residents to save water. But besides that, it would also reveal what could be considered excessive shower habits, but also odd routines. Smart home data could then manifest new boundaries between

residents that further undermine privacy. As such, there is a need for future design to investigate, how smart objects can adapt their role in certain contexts. For example, depending on where a smart object is situated, it might only reveal what it was designated to do. A smart shower for example, should be constrained to help saving water, but not reveal individuals' showers routines. This might be accomplished by internal data aggregation (e.g. daily reports) that prevents fine granular raw data access and prevents to relate usage data to individual users. Relating sensor data directly to individual residents must only be considered for really good reasons.

Reconfiguring the Information Dimension

Previous work in the realm of appropriation of smart home applications, has usually proposed smart sensor applications that allow residents to connect pre-interpreted sensor data to predefined meanings [4]. Our findings show that with *Sensorstation* residents could go beyond predefined sensor applications and were successfully enabled to design sensor applications precisely tailored to their living situation. These self-designed sensor applications revealed, however, a number of tensions around shared and private places, spaces, and data.

Our findings indicate, that it is easy to share data in a shared apartment when nothing is at stake. Indeed, if we look at the smart home applications designed, we notice that the group shared their sensor data with each other without feeling their privacy was overly infringed, precisely because there was nothing at stake. Possibly, the novelty effect of *Sensorstation* added to this effect, too. Another reason is the friendly relationship within the group, expressed through common interests and group activities like cooking together. This is common in a shared apartment among students as they not only share the cost of living but also share housing as a way to mingle with like-minded people [35]. Our findings underline, that there was indeed a strong consensus in not revealing data that are considered private. The residents in *our study* drew the line at bio-data and intimate belongings like the underwear drawer. Residents in our study seemed to follow the rationale, that data from private rooms and sensed directly from people, are off limits. Residents of our study had agreed to only share data, that already 'exists' within the apartment. They considered it only logical, to have access to digital information, when they have access to that information in "*normal life*" as well. Residents argued that *Sensorstation* only exhibited data 'that was already there'. What they meant was, that *Sensorstation* is only showing data about sensed conditions within the physical space of the apartment.

Implications: By gathering and displaying sensor data, *Sensorstation* has reconfigured the information dimension within the shared apartment. While it is in theory possible to check if someone opened the fridge at 3 a.m. in the morning, smart sensor technology logs and visualizes, and further allows to prove, whether someone opened the fridge door, when and how often. The collected data is persistent, it can be stored and it could be further processed. Smart home applications have the power to make things visible, that would normally not be visible in the apartment. By just being there, smart technology has the power to test trust and to eventually undermine it.

Our findings further show, that when the participants of our study were specifically addressed during the group discussion as to whether they had monitored each other, they consistently denied this— they had "*not thought that way at all*", and if they were to develop such scenarios, then just for "*fun*". Perhaps the forced openness of shared data and its public use have prevented such monitoring scenarios. In addition, the participants expressed little interest in tracking sensor notifications from other participants. As Martin pointed out, this could only happen as the relationship within the group was so close. But what if people, who are less familiar with each other might not be as open in sharing their data? What if a potential future resident who is looking for a room in a shared apartment, does not want to consent to the smart technology used by existing residents, but desperately needs a room?

Implications: Long-term tenants are in a more powerful position and they may force potential future residents, into consenting to certain technology use. There is a possible power distance between long-term residents, who are versed with technology, and future residents who might not know the capabilities of this very technology. Or, what happens if someone does not want to share any data? There is an opportunity to design smart objects and services that acknowledge boundaries, and help navigating them. There is an opportunity to design "Smart Home" systems that allow to configure spaces within shared apartments that reflect personal spaces like physical places do. For example, a resident could use such a system to define a shelf in the shared fridge as their private space, or certain places in the apartment where they do not want to be traced. Mechanisms of the physical world that define the boundaries between shared and personal spaces might be transferred and used in the data space. Walls, doors, and locks as well as curtains and shades might find their equivalent in such digital data spaces.

Reconfiguring Power Structures

Prior work on the social foundations of shared apartments has shown, that the concept of shared apartments in Germany is shaped by the student movement of the 1960s, that fostered values such as equality and equal power relationships [35, 41]. Nowadays, such values are challenged by responsibilities that some of the residents carry. For example, one tenant might be the main tenant and would bear the financial responsibility for the apartment. Likewise, some residents might already share the apartment for a longer period of time and know each other well, while some new resident has moved in just recently. This both can lead to significant shifts in shared knowledge and dependencies, leading to higher power distances between residents [13].

