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In pursuit of thermal comfort: An exploration of smart heating in everyday life

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ABSTRACT

Smart Home Heating Technologies (SHHT) have been designed to improve demand flexibility and energy conservation. SHHT rely on rational theories of energy use postulating that people will use less energy when the energy cost is higher. The inclusion of AI within SHHT is poised to optimise energy use in the future as the introduction of lower carbon energy sources place new demands on the grid. When SHHT is introduced in the home, however, they become situated in temporal heating practices that are shaped by an interplay of materiality, meanings, and competencies. We report findings from a mixed methods field study involving eleven households utilising an AI-enabled SHHT probe 'Squid'. Taking a temporal focus throughout, our study contributes a new lens as to why households may not fully engage with SHHT's rational design, given that energy conversation is already embedded in their ongoing socio-material practices with heating. Focusing on the AI-human relation, we articulate the necessity for human agency where heating is involved, whilst also advancing an understanding of the new forms of hidden labour that households incur before they can engage with the AI. Crucially, our research informs the ongoing HCI concern over how humans understand AI, raising the question of who is responsible to assess the appropriateness of AI when the effects of human-AI performance remain opaque. Our findings contribute a new theoretical perspective into the intricate relationship between individuals and AI in the home and raise several new design implications for SHHT.

1. Introduction

Smart home heating technology (SHHT) has become a lived reality for many households in recent years. For example, in the UK, energy providers are obliged to offer households a smart meter by 2025 (Department for Energy Security and Net Zero, 2023), with 31.3 million UK households and small business reporting to have installed one already (Department for Energy Security and Net Zero, 2023). At the same time, a range of commercial SHHT are in use by household consumers (e.g., Honeywell home smart thermostat, Google Nest, degrii smart thermostat). SHHTs are designed and marketed to reduce how much energy household occupants use (i.e., conservation) and/or optimize when they consume it (i.e., demand flexibility) (Gram-Hanssen and Darby, 2018; Larsen and Gram-Hanssen, 2020; Strengers, 2014). They comprise of *sensors* that monitor energy use, *feedback* interfaces that visualize consumption and costs during different times of the day and *networks* that connect physical devices together. Additionally, whereas some SHHT support monitoring by leaving the action to the user, others act as automatic managers with *artificial intelligence* (*AI*) or other algorithms automating heating (Cook, 2012; Jensen et al., 2018). The present research is motivated by the continued commercial relevance of SHHT as a way to manage heating in the home (Shove and Walker, 2014). In contrast to SHHT that require users to exercise heating decisions through manual controls, AI is ideally suited to manage demand flexibility (Alan et al., 2016). As such, AI-enabled SHHT is poised to optimise energy use in the future as the introduction of lower carbon

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energy sources (e.g., administered with heat pumps) place new demands on the grid (Jensen et al., 2018).

SHHT are premised on a rational economic model assuming that household occupants will be compelled to conserve energy if they are aware of when it is most costly (Alan et al., 2016; Strengers, 2011a, 2014). Previous research has established that an everyday lens can support an understanding of the specific tensions that inhibit SHHT from reifying these design intensions (Strengers, 2011a). In response to this, within the social sciences, it has been proposed that technologies for energy, including SHHTs, must be understood in relation to the temporalities of the home (e.g. seasonal changes, heating routines) and the digital, material, sensory qualities that shape people's interactions with such technologies (Hargreaves et al., 2018; Larsen and Gram-Hanssen, 2020; Pink et al., 2017, 2013; Royston, 2014; Shove and Walker, 2014; Tuomela et al., 2020). Despite this recognition, there has been limited HCI research with AI-enabled SHHT that applies this perspective. HCI research in the home context has tended to focus its investigation on users' interaction with bespoke SHHT design features that enable behaviour change without fully considering the existing socio-material relations in which energy use is a part of (e.g. Alan et al., 2016; Shann et al., 2017; Yang and Newman, 2013a).

Our paper addresses this underrepresented area with a focus on how temporality shapes and is shaped by AI-enabled SHHT in the home. Our first research question is concerned with how households relate to and align with SHHT's rational design in the context of their everyday practices with heating. This builds on previous research showing that people's heating practices are contingent to temporal everyday routines, and rational SHHT, which separate energy use from the practices energy is part of Shove and Walker (2014), can have a bounded influence on energy decisions (Strengers, 2011a, 2014). We contribute to this literature with a temporal examination of heating before and after the introduction of AI-enabled SHHT. This informs the current limited understanding of how everyday heating practices in the home are negotiated within households against the emergent possibilities AI introduces to make rational heating decisions. Our second research question explores how households embed the AI aspect of SHHT in the temporality of home life. This is in recognition that time is at the heart of how technology works and technology design can re-organise time in new ways (Jalas and Rinkinen, 2016; Wiberg and Stolterman, 2021). Recent HCI research has proposed that temporality should be theorised in relation to specific technologies and the needs they are designed to serve (Rapp et al., 2022). In line with this, the introduction of AI into SHHT raises new requirements for users to periodically interact with and influence algorithmic decisions to control their heating (Yang and Newman, 2013b). Our research extends previous work showing that AI's daily time demands can be misaligned with the heating routines of the home (e.g. Alan et al., 2016; Jensen et al., 2018) through a nuanced temporal examination of when/how these mis/alignments happen and how they impact human-AI agency over time.

These research questions are addressed in a qualitative field study with eleven middle-class households in the UK who used an AI-enabled SHHT technology probe called Squid. Squid's AI optimises and visualises tariff costs against temperature preferences, encouraging energy use during off-peak times. Installed on one radiator, Squid was designed as a testbed in a broader project that explored approaches for involving users in the cybersecurity of their smart devices and raising the opportunity to investigate how households interpret and make meaning of AI-enabled SHHT. Probes are technological artefacts used in exploratory research at the intersection of theory, design, and engineering, emphasising simplicity through their focus on the most crucial design features. In fostering users' interactions and reflections, probes can generate new theoretical insights, design directions, and test the feasibility of early ideas (Hutchinson et al., 2003). Given the need to renew a nuanced temporal understanding of AI as part of SHHT, the simple and generative nature of probes were deemed appropriate in the context of our aims. Our focus on middle-class households was both pragmatic and intentional given that SHHT are often marketed to this group. To understand home temporalities in the proposed context, our research