Data Probes: Reflecting on Connected Devices with Technology-Mediated Probes

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ABSTRACT

We introduce Data Probes, technology-mediated probes designed to reveal some of the inner workings of connected devices, including common embedded sensors and the data they collect. By making these common features both accessible and unfamiliar, the probes supported research participants in looking at these technologies from a different perspective and reflecting on capabilities and behaviours that may be obscured by the design of commercial products. During a study where participants lived and travelled with the probes for a month, we were able to gain generative design insights into people's attitudes towards and relationships with connected devices, suggesting new opportunities for designs that take alternative approaches to currently entrenched visions of the Internet of Things. We present this exploratory study as an illustration of how a technology-mediated probe might prompt reflection on their technologies and open up new design spaces.

CCS CONCEPTS

• **Human-centered computing → Human computer interaction (HCI)**.

KEYWORDS

Probes, connected devices, Internet of Things, design research, research through design.

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1 INTRODUCTION

Internet-connected devices collect and report increasing amounts of data about their users, their homes and the world around them. Technologies such as location awareness and far-field microphones have enabled many useful devices and user experiences, but they have brought with them concerns about privacy and surveillance and questions about how the data collected by these devices might be used. The combination of inscrutable platforms and devices powered by distant cloud services renders these collections of data, sensors, networks and algorithms unknowable to most users, but leaves room for speculation and folk theory [13]—or simply indifference [9]. Responding to visions of calm technology [45] and invisible or disappearing computers [30, 38], product and interface designs have tended towards devices that "kindly shield us from computational and infrastructural complexity [but] also mask creepy vibes and lurking edge cases" [33]. A challenge for HCI now is to consider how we can design devices that support users in navigating and understanding these complexities rather than hiding them completely, and imagine what alternatives to these currently entrenched visions of the Internet of Things might be possible.

As part of a wider project exploring this challenge, we set about exploring people's relationships with connected devices, sensors and data as a means of gaining insights into possible alternative approaches. As internet-connected and data-driven technologies have propagated, so have popular discourses around data and privacy, such as common speculation and debate about whether internet advertisements are driven by surveillance through microphones [23]. Like Dunne and Raby's [14] provocations around electromagnetic fields at a time when mobile telephony—and accompanying speculation about the behaviours and effects of radio signals—was becoming widespread, this mix of interest and mystery provides opportunities to prompt reflection on connected devices and suggest novel ways of thinking about current uses of technology and directions of future travel. In trying to do this, we turn to cultural probes [18], a design-led method that uses creative and ambiguous prompts to encourage participants to look at something from a new and perhaps unexpected perspective as a way of mediating between participants and designers.

This paper documents our attempts to use probes to examine connected devices from new perspectives, with a view towards generating design insights that suggest avenues of exploration and alternative approaches to designing such technologies. To this end, we developed Data Probes: handheld devices that package together common sensors found in modern devices, intended to allow one to interrogate sensors and data in new ways. During an exploratory study with the Data Probes, participants lived and travelled with for up to a month, meeting regularly with each other and the research team to report on and discuss their experiences. Through this work, we contribute: 1) the Data Probe itself as a design research artifact that acts as a technology-mediated probe; 2) an exploratory study using the Data Probe with participants, resulting in a series of generative design insights drawn from their experiences with and

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discussions around the probe; and 3) reflection on the properties of our Data Probes that allowed this and the ways in which others might configure their own technology-mediated probes.

2 BACKGROUND

Our work is informed by a long history of existing research around the use of probes as a design-led research method and by more recent work around people's relationships with sensors and data. Before describing the design of our own probes, we revisit existing research around probes in their various forms, especially through the introduction of more technology-focused probe designs, and explore how HCI research has already understood the way that people access and interpret data, particularly that generated by connected devices.

2.1 Probes in HCI

Cultural probes were initially conceived to provoke inspirational responses from research participants that would give an impressionistic view of participants' lives to lead designers in interesting directions [18]. Formatted as a range of activities that enable different forms of inquiry—for instance, maps, postcards, audio recorders and disposable cameras—probe packs are typically left with participants to return completed materials over time. While this remoteness of the researcher from the participant is replicated in ethnographic methods such as experience sampling [27], including technology-led interpretations that report constant data [42], a distinguishing characteristic of cultural probes is their use of "ambiguity, absurdity, and mystery" [18] to prompt participants to look at their world through new eyes and return more unconventional insights. Although the form of probes has often closely followed the originally published probe packs, most notably through the use of disposable cameras, their potential forms are much more varied and may be adapted for the specific project and topic being explored [44]. Wallace et al.'s [44] design probes, for example, took inspiration from craft practice to create objects reminiscent of mementos or souvenirs while exploring sensitive topics around dementia.

Beyond the use of cameras and audio recorders, early adaptations of the method made more extensive use of technology in their design. Technology probes [22] used open-ended exploratory deployments as a means of simultaneously field-testing a technology while learning about users. Although this is a quite different proposition from the original cultural probes, they align with Boehner et al.'s [5] description of probes as both a method and methodology. As a method, probes involve the distribution of creative materials as a way of collecting data. As a methodology, probes are an "alternative account of knowledge production in HCI design" [5] that acts to mediate between designers and participants, generating inspiration and insights for use as part of a design process. While common usage of the term technology probe has subsequently evolved away from this methodology, we are intentionally positioning our work as part of a category of designed interactive objects that engage with probes as a methodology.

More recently, the use of technology in probes has been revisited through ProbeTools [7], which offered a collection of electronic devices that could be used as part of a cultural probe. TaskCam [8], one of the designs in the series, reformats the familiar disposable camera as an Arduino shield (an add-on for the common electronic prototyping platform) that can be housed in custom enclosures to suit the needs of a given project. We can see in these tools opportunities for technology to extend the ability of probes to create new kinds of experiences. Finally, and closest to our own work, Berger et al.'s [2] probe-like IoT toolkits have demonstrated the ability to support people in speculating around future products. Their tools allowed participants to build simple pairings of sensors and actuators, with an accompanying card deck that invites them to imagine these components in particular contexts. Most interesting to us here is the way in which these toolkits introduce a degree of reflexivity, helping participants to speculate and tell stories about the kit's constituent parts. Taken together, these recent examples provide us with a starting point to think about how probes might help us to interrogate and reimagine new possibilities for connected devices.