Unsurprisingly, the findings of our study reveal, that technology seems to configure power structures that favor those that already have more power to begin with. In contrast to a home consisting of parents with children, there is no natural hierarchy within the members living in the shared apartment. Yet, smart technology was able to change that, as we can see in the example above. Residents in our study repeatedly agreed on using sensor technology for behavioral change and even nudging towards 'compliant' behavior. Technology might support

people to change their behavior according to their wishes, like improving organic waste separation. Such forms of control could be considered positive and wanted, because they are done 'for good' — to save the environment by changing just a tiny bit of people's behavior. Residents welcomed the idea that sensor technology could give them concrete recommendations for action. They delegated responsibility to the smart sensors, so that notifications were perceived and implemented as an instruction. Martin is the most established resident, while Sahra is the newest. It might be completely by chance, that Martin was a rather outspoken advocate for imposing behavioral change towards 'compliant' behavior by residents. Sahra on the contrary was rather critical of such endeavors. She felt, that if a change of behavior is imposed on people against their wishes, it could lead to serious challenges. As the principal tenant, Martin has a different agenda and motivation. He has to bear responsibility for the apartment towards the landlord. Martin explicitly expressed some power leverage, when he acknowledged that the landlord, as the owner of the apartment, 'has a right to know' what is happening in his apartment. And simultaneously it is easy to consider Sahra having even less power, when she is still new or is in the process of moving in.

Implications: It can be seen as problematic, when behavior change is implemented and enforced by those with a power surplus. People may eventually decide for themselves whether they move into an apartment where the landlord monitors the humidity, or where the main tenant is doing so. Acceptance among users is just as important as making it transparent who has access to data and what it is being used for. The decision against imposed behavioral change can also lead to exclusions within the group. If a group member does not participate in the cleaning plan, for example, he might be sanctioned. But such options can lead to a reconfiguration of power through smart home applications. There is an obligation for design to consider, how smart technology for shared places entrenches, extends, or equalizes power. For example, through negotiations leading to scenarios of shared living, where power is be balanced in favor of those who have less. Smart home technology for shared homes can either reiterate high power distances between residents, or reflect value propositions of equality, such as in earlier shared apartments in the 1960s. Shared use of smart objects and their data might result either in shared access and shared use or in no access and no usage at all. Obviously, it is not this easy all the time, but design research has an obligation to define frameworks that make navigating shared data within shared living arrangements transparent and fair.

STUDY LIMITATIONS

We acknowledge that the study length of 19 days is relatively short. As we saw a decline in usage of *Sensorstation* by the group over time, we believe that a relatively short deployment can be enough to empower people to create and understand smart home applications and also speculate and discuss about possible future smart home applications. Naturally, a long-term deployment might lead to further findings about long-term impacts of smart home technology within a group living together. Gathered knowledge from a small sample size might not always be universally applicable. Still, we believe our findings are salient in the sense that in addition to a number of novel smart applications, the impact of those smart application on the residents of the shared apartment have clearly emerged.

Also, a field trial in another cultural context might unfold different insights, and even a deployment in another shared apartment would be used in different ways. However, we believe that our examples and subsequent discussion are salient in the sense, that the reconfiguration of power structures and information spaces have unfolded clearly and substantially. As such, we argue that future design has the obligation to consider smart objects and services that acknowledge boundaries in shared places and that smart technology needs to provide a negotiation space to configure agency within these. In particular, it has to enable residents to negotiate boundaries and to equalize the power distances towards those who have less. In that sense, our study is a mere starting point for further participatory research into shared households, the values and idiosyncrasies those entail.

CONCLUSION

We have presented *Sensorstation*, a research product aimed at providing insights into how residents in shared apartments co-design, co-speculate, and appropriate smart sensor application in their home. By utilizing customizable sensors and an output device in a shared space in the apartment that displayed a steady data stream of sensor based notifications, *Sensorstation* enabled people to explore how smart home apps based on simple sensor data like humidity, light, movement, temperature, and air pressure has effects on their communal life.

With this paper we have presented a number of smart home applications co-designed by the residents of a shared apartment. They used *Sensorstation* to create positive connections, they also developed and tested self-monitoring applications. But more importantly, they also co-designed and co-speculated sensor scenarios that are capable to exercise control over others and that would reward residents for compliant behavior. These smart home applications disrupted the communal life of residents — while surprisingly, residents did not necessarily saw it that way.

We have discussed these smart home applications designed and tested by the residents towards a nuanced understanding of the frictions emerging from these practices. We have shown, that previously acknowledged physical boundaries in the home, such as closed doors that would demarcate private rooms, have been compromised by smart home applications. We also unraveled how power distances between seemingly eye-level people can be disturbed by technology for shared apartments. Lastly, we showed that technology can reconfigure the information dimensions between residents and spaces within the shared apartment.

ACKNOWLEDGEMENTS

We want to thank the participants for working with us and giving us insight into their residential community. This research is partly funded by the German Ministry of Education and Research (BMBF) under grant number FKZ 16SV7116.

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