Interactive Privacy Preferences Management for Shared Spaces in Internet of Things

BAYAN AL MUHANDER, Cardiff University, UK
JASON WIESE, University of Utah, US
OMER RANA, Cardiff University, UK
CHARITH PERERA, Cardiff University, UK

The balance between protecting users’ privacy while providing cost-effective devices that are functional and usable is a key challenge in the burgeoning Internet of Things (IoT) industry. While in traditional desktop and mobile contexts the primary user interface is a screen, in IoT screens are rare or very small, which invalidate most of the traditional approaches. We examine how end-users interact with IoT products and how those products convey information back to the users, particularly ‘what is going on’ with regards to their data. We focus on understanding what the breadth of IoT, privacy, and ubiquitous computing literature tells us about how individuals with average technical expertise can be notified about the privacy-related information of the spaces they inhabit in an easily understandable way. In this survey, we present a review of the various methods available to notify the end-users while taking into consideration the factors that should be involved in the notification alerts within the physical domain. We identify five main factors: (1) data type, (2) data usage, (3) data storage, (4) data retention period, and (5) notification method. The survey also includes literature discussing individuals’ reactions and their potentials to provide feedback about their privacy choices as a response to the received notification. The results of this survey highlight the most effective mechanisms for providing awareness of privacy and data-use-practices in the context of IoT in shared spaces.

CCS Concepts: • Human-centered computing → Interaction paradigms; Ubiquitous and mobile computing: • Security and privacy → Human and societal aspects of security and privacy.

Additional Key Words and Phrases: Internet of Things, sensors, privacy awareness, notification methods, data management, shared spaces, choice, interaction.

1 INTRODUCTION

The built environment is currently undergoing a rapid transformation as homes [144], offices [52], cars, and even cities are being infused with sensors, actuators, and interfaces and then labeled “smart” [2][103]. An increasing number of people are interacting with data each day (estimated to be 5 billion in 2018 and growing to 6 billion by 2025 [131]). Further, fueled by the proliferation of IoT devices, it is estimated that in 2025 “each connected person will have at least one data interaction every 18 seconds” [131]. Each of these interactions has the potential to be recorded, analyzed, and shared. Today, the vast majority of those interactions are invisible. When a person walks into a “smart” space, they have no way of knowing what technology is in that space, what data it captures, and what happens to that data.

Spreading awareness poses a challenge in the IoT domain. That is due to three primary reasons: (1) the nature of the data the IoT device collects, (2) the nature of the people using the IoT device, (3) and the nature of the service or task the IoT device provides/perform. The challenge is even more complicated when the IoT device is being used in a home environment, owing to the fact that most people consider home a private place, and the data collected from it can be highly sensitive. In some countries, manufacturers are obligated to disclose what data each IoT device collects and how that data is used. Unfortunately, even in these situations where this information is disclosed...
and made available, most consumers remain unaware of the capture and use of their data. The lack of consumer knowledge is mostly due to the way the information is being presented to them, which typically follows the End User License Agreements (EULA) format. Similar to the EULA presentation of information, the information describing the use of the data by the IoT device is presented in a lengthy and very disruptive way, leading the consumer to ignore them most of the time [1][56][76]. Or when a cautious consumer chooses to read every single term, he or she would, at last, be confessed into agreeing, because they are in an urgent need to use that technology. So, even the cautious consumers are left with no choice. The disclosure of the information is more challenging in the IoT domain due to their wide distribution and passive capability in collecting users information [114][104]. Consequently, manufactures frequently are complaining about the complexity and challenges the disclosure of their terms and use of personal data pose [1].

**Existing Surveys:** Various pieces of literature have investigated the importance of individuals’ privacy awareness. The difficulty faced by individuals when making privacy decisions and the hurdles faced by developers trying to comply with privacy policies is discussed in [102][138][127]. Individuals behaviour and how individuals’ privacy awareness in the context of IoT can be elevated through conducting practical experiments that deliver informed privacy decision making has been studied and analysed by [96][158][69][118]. Also, studies that support individuals privacy and security awareness through studying users needs, preferences, and reactions to notifications are presented in [1][107][120][31][133][122]. This survey is a result of a thorough review of literature in the area of awareness. In this paper, we draw from the results and findings in this area to deliver an organised summary of the available notification methods that are (or can be) incorporated into the IoT domain. Based on the past research we present the main factors needed in order to have an informed notification method that can increase the individuals’ privacy awareness in the IoT domain.

**Novelty of this Paper:** It is important to note that none of the existing surveys has reviewed the relation of IoT sensors to human sensors. The novelty of this survey is presented in categorising the IoT sensors based on human sensors, allowing simplifying and understanding the way an IoT device is collecting and using individuals’ data. Similarly, this paper organises a considerable number, 31 studies, of prior work on notification methods into four human-related classifications. Our objective is to identify major factors that the IoT domain needs to support especially toward creating a privacy-aware environment. For this end, after conducting a thorough literature review, we developed a taxonomy of common factors and present multiple use case scenarios. We compared several research findings and efforts as well as identifying research trends and gaps and highlighting research challenges.

The General Data Protection Regulation (GDPR) act [151] and the California Consumer Privacy Act (CCPA) [28], have confirmed the importance of people awareness regarding the use of their personal data. However, until now, and based on our knowledge, there is no known technology or used technique that notifies people about the use of their data in a short and direct form. For that this paper contributes to the following:

- Assess the available techniques, protocols, models, and literature pertaining to individual’s data privacy awareness.
- Propose and use a taxonomy to categorise available models, as well as to compare and contrast past approaches.
- Review data privacy factors collected by most IoT devices.

**Paper structure:** The paper is divided into six sections and is structured as follows: The used and followed methodology is presented in Section 1, which includes the data extraction method and a list of the used search queries. Section 2 presents the available individuals’ data privacy model,
Interactive Privacy Preferences Management for Shared Spaces in Internet of Things 9999:3

with a focus on the P3P protocol. The main content of the survey is presented in Section 3. It is divided into five main subsections, where each discusses one of the main factors pertaining to individuals’ awareness. The five subsections are Data type, data usage, data storage, data retention period, and notification methods. In Section 4, we include a discussion about the IoT user awareness and presents the main available gaps in this area. Section 5 discuses the research challenges and opportunities. Lastly, Section 6 concludes the privacy awareness survey.

1.1 Methodology

We followed an analysis and comparison methodology in order to build this survey. The central search platform we used is Google scholar, where we used specific keyword queries to find relevant literature. We further filtered the used search queries to include more specific terms, where we used them in locating papers from the most reputable libraries and journals, such as ScienceDirect, Scopus, IEEE Xplore, Springer, ACM, etc. The list of keywords, queries, and terms we used is presented in Table 1. The literature referenced in this survey span a wide period, with a focus on the papers published in the last five years. Doing so was to ensure the broad coverage of the available literature while maintaining an up to date research.

We collected 78 related research papers from automatic and manual search. We then filtered them based on the data privacy factors to have 48 papers, which we used on our survey. Based on the keywords list, we started the data extraction process. While extracting the data for this survey, we mainly paid attention to the literature that addresses at least one of the notification methods. Furthermore, we obtained data from papers that involve strategies for human interaction and awareness in the IoT context. As this paper considers elevating the users’ awareness, we have dedicated a section to explain the Platform for Privacy Preferences Project (P3P). The P3P protocol is relevant to our study as it grants users control over their data, which adds to their level of privacy awareness. Lastly, we performed data analysis and comparison to produce this survey. It is worth noting that we, generally, followed sections of Kitchenham approach [81] throughout our collection and extraction process. Papers that include experimental methods, such as [125][112], were considered mostly since they usually have documented results.

Table 1. Search queries and terms used in acquiring the literature either from Google Scholar or online libraries.

| Category               | Search queries and terms                                                                 |
|------------------------|------------------------------------------------------------------------------------------|
| General search queries | "Notification" "IoT" | "Pervasive" | "Sensor" "Privacy" & "Awareness" & "Interaction" "Data type" | "Data purpose" | "Data storage" | "Data retention" & (combination of the above) "Smart homes" & (combination of the above) "P3P" |
| Specific search queries| In all used libraries and journals: Set the language to English AND Limit subject to Computing ((("Notification") && "IoT") && "privacy") ((("data type") | "data purpose") | "data retention") | "data storage") && "IoT") && "privacy") ((("Awareness" && "IoT") && "privacy") |
2 END USER DATA PRIVACY AWARENESS

Individuals (End Users) privacy awareness is a deep-rooted topic that has captured the researchers’ interest from a long ago. There have been plethora pieces of research and techniques which either proposed or developed a method that supports increasing the individuals’ privacy awareness. Most of the known and used techniques or methods are web-based solutions.

One of the most known methods that support increasing individuals’ data privacy awareness is the Platform for Privacy Preferences Project (P3P) [129]. Laurel Jamtgaard developed the protocol in the World Wide Web Consortium (W3C), where it was officially recommended on April 16, 2002. However, the protocol has not been widely used and ceased due to its difficulty and lack of value [39][73].

Although the P3P protocol has failed, it is crucial to study how P3P works, how it was designed, and why it failed for the purpose of proposing a developed approach to manage privacy awareness, especially in the IoT domain. P3P is, in fact, a web-based method aiming at delivering a trusted web environment to individuals. It uses privacy policies to manages the information, and It functions as follow:

- A website or a user using a P3P protocol is called participant.
- The participated websites use an XML mark-up language to include in their privacy policy their intended use of personal information they collect from their site visitors. Figure 1 (a) shows how websites are incorporating P3P.
- The participated users declare in their privacy policy the information they are willing to share with other websites.
- P3P protocol will compare the two policies whenever a user visits a site. Based on the comparison, the user will either access the desired website or receive a warning of a mismatch in the privacy policy with an option to proceed to the website. Figure 1 (b) shows the P3P functionality.

The use of P3P protocol can help users get more control of their data and decide whether to share them or not. In addition to what the protocol offers, the Internet Education Foundation developed P3P toolbox, which describes to the users how companies are using their personal information for commercial purposes without the user consent [72]. However, there are many criticisms related to the development of P3P, which causes its cease of action. The two main problems with P3P were: (1) its difficulty, and (2) lack of value. First, setting a P3P privacy policy is confusing to the average Internet user and average service provider. Second, even if the users/ service providers overcome the difficulty of setting the P3P privacy policy, they sometimes fall into helpless situations, where they are faced with limited options to proceed. This happens, for instance, when a website is mainly depending on the users’ habits to deliver a service, and the users are blocking their cookies collection. When the previous situation happens, neither the websites nor the users will benefit from their P3P privacy policy and would usually sacrifice their privacy to advance their browsing experience. Moreover, the users will miss thousands of search results while using P3P filter. In [42], they stated that P3P protocol is only adopted by 15% of the top 5000 websites. As a result, when users are using the P3P website filter, they might miss the opportunity to view several sites, which some are having high privacy standards [39]. With increasing user awareness, users would need to have control over their data, and this is the main feature of the P3P protocol. P3P allows users to specify their privacy preferences, giving them dominance on their data. By employing the P3P protocol, the users are aware that their data is being collected, used, and sent to other parties. Similarly, in our proposed model, when home users are aware of the sensors collecting their data, they would demand tools that preserve their privacy according to their needs.
In home environment, households should be able to notice the IoT sensor with minimal to no efforts; they also need to be reminded that the IoT sensor still exists after noticing it. That is to say, if someone walks into the room and sees through a sign, for example, the CCTV recording camera, he probably would forget that something is recording him after 1 to 2 hours, and might perform a personal action that he does not wish to be recorded. P3P protocol sets the stone in involving the users into preserving their data online, and it gives them choices on where and with whom they could share their data. Having a privacy awareness model using a predefined logic enhances the ability of individuals’ notification criteria.

One of the primary purposes of the awareness model is to notify people about the existence of an IoT sensor in their vicinity, which could be done in various ways. P3P has the warning technique that notifies users about a conflict between their privacy policies and the policy of the websites they are trying to reach. Furthermore, P3P grants the users a choice of either rejecting visiting the website or proceeding despite the conflict. To have an aware IoT home user, he needs to be continuously warned about the IoT sensor in operation. Adding to that, the home user should also

Fig. 1. Basic P3P protocol functionality based on [36], (a) is how to make a website P3P compliant. (b) is a simple HTTP transaction with P3P incorporated.
be able to set his privacy preferences, without compromising his experience of the chosen IoT sensor.

But why would manufacturers incorporate the warning technique into their sensors? Mainly, to build a trust relationship with the consumer. When it comes to the home environment, the user, typically, would prefer to be aware of everything happening in his place. Households would feel more confident in buying the sensor that tells them to be cautious in some particular situations. As a result, manufacturers’ sales will increase, which will add to their revenue.