2.2 Experiencing Sensors and Data

As sources of data have become more numerous, so too have encounters with that data through a growing variety of commercial products, particularly personal informatics products such as fitness trackers, and smart home devices that might include various ways of sensing the home environment. HCI has engaged with these by attempting to understand how people encounter and make meaning from these trails of data [11, 35] or reason about activity in the home [40]. But research has also explored alternative approaches to sensors and data that imagine new ways of experiencing them. Building on the probe methods described above, we focus here on uses of data and connected technology as research tools and as ways of creating new types of experience.

Datacatcher [20] was a handheld, location-aware device that presented snippets of localised information, such as the local unemployment rate and how many actual people that number represented. The underlying data was typically drawn from official sources such as government statistics, so encountering this high-level data in situ served to ground it in the experience of an actual place. The intention of these devices was to prompt engagement with societal issues, especially around inequality, and its relationships with big data. Like our Data Probes, Datacatchers supported people in engaging with data in different ways, although in this case the sort of data more typically encountered in media headlines. Datacatcher also highlights how we can leave room for interpretation in data, something we can likewise see in Dear Data [28]. Undertaken by two visualisation designers, their project involved them actively paying attention to some aspect of their lives and synthesising that into a unique and beautiful representation of that data that they exchanged by postcard. The kit that they subsequently developed for others to use [29], including postcard prompts to record and visualise challenging concepts like jealousy, bears similarity to cultural probe packs in both its form and its attempt to prompt people to look at the world differently.

Recent work has also explored how people make meaning in data, especially in the home context. Most similarly to our work, Kurze et al. [24] created a sensor platform that enabled participants to place small, simple sensors around the home and attempt to guess what

the data might represent or tell them. This work primarily aimed to understand how people made sense of data and put this data to use, contributing to our understanding of data work [15]. However, we can see in this work the value of giving people the ability to interrogate sensors and see the world in unfamiliar ways through them. Combining this with probe approaches, we see opportunities to use similar approaches to prompt wider reflection on connected devices both within the home and beyond as a means of opening up new avenues for design.

3 DESIGNING DATA PROBES

Data Probes were technology-mediated probes that would let participants experience the data and sensors used by many connected devices in new ways, aiming to prompt reflection on these technologies and generate design insights to inform alternative approaches. Probes are by their nature carefully designed artefacts, and so the design of the Data Probe itself was carefully considered in the way that it presented itself to its user and to others. This was guided by a set of core design principles that aimed to balance its ability to act as a probe while remaining trustable as a data-driven device. Firstly, we aimed to create an object that was obtrusive and unusual, which announced itself to the world and yet was not alarming. Likewise, it was intended to expose its functionality and workings to the user, inviting interrogation, while still appearing to be a finished product rather than a tangle of electronics. As a probe, it was intended to remain open to interpretation, presenting data in an unrefined form that required effort to interpret. Finally, the device was to be self-contained, relying on no external services or third parties, allowing the participant complete control over the data it collected. This section details our first contribution, introducing the resulting Data Probe design in terms of its physical form, its electronics and its data collection and visualisation, including how each of these aspects was designed with these guiding principles in mind.

3.1 Physical Form

The physical design of the Data Probe (Figure 1) was driven by an intention to be somewhat confrontational, making its presence in the world felt. It was centred on an exposed Printed Circuit Board (PCB), with a clear acrylic back and front that sandwiched and protected the circuit board while leaving its components visible. The sensors were mounted prominently on the front of the board, with other components and the battery visible through the clear back plate. The exposed circuit board lent the probe a distinctive appearance, somewhat inspired by the Defcon hacker conference's Badgelife badges [31] and automato.farm's [1] Believe it Yourself machines.

The entire device measured 10cm by 10cm, a little over 2cm thick, and weighed 177g—about the same as a standard smartphone. This form meant that it was mobile and handheld, but too large to be slipped comfortably into a pocket, and large and distinctive enough that when either laid flat or stood upright on a surface it had a certain physical presence and noticeability that invited conversation. Odom et al. [32] described attributes of research objects including finish and fit that can support objects in integrating with (or deliberately disrupting) the world once deployed. In these terms the Data Probe was intentionally designed not to fit—instead, it was an unusual object that was intended to stimulate and reward curiosity over a period of weeks.

At the same time, we wanted participants to feel assured that the Data Probe was safe and were also wary that unusual electronics in public can cause concern [25, 46], so it was designed to demonstrate a high degree of finish. The use of a PCB, rather than a prototyping material like stripboard, presented a more finished and deliberate intention and legibility than a tangle of cables. If challenged, the probe was intended to give a coherent account of itself, including the legitimacy afforded by institutional logos and an explanatory website engraved on the reverse. The surface of the PCB was illustrated with a white silkscreen print that represented an abstracted view of the device's architecture, with sensors visibly "connected" to a bank of physical switches. These switches allowed participants to directly turn individual sensors on and off, choosing which data they were comfortable collecting, and to do so in a visibly evident way.

3.2 Sensors and Electronics

The electronics were built around an Adafruit Feather ESP32-based development board, with a LiPo battery that could power the device for approximately 12 hours. This supported portability but meant the device was expected to be plugged in when at home. We chose sensors that would collect data reflecting different scales and complexities of data, from extremely simple light sensors to complex location sensing, all of which might be typically found inside connected devices. These sensors measured:

- **Light:** A photoresistor measured ambient light levels of the local environment, returning a higher value when light around the device was brighter. This was intended to explore very low-level sensors and what we might infer from even the simplest data that a device could detect.
- **Sound:** A microphone detected local noise levels, broken down and recorded as five frequency bands. This was intended to reflect the prevalence of microphones in devices like smart speakers without needing to record any sound.
- **Wireless:** The ESP32 chip itself detected nearby wireless networks and recorded the name of the strongest detected network at any given time. This was intended to provide a glimpse of the wireless landscape around the device and the traces left by other devices and networks.
- **Movement:** An accelerometer, commonly used in smartphones and fitness trackers, measured the acceleration of the probe in three dimensions. This data was represented as a frequency of movement from 0 to 20 Hz, where a steady walk would be approximately 2Hz and at rest the frequency was zero.
- **Location:** A GPS chip recorded the device's global geographic location. For privacy, the longitude and latitude were rounded to three decimal places before being stored, giving a resolution of roughly 100m. Limitations in the GPS receivers we used meant a successful location fix was only achieved sporadically.