It is worth noting here that the P3P protocol has provided an important concept of granting users the right to set their privacy preferences. It is, however, was developed for the web environment, which carries many differences when compared to the IoT environment. The nature of the IoT environment makes it involved in sensitive aspects of people’s lives, which, as a result, will increase the emerging privacy risks. For that reason, the IoT domain would need an extensive approach to manage the privacy risks compared to the web environment. Adding more to that, the difficulty of the P3P places a hurdle to the users even in the web environment, which we are trying to overcome in the IoT domain. The value of the IoT sensors lies in facilitating the users’ everyday life; hence, when people are given the right to set their privacy policies in the IoT domain, they should be able to set it hurdle-free and with minimal efforts as possible. Table 2 presents the main differences between the IoT domain (current and proposed) and the P3P protocol.

The P3P being a web protocol used the warning notification method to raise any privacy issue to the users. Besides the warning method, several notification methods can be incorporated in the IoT domain to support extending the individuals’ awareness. The next section discusses the IoT domain and some of the existing notification methods that have been used previously.

### 3 PRIVACY MANAGED INFRASTRUCTURE

The widespread of IoT sensors makes them an essential part to go with everyday life activities. Users of all ages have an interaction with at least one IoT sensor daily, which in return relays on collecting and processing their information. It is an alarming issue of how could these sensors collect and process a massive number of users’ data without any consciousness from the user. Users might not have a clue about the IoT sensor in the room and may not know its data collection and processing functionality. Users also may not have the option of whether to disclose their data or not after noticing the IoT sensor.

In this section, we provide an assessment of the literature that discuss the available or proposed mechanisms which looked into increasing the users’ awareness regarding IoT exposure. By the term IoT exposure here we mean: the existence of one or more IoT sensor, the sensor is collecting the user’s information, processing this information (retaining them, sending them somewhere, selling them to other parties, etc.) without the user notice.

There are five main factors the user is required to be aware of in order for him to know about the data collection and processing that is done through an IoT sensor presented in Figure 2. We have defined these factors based on prior work that study the individuals’ privacy [112][22][82][92][94][95][98]. First, the user would need to be aware of the collected data type, such as audio, video, and(or) temperature data. Second, is the data usage, which defines the purpose of the data collection, whether it is for telemarketing, energy-saving, entertainment, security, improving health or for other various reasons. Following that is data storage. Can the collected data only be stored within the device or it is possible to store them company-wide or even in third-party storage? The fourth factor the requires the user’s attention is the data retention period, which lays out the time of which the data has been used, and the collection frequency of the sensed data. Lastly and importantly, the user needs to notice the existence of such sensor in the room.
Table 2. Differences between the IoT domain (current and proposed) and the P3P protocol regarding the user data control.

|                     | P3P                      | IoT: Smart Home Sensors (now) | IoT: Smart Home Sensors (Proposed) |
|---------------------|--------------------------|------------------------------|------------------------------------|
| **Choice**          | User can define his privacy policy | User is required to agree to the privacy policy for the chosen IoT device | User can modify the privacy policy according to his needs |
|                     | Difficult for average user | Average user can set it      | Average user can set it            |
| **Setup language**  | Website: XML User: user agent | N/A Required to agree cannot setup | Short instructions e.g., buttons |
|                     | Difficult for average user |                              | Average user can set it            |
| **Delivery language** | Lengthily terms & polices User: lengthily terms & polices | Lengthily terms & polices Difficult for average user | Precise terms, short notifications Average user can understand |
|                     | Difficult for average user |                              |                                    |
| **Data Collection** | Web data collected by the website Cookies, user provided data: emails, birth date etc. User usually is not aware of the collection | Personal data either provided by the user, collected by the device or both User usually is aware of the collection, but does not have control | Personal data either provided by the user, collected by the device or both User usually is aware of the collection and have control |
|                     | Users web data is being used in other services. e.g., improve browsing habits, statistics, ads, etc. User usually is not aware | Users data is being used or sold to other services. e.g., improve sensors, statistics, ads, etc. User usually is not aware, usually have control | Users data is being used or sold to other services. e.g., improve sensors, statistics, ads, etc. User usually is aware and have control |
| **Data usage**      | Adults (usually people with computer background) | Home users (including elderly, children) | Home users (including elderly, children) |

### 3.1 Data Type

To begin, we will start analysing the pieces of literature of the first factor of the user’s awareness. In the context of IoT, there exists a multiplicity of sensors, which each collects one or more data types. Collected data will then be processed to deliver a variety of services to the user. The provision of these services depends mainly on analysing the data that are collected from human activities, e.g., body posture and movement. Although the possession of IoT sensors gives the user a luxury feeling along with higher productivity and automation, users usually are not aware of the type of data collected by these devices. Moreover, users do not know what other information could be derived from the collected data to provide them with the desired level of service they acquire. What is worse is that some of the collected data are not required at all to deliver a service to the user, giving the sense that it is being collected for other purposes. In [64], for instance, they have stated that around half of smartphone apps are collecting location data without the need to; They are, in fact, collecting it for the use of a third-party library. In this section of the survey, we are outlining
Fig. 2. Essential awareness factors that must be incorporated in order for the user to be aware of the data collection and processing done through an IoT sensor.

the major data types that have been discussed in previous literature and that relate to a smart home or office environment.

In a smart home or office environment, the types of sensors that are used are directly or indirectly related to enhancing the efficiency of the user’s daily activities. These sensors, despite their heterogeneous, they share the collection of common data types to provide the user with the task he requires. Given that, it can be seen that the IoT sensors, when working together, can mimic the human’s sensing ability in collecting the information [75]. Through the sensors in the human body, the brain receives information and make decisions. A typical scenario is, a person sensing a burning smell from his kitchen, will immediately turn off his oven. The human sensor here is the nose, the action is turning off the stove, and the collected data type is the smell. In the IoT context, sensors will have a similar working schema. A smoke detector being the sensor, for instance, will trigger an alarm and cause the oven to be turned off (action) when smoke is detected (collected data).

Gartner has defined the IoT as a network of physical objects, i.e., IoT sensors, in which each object has an embedded technology that senses and/or interacts internally and/or externally [109]. Consequently, the different types of IoT sensors and the various data they collect can be divided into similar categories as the human sensors. Doing so offers a more natural way of relating the data to its sensor. Using natural interfaces has shown its effectiveness in attracting users’ attention [113][141]. As depicted in Figure 3, there are five primary human sensors, namely: eyes, nose, ears, skin, and mouth. In addition, there are many indirect human sensors, such as blood vessels, which sense the amount of blood to get medical diagnoses. For that, we have adopted human sensors categorisation to categorise the types of data collected through IoT sensors. Table 3 presents the common data types collected through IoT sensors and classifies them according to human sensors. With referring to Gartner definition mentioned earlier in this paragraph, it is worth noting that, in a smart home, beside sensing the users’ activities, there are other sensors that senses externally, e.g., sensing the environment, not the user, to provide the user with a better experience. An example
of these sensors is the smart thermostat, which can detect the room temperature and turn on the heating system in the house accordingly. As it is the case with the human sensors, where the human’s brain might use more than one sensation to make decisions. Many IoT devices might also collect data using more than one sensor, moving the data between the multiple devices to provide accurate information to the user.

3.2 Data Usage

The pervasive nature of IoT devices created new ways to use the data. As a result, these new ways fetched new privacy challenges, in which it becomes essential for the user to know the purpose of the IoT data collection. Average users, despite their possession of one or more IoT devices, think that the devices are using their data only to provide them with a better experience. User’s benefit is undoubtedly one of the primary purposes of the usage of the sensed data. However, there is a good deal of other data usages purposes that neither the user nor the developer – in some scenario- are aware of [139][18]. To make matters worse, besides the basic usage of the collected data, additional information could be inferred from the collected data and be used to build more knowledge. In the next two subsections, we conclude the main purposes of data usages that have been brought up by prior work.

3.2.1 The primary purpose of data usage: When it comes to defining the purpose of collecting the data, there is a considerable variation, especially within the context of a smart home. That is because the home is considered one of the most private places. Generally, the IoT devices at home should follow the user’s expectation of the western tradition of public/private dichotomy. That is “what happens at home stays at home.” Unfortunately, even for only the purpose of acquiring user benefit, collected data are usually shared with other manufacturers, at least for research and analysis. Based on the data types defined in the previous section, [128] illustrated the different data usage purposes depending on the IoT endpoint market in billion sale from 2018 until 2020. There
Table 3. Data types collected through IoT sensors and their equivalent human sensor based on [7][137][16][149].

| Sensor Type       | Data Type detected          | IoT device Application                  |
|-------------------|----------------------------|----------------------------------------|
| Ear               |                            |                                        |
| • Sound Sensor    | • Audio                    | • Voice recognition systems            |
|                   | • Ultrasonic waves         | • Distance measurements                |
| Eye               |                            |                                        |
| • Camera Sensor   | • Images and Video         | • Monitoring systems                   |
| • Colour Sensor   | • Lights illumination      | • Face recognition systems             |
| • Light Sensor    | (Colours Photodiodes)     | • Smart lightning systems              |
| • Fire Sensor     | • Ultraviolet radiation   |                                        |
| Nose              |                            |                                        |
| • Smoke Sensor    | • Smoke and Gas            | • Air quality monitoring               |
| • Gas Sensor      | • Oxygen and carbon dioxide levels | • Smoke detection systems             |
| • Odour Sensors   | • Infrared signals         | • Smart Gardening                      |
| Mouth             |                            |                                        |
| • Level and Temperature Sensor | • Temperature level | • Alcohol monitoring systems           |
| • Alcohol Sensor  | • Oral data                | • Diet monitoring systems              |
| • Moisture Sensor | • Breath                   | • Food tasting systems                 |
| Skin              |                            |                                        |
| • Touch Sensor    | • Biometrics               | • Fingerprint scanner                  |
| – Force Sensor    | • Pressure applied         | • Galvanic skin response               |
| • Skin Sensor     | • Skin’s electrical conductivity | • Medical systems                   |
| • Electromyography | • Ultrasonic waves        | • Security systems                     |
| • Proximity sensor | • Magnetic forces         | • Smart toys                           |
| • Temperature Sensor | • Body temperature     | • Automatic Lightning                  |
| • Vibration Sensor | • Body movement           | • Smart appliances                     |
| • Line Finder     | • Capacitance change      | • Vehicles seat monitors               |
| • Distance sensor | • Infrared Signals        | • Smart vacuum                         |
|                   | • Orientation             | • Activity trackers                    |
|                   | • Impact                  | • Smart transportation                 |
|                   |                            | • Smart locks                          |
| Additional sensors e.g., blood vessels |          |                                        |
| • Heart rate sensor | • Blood movement       | • Sleep monitors                       |
| • Optical Sensors | • Muscles Signal          | • Heartrate monitors                   |
| • Gesture Sensor  | • Velocity (Speed)        | • Wearable sensors                     |
| • Rotary Sensor   | • Acceleration            | • Baby monitors                        |
| • Motion Sensor   | • Proximity               | • Blood sugar monitor                  |
| – Gyroscope       | • Resistance              | • Transponders on animal               |
| – Accelerometer   | • Infrared Signals        | • DNA analysis devices                 |
| – Magnetometer    | • Rotation (direction)    | • Smart navigation systems             |
|                   |                            |                                        |
| Sensors not directly related to human sensors |          |                                        |
| • Temperature Sensor | • Temperature and Humidity level | • Tank systems                        |
| • Humidity Sensor | • Atmosphere pressure     | • Smart appliances                     |
| • Water Sensor    | • Capacitance change      | • Sewage systems                       |
| • Turbidity Sensor | • Ultraviolet radiation  | • Liquid sensing applications          |
| • Ultraviolet Sensor | • Light               | • Pharmaceuticals                      |
| • Dust sensor     | • Slop                    | • Dyeing process                       |
|                   | • Dissolved solids        | • Elevators systems                   |
|                   | • Hydrogen ion            | • GPS                                  |
|                   | • Dust concentration      | • Smart meter                          |
|                   |                            | • Smart thermostat                    |
Table 4. Sample of data usage purposes for: User, IoT device, and Manufacture respectively.

| User Purpose               | IoT device                  | Manufacture Purpose                      |
|----------------------------|-----------------------------|------------------------------------------|
| Improve safety             | Security alarm systems      | Improve advertisements                   |
| Improve security           | Smart locks                 | • Targeted ads                           |
| Improve health             | Pacemaker                   | Improve productivity                     |
| Energy saving              | Smart thermostat            | Increase revenue                         |
| Improve spending           | Smoke detector              | • Improve selling                        |
| Entertainment              | Smart appliances            | • Improve spending                       |
| Improve lifestyle experience| Wearable device             | • Reselling                              |
|                            | Smart audio recognition     | Improve research                         |
|                            |                             | Improve analytics                        |
|                            |                             | Improve statistics                       |
|                            |                             | Improve security                         |
|                            |                             | Improve safety                           |
|                            |                             | Improving health care                    |
|                            |                             | Surveillance                              |

has been a considerable increase (almost doubled) from year 2018 to year 2020 in the sales of IoT building automation products.