The Data Probe polled each of the data sources once per minute and the output was recorded on a Micro SD card (assuming that a particular sensor was turned on at the time). The collection and

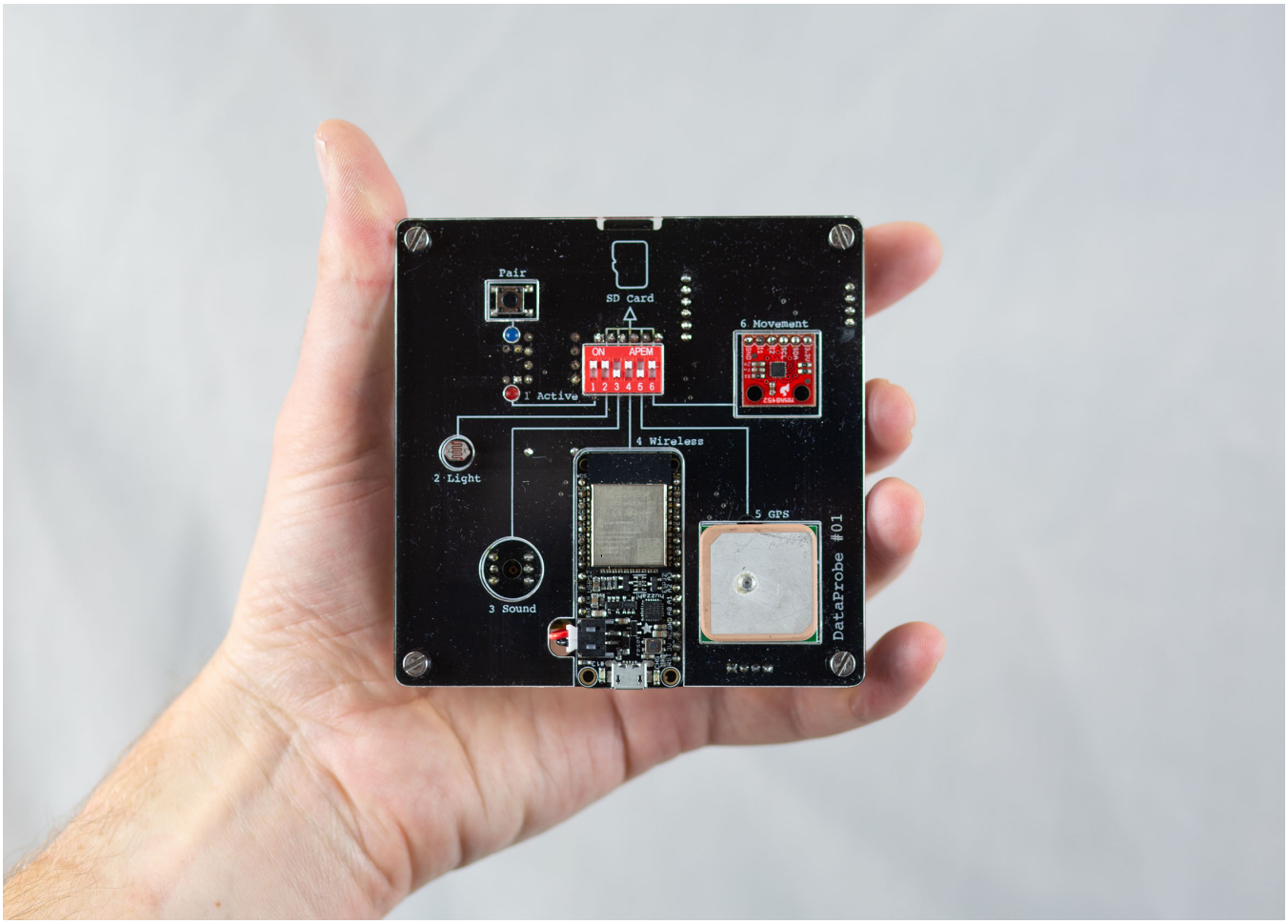

Figure 1: The Data Probes were designed to provide transparency, both literally and figuratively, around the components and their purpose.

storage of data were designed to be entirely self-contained and support scrutiny by the participants if they wished. Data was stored in a somewhat human-readable JSON format, associated with a timestamp, and the SD card was easily removable, making it possible for participants to explore this data themselves or even create alternative visualisations, which several participants chose to do. No cloud services were used and data was never transmitted either to the research team or any third party—the data being collected was entirely for their own use.

3.3 Displaying Data

Without access to any external services, the Data Probe needed an alternative method of providing access to the data it collected. To achieve this, the device itself hosted a webserver and password-protected wireless network which was activated by pressing the 'Pair' button. On connecting to the network with one of their own devices, the participant would see a captive portal—the type of pop-up login screen commonly encountered when using a wireless network in a public place or hotel—displaying a visualisation of the data stored on the device (Figure 2). The use of a captive portal drew on other recent examples [17, 19] and allowed us to make use of all the features of the participant's web browser without needing them to manually access a website or app.

The web interface was presented as a scrollable timeline using a combination of monospaced type and sparkline style graphics [41], a visual design reminiscent of a command line interface and consistent with the Data Probe's aesthetic and sense of viewing a device's inner workings. The default view showed the data row-by-row in one-hour summaries, which could be expanded to ten minute summaries when clicked. The first column denoted the day and time, then each subsequent column displayed data from a different sensor. The light level was drawn as a continuous line down the page, moving from left to right and growing thicker as light increased. The sound was displayed as five frequency bars, from low on the left to high frequency on the right, reminiscent of a graphic equaliser on audio equipment. The wireless network was simply the name of the strongest Wi-Fi network seen over the period. The GPS was shown as the truncated longitude and latitude