The purpose of using the collected data would mainly depend on the device that is collecting it. Usually, when the user purchases a particular sensor, the privacy policy attached to the device would mention one or more specific purposes of the data usage. That is similar to the privacy policy on the web, which users habitually ignore and accept without any further reading. Figure ?? is a sample of the purposes specified by one website. Based on the common types of the used sensors and the common data usage purposes specified in previous literature [64][112][1][34][79], we have concluded the main purposes of smart home data usages that are classified in Table 4. It is worth noting here that the purposes classified in Table 4 are the abstract purposes defined by the device, which usually do not reveal information of what is being done with the data. That is to say that, in order for the device to comply with the standard device’s privacy policy, it must specify the purpose of the data collection. Manufactures usually tend to use a dim view when presenting the purpose of the data collection. For example, manufacture producing a smart smoke detector might specify in the privacy policy that they are using the user data to improve research and analytics, which will help in providing better user experience. However, the underlying mechanism is different. The manufactures are collecting the user’s activities, such as how often and for how long did he smoke, how many people in the home are smoking, did the smoke comes from a cigarette or from another burning object, etc. Such purposes of the data collection are usually not included in the privacy policy, while average users are providing their data without realizing the privacy impact on them. This information is usually referred to as the inferred knowledge of the data collection purpose, which is further described in the next subsection.

3.2.2 The secondary purpose of data usage: As described above, the purpose of using the collected data does not only cover the abstract meaning of improving research, for instance. It, however, spans a much wider area. The more data the devices can collect, the more knowledge it will have and can build, where the accumulation of the knowledge could lead to building a complete human profile. Figure 5 depicts how can an inferred knowledge can be determined from a simple ride
Fig. 5. Sample of a ride share app, showing how can an additional knowledge can be inferred from the specified data usage purposes. The red boxes represents the inferred knowledge, and the black boxes represent the specified data usage purposes.

To describe the value of the collected data, let us here provide two smart home scenarios to show how the inferred knowledge could benefit the service providers and affect the individual’s data privacy.

1) Security alarm systems: Sara is a frequent traveller, and therefore needed to monitor her home instantly. She is using a monitoring camera that can take images and stream videos whenever it detects motion. The recordings of her camera travel through different nodes until it reaches the application that provides her with the remote monitoring feature. Theses nodes include but not limited to third party network providers, third-party storage services, and third-party service providers. One or more of these nodes could sell or share Sara’s data to other parties for analytical purposes. In this scenario seen in Figure 6.

Sara’s thoughts of her data usage:

- Her home will be monitored, safe, and secured.
- Her videos are only stored on her camera and her remote monitoring application.
- Only she has access to her data.

Sara’s actual data usage:

- She gave her consent to her service provider to use, access, and store her data.
- Her data is being shared or sold to other parties for analytical purposes, with her approval.
- The companies using the analytics might be the police department, where they use the individuals’ data for surveillance and crime prevention.
- Using facial recognition and motion detection features, Sara’s images and videos can be used to know when, where, and who is in her home (inferred knowledge).

Sleeping time, travelling habits, number of visitors, number of occupants in a specified area, and much other knowledge can be inferred from the security monitoring camera. It functions as an extra eye in your home that is always watching and recording information. A similar real scenario has been raised in 2019, where Amazon Ring video doorbell announced that the videos recorded on their “Neighbours” app are used by at least 400 law enforcement agencies nationwide to help in...
criminal investigations. Ring video doorbell is an IoT device that is installed in front of an individual’s property and continually detects motion and captures videos, offering the user the ability to communicate via audio and video with the people passing by his property. The “Neighbours” app also provides users with real-time safety alerts from the local police department and the residents living in the same area. Although Ring’s app grants the users the choice in opting out from sharing their videos with the authorities, there were many privacy concerns of the knowledge that can be inferred from the collected data, which can lead the police to obtain an official search warrant requesting individual’s videos [146][117][132].

2) Voice recognition systems: Tom works on a full-time job with changing shifts, takes care of his two children and volunteers in his town elderly day-care centre. To balance his daily activities and save time, Tom is using a voice assistant device that has a microphone, which can detect his voice commands and help him automate him home. Similar to the monitoring camera, the commands heard by the voice assistant system travel through many nodes in order for the device to perform its functionality. The commands are sent to a cloud-based system for processing, from which either a response is returned, or an action is performed on behalf of the user [89]. The more voice commands the device hears, the smarter it becomes, resulting in a massive collection of data that serve various purposes. For that, given the broad applicability of voice assistance systems, the data here are not only shared between the device and its required processing mechanisms; the data, however, is exchanged with multiple devices, which each has a different privacy policy. In our scenario seen in Figure 7, when Tom asks the voice assistance to turn on the light,

Tom’s thoughts of his data usage:
• He will improve his experience, save time, and automate his home
• His voice assistance device only hears his voice interactions.
• Only he has access to his data.
Tom’s actual data usage:

- He gave his consent to his service provider to use, access, and store his data.
- His data is being shared or sold to other parties for analytical purposes, with his approval.
- His data is being shared with devices, other than the voice assistant device, for the purpose of providing home automation.
- Even if the voice assistant device has a strict privacy policy, the other compatible devices might not.
- Using the time mapping and network traffic, Tom’s voice commands can be used to know when, where, and who is in his home (inferred knowledge).

The fact that voice interfaces are considered more natural and do not require as much interaction as other interfaces [110], they span many other applications that have different sensing abilities. These applications, with their sensing feature, collect a considerable amount of data, which is quite enough to build a complete human profile, only through voice commands. The voice assistant device is somehow considered as an extra ear, which is always listening. In 2018, a case was raised by an Amazon Alexa customer, where their private conversation has been shared with others without their consent [40]. Moreover, according to the transparency reports released by Amazon, Apple, and Google [4][6][58], law enforcement has sought data from 700,000 user accounts, which all have personal and sensitive information, and the companies have provided the information about two-third of the time.

### 3.3 Data Storage

The common phenomena with IoT users, especially non-technical users, is that their data is safe and only stored in their owned device(s). However, with the technology development and the raise of high capability hardware along with the Cloud service, the cost of storing data has dropped. Resulting in many organisations moving towards storing an increasing volume of data, and more people relying on the Cloud services [157]. In the IoT context, the storage of the generated data is
complicated. One IoT device might depend on multiple sensors to provide a service, in which each sensor requires different types and forms of data. The collected data will then be kept in the storage location(s) to be processed, and based on that; the IoT device will deliver the requested service.

Storage locations and where the data is kept vary depending on the IoT device, the type of service it provides, and the producing manufacture. First, the top layer is that the data is only stored within the device. Then, there is data that is stored within multiple devices in the same network. Getting out of the network boundary comes the data that is stored on the producing manufacture storage (private cloud). After that, is the data that is stored on third-party devices (public cloud). The last two differ in the location of the data, which might be within the country, or spans the entire world. Figure 8 presents different data storage locations.

The feasibility and the efficiency of the internet-connected devices depend mainly on the collection of data that is done continuously without interruption. Giving that, the IoT sensors will collect a high volume of data, which requires a computing power that cannot be handled by the small sensor. In addition to the sensor’s collected data, storage space is also needed for the data analysis and annotation that are used to extract knowledge and patterns that are beneficial for the user. Hence, big data are produced, and Cloud services become an essential factor in providing data storage to IoT organisations \[157]\[130]. Most organisations adopt the use of the Cloud for IoT data storage. Medical, surveillance, energy, and many other data collected by IoT sensors are stored in the cloud \[89]\[7]. Arkessa [9]. ThingSquare [148]. WoTkit [23]. Axeda [13] are examples of platforms that provides Cloud storage for IoT big data.

3.4 Data Retention

IoT builds its intelligence from data. An IoT device becomes better “smarter” as it collects and learns more data. Hence, devices that store data for an extended period or forever tend to function better than others. According to Amazon voice assistance services, Alexa smart voice assistant IoT device gets smarter with age and serve better after several usages [134]. As depicted in Figure ??, along with specifying the purpose of the data collection, websites’ privacy policy usually mention the period of data retention. However, in the IoT domain, restricting the retention period is complex. That is due to the fact that it has been mentioned earlier of IoT intelligence. Moreover, different sensors differ in memory size, application requirements, bandwidth, and throughput, which result in variation of the required retention period [27]. Adding time constraints to the IoT sensors is
even more complicated in the smart home environment, given the purpose the user is demanding. Most home users, when transitioning into smart home demand home automation. In order for the sensors to provide that and ensure the user with a unique experience each time, it must learn from the user and compare with previous data. For instance, Amazon stated that Alexa voice user interface gets smarter over time [3], which means that the more Alexa listens to you, the better your home will be. Surprisingly, many users rejected the idea of retaining their data for an extended period by the various sensors. Leon et al. [32] concluded that retention period plays a significant factor in the willingness of the users to share their data. Based on their study, users will less likely share their data when they are confronted that the retention period will exceed a week.

Let us here lay down, how long data is kept by most IoT devices, especially devices that are used in the context of a smart home. Since IoT devices used inside the smart home usually has more than one sensor, the time period for data retention differ within one IoT device. An example of that is the smart thermostat, which adjusts the temperature, turns off the appliances, and sends alerts when it detects smoke. Given that, it is obvious that within the smart thermostat, there are at least three different sensors: temperature and humidity sensor, smoke sensor, and motion sensor. Each one of these sensors stores data for a specific amount of time, which can be session-based, days, months, years, or an infinite period. In addition, theses sensors collect data on a regular basis, which can be every second, every hour, every day, etc. It is worth noting that, the retention period for most organisations tend to be over 12 months, which is the ideal time to perform analytics on the data, as well as acquiring other data [86][106]. The privacy policy of Nest thermostat, which is one of the smart thermostats that receives wide attention from buyers, declared the retention period for the collected data. They stated that some of the data are kept forever unless deleted by the user, while other data are kept for the period of thirteen months [115].

3.5 Notification Methods

In order for the user to notice an existed sensor, he needs to be notified about its existence. That is basically done through the notification mechanism. The importance of the notification mechanism derived from the extensive growth of IoT devices, where they have become deeply penetrated in everyday life in a way that made them unnoticeable by people. In 1991, Marc Weiser [154] had described the "computer of the 21st century" as “The most profound technologies are those that disappear. They weave themselves into the fabric of everyday life until they are indistinguishable from it.” Given the extent the IoT technology has reached, we can almost undoubtedly say that it represents Marc Weiser phrase. In the following section, we are presenting several works of literature that have investigated various ways of users’ notification methods in different contexts.

We are categorising the research papers according to the notification methods they discuss Figure 9. As presented in Table 5, most of the notification methods fall into one of four categories: (a) Visual: including light, and motion notification methods. (b) Audio: including sound and motion notification methods. (c) Sensory: including vibrate, touch, and airflow notification methods. And (d) Tangible/physical: including wearable and cube format notification methods.

3.5.1 Visual: The notification methods in this category are the widest used methods [67] due to their higher bandwidth, convenient setup, usage and access, and clear user delivery. Visual includes any notification technique that can deliver its message through the visible way, in which the receiver could understand the entire message only through his eyes. This is like alert labels, warning messages from websites, blinking light, and moving items, e.g., the movements of a swivelling camera.
Kohanteb O., et al. [83][84] have proposed an interesting notification method called 'Signifiers'. A signifier is an add-on feature that can be added to a device in order to deliver information to the user about the available active sensor. In their research, they have provided several visual notification techniques, which act as signifiers and can be implemented with minimal effort to guide the users' awareness of the sensors around them. They have tested their approach on eight IoT devices and their corresponding sensors. Their selection of the IoT devices was based on the devices that can have different usages within the house, different sensor modalities, and that can span to several domains. The main aspect of the research was to notify the users about the activity of the sensors around them in the least complex and annoyance method. For that, they have used a mechanism that represents what the device is collecting and that the average user could easily interpret. For instance, a flashing light on a camera can indicate that the camera is recording. In addition, pop-up signals on the sides of a device can indicate that the device is collecting audio data, i.e., the signals are placed on the device side to mimic human ears. Although their method can only inform the user about the collection of his data with no additional information, the user can easily understand it and the developer can develop it with minimal effort. Furthermore, the uniqueness of the information the signifier provides makes it readily adaptable by the developing manufactures. Their method of notification also has the feature of reducing the disruptiveness the user usually faces within different devices notifications [126][25], especially smartphone notifications. In [25], the authors have discussed a method of showing a small notification at the top of the screen, which can reduce the user annoyance when he receives a call, and the notification abrupt the full phone screen.

Kubitza T., et al. [88] has presented an infrastructure that uses the ubiquitous nature of the IoT devices to deliver information to the users. They argued that the notifications must be delivered to the users in a context-sensitive and multi-modal way, reducing the need for smartphone usages. For that, they proposed a design that uses the meSchup IoT platform due to its intuitive setup and wide adaptability. Through the meSchup platform, users are able to get notified visually without the need to check their smartphone regularly. Whenever the smartphone receives a notification, it will be sensed through the meSchup notification gateway. It will be displayed to the user visually based on...
Table 5. Pieces of literature presenting the notification methods, the methods are divided into four categories, with each having different format.

| Author | Citation | Visual | Auditory | Sensory | Tangible | Control parameters | Intensity, frequency, duration, modulation, sequences |
|--------|----------|--------|----------|---------|----------|--------------------|--------------------------------------------------------|
| Mehta, V., et al. | [108] | X | X | X | X | | I, F, D, M, S |
| Houben, S., et al. | [67] | X | X | X | X | I | F |
| Kohanteb, O., et al. | [84] | X | X | X | X | I | F, M |
| Hornecker, E. and Buur, J. | [65] | | | | | X |
| Ishii, H. and Ullmer, B. | [71] | | | | | X |
| Jansen, Y., et al. | [74] | | | | | X |
| Kohanteb, O., et al. | [83] | X | X | X | X | I | F, M |
| Kubitza, T., et al. | [88] | X | X | X | | | F |
| Chernyshov, G., et al. | [30] | | | X | | I | F, M |
| Haslgrübler, M., et al. | [63] | X | | | | I | F |
| Bodnar, A., et al. | [24] | | | | | X |
| Kaye, J. | [77] | | | | | X |
| Emsenhuber, B. and Ferscha, A. | [49] | | | | | X | I, M |
| Olalere, I., et al. | [119] | | | | | X | I, F, D |
| Kumari, P., et al. | [90] | | | | | X | I, F, D, S |
| Corno, F., et al. | [37] | | | | | X | I, F, S |
| Pousman, Z. and Stasko, J. | [126] | | | | | X |
| Böhmer, M., et al. | [25] | | | | | X |
| Leonidis, A., et al. | [99] | X | X | | | | I, F, M |
| Banerjee, S. and Mukherjee, D. | [21] | | | | | X |
| Emami-Naeini, et al. | [47] | | | | | X |
| Ardissono, L., et al. | [8] | | | | | X |
| Simons, D. and Chabriss, C. | [142] | | | | | X |
| Most, S., et al. | [111] | | | | | X |
| Wolpert, D., et al. | [156] | X | | | | I | M |
| Emsenhuber, B. | [48] | | | | | X | I, M |
| Com, N | [35] | | | | | X |
| Greco, P., et al. | [60] | | | | | X |
| Kowalski, R., et al. | [87] | | | | | X |
| Lin, S., et al. | [101] | | | | | X | F, D, S |
| Matscheko, M., et al. | [105] | | | | | X |

the available IoT sensor in the room. For instance, differences in an LED colour scale would indicate to the user a specific notification received on his smartphone. A more informative notification
about the received notification could also be visualized to the user through, for example, smart TV and/or smartwatches. In order to protect the user privacy, the selection of the notification type is specified by the user depending on his criteria, and the availability of the sensors. Their method is similar to the approach presented in [8], where they adopted a way that predicts the user’s activities and based on that makes the decision of delivering, postponing or deleting the notification. This approach can effectively increase users’ awareness about the surrounding sensors due to its unique sensor delivery modality. Here instead of the notification arriving at the user’s smartphone, it will be forwarded to the most related sensor it is notifying about. As an example, a reminder about an appointment with the dermatologist could be displayed at the electronic mirror, which might get ignored when posted at the smartphone screen. The main limitation of this approach is the difficulty of its adoption in shared spaces, due to privacy risks it might trigger.

Using the visual approach to deliver notifications to the user plays an essential factor in increasing user awareness about his privacy. Various other studies and projects are using this type of notification, such as [99][21]. When the user sees - through his eyes- a unique signal produced by a sensor, it will automatically lead him to take action regarding that sensor’s which is collecting his information. The action that will be made by the user will depend on the level of awareness the user has about how the device is processing his data. The authors in [47] presented a privacy label prototype, and they found that individuals purchase behaviour tends to change when they know the privacy implication of the IoT device.

3.5.2 Auditory: This category includes the notification methods that can be heard., in which the receiver will get notified through his ears. Similar to the visual techniques, this method has higher bandwidth which is also considered a popular notification technique [67]. Examples of audio notification are fire alarm, microphone announcements, mobile phones rings and the sound of the moving items, e.g., camera shutters.

Chernyshov G., et al. [30], presented a novel audio notification approach. The approach proposed by the authors can help average users understand the status of the IoT device with no previous knowledge about the meaning of the audio notification. They used melodic rhythm to deliver information so that the user can perceive the information in an interesting hand-free and eye-free way. In order for straightforward interpretation, the sound samples they used in the melodic rhythm are associated with the process it is representing, i.e., they recorded the sound of the printer to represent printing. The rhythmic method used in this paper has many significant advantages. It does not only notify users about the active IoT device, but it also provides a continuous notification about its statutes, which is useful especially in the IoT domain since users might forget about the existence of the device after a while. Another advantage is that this approach uses rhythms, which can convey more information to the user in a less obtrusive way when compared with the discrete sound notifications. However, having all the ambient audio notifications to be delivered to the user in one melodic rhythm might cause confusion and difficulty in distinguishing the type of device generating the specific effect, which is discussed in [37]. In [37], the authors used a machine-learning algorithm to manage the notification based on the context and the user habit. Their system design has the ability to decide the person receiving the notification, the device, the perfect time and the ideal mode.

Haslgrubler M., et al. [63], described a set of different notification methods that can be used in an industrial environment. Their purpose was to develop the best approach that can direct and alert the industrial workers about potentially harmful situations. Apart from the visual and haptic methods they have proposed, they described the effectiveness of the auditory notification, especially in an area with workers of different background. Because of the environment of the research, i.e., industrial environment, they have used stationary speakers to send audio notifications. The sensors
in the speakers will send warning sounds whenever the working machines reach a specified level of danger. It is also worth noting here, that the type of the audio notification delivery can differ based on the environment, in a similar environment, earplugs audio notifications, for example, will not be as effective as the stationary speakers as they might withdraw the user attention of his surroundings. The drawback of this technique is as described by several other studies that even if the notification is delivered in the correct time and modality, it might get unnoticed [142][111], leading to the lack of attention that might occur in an environment with a loud noise. The preceding, however, can be mitigated with only delivering the notification that is task-relevant [156] and increasing the notification intensity.

The audio notifications offer a more natural way of communication with the user. Users are easily notified, even when they are busy with other tasks with minimal to no interruption as opposed to other methods like the visual method, which requires eye contact. Many other pieces of research presented audio notification as well, where some papers we have discussed in our survey. As an example, the sounds generated by the camera is considered as an audio notification method in [83][84], e.g., the sound of shutter opening and closure and camera swivels. The sound of the push notifications in the smartphones and Amazon Alexa is perceived as an audio notification method in [88].

3.5.3 Sensory: The sensory notification is a method that sends the information to the user through various sensing mechanism, and the user as well receives the information through his sensing ability. It includes touch, smell, feel and taste to send and receive the information. For instance, mobile phones vibration is considered a sensory notification method. The smell and feel of the smoke are also considered sensory notification methods. This category is not widely used like the visual and auditory notifications since it is hard to set and interpret [24][77].

Olfactory notification approach has been discussed in several pieces of literature [49][48][35][60]. Emsenhuber and Ferscha [49] proposed the olfactory interaction zones (OIZs) as an effective mean of communication. They discussed that the odours emitted either by humans or other entities convey information, which can be detected through the available sensors, e.g., gas sensors or electronic nose. This process of detection and processing the olfactory information is what they referred to as OIZs. The OIZs, as they proposed, provides a spontaneous interaction that can be identified by people and machines. They argued that although odours may be hard to be applied and volatilise fast, they can be easily recognised and usually refer to the specific situation of data. This feature distinguishes the olfactory method, as it provides in-depth information to the user comparing it with the other techniques, which provides the user with abstract information only.

The sensory notification mechanism can also be used to send fault-tolerance alerts, in which it notifies the users about a potential fault in the used system. Olalera I. et al. [119], proposed the use of remote condition monitoring (RCM) as a method that can support proactive machine maintenance through vibration notification. Whenever there is a fault in the machine, it will send a vibration signal, and based on the severity of the vibrations, the users will be notified. Using this approach has proved the ability to proactively detect malfunctions in the system and respond respectively. While the vibration method is simple to adopt, it can provide a unique notification way to the user. In another paper [67], for instance, the vibration mechanism has been used as a notification method, even after the vibration has stopped. They examined the use of an object, e.g., a plant, which can be placed over a vibrated cube, in which based on the direction of the object, the user will understand the desired notification.

The sensory notification method provides a unique tactic of notifying the user. Its characteristics make it deployable to span a wide range of people, including people with special needs [90]. It also delivers a timely notification more smoothly and intuitively, eliminating the disruptiveness the
user might encounter with other notification methods.

3.5.4 **Tangible/physical**: One of the new notification techniques is the tangible or physical method. It is when the user receives information through an available object. An example of that is the wearable Fitbit watches, in which they could send sensory information such as heat when overused. Although it is using a sensory notification, it lies in this category due to the fact that the tangible object must exist in order for the information to be delivered to the user. This approach is new but growing, where it does not substitute the available notification methods, but instead provides a hybrid way of notifying the user.

A 'human data design' approach was proposed by Houben et al. [67], where they developed what they called a Physikit. The Physikit is a toolkit and technology probe which uses several physical cubes called PhysiCubes. It allows the users to receive notifications about the usage of their data in a physical, tangible format. The Physikit requires two elements to perform. First, several tangible physical cubes, which each deliver one unique notification, such as movement, light, air or vibration. Second, a web-based end-user configuration tool, which provides the user with an easy way to connect his data sources. Through developing this Physikit, the authors argued that when tangible physical objects are made available to users, it will give them the urge to explore more about the collection and processing of their data. As a result, the users will have the confidence to make thoughtful decisions regarding the share of their data. In their research, they have implemented the Physikit and conducted a field study to assess the usability of the tangible physical notification method. The overall results were satisfying, in which users - households mainly - of different background showed positive engagements with the physical cubes. The users' data awareness has improved in a way that some users were interested to know how to set rules to manage their data. Despite that the Physikit provided a powerful technique in spreading the awareness, it, unfortunately, holds some limitations. Since users are given a choice to set up the information the cube notifies them about, it creates a hurdle in setting the rule, understands the rule, and memorise the information the cube is trying to notify about. It also led to conflicts of interests, since each house member could set the cube to notify him about a different data change. Furthermore, the approach being connected to a web-based technique puts a limitation in front of non-technical people (e.g., elderly) trying to set it up. The cube idea has also been used in [87], as an effective way of notifications. In this paper, the cube has been used as a mean of communication to people in a long-distance relationship. The cube has similar functionality to the Physikit cube in which it shows light, vibrates or heats up whenever to notify the users.

Another tangible notification technique was presented by Mehta et al. [108], in which they explored the efficiency of the on-body notification methods. The authors argued that using on-body haptic interfaces could provide the user with awareness regarding the use of his data while preserving his privacy. They presented two main functionalities using the metaphors 'privacy itch and privacy scratch' in their proposed wearable tangible device. (1) Privacy itch: which causes an itch in the user’s arm to warn him about potential personal data breaches, and (2) Privacy scratch: which allows the user to scratch his arm as a response to the itch, providing a real-time, contentious and eye free control of his privacy preferences. The on-body privacy management notification method offers a practical and useful way of real-time notification. Its ease of use makes it span not only to technical people but also to users with different backgrounds providing them with convenient interaction way with their data. In addition to that, the on-body notification provides the users with distinct interaction feature, which gives them trust through having the dominance in controlling their data. However, this technique could convey only a limited number of information, resulting in the user uncertainty when dealing with his private data which either will lead to
ignorance or great concern. Moreover, since this notification method is attached to the body, it can be really obstructive to users as described by [101][105] especially when multiple warnings are sent in a limited amount of time.