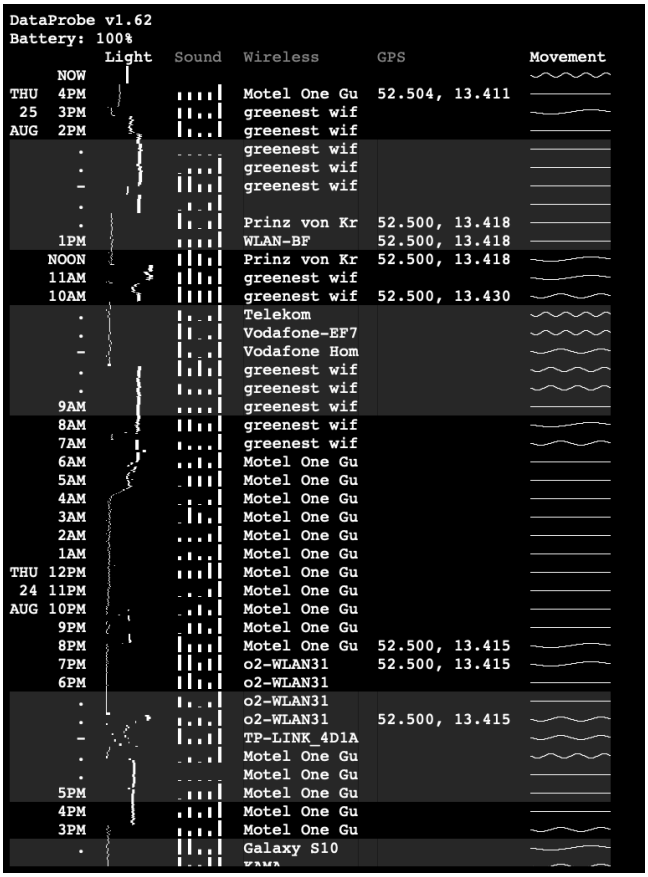

Figure 2: The Data Probe interface displayed data hourly, but each entry could be expanded into 10-minute increments. This figure shows illustrative data closely based on a researcher's trip to Berlin.

previously described. Finally, the movement was displayed as a sine wave, a repeating pattern where the number of repetitions corresponded with the frequency.

The top line of the table showed the current live data from the sensors, an alternative mode of operation that was available only when the visualisation was being viewed. This allowed the user to get a more immediate feel for the sensors, allowing them to see the readings respond to changes in their environment in real-time, supporting experimentation.

4 EXPLORATORY STUDY

Our exploratory study with the Data Probe had the dual goals of gaining generative design insights about connected devices that could inform our subsequent work, offering the starting points for considering alternative approaches, while also testing the Data Probe's ability as a tool to achieve this. To do this, we gave Data Probes to participants to use for a month, during which time they were asked to live with the probe, carry it with them as they went about their day, and report their experiences. This was structured as a group study and styled as a "book club", where the group of participants would meet weekly to discuss their data and observations from the past week and be given activities and ideas for things to explore over the coming week. The intention behind this approach was to support shared exploration amongst the group and create an environment in which the contributions of others in the group would prompt individual participants to reflect on their own data in new or unexpected ways. Five group meetings were held via Zoom once a week in the evening and participants were encouraged to attend all the meetings, but it was expected that participants might need to skip meetings due to other evening commitments.

We recruited five participants (P1–5), a number which was driven primarily by our desire to support meaningful small group discussion. Our approach aligns with low-volume batch production [6], which supports work with small groups where feedback is "captured in broad strokes and through intense fragments gathered from the more occasional contact with participants within a group" [6]. Of the participants, one reported their age as 25–34, two as 35–44 and two as 55–65. Two participants identified as female with the remainder identifying as male. Participants were recruited via social media and internal university mailing lists and as a result, participants were all university staff and students, although none had any prior contact with our research team or group and all worked outside our discipline area.

We met with each participant individually to give them their Data Probe, provide context for the project and demonstrate how to use the device, including explaining the features intended to protect their privacy. Initially, we simply asked participants to reflect on their daily activities and try to find evidence of this in the data recorded. In the second week, we asked participants to explore their homes to see how different rooms looked, how the rhythms of home life were manifested in the data, or whether they could see evidence of the home's other occupants. Next, we suggested they tell a story through the data, but also think about counter-narratives and what alternative stories the same data might support. Finally, we asked participants to explore public spaces, take the Data Probe to different types of space or take it on a walk and have someone else try to recreate the route (or vice versa). These tasks were intended to encourage experimentation with the capabilities of the sensors and how they saw the world and to prompt reflection on what could be inferred from relatively simple data. These tasks were not prescriptive, but provided starting points for participants to engage with the probes.

Through this study our intention was to capture the way that participants personally responded to the Data Probes and data they collected, and the reflections on connected devices that this prompted. We did not intend to use the collected data itself to learn about the participants, and we did not have access to it. Instead, we drew on the conversations we had with participants through the regular group sessions and individual exit interviews. Each of these interactions was audio recorded and transcribed. The focus of these interviews was informed by the contents of the group meetings, where we aimed to revisit interesting topics that each participant had raised and give them the opportunity to expand on these points and reflect on the entire study.

Probe-based approaches are intended to return material piecemeal over time for consideration by research and design teams. In

our interactions with the participants, we were looking for moments that were surprising or evocative and which offered small revelations about their experiences and personal reflections, helping to look at connected devices from a different perspective. Dialogue within the research team helped us to direct the discussion and prompts while beginning to assemble an overall sense of the most interesting areas that were emerging. Once the study had concluded, we returned to the discussion and interview transcripts, re-identifying those interesting and evocative moments and clustering insights that guided us in similar directions. These outcomes are necessarily partial and specific to our interests, raise more questions than answers and can not reflect a complete picture of our participants' relationships with either the Data Probe itself or with technology in general. Instead, we have gravitated towards material that resonates with us and offers glimpses of an alternative offer for our relationships with connected devices.

5 DESIGN INSIGHTS

The exploratory study furnished us with rich reports from participants of their experiences with the Data Probe and reflections on existing technologies. Our second contribution takes the form of six generative design insights that are suggestive of alternative relationships with connected technologies and might offer starting points for future design explorations, alongside the participants' reports that inspired them.