Considering the above papers and the studies in [65][71][74], we can see that tangible and physical notifications can - with some improvements - be a promising method in increasing the users’ awareness. Their physical feature makes them at the sight of the user’s eye most of the time, triggering the user’s curiosity in learning about his data. In addition, based on the tangible interface, it can provide the user with various location properties unlike the usual notification methods, i.e., they can be moved between different rooms in the house, or shared between different members.

3.5.5 Control Parameters. With the various notification methods available, each and every method could convey different information based on how it is controlled. The visual light notification, for example, can have a different intensity to indicate the severity of the delivered notification, e.g., strong red represents very sensitive data. It can also have different colours, in which each colour represents a particular data type, e.g., green represents normal generic data, i.e., data that is generally accepted to be shared. There are mainly five different ways that can play as a control parameter within the available notification methods. They are intensity, frequency, duration, modulation and sequences. The five control parameters could be applied mostly to every notification method to deliver a wide diverse range of notifications to the user. Table 5 presents the papers that incorporate the different control parameters in their used notification criteria.

3.5.6 Notification-based Interaction. Understanding user behaviour is an essential piece in choosing or designing the appropriate notification technique. Based on individuals’ behaviour, reactions, and interactions with a particular device, the privacy policy can be adjusted and modified. Several pieces of literature have confirmed the importance of human-factor in supporting the setting of the privacy policies and aspects [15][121]. Furthermore, different researchers have discussed the importance of embedding the feedback feature while developing a device that interacts with individuals. In this section, we extend on including some of the research papers that discussed allowing the users to interact and submit feedback based on the notification he/she receives from a particular used device.

Most devices, especially IoT sensors, if incorporating an interaction mechanism with the user are employing a mobile application to send notifications and receive feedback to/from the users [85]. Gordon et al. [59], have designed an interactive application that can track users health. The application allows the health provider to send notifications, and respectively allow the patients to specify what information they want to share with their health provider. [93][80] discussed similar contribution in their papers. The development of these applications provide the users with interaction with their devices which allow them to set their privacy choices, however, it usually gets neglected by the users due to their setting requirements difficulty. On-body interactions, in which a person performs a body action or movement like smiling or blinking, have also been used as a feedback option to assist privacy choices [105][108][140]. In [108], Mehta et al. presented a privacy band that uses an on-body haptic interaction to send notifications to the user. Based on the received notification, the band allows the user to replay to the notification by submitting feedback which includes his/her privacy preferences. The on-body interactions have shown its promise in preserving individuals privacy, but it suffers from the annoyance the users incorporate from multiple notifications.
4 DISCUSSION

This survey aims to discuss the available efforts done in increasing users’ awareness and apply them in the domain of IoT sensors. There is plenty of work that has been done in supporting this endeavour, such as [97][63][24][77]. However, based on our knowledge, most of them either address limited ways of enhancing user’s awareness, require web-based tools, or are directed into specific, usually technical, users. Furthermore, there is a lack of having a basic development language that involves the necessary information an average user can understand. Consequently, there is also a lack of a formal interaction language between the user and the IoT sensor. Given that, in this survey, we did an intensive review of the available literature. We concluded the leading 5 factors needed to be considered while presenting any IoT sensor to the user, with an increased focus on the fifth factor, which is the notification method.

The importance of the fifth factor stems from the fact that we now live in a world of connected things, where notifications are everywhere [123]. Smart devices and sensors now have the ability to generate and deliver numerous notifications in a matter of seconds. We passed the problem of not having a notification. The problem that arises now is how to maintain the privacy of the user using the notification method? Additionally, given the intensity of the notifications, the users receive every day, users’ attention to the notifications tends to get affected, i.e., reduction in task execution. [14][17][66][43]. Obviously, there is a lack of a unified model for notifying the users about their privacy.

Based on the literature that we have reviewed, and as stated in [37], the available notification models do not cover the entire privacy image the user needs to understand. For instance, some methods only inform the user about the operation of a sensor in the room but do not specify the purpose of the sensor operation neither specify the length of the period the sensor will operate [125]. With the massive growth of the IoT gadgets, it is alarming how these sensors can sweep data without the user’s knowledge. The usage of the collected data certainly provides user benefit, but what is unknown is that the large volume of the collected data could make a personal data market which is created through users’ trust [150]. Manufactures usually obtain their customers’ consent regarding the collection of their data; however, a considerable gap and trade-off are facing the customers’ perception. Often customers feel hopeless when it comes to the possession of an IoT device. They feel lost in front of the long privacy policies, leading them to provide their consent only to be able to acquire the benefit of the IoT device.

Most users are not aware that by providing their consent, their data is usually collected in a large amount. That is because each IoT device has more than one sensor that is collecting data on a regular basis. With that happening, the volume of the collected data proliferates beyond the ability of the manufactures’ servers’ storage, leading to the necessity of cloud involvement. When the cloud comes into the picture, it opens the horizon to third-party companies to have access to customers’ data. Average users might trust their IoT device company, but not the third-party. Third-party companies, in this case, have access to data, which might contain personal information, and would use them for various purposes under the cover of already obtained user consent. [29][147] presented several privacy concerns, such as profiling, stealing and targeted ads that have been raised arguing that users confidently have been revoked. In addition, user’s data are not only accessed by third-party, but data is also retained and/or archived for a period of time, which sometimes can be infinite. According to [112], when people were confronted with the location of their data and how long the data is kept, most of them show preferences to devices that either offer a short retention period or an option of data deletion. Furthermore, several studies like [22][94][95] show how individuals care about their privacy and demand the possession of the data, which is collected based on their habits and behaviour.
There are some new solutions that have been produced in the market to support preserving the privacy of the user. Somfy, Figure 10 (a), created a monitoring camera with a privacy shutter, where the shutter closes whenever a person enters his private area. They have guaranteed that if the shutter is closed, nothing is recorded or stored in the cloud [143]. Google has a smart speaker, Figure 10 (b), with a physical microphone switch that can be turned on and off, according to the user desire [57]. It can be challenging to assume that all IoT devices can involve a privacy feature since each device is equipped with different sensors that are collecting different information. However, it is essential to have a common phenomenon of preserving user privacy and informing the users about any related mean performing data collection. IoT devices manufactures should work with the application developers to satisfy the end users’ privacy needs.

IoT developers and manufacturers need to consider the privacy aspects of the device and how it could impact the customers throughout the entire device development cycle. Sensors in the connected world have introduced new ways of data collection, which, as a result, bring multiple privacy challenges. Adopting the P3P protocol ontology, as described earlier, could help in addressing some of these challenges. For instance, granting the user the choice to control his data was one of the essential features of the P3P protocol. Although the P3P was a web-based tool, its mechanism can help in reducing the privacy issues faced in the IoT domain. Another effort has also considered the privacy challenges and presented a way of allowing the user to specify the location, the duration, and the kind of data he wishes to be stored within the company cloud service has been discussed in [136].

Perhaps the most significant challenge regarding the users’ IoT privacy is how to get the users to absorb and understand the sensitivity of the operations and the processes done on their data. Especially for non-technical users, classic visualisation, i.e., similar to usual privacy policies, carry little to no meaning to the users about their data collection and usage [19][20]. Current research is focusing their attention on developing a notification method that is easy to understand and does not disrupt the user while simultaneously enhance user awareness. The more aware the user is, the better the privacy policy can be built, which serves both the users and the IoT developers [135]. The privacy label prototype presented in [47] is an example of an easily grasp users’ data usage notification.
5 RESEARCH CHALLENGES AND OPPORTUNITIES

With the new growing modes of interactions introduced through the IoT devices and their associated sensors, challenges of people understanding the underlying idea of these interactions arise [145][51][41]. The notification mechanism is employed extensively in the digital space to notify users of how websites are using their interactions. For instance, a user surfing the web, is usually, get informed that his data is being collected and used to provide him with the service. Besides, in most cases, users are deliberately accessing web services, with their choice and knowledge. However, the circumstances are different in the IoT context [46]. The IoT devices and sensors are widely adoptable, implemented in physical spaces, and are considered small in size, creating them the perfect environment to go un-noticed. Figure 11 depicts how different data can be collected about individuals in various spaces, without their knowledge.

In this section, we elaborate on the gaps discussed previously in section 4, and present some of the research challenges and opportunities for future research. In Section (5.1) we discussed whether having a formal notification infrastructure can help in increasing the users awareness? If yes, what development language should be used to develop the infrastructure (section 5.2)? Furthermore, there is a lack in having a unified interaction patterns between the user and the IoT device, which is discussed in section (5.3). We then highlight additional IoT interaction challenges that can offer new research opportunities.

5.1 Privacy Infrastructure

Unlike the websites in digital spaces, which the person utilise with his/her choice, the collection of data done through IoT devices in physical spaces is often unbeknown to the people [152][53]. Although, after the enforcement of the GDPR and the CCPA regulations, most public spaces under surveillance, such as banks, universities, shopping malls, etc., are employing some notification methods, this appears to be not sufficient. The notification method that is often used is usually a warning sign indicating that there is, for example, a camera in progress, with no further information. These signs, despite their benefit, convey little to no meaning about what is done with the collected
data. Additionally, in most cases, people will forget about their existence [50][62]. There is a clear lack in the availability of the resources that inform people about the surrounding technology that collect and process their information.

A novel contribution by [44], where they designed an IoTPI app. The app will inform the users about the registered IoT devices available within their vicinity. Based on the registered devices policy, the user is able to browse the processes done on his/her data, as well as, some devices will offer the option of opt-in or opt-out. A research question that can be raised here, is whether a similar approach can be followed to span a wider audience. How can a person be notified and reminded about the existence of an IoT device without the need for a smartphone? Additionally, how can an average person understand the collected data type, how it is used, stored, or how long it is retained? Can the IoT device itself incorporate a notification mechanism? Or it has to be done through an external device that can comprise more than one IoT devices, i.e., devices that use each other?

Augmenting existing IoT devices in such one IoT device can use the capabilities of other IoT devices has been introduced in [5][124][61]. An example of that is, a touch screen on a smart fridge can display the settings of a nearby coffee machine, allowing the user to acquire more than one service at the same time. Although this technique has shown its advantages in aiding energy-saving and minimising the time-spent while using an IoT device. However, individuals' privacy can get compromised. The devices sharing capabilities drive at having the user’s consent to exchange his/her data between two or more IoT devices. Doing so indicates that the user’s data can be processed and stored at different manufactures' storage without the users’ knowledge, where some might not be following strict privacy policies. Having a privacy infrastructure that conveys to the user the processes done on his data in similar scenarios will help in increasing the user’s privacy awareness.

5.2 Development Language

A major challenge that arises with the IoT emergence is the diverse nature of its developers. IoT devices in the market are not only developed by known reputable companies that have access to resources, but also are developed by small entities or individuals that may lack essential resources and/or experience. Consequently, IoT devices are acquired and used by almost all levels of society. So, in order for having an IoT device that supports the user’s privacy, it is essential to employ a development language that is fast and reliable. More importantly, there is a need for a development language that contains the privacy required information to serve both the developer and the device user.

As described earlier, the P3P protocol gives the user control regarding the use of his data. The inclusion of P3P into the IoT domain as a mean that can increase individuals’ awareness has been proposed by Langheinrich [91]. Langheinrich proposed a model that uses the P3P machine-readable privacy policies to communicate with nearby IoT sensors, allowing the users to manage their preferences regarding their personal information. Ghazinour et. al [54], have built upon the use of P3P in presenting a model that does not only provide the privacy policy to the user but also ensure the enforcement of the use of the privacy policy by both the user and the service provider. Other languages, such as EPAL [12] and PPVM [55] have also incorporated privacy policies that can support in the IoT domain. Although with the IoT sensors, there is a considerable amount of sensed data, it is practical to have the employment of the P3P protocol, sue to the fact that the enforcement of policy is usually task-based.

There are various development languages that are available for developers, such as [10][155][78] [153]. Although these languages are powerful, they mostly require web-based tools and are directed to individuals with a technical background [112]. Considering that the IoT devices, specially the
small and unnoticeable devices, are developed by individuals and small entities, the privacy requirements are usually get neglected due to their complexity, cost, and building difficulties. Moreover, the developers of these devices have a little experience of employing any device privacy updates [64]. Will having a development language that is reliable, and cost-effective help in incorporating the privacy requirements into the IoT devices? Or can there be templates that is needed to be followed in order for a device to pass a privacy check? Will third-party involvement help in tackling this issue?

5.3 Interaction Patterns and Personalisation

Considering the diversity of the IoT devices, devices that lie in the bottom-tier layer [64], are those that usually fall from a person’s attention. That is due to their size and multiplicity, where an individual can have hundreds of them [64]. Having this great number of devices around a person rise the privacy issue of the amount of data that is collected through them. In particular, these devices have low awareness models while collecting individual data, making them a threat to the person’s privacy [118][116][38].

To elevate the devices’ awareness models, an interaction pattern between the individual and the IoT device is needed. This interaction pattern should be reliable and effectively communicate the flow of data to and from the device [91]. Moreover, the interaction pattern must be readily deployable considering the size of the sensors and the experience of the device user. Can there be an interaction pattern that conveys to the user an essential device’s functionality in a straightforward way, e.g., red blinking light indicating sensitive data collection or loud sound indicating an urgent needed interaction? Will the interaction pattern cope with the number of sensors acquired by a single individual? Can we have a cost-effective model that balances the number of needed notification with user’s annoyance?

The availability of such an interaction pattern requires an understanding of both the user and the device. In the case of IoT, a comprehensive understanding of the users’ social context and the IoT sensor functionality is a must. That is because, the IoT sensors are shared in nature, i.e., either they are deployed in a shared space or are used by more than one person. There exist multiple designs and frameworks that support understanding individuals’ awareness level, such as [118][33][70][11][159][26]. However, most of these frameworks are situated to target experienced developers and users, making them difficult to be adopted in the IoT domain, since a great amount of IoT sensors are developed and used by individuals or small entities. In addition, the available frameworks and designs are difficult to operationalise in IoT shared spaces. There is a persistent need for a unified interaction pattern toolkit that serves both the developers and the device users. We suggest having a toolkit for IoT interaction patterns since it will simplify the privacy awareness check for both the developers and the IoT device user. The toolkit can serve as a catalogue that includes different types of privacy interaction patterns, each with its advantages and disadvantages, where the developer and/or the device user can create or choose from the recommended personalised patterns according to their needs. In addition, the toolkit can also be adjusted to cope with the number of IoT sensors occupied in one shared space, and the number of the notifications they arise. Having a framework or toolkit that is easily adoptable and deployable will serve in setting the first stone for the developer in taking into consideration the individuals’ privacy while developing an IoT device. It will also give the IoT users’ control over their data, which will increase their privacy awareness.

5.4 Additional challenges

In this section we present an overview of two more challenges that can be studied by researchers in term of IoT sensors. First, is whether employing the notification methods in the IoT sensors can
add up to increasing the individual’s awareness and affect their decision making? Specially, will a person be nudged by the notification method and adjusts or alters his habits due to having a sensor in the room? Will the notifications have the same level of influence on all users or will there be different scale of influence depending on the user age and personality? Second, can there be a unified approach to deliver the notifications to the user? Will having a unified approach help in reducing the notification annoyance? Or can this approach help users in understanding the type of notification being presented [100]? And like the previous challenge, will a unified approach fits all types of users despite their different age, personality, and life style?

6 CONCLUSION

In this survey, we have reviewed a number of the available literature that address different mechanisms of user’s notifications. The goal is to provide an in-depth study, which can help in improving the internet-connected devices users’ awareness. For that, we have classified the available notification methods into four main categories: visual, auditory, sensory, and tangible or physical notifications, along with providing a look into the pieces of literature that proposed the possibility for the user in replying to the raised privacy notifications.Furthermore, we have provided a look at the literature that discussed the most critical factors that should be taken into consideration while developing an IoT notification method. These factors are the collected data type, the purpose of data collection, the data storage location, and the data retention period. A number of gaps and challenges have been identified along with the survey, as well as recommending some opportunities and schemes which can serve as future research questions and help in addressing the suggested gaps.

REFERENCES

[1] Alessandro Acquisti, Idris Adjerid, Rebecca Balebako, Laura Brandimarte, Lorrie Faith Cranor, Saranga Komanduri, Pedro Giovanni Leon, Norman Sadeh, Florian Schaub, Manya Sleeper, et al. 2017. Nudges for privacy and security: Understanding and assisting users’ choices online. ACM Computing Surveys (CSUR) 50, 3 (2017), 1–41.

[2] Muhammad Raisul Alam, Mamun Bin Ibne Reaz, and Mohd Alauddin Mohd Ali. 2012. A review of smart homes—Past, present, and future. IEEE transactions on systems, man, and cybernetics, part C (applications and reviews) 42, 6 (2012), 1190–1203.

[3] Amazon alexa. [n.d.]. Axeda Corporation - IoT Global Network. Alexa Skills Kit ([n. d.]). https://developer.amazon.com/en-US/alexa/alexa-skills-kit/conversational-ai

[4] Amazon. 2018. Amazon Information Request Report. (Aug. 2018). https://d1.awsstatic.com/certifications/Information_Request_Report_June_2018.pdf

[5] Leonardo Angelini, Elena Mugellini, Omar Abou Khaled, and Nadine Couture. 2018. Internet of Tangible Things (IoTT): challenges and opportunities for tangible interaction with IoT. In Informatics, Vol. 5. Multidisciplinary Digital Publishing Institute, 7.

[6] Apple. 2019. Privacy Transparency Report. (June 2019). https://www.apple.com/legal/transparency/

[7] Noah Apthorpe, Dillon Reisman, and Nick Feamster. 2017. A smart home is no castle: Privacy vulnerabilities of encrypted iot traffic. arXiv preprint arXiv:1705.06805 (2017).

[8] Liliana Ardissono, Gianni Bosio, Anna Goy, Giovanna Petrone, and Marino Segnan. 2009. Managing context-dependent workspace awareness in an e-collaboration environment. In 2009 IEEE/WIC/ACM International Joint Conference on Web Intelligence and Intelligent Agent Technology, Vol. 3. IEEE, 42–45.

[9] Arkessa. [n.d.]. Arkessa Global Enterprise IoT Connectivity. https://www.arkessa.com/

[10] Ken Arnold, James Gosling, David Holmes, and David Holmes. 2000. The Java programming language. Vol. 2. Addison-wesley Reading.

[11] Jatin Arora, Kartik Mathur, Manvi Goel, Piyush Kumar, Abhijeet Mishra, and Aman Parnami. 2019. Design and Evaluation of DIO Construction Toolkit for Co-making Shared Constructions. Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies 3, 4 (2019), 1–25.

[12] Paul Ashley, Satoshi Hada, Günter Karjoth, Calvin Powers, and Matthias Schunter. 2003. Enterprise privacy authorization language (EPAL). IBM Research 30 (2003), 31.

[13] Axeda. [n.d.]. Axeda Corporation - IoT Global Network. ([n. d.]). http://www.axeda.com/
Interactive Privacy Preferences Management for Shared Spaces in Internet of Things

[14] Mark B. Edwards and Scott D Gronlund. 1998. Task interruption and its effects on memory. *Memory* 6, 6 (1998), 665–687.

[15] Tim Baarslag, Alan Alper, Richard Gomer, Muddasser Alam, Perera Charith, Enrico Gerding, et al. 2017. An automated negotiation agent for permission management. (2017).

[16] Jianmin Bai, James Geza Deak, Hua Iv, and Weifeng Shen. 2018. Magnetoresistive gear tooth sensor. US Patent 10,060,941.

[17] Brian P Bailey, Joseph A Konstan, and John V Carlis. 2000. Measuring the effects of interruptions on task performance in the user interface. In *Smc 2000 conference proceedings*. 2000 ieee international conference on systems, man and cybernetics. cybernetics evolving to systems, humans, organizations, and their complex interactions (cat. no. 0). Vol. 2. IEEE, 757–762.

[18] Rebecca Balebako, Abigail Marsh, Jialiu Lin, Jason I Hong, and Lorrie Faith Cranor. 2014. The privacy and security behaviors of smartphone app developers. (2014).

[19] Mara Balestrini, Tomas Diez, and Paul Marshall. 2014. Beyond boundaries: the home as city infrastructure for smart citizens. In *Proceedings of the 2014 ACM International Joint Conference on Pervasive and Ubiquitous Computing: Adjunct Publication*. 987–990.

[20] Mara Balestrini, Tomas Diez, Paul Marshall, Alex Gluhak, and Yvonne Rogers. 2015. IoT community technologies: leaving users to their own devices or orchestration of engagement? *EAI Endorsed Transactions on Internet of Things* 1, 1 (2015).

[21] Snehasis Banerjee and Debnath Mukherjee. 2013. Towards a universal notification system. In *2013 IEEE/WIC/ACM International Joint Conferences on Web Intelligence (WI) and Intelligent Agent Technologies (IAT)*. Vol. 3. IEEE, 286–287.

[22] Debianee Barua, Judy Kay, and Cécile Paris. 2013. Viewing and controlling personal sensor data: what do users want?. In *International Conference on Persuasive Technology*. Springer, 15–26.

[23] Michael Blackstock and Rodger Lea. 2012. IoT mashups with the WoTKit. In *2012 3rd IEEE International Conference on the Internet of Things*. IEEE, 159–166.

[24] Adam Bodnar, Richard Corbett, and Dmitry Nekrasovsky. 2004. AROMA: ambient awareness through olfaction in a messaging application. In *Proceedings of the 6th international conference on Multimodal interfaces*. 183–190.

[25] Matthias Böhmer, Christian Lander, Sven Gehring, Duncan P Brumby, and Antonio Krüger. 2014. Interrupted by a phone call: exploring designs for lowering the impact of call notifications for smartphone users. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. 3045–3054.

[26] Jan O Borchers. 2008. A pattern approach to interaction design. In *Cognition, Communication and Interaction*. Springer, 114–131.

[27] Hung Cao and Monica Wachowicz. 2019. An Edge-Fog-Cloud Architecture of Streaming Analytics for Internet of Things Applications. *Sensors* 19, 16 (2019), 3594.

[28] DEFINITIONS UNDER CCPA. 2020. California Consumer Privacy Act (CCPA) Website Policy. *Policy* (2020).

[29] Dunrren Che, Mejdil Safran, and Zhiyong Peng. 2013. From big data to big data mining: challenges, issues, and opportunities. In *International conference on database systems for advanced applications*. Springer, 1–15.

[30] George Chernyshov, Jianjun Chen, Yenchin Lai, Vontin Noriyasu, and Kai Kunze. 2016. Ambient rhythm: Melodic sonification of status information for IoT-enabled devices. In *Proceedings of the 6th International Conference on the Internet of Things*. 1–6.

[31] Chola Chhetri. 2019. Towards a Smart Home Usable Privacy Framework. In *Conference Companion Publication of the 2019 on Computer Supported Cooperative Work and Social Computing*. 43–46.

[32] Chia-Fang Chung, Nanna Gorm, Irina A Shklovski, and Sean Munson. 2017. Finding the right fit: understanding health tracking in workplace wellness programs. In *Proceedings of the 2017 CHI conference on human factors in computing systems*. 4875–4886.

[33] Eric S Chung, Jason I Hong, James Lin, Madhu K Prabaker, James A Landay, and Alan L Liu. 2004. Development and evaluation of emerging design patterns for ubiquitous computing. In *Proceedings of the 5th conference on Designing interactive systems: processes, practices, methods, and techniques*. 233–242.

[34] Nazi C Cila, Iskander Smit, Elisa Giaccardi, and Ben Kröse. 2017. Products as agents: metaphors for designing the products of the IoT age. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. 448–459.

[35] N Com. 2008. Movie enhanced with internet-based fragrance system.

[36] World Wide Web Consortium et al. [n.d.]. P3P 1.0: A New Standard in Online Privacy.

[37] Fulvio Corno, Luigi De Russis, and Teodoro Montanaro. 2015. A context and user aware smart noti. In *2015 IEEE 2nd World Forum on Internet of Things (WF-IoT)*. IEEE, 645–651.

[38] Andy Crabtree and Tom Rodden. 2004. Domestic routines and design for the home. *Computer Supported Cooperative Work* 13, 2 (2004), 191–220.