5.1 Dealing with Unfamiliarity

We designed the Data Probe as an unfamiliar object that did not resemble any other commonly encountered technology. It was designed to attract attention, leading we hoped to numerous interesting and reportable social encounters. Early in the study, P2 described attending a dinner party with friends and taking the Data Probe with him. As other attendees set their phones on the table after dinner, he decided to set his Data Probe alongside them, prompting a conversation about his participation in the project and how it worked: "*I said, well, it's just trying to shake hands with whatever's going on here and hopefully we'll record those interactions* [...] *nobody's identified or anything like that*". We can see here the forms of etiquette that already exist around technology, but also a process of deciding how an unfamiliar technology fits into those existing practices and the category of existing technology that it sits alongside. This also triggered conversations about other technologies, including a story in which P2 had been discussing specialist terminology (precision agriculture) near his smartphone and subsequently saw this reflected in online advertisements. While the Data Probe was noteworthy to P2's companions and scaffolded conversations relevant to our research, it also seemed to be accepted into existing social situations with relatively few concerns. By comparison, P5 had the device with her when she spent an evening with friends in a pub, and aside from questions about how it worked, her friends were primarily concerned about whether it was actually self-contained: "*They all had questions about it [...] are you sure they can't get access to it? I think that was asked a couple of times* [...] *making sure that it was actually mine and that it wasn't being transmitted*". Here, the unfamiliarity of the probe led to a productive critical discussion of its capabilities.

We had anticipated that our design of the Data Probe might raise suspicion in some situations and had cautioned participants not to take their device anywhere considered especially sensitive, such as an airport. However, in general, participants reported that their friends and family appeared curious but unfazed by the probes. P4 described having his family being comfortable with it, but also keeping it hidden during a first aid course to avoid having to explain it repeatedly to other attendees. By comparison, P3 said he was reluctant to be seen with the probe and kept it in his bag when he was not at home, which he felt limited how useful the data was when on the move. In the follow-up interview, he described how being an international student influenced this: "*in my country, I would have no issue to pick it out and move around because I know people around me and I know about the local culture*". In this case, the unfamiliarity of the technology limited the social encounters it could structure and intersected with the unfamiliarity of the local environment and culture.

As a design insight, these instances highlighted to us the possibilities of unfamiliarity as a tool to support discussion and disclosure around the capabilities of technology, but also the challenge of finding the appropriate point between discomfort and indifference. Responding to this as designers, we are led to consider how we might design technologies that attempt to draw attention to themselves and provoke this kind of disclosure and discussion intentionally, or otherwise create the circumstances where this might happen. If unfamiliarity is a design space, most commercial technologies have gravitated towards one end of it, with an overarching design trend towards products that obscure increasingly sophisticated capabilities behind unassuming and unobtrusive exteriors, aiming for familiarity and ultimately indifference. Other approaches are possible: we might pay particular attention to those times when a new technology enters an environment in a familiar form, as it has with objects like doorbells and speakers, to consider ways that these might be intentionally defamiliarised, thereby doing more an announce their presence and prompt consideration.

5.2 Trust Through Provenance

As participants began to see evidence of their routines in the data, they also reflected on what some person or system with access to this data might be able to do with it and the potential harm this could cause. Although P5 was one of the most enthusiastic participants, she also disclosed to the group that she had previously been the victim of stalking using exactly the type of location-based data collected by the probe: "*I have had people get hold of my data and look through my phone and find out what my routines are and then stalk me with it, and this stuff has been used to literally be a threat upon me*". Her experiences were a timely reminder that while we were engaging with these technologies playfully, their implications are not trivial or without potential consequences. At the same time, she was satisfied with the safety of the Data Probes ("*there are enough protections in place that it wouldn't be that big of a deal*"). As we have described, considerable thought was put into designing in this reassurance, for example by providing granular ways of turning certain sensors on or off, yet none of the participants reported having used this capability. This led us to be curious about the sources of participants' apparent trust in the device.

Attitudes towards trusting in general technology varied across participants—while some had relaxed or indifferent attitudes (P2: "*I don't massively suffer from anxiety about it*", P4: "*There's not a huge amount you can do about that*"), others' trust was more conditional. P3 described negotiating with his wife around the probe when he first brought it home, and she was suspicious of the data it might be collecting: "*she said okay, you have this probe but I don't have any idea what are the sensors inside it*". In this instance, eventual trust in the probe stemmed from the fact that it was a university project and they had confidence in the institution's reputation and policies. By comparison, a similar device from a commercial organisation would not have been invested with the same trust "(*some private organisation, maybe I would have not participated in this investigation*"). This kind of institutional trust was also not unconditional: P5 contrasted the probe with a university safety app that she refused to use since she was unsure of how that data might be used by third parties involved in the app. By contrast, P1's trust in the device stemmed from her technical knowledge ("*I know enough to know it's not available on the internet outside*"), while several participants noted their ability to scrutinise the probe's components, including P5 who had spent time inspecting the markings on chips to identify what they were.

We can see that trust in the probes came from multiple sources: its relationship with a trusted organisation was one source, as was the ability to identify individual components to gain some clue as to what it might be capable of. It no doubt also helped that there was a direct line of communication with the developer of the device and perhaps a sense of accountability, certainly given that we were responsive to problems and distributed fixes over the course of the study. This is not necessarily surprising—consider, for example, the trust brought by a well-known device brand, or even the different levels of trust that might be placed in Apple and Meta. Yet this idea of provenance is more nuanced for other types of products and services. In food, for example, trust in the quality of an item might stem from its brand name, but it might also be grown locally, or perhaps even sold to you directly by the farmer and readily inspectable. In craft, too, the relationship between the producer and consumer of goods might be much more direct. We once jokingly described the probes to participants as "*small batch artisanal electronics*", but these insights highlighted opportunities for different relationships with technology beyond mass production, as well as different relationships with technology producers.

5.3 Finding Meaning in Data

Our design emphasised simple unrefined sensors and visualisations and participants were quick to report evidence of their daily routines at home and outside even in these simple readings. For example, P4 moved the sensor around different rooms in the home, observing differences in sound ("*when it was in the kitchen, obviously it gets quite loud early in the morning and later on the afternoon*") and light ("*when it's in the little one's room, then obviously it gets dark a bit earlier because we shut the curtains*") that gave indications of what the room might be and the rhythms of family life. Likewise, P3 saw clear evidence of his eating habits based on the kitchen light ("*I can see those dips and highs* [...] *when I used to cook something, and when I used to just eat something* [...] *and when I just go to get some coffee*"). P2 was particularly drawn to odd patterns of light late at night and speculated over whether it might be caused by light from his television or by a nearby streetlight filtering through trees.

More surprising for participants was the way that the data evidenced their movements outside the home, where wireless networks clearly painted the broad strokes of their daily activities. As P5 described: "*when I went to a cafe, you could see exactly what cafe I went to*" whereas at the university library "*it kept bouncing between Eduroam,* [my] *University and like some Wi-Fi guest thing*". She furthermore realised that she could also see wireless networks offered on public transport ("*I can map not only when I went somewhere, but how I went there*"). Similarly, P4 was vacationing at a caravan park and described being able to identify his neighbour's routines based on his wireless network coming and going ("*there's a guy next door who uses it for work, so he has Wi-Fi but as soon as he's not there there's no sign of it*"). While GPS would seem to be the more obvious means of determining location and movement, these wireless networks were both human-readable and often provided context through the network names.

P5 was particularly drawn to the simplest of sensors, describing a fascination with the light reading as it changed over the course of the day. This related partly to caring for plants and for herself, ensuring that both were getting enough sunlight, but also the simple satisfaction of seeing consistently repeating patterns from day to day ("*there's this little blip right before I go to bed where I'm cleaning up the flat*"), or the way this changed during a heatwave when she was closing her blinds during the day, which had the effect of reducing the light reading by a uniform amount each day.

While these responses cover a wide range of responses to different forms of data, what they share is evidence of interpreting the data, spotting patterns, and reasoning about what they told the participants about themselves and the world around them. The Data Probe cast participants as detectives sifting through evidence, but as we saw with P2's patterns of light, the answer was perhaps less interesting than the process of trying to figure it out. To us, this suggested opportunities for connected devices that reward curiosity and investigation rather than just providing answers. One of the ways that connected devices hide complexity is through abstraction: a fitness tracker might refine masses of accelerometer data into a simple step count, then further into an indication of whether a goal has been achieved or not. We see here the potential to design for less authoritative interpretations and allow people to find meaning in their own way.

5.4 Investing and Responding Emotionally

As we saw above, participants responded to exploring the sensors with mixtures of curiosity, fascination and satisfaction. We were struck throughout the project by how invested participants remained with the devices and with their data, even when they encountered adversity in using the probe. For example, P2 remained strongly engaged with the project despite frequently not being able to access the data on his device, initially due to a technical problem and then by illness that prevented us from delivering a fix to him. He still reported carrying the device around "religiously", trusting that the device was collecting data that he would be able to access

Figure 3: A participant took their Data Probe sight-seeing in Paris. Images © P2.

later. Following the conclusion of the main study, he posted images on social media showing the Data Probe "on holiday" in Paris (Figure 3), including the nickname he had given the device. His relationship with the probe struck us as resembling caring for a pet, or perhaps more accurately a Tamagotchi.

Many participants were also closely invested in the data itself and collecting the data, to the extent that they expressed feeling sad or disappointed in instances where either they forgot to carry the probe, or it failed to collect data. Participants sometimes encountered gaps in the data when the device had been accidentally switched off, run out of battery, or encountered some other glitch. This prompted surprisingly strong reactions (P1: "*if you can't see anything, what happened to my life that day?*"), particularly when it related to an activity that they had thought might yield interesting data and especially wanted to capture (P5: "*I did go out of town and I forgot it, and that made me really sad*"). In response, one of the research team shared his own running habits, which were strongly motivated by logging associated data such that he might not go for a run if he would not be able to log it for any reason.

Seeing one's routines and movements in the data also prompted reflection on and responses to one's own life and behaviours. P3 saw his working hours reflected in the data, which helped him to understand how his time was split between studying and household tasks ("*it will help me to be more, you know, a bit more strict in my planning*"). P5 related it to her separate efforts to change certain habits, speculating that a device like the probe "*would be* [a] *log, that's also a truth keeper*". Recurrent in these discussions was the idea of the data as a record that could verify or dispute their own account of their activities as a means of keeping themselves in check.

We had designed the probes and activities hoping that they might be fun and surprising, while also recognising that they had the capacity to cause unease. But in these reports, we saw a wider range of reactions, including investment in the device, data and collection activities, but we also saw feelings of disappointment or even guilt. While emotional responses to connected technologies are widely recognised, this re-emphasised to us the double-edged nature of these responses. Considering how we might respond to this as designers, we are reminded of early IoT products like Berg's

Little Printer or Nabaztag that suggested a much more experimental, delightful and playful version of connected devices than the more functional one that has subsequently taken hold [12]. If we are aiming to design for different relationships with connected devices, avoiding the kinds of anxieties that have emerged with current models, what emotional qualities do we want those relationships to have instead?

5.5 Exposing Sensors' Limitations

As participants became more comfortable with the Data Probe and began to experiment more, led by our prompts to try and explore the world around them in a little more depth than their initial read of the data, they were increasingly sensitive to what the probe did and did not capture. Despite P5's description of the probe as a "truth keeper" in relation to tracking habits, the probe was an imperfect record and some of the design decisions we made—including the properties of the sensors and the device's strategy for sampling them—strongly influenced the characteristics of the data and what it would capture. As the probe only sampled each sensor once per minute, this meant that it was likely to miss brief events entirely. The way that the interface collapsed these samples into either one-hour or ten-minute summaries further obscured brief events and favoured a higher-level perspective. While these were practical design decisions related to battery life and intelligibility respectively, they also reflect the factors that might impact the perspective of any data-driven device.

We saw participants grappling with this most clearly in their attempts to capture specific events. Several participants set the probes up in particular places after a suggestion to explore spaces like cupboards or refrigerators. P2 planned to set his probe up to monitor snacking habits ("*there's a sort of a stock cupboard that includes essentially the cookie jar* [...] *and I was going to put it into one of them and just see how often that gets raided*") and hoped to capture the sound of his dog running across the house in the morning as the family woke up. Similarly, P5 set the probe up in her bathroom overnight hoping to capture her night-time visits. However, both failed to see any evidence of these events. As discussed in the previous section, there was a sense of disappointment in their absence, but it also caused P5 to question whether they had happened at all: "*I just assumed that it would be captured, but I didn't really see anything on there. So, I don't know if it was really short or if I actually didn't have to get up in the middle of the night* [...] *I have this narrative in my head that I always get up to go to the bathroom several times and I'm like, well, maybe I didn't*". In this example, we can see P5 questioning herself rather than the device, which is assumed to have a complete record.