[39] Lorrie Faith Cranor, Alecia M McDonald, Serge Egelman, and Steve Sheng. 2007. 2006 privacy policy trends report. *CyLab Carnegie Mellon University, Pittsburgh* (2007).
[40] Ry Crist. 2018. Alexa sent private audio to a random contact, Portland family says. cnet (May 2018). https://www.cnet.com/news/alexa-sent-private-audio-to-a-random-contact-portland-family-says/

[41] Dylan Curran. 2018. Are your phone camera and microphone spying on you. The Guardian. Available at: https://www.theguardian.com/commentisfree/2018/apr/06/phone-camera-microphone-spying (Accessed 14 Apr 2019). (2018).

[42] CyLab. [n.d.]. CyLab Security & Privacy Institute. https://www.cylab.cmu.edu/

[43] Mary Czerwinski, Edward Cutrell, and Eric Horvitz. 2000. Instant messaging: Effects of relevance and timing. In People and computers XIV: Proceedings of HCI, Vol. 2. 71–76.

[44] Anupam Das, Martin Degeling, Daniel Smullen, and Norman Sadeh. 2018. Personalized privacy assistants for the internet of things: providing users with notice and choice. IEEE Pervasive Computing 17, 3 (2018), 35–46.

[45] Bernadette Emsenhuber. 2006. Integration of olfactory media and information in pervasive environments. In Proceedings of the First International Doctoral Colloquium on Pervasive Computing, Linz.

[46] Bernadette Emsenhuber and Alois Ferscha. 2009. Olfactory interaction zones. In Conf. on Pervasive Computing.

[47] Pardis Emami-Naeini, Henry Dixon, Yuvaraj Agarwal, and Lorrie Faith Cranor. 2019. Exploring how privacy and security factor into iot device purchase behavior. In Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems. 1–12.

[48] Bernadette Emsenhuber. 2006. Integration of olfactory media and information in pervasive environments. In Proceedings of the First International Doctoral Colloquium on Pervasive Computing, Linz.

[49] Bernadette Emsenhuber and Alois Ferscha. 2009. Olfactory interaction zones. In Conf. on Pervasive Computing.

[50] Steven Houben, Connie Golsteijn, Sarah Gallacher, Rose Johnson, Saskia Bakker, Nicolai Marquardt, Licia Capra, and Yvonne Rogers. 2016. Physiskit: Data engagement through physical ambient visualizations in the home. In Proceedings of the Seventh International Conference on the Internet of Things, 1–8.

[51] Jason Hong. 2017. The privacy landscape of pervasive computing. IEEE Pervasive Computing 16, 3 (2017), 40–48.

[52] Eva Hornecker and Jacob Buur. 2006. Getting a grip on tangible interaction: a framework on physical space and social interaction. In Proceedings of the SIGCHI conference on Human Factors in computing systems. 437–446.

[53] Edward Cutrell Mary Czerwinski Eric Horvitz. 2001. Notification, disruption, and memory: Effects of messaging interruptions on memory and performance. In Human-Computer Interaction: INTERACT, Vol. 1. 263.

[54] Al Muhander et al. 2018. A lattice-based privacy aware access control model. In 2009 International Conference on Computational Science and Engineering, Vol. 3. IEEE, 154–159.

[55] Kambiz Ghazinour, Maryam Majedi, and Ken Barker. 2009. A model for privacy policy visualization. In 2009 33rd Annual IEEE International Computer Software and Applications Conference, Vol. 2. IEEE, 335–340.

[56] Robert W Gomulkiewicz and Mary L Williamson. 1996. A brief defense of mass market software license agreements. Rutgers Computer & Tech. L 22 (1996), 335.

[57] Google. [n.d.]. Privacy Features of Google Home Mini – Google Store. https://store.google.com/gb/product/google[_]home[_]mini[_]security

[58] Google. 2018. Google Transparency Report. (Dec. 2018). https://transparencyreport.google.com/?hl=en

[59] Marla Gordon, Rebecca Henderson, John H Holmes, Maria K Wolters, Ian M Bennett, and SPIRIT (Stress in Pregnancy: Improving Results with Interactive Technology) Group. 2016. Participatory design of ehealth solutions for women from vulnerable populations with perinatal depression. Journal of the American Medical Informatics Association 23, 1 (2016), 105–109.

[60] Paul M Greco, Stephen D Hunt, and Joseph W Seuck. 2007. Communication device having a scent release feature and method thereof. US Patent 7,200,363.
Interactive Privacy Preferences Management for Shared Spaces in Internet of Things

[68] HowStuffWorks. [n.d.]. How Amazon Echo Works | HowStuffWorks. https://electronics.howstuffworks.com/gadgets/high-tech-gadgets/amazon-echo.htm

[69] Euijin Hwang, Reuben Kirkham, Andrew Monk, and Patrick Olivier. 2018. Respectful Disconnection: Understanding Long Distance Family Relationships in a South Korean Context. In Proceedings of the 2018 Designing Interactive Systems Conference. 733–745.

[70] Giovanni Iachello and Gregory D Abowd. 2008. From privacy methods to a privacy toolbox: Evaluation shows that heuristics are complementary. ACM Transactions on Computer-Human Interaction (TOCHI) 15, 2 (2008), 1–30.

[71] Hiroshi Ishii and Brygg Ullmer. 1997. Tangible bits: towards seamless interfaces between people, bits and atoms. In Proceedings of the ACM SIGCHI Conference on Human factors in computing systems. 234–241.

[72] Laurel Jamtgaard. [n.d.]. IEF, W3C, “The P3P Implementation Guide,” P3P Toolbox, December 2005.

[73] Laurel Jamtgaard. 2003. The P3P Implementation Guide.

[74] Yvonne Jansen, Pierre Dragicic, Petra Isenberg, Jason Alexander, Abhijit Karnik, Johan Kildal, Sriram Subramanian, and Kasper Hornbaek. 2015. Opportunities and challenges for data physicalization. In Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems. 3227–3236.

[75] Kaivan Karimi. 2020. The role of sensor fusion in the internet of things. Accessed on: January (2020).

[76] Keshav Kalushik and Susheela Dahiyai. 2018. Security and privacy in IoT based E-business and retail. In 2018 International Conference on System Modeling & Advancement in Research Trends (SMART), IEEE, 78–81.

[77] Joseph Nathaniel Kaye. 2001. Symbolic olfactory display. Ph.D. Dissertation. Massachusetts Institute of Technology.

[78] Brian W Kernighan, Dennis M Ritchie, et al. 1988. The C programming language. Vol. 2. prentice-Hall Englewood Cliffs, NJ.

[79] Damla Kilic, Andy Crabtree, Glenn McGarry, and Murray Goulden. 2020. The Cardboard Box Study: Understanding Collaborative Data Management in the Connected Home. 1–32. https://drive.google.com/file/d/1PQYmB38L_rIBWepdTTL5SzGNBkXv/view

[80] Jussi Kiljander, Alfredo D’elia, Francesco Morandi, Pasi Hyttinen, Janne Takalo-Mattila, Arto Ylisaauko-Oja, Juha-Pekka Soininen, and Tullio Salmon Cinotti. 2014. Semantic interoperability architecture for pervasive computing and internet of things. IEEE access 2 (2014), 856–873.

[81] Barbara Kitchenham and Pearl Brereton. 2013. A systematic review of systematic review process research in software engineering. Information and software technology 55, 12 (2013), 2049–2075.

[82] Predrag Klasnja, Sunny Consolvo, Tanzene Choudhury, Richard Beckwith, and Jeffrey Hightower. 2009. Exploring privacy concerns about personal sensing. In International Conference on Pervasive Computing, Springer, 176–183.

[83] Omead Kohanteb, Owen Tong, Heidi Yang, T Saensukospa, and Saba Kazi. 2015. Decoding sensors, creating guidelines for designing connected devices. Carnegie Mellon University (Summer 2015).

[84] Omead Kohanteb, Owen Tong, Heidi Yang, T Saensukospa, and Saba Kazi. 2015. WHEN WALLS CAN TALK:Investigating Privacy Implications of Sensors in the Home. Carnegie Mellon University (Spring 2015).

[85] Treflyn Lynch Koreshoff, Toni Robertson, and Tuck Wah Leong. 2013. Internet of things: a review of literature and products. In Proceedings of the 25th Australian Computer-Human Interaction Conference: Augmentation, Application, Innovation, Collaboration. 335–344.

[86] Peter Kowalke. 2016. Six Tips for Storing IoT Data. TOOLBOX tech (2016). https://it.toolbox.com/blogs/erpdesk/six-tips-for-storing-iot-data-082916

[87] Robert Kowalksi, Sebastian Loehmann, and Doris Hansen. 2013. Cubble: A multi-device hybrid approach supporting communication in long-distance relationships. In Proceedings of the 7th International Conference on Tangible, Embedded and Embodied Interaction. 201–204.

[88] Thomas Kubitza, Alexandra Voit, Dominik Weber, and Albrecht Schmidt. 2016. An IoT infrastructure for ubiquitous notifications in intelligent living environments. In Proceedings of the 2016 ACM international joint conference on pervasive and ubiquitous computing: Adjunct. 1536–1541.

[89] Aparna Kumari, Sudeep Tanwar, Sudhanshu Tyagi, Neeraj Kumar, Michele Maasberg, and Kim-Kwang Raymond Choo. 2018. Multimedia big data computing and Internet of Things applications: A taxonomy and process model. Journal of Network and Computer Applications 124 (2018), 169–195.

[90] Pushpanjali Kumari, Pratibha Goel, and SRN Reddy. 2015. PiCam: IoT based wireless alert system for deaf and hard of hearing. In 2015 International Conference on Advanced Computing and Communications (ADCOM), IEEE, 39–44.

[91] Marc Langeheinrich. 2002. A privacy awareness system for ubiquitous computing environments. In international conference on Ubiquitous Computing. Springer, 237–245.

[92] Scott Lederer, Jennifer Manko, and Anind K Dey. 2003. Who wants to know what when? privacy preference determinants in ubiquitous computing. In CHI’03 extended abstracts on Human factors in computing systems. 724–725.

[93] Hosub Lee, Richard Chow, Mohammad R Haghighat, Heather M Patterson, and Alfred Kobsa. 2018. IoT service store: A web-based system for privacy-aware IoT service discovery and interaction. In 2018 IEEE International Conference on...
Pervasive Computing and Communications Workshops (PerCom Workshops). IEEE, 107–112.

[94] Hosub Lee and Alfred Kobsa. 2016. Understanding user privacy in Internet of Things environments. In 2016 IEEE 3rd World Forum on Internet of Things (WF-IoT). IEEE, 407–412.

[95] Hosub Lee and Alfred Kobsa. 2017. Privacy preference modeling and prediction in a simulated campuswide IoT environment. In 2017 IEEE International Conference on Pervasive Computing and Communications (PerCom). IEEE, 276–285.

[96] Hosub Lee and Alfred Kobsa. 2019. Confident Privacy Decision-Making in IoT Environments. ACM Transactions on Computer-Human Interaction (TOCHI) 27, 1 (2019), 1–39.

[97] RG Leiser. 1989. Improving natural language and speech interfaces by the use of metalinguistic phenomena. Applied Ergonomics 20, 3 (1989), 168–173.

[98] Pedro Giovanni Leon, Blase Ur, Yang Wang, Manya Sleeper, Rebecca Balebako, Richard Shay, Lujo Bauer, Mihai Christodorescu, and Lorrie Faith Cranor. 2015. What matters to users? Factors that affect users’ willingness to share information with online advertisers. In Proceedings of the ninth symposium on usable privacy and security. 1–12.

[99] Asterios Leonidis, George Baryannis, Xenofon Fafoutis, Maria Korozo, Niki Gazoni, Michail Dimitriou, Maria Koutsoiannaki, Aikaterini Boutsika, Myron Papadakis, Haridimos Papagiannakis, et al. 2009. Alertme: A semantics-based context-aware notification system. In 2009 33rd Annual IEEE International Computer Software and Applications Conference, Vol. 2. IEEE, 200–205.

[100] Jiali Lin, Shahriyari Amini, Jason I Hong, Norman Sadeh, Janne Lindqvist, and Joy Zhang. 2012. Expectation and purpose: understanding users’ mental models of mobile app privacy through crowdsourcing. In Proceedings of the 2012 ACM conference on ubiquitous computing. 501–510.

[101] Shu-Yang Lin, Chao-Huai Su, Kai-Yin Cheng, Rong-Hao Liang, Tzu-Hao Kuo, and Bing-Yu Chen. 2011. Pub-point upon body: exploring eyes-free interaction and methods on an arm. In Proceedings of the 24th annual ACM symposium on User interface software and technology. 481–488.

[102] Tom Lodge and Andy Crabtree. 2019. Privacy Engineering for Domestic IoT: Enabling Due Diligence. Sensors 19, 20 (2019), 4380.