Building on our previous insight around offering opportunities for people to find their own meaning in data, these experiences served as a reminder that the underlying data itself does not represent an omniscient recording of the world and that sensors can introduce their own biases into data. While these are benign examples, as data-driven technologies are increasingly being used to make decisions that might have significant impact on people's lives, it is likewise increasingly important to understand their capabilities and limitations. One avenue of exploration suggested to us by these insights is how to surface those qualities of data and the way it is collected, making it clearer to users of technology that devices have a particular perspective on the world shaped by numerous factors. Rather than implying accuracy, we might design things that help users to understand how these properties might affect the way that the device behaves, or design devices that offer multiple perspectives and embrace uncertainty.

5.6 Data Ambitions

Beyond the set of sensors and features provided by the Data Probe, using the devices prompted some of the participants to reflect on other types of sensors they might find interesting and especially ways they might want to be able to use data. We saw this in its most obvious form when P1 and P3, two of the most technically adept participants, developed their own visualisations of the data from the probe. P3 fed this data into Excel, while P1 gave it to her son who was interested in learning how to use R Shiny, a tool for making interactive data visualisations. Whereas the probe's web interface had been designed to give a more impressionistic overview of activity rather than supporting forensic scrutiny, the interfaces created by the participants were more conventionally functional, charting sensor data as graphs over the course of the day. This seemed to be partly driven by a desire to see a more complete overview of the data and contrast one day with the next, but also by a sense that data was a material that asked to be played with (P1: "*leave me alone with it long enough, I'll come up with things to do with it*").

For P1 in particular, the Data Probes prompted both creativity and frustration about current uses of technology. On the one hand, using the probes inspired her to start experimenting with her own ideas for networking temperature and humidity sensors around her house. But she also spoke frequently about frustrations around the untapped potential of data to improve services, particularly in cases where she might need to evidence something (P1: "*there are things that we can do to make our lives [...] so much better by using these things properly*"). For example, she described a recent instance where she had left her phone on a bus, where despite being able to track the phone, she eventually lost the signal and the bus operator was unwilling to act. While this would be frustrating in any circumstance, this was exacerbated by the fact that P1 had access to better knowledge than the bus operator did but was unable to use it. Other examples included using data to support discussions with doctors about health conditions.

Although this response to the probes was only seen amongst the most technologically skilled participants, we did see hints of other participants considering these factors. For example, P2 spoke on several occasions about how his purchasing habits were shaped by a preference for openness, or at least interoperability over closed platforms (P2: "*I don't like it when you're* [...] *tied so much into an ecosystem that you can only use one product*"), while all the participants showed some interest in creating their own visualisations had they been capable.

Responses to the probe showed us that participants both recognised the value of sensor data and its potential uses, as well as the barriers that might exist to doing so. While on the one hand, this points us towards the design of more open technologies that might provide opportunities for end users to collect, access and use

data about themselves and their environment, we also saw that this is not something that technology alone can address—as P1 found when dealing with her bus operator. While our work is oriented towards the design of devices and interfaces, these do not exist in a vacuum, and it leads us to question wider systems in place that might support or hinder this. Closed platforms underpin the business models of many connected devices, making it particularly challenging to design around, but we might at least design to highlight and demonstrate alternative models.

6 REFLECTING ON DATA PROBES

Having described the experiences our participants reported and the design insights that they led us to, we turn now to consider how the form and function of the Data Probes themselves supported participants in reflecting on their relationship with technology, and how we might configure these properties in similar technology-mediated probes. The final contribution of this work comprises our own reflections on using a technology-mediated probe as part of our research. We discuss key qualities of the Data Probes and their effects, including the choice to design them not to easily fit into their environment, their ability to support consideration of their constituent parts in isolation, and their role in communicating our own values and hopes for technology as designers.

6.1 On Not Fitting

One of our guiding design principles for the Data Probe was to make it stand apart from commonly encountered connected devices and sit somewhat uncomfortably in a way that drew attention to itself. This was most obviously manifested in the unfamiliar and slightly provocative physical form and exposed electronics, which do not align with common commercial design languages. It also extended to the sensors themselves, all of which participants carried on a daily basis as components inside their smartphones, but which were disaggregated and highlighted in a way that drew attention to quiet yet critical components underpinning devices and services. The representations of the data were likewise visualised in unfamiliar ways that took effort to interpret—for example in representing motion as a sine wave without any obvious point of reference rather than more processed and familiar representations like step count. We can see this kind of defamiliarisation at play in other probe examples—such as repackaging a common drinking glass so as to reinvent it as a dedicated listening device [4]. In making these choices, we were attempting to court the ambiguity and absurdity central to probe methods, evoking a sense of mystery that invited exploration.

We saw the impact of these design decisions clearly in the way participants reported various negotiations around the device and its capabilities, such as when P3 discussed the safety of the device with his wife, or P5 brought it out in the pub. It also created opportunities for the mildly illicit experience of ferrying strange electronics through an airport baggage system and museum metal detectors that P2 encountered on his trip to Paris, something we later encountered ourselves when travelling to international events with the Data Probe. This helped us to capture rich snippets of those moments of negotiation that happen when a new technology arrives and one must decide where it fits within their life and the lives of others—or perhaps where those moments fail to happen when devices quietly become "smarter" and more connected than they used to be.

As an inquiry-driven physical device, we can see the Data Probe as a form of research product [32], intentionally designed to scaffold and probe specific phenomena. While there would have certainly been less work required in developing a smartphone app to collect similar data, where the modules and sensors were already stably integrated as one cohesive unit, developing it as physical research product meant we could choose how to expose these features, divorced from their familiar housing. This leads us back to consider the Data Probe against the research product's dimension of fit. Odom et al. describe fit in terms of "balanc[ing] the delicate threshold between being neither too familiar nor too strange", suggesting the designer's active role in configuring where that balance sits for a particular object and inquiry. Their example of the table non-table [21], a table-like structure that moves slowly around the home, fits well into the home in terms of its aesthetic qualities, but is at the same time an uncanny object that does not behave like similar household products. The property of fit is therefore something we can manipulate, choosing where we sit in relation to that threshold, as a means of creating a particular experience and drawing attention to different aspects of the design—choosing the ways in which the object should "confront the world" [36].

6.2 Reflexivity to Interrogate Technology

Where our approach with Data Probes most differed from previous examples of technology-mediated probes was in their attempt to draw attention to their own constituent parts. In general, technology-mediated probes have been used as tools to probe some other aspect of the world around them—for example, the Digital Question Box [10] used a mobile phone housed in a cardboard enclosure to deliver prompts exploring the rituals of family life. However, our experiences in developing and using the Data Probe have helped to explore how a probe might direct attention back onto itself and thereby onto the technology landscape that it represents. Reversing the gaze in this way was interesting to us since the abilities that the Data Probes explored underpin modern devices and services, but for most users are inscrutable. Our approach with the Data Probe was to "explode" connected devices by teasing apart and isolating particular capabilities, disaggregating them from a wider system or product into individual features that could be examined on their own, creating new ways of experiencing these technologies. Our approach here complements prior work including Ritual Machines' [10] use of mobile phones in enclosures to selectively expose only certain parts of the device's full capabilities while causing others to disappear, and Taylor et al.'s [39] deconstructed biometric prototypes that allowed participants to interrogate the abilities and limitations of individual biometric technologies that normally resist scrutiny.

Isolating aspects of a system enabled participants to experience them in a way that they might not have been able to do otherwise. This is particularly striking in the case of the light sensor, a very simple sensor that might easily be overlooked when combined into a larger device, but which proved to be both informative and intriguing. Participants were able to see evidence of their home life

but also enjoyed attempting to understand less obvious patterns that appeared and reflect on their own habits. Likewise, awareness of nearby wireless networks elevated this from a background utility into a central and prominent position, and in doing so exposed something of the invisible landscape around us and the traces that these networks left through a person's day. Normally not accessed so directly, these simple sources of data painted surprisingly rich pictures of the world, but also hinted at different ways of experiencing connected devices by helping participants to reveal and think around systems that are otherwise intangible and difficult to grasp. We can see this effective strategy at play in other work, especially the IoT toolkits [2] described earlier, which both deconstructed these components and let participants reconstruct them in new configurations.

While exposing individual components is only one way of supporting reflexivity, it does open up many possibilities for emphasising different aspects of a system. As with the fit, we can imagine configuring probes to expose different aspects of a technology as a way of directing the inquiry. With the Data Probes, we chose to emphasise the sensing behaviour of connected devices, but we might equally cause different aspects of a connected device to make their presence felt, such as its connections with remote services. It is also useful here to consider the degree of functionality that is necessary, especially when we consider the experiences of P2 who had only limited access to the data but engaged wholeheartedly with the study regardless. Although we chose to develop a probe with significant technical capabilities, choosing which technologies to emphasise might mean choosing which are functional and which take on more speculative forms. We are especially reminded of Kuznetsov et al.'s [26] Sensor Probes, which were non-functional objects acting as proxies for sensors, but which nonetheless were able to generate rich insights into the way people might like to use sensors in the urban environment.

6.3 Articulating Our Values

Finally, while the Data Probe's primary goal was to act as a prompt and provocation and our design choices were primarily driven by that, our own position on connected devices bled into the designs and participants responded to that. Our values had led us to design an artefact that was self-contained and supported scrutiny by the participants if they wished: set against current trends in technology design, this was a somewhat radical choice. Developing the probe with an internet connection that reported data to a cloud service and made it available to participants through the web would have been a more straightforward and familiar proposition than designing it to be strictly self-contained. So too would have been an enclosure that hid the device's workings and any messiness inside rather than a form that needed to be transparent, neat and publicly legible. While there were practical reasons for rejecting these approaches—specifically ensuring that participants were comfortable with the probe—it also acted to direct the inquiry that we undertook.

Through these design choices, the Data Probe offered a glimpse of another possibility for technology design, directing participants' responses towards particular aspects of their relationships with technology. We can see this most clearly in discussions around trust in the devices, where participants drew direct comparisons between the Data Probe and commercial technologies when describing why they did or did not trust their behaviours. This then becomes a way of configuring the probe to explore particular facets of our participants' relationships with technology just as much as our choice of tasks or the ways in which we directed the discussion groups. We might equally choose to direct the inquiry towards something less comfortable in order to probe less desirable futures, although this must be done carefully. Examples of these types of approaches in practice have used depictions of "questionable" [3, 43] uses of technology that are intentionally provocative.

Viewed from this perspective, we can also see the Data Probe sitting alongside other means by which designers express their own agendas for alternative configurations of technology. Fritsch et al. [16] draw attention to manifestos as one way that designers have expressed "frustration and uncertainty as they struggle to negotiate between the possibilities that IoT technologies offer, and the ethical concerns they engender" [16]. While these manifestos offer starting points for challenging dominant models and developing new visions of technology, the next step is to demonstrate what these visions might look like in practice. We can see this in more speculative design research around connected devices like Our Friends Electric [34] and commercial concepts like Uniform's Scout [37], a speculative network device that visualised the data being sent by connected devices and where it was being sent to, and allowed device owners to automatically query suspect transmissions through legal means. The Data Probes represent our own effort to expand our design practice, embedding propositions for alternative approaches to connected devices in our own work. While they act to start a conversation with participants, they also have something to say themselves.

7 CLOSING REMARKS

This paper has introduced Data Probes, technology-mediated probes that supported research participants in exploring sensor data as a means of exposing and reflecting on their existing relationships with technology. Motivated by our interest in exploring, imagining and ultimately designing alternative models for connected devices, Data Probes created new experiences with data and devices, drawing attention to themselves and to other technologies and their associated systems, allowing us to collect generative design insights pointing to possible avenues of exploration. In doing this, we have explored approaches to technology-mediated probes and how they might be configured to explore these issues, but the Data Probes were also themselves designed objects that responded to some of the concerns around connected technologies, acting as a first step towards envisioning futures for technologies that attempt to resolve some of the tensions and anxieties in current products. Alongside the design insights gained through the research, our intention is that this work can contribute towards more responsible models for the design of connected devices.

DATA ACCESS STATEMENT

The data used in this study is openly available in the Newcastle University Research Repository at https://doi.org/10.25405/data.ncl.24289900.v1.

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