[103] Michal Luria, Guy Hoffman, and Oren Zuckerman. 2017. Comparing social robot, screen and voice interfaces for smart-home control. In Proceedings of the 2017 CHI conference on human factors in computing systems. 580–628.

[104] Ashok Maranan, Manoj Nagarajan, and Priyanka Nayek. [n.d.]. Study on Software Agreement (EULA). ([n. d.]).

[105] Michael Matscheko, Alois Ferscha, Andreas Riemer, and Manuel Lehner. 2010. Tactor placement in wrist worn wearables. In International Symposium on Wearable Computers (ISWC) 2010. IEEE, 1–8.

[106] Patrick McFadin. [n.d.]. Internet of Things: Where Does the Data Go? | WIRED. https://www.wired.com/insights/2015/03/internet-things-data-go/

[107] Abhinav Mehrotra and Mirco Musolesi. 2017. Intelligent notification systems: A survey of the state of the art and research challenges. arXiv preprint arXiv:1711.10171 (2017).

[108] Vikram Mehta, Arosha K Bandara, Blaine A Price, and Bashar Nuseibeh. 2016. Privacy itch and scratch: on body privacy warnings and controls. In Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems. 2417–2424.

[109] RVD Meulen. 2017. Gartner Says 8.4 Billion Connected ‘Things’ Will Be in Use in 2017, Up 31 Percent From 2016. Gartner Newsroom (2017).

[110] Yohan Moon, Ki Joon Kim, and Dong-Hee Shin. 2016. Voices of the internet of things: An exploration of multiple voice effects in smart homes. In International Conference on Distributed, Ambient, and Pervasive Interactions. Springer, 270–278.

[111] Steven B Most, Brian J Scholl, Erin R Clifford, and Daniel J Simons. 2005. What you see is what you set: sustained inattentional blindness and the capture of awareness. Psychological review 112, 1 (2005), 217.

[112] Pardis Emami Naeini, Sruti Bhagavatula, Hana Habib, Martin Degeling, Lujo Bauer, Lorrie Faith Cranor, and Norman Sadeh. 2017. Privacy expectations and preferences in an IoT world. In Thirteenth Symposium on Usable Privacy and Security ( {SOUPS} 2017). 399–412.

[113] Clifford Nass and Kwan Min Lee. 2001. Does computer-synthesized speech manifest personality? Experimental tests of recognition, similarity-attraction, and consistency-attraction. Journal of experimental psychology: applied 7, 3 (2001), 171.

[114] Ricardo Neisse, Giammarco Baldini, Gary Steri, Yutaka Miyake, Shinsaku Kiyomoto, and Abdur Rahim Biswas. 2015. An agent-based framework for informed consent in the internet of things. In 2015 IEEE 2nd World Forum on Internet of Things (WF-IoT). IEEE, 789–794.

[115] Nest. [n.d.]. Nest Retention Statement | Nest. https://nest.com/data-retention/

[116] Carman Neustaedter and AJ Bernheim Brush. 2006. " LINC-ing" the family: the participatory design of an inkable family calendar. In Proceedings of the SIGCHI conference on Human Factors in computing systems. 141–150.
[117] CBS NEWS. 2019. Ring security system program with law enforcement raises privacy concerns. CBS NEWS (Aug. 2019). https://www.cbsnews.com/news/ring-security-system-program-with-law-enforcement-raises-privacy-concerns/

[118] Karin Niemantsverdriet, Harm Van Essen, Minna Pakanen, and Berry Eggen. 2019. Designing for awareness in interactions with shared systems: the DASS framework. ACM Transactions on Computer-Human Interaction (TOCHI) 26, 6 (2019), 1–41.

[119] Isaac O Olalere, Mendon Dewa, and Bakhe Nleya. 2018. Remote Condition Monitoring of Elevator’s Vibration and Acoustics Parameters for Optimised Maintenance Using IoT Technology. In 2018 IEEE Canadian Conference on Electrical & Computer Engineering (CCECE). IEEE, 1–4.

[120] Daniel Orth, Clementine Thurgood, and Elise Van Den Hoven. 2019. Designing meaningful products in the digital age: how users value their technological possessions. ACM Transactions on Computer-Human Interaction (TOCHI) 26, 5 (2019), 1–28.

[121] Sameer Patil, Roberto Hoyle, Roman Schlegel, Apu Kapadia, and Adam J Lee. 2015. Interrupt now or inform later? Comparing immediate and delayed privacy feedback. In Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems. 1415–1418.

[122] Charith Perera, Arkady Zaslavsky, Peter Christen, and Dimitrios Georgakopoulos. 2013. Context aware computing for the internet of things: A survey. IEEE communications surveys & tutorials 16, 1 (2013), 414–454.

[123] Martin Pielot, Karen Church, and Rodrigo De Oliveira. 2014. An in-situ study of mobile phone notifications. In Proceedings of the 16th international conference on Human-computer interaction with mobile devices & services. 233–242.

[124] Boris Pokric, Srdan Krc, and Maja Pokric. 2014. Augmented reality based smart city services using secure iot infrastructure. In 2014 28th International Conference on Advanced Information Networking and Applications Workshops. IEEE, 803–808.

[125] Benjamin Poppinga, Wilko Heuten, and Susanne Boll. 2014. Sensor-based identification of opportune moments for triggering notifications. IEEE Pervasive Computing 13, 1 (2014), 22–29.

[126] Zachary Pousman and John Stasko. 2006. A taxonomy of ambient information systems: four patterns of design. In Proceedings of the working conference on Advanced visual interfaces. 67–74.

[127] Laura Rafferty, Patrick CK Hung, Marcelo Fantinato, Sarajane Marques Peres, Farkhund Iqbal, Sy-Yen Kuo, and Shih-Chia Huang. 2017. Towards a privacy rule conceptual model for smart toys. In Computing in Smart Toys. Springer, 85–102.

[128] Steve Ranger. 2020. What is the IoT? Everything you need to know about the Internet of Things right now. ZDNet, February 19 (2020).

[129] Joseph Reagle and Lorrie Faith Cranor. 1999. The platform for privacy preferences. Commun. ACM 42, 2 (1999), 48–55.

[130] Daniel Reed, James R Larus, and Dennis Gannon. 2011. Imagining the future: Thoughts on computing. Computer 45, 1 (2011), 25–30.

[131] David Reinsel, John Gantz, and John Rydning. 2018. The Digitization of the World From Edge to Core). IDC White Paper by Seagate (Nov. 2018). https://www.seagate.com/files/www-content/our-story/trends/files/idc-seagate-dataage-whitepaperpdf/

[132] Ring. [n.d.]. Video Doorbell – Ring. https://en-uk.ring.com

[133] Marco C Rozendaal, Boudewijn Boon, and Victor Kaptelinin. 2019. Objects with Intent: Designing Everyday Things as Collaborative Partners. ACM Transactions on Computer-Human Interaction (TOCHI) 26, 4 (2019), 1–33.

[134] Kevin J. RyanStaff. 2019. Amazon Says Alexa Will Get Smarter With Age. Here’s How Two of Alexa’s top executives spoke about the ways the company is improving its technology. Inc. (May 2019). https://www.inc.com/kevin-j-ryan/amazon-alexa-future-of-everything.html

[135] Norman Sadeh, Jason Hong, Lorrie Cranor, Ian Fette, Patrick Kelley, Madhu Prabaker, and Jinghai Rao. 2009. Understanding and capturing people’s privacy policies in a mobile social networking application. Personal and Ubiquitous Computing 13, 6 (2009), 401–412.

[136] Mahadev Satyanarayanan, Pieter Simoens, Yu Xiao, Padmanabhan Pillai, Zhuo Chen, Kiyong Ha, Wenlu Hu, and Brandon Amos. 2015. Edge analytics in the internet of things. IEEE Pervasive Computing 14, 2 (2015), 24–31.

[137] Seedstudio. [n.d.]. Sensors - Seed Studio Electronics. https://www.seedstudio.com/category/Sensor-for-Grove-c-24.html

[138] William Seymour, Martin J Kraemer, Reuben Binns, and Max Van Kleek. 2020. Informing the Design of Privacy-Empowering Tools for the Connected Home. In Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems. 1–14.

[139] Yun Shen and Pierre-Antoine Vervier. 2019. IoT Security and Privacy Labels. In Annual Privacy Forum. Springer, 136–147.

[140] Carl Sherrick. 1991. vibrotactile Pattern Perception: Some Findings and. The psychology of touch (1991), 189–218.
[141] Dong-Hee Shin. 2013. Defining sociability and social presence in Social TV. *Computers in human behavior* 29, 3 (2013), 939–947.

[142] Daniel J Simons and Christopher F Chabris. 1999. Gorillas in our midst: Sustained inattentional blindness for dynamic events. *perception* 28, 9 (1999), 1059–1074.

[143] Somfy. [n.d.]. somfy 2401507 Indoor Camera, Full HD Security Camera for Home Security Systems, Smart Device with Integrated App and Simple Installation: Amazon.co.uk: DIY & Tools. https://www.amazon.co.uk/SOMFY-Home-Indoor-Security-Camera/dp/B07D7JKSMJ?ref_=ast_sto_dp

[144] Statista. 2019. Number of Smart Homes forecast worldwide from 2017 to 2024 (in millions). [Statista Chart](https://www.statista.com/statistics/887613/number-of-smart-homes-in-the-smart-home-market-worldwide/)

[145] Joseph Steinberg. 2014. These devices may be spying on you (even in your own home). *Forbes*, viewed 3 (2014).

[146] Bob Susnjara. 2020. Fighting crime or invading privacy? Police deals with Ring video doorbell have advocates and critics. *Daily Herald Media Group* (Feb. 2020). https://www.nwherald.com/2020/02/11/fighting-crime-or-invading-privacy-police-deals-with-ring-video-doorbell-have-advocates-and-critics/aqyji1n/

[147] Omer Tene and Jules Polonetsky. 2011. Privacy in the age of big data: a time for big decisions. *Stan. L. Rev. Online* 64 (2011), 63.

[148] THingsquare. [n.d.]. Internet of Things, from concept to solution - Thingsquare. https://www.thingsquare.com/

[149] Vamshidhar Thonti. 2018. Different Types of Sensors and their Working ELECTRONICS. (Jan. 2018). https://circuitdigest.com/tutorial/different-types-of-sensors-and-their-working

[150] Elias Z Tragos, Jorge Bernal Bernabe, Ralf C Staudemeyer, J Luis, H Ramos, A Fragkiadakis, A Skarmeta, M Nati, and A Gluhak. 2016. Trusted IoT in the complex landscape of governance, security, privacy, availability and safety. *Digitising the Industry-Internet of Things Connecting the Physical, Digital and Virtual Worlds. River Publishers Series in Communications* (2016), 210–239.

[151] European Union. 2016. Regulation 2016/679. [Official Journal of the European Communities 59. L 119 (2016), 1–88.](https://doi.org/pri/en/oj/dat/2003/l_285/l_28520031101en00330037.pdf arXiv:arXiv:1011.1669v3)

[152] Max Van Kleek, Ilaria Liccardi, Reuben Bims, Jun Zhao, Daniel J Weitzner, and Nigel Shadbolt. 2017. Better the devil you know: Exposing the data sharing practices of smartphone apps. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. 5208–5220.

[153] Guido Van Rossum et al. 2007. Python Programming Language. In *USENIX annual technical conference*, Vol. 41. 36.

[154] Mark Weiser. 1991. The Computer for the 21 st Century. *Scientific american* 265, 3 (1991), 94–105.

[155] Michael Wilde, Mihael Hategan, Justin M Wozniak, Ben Clifford, Daniel S Katz, and Ian Foster. 2011. Swift: A language for distributed parallel scripting. *Parallel Comput.* 37, 9 (2011), 633–652.

[156] Daniel M Wolpert, Jörn Diedrichsen, and J Randall Flanagan. 2011. Principles of sensorimotor learning. *Nature Reviews Neuroscience* 12, 12 (2011), 739–751.

[157] Arkady Zaslavsky, Charith Perera, and Dimitrios Georgakopoulos. 2013. Sensing as a service and big data. *arXiv preprint arXiv:1301.0519* (2013).

[158] Serena Zheng, Noah Apthorpe, Marshini Chetty, and Nick Feamster. 2018. User perceptions of smart home IoT privacy. *Proceedings of the ACM on Human-Computer Interaction* 2, CSCW (2018), 1–20.

[159] John Zimmerman. 2009. Designing for the self: making products that help people become the person they desire to be. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. 395–404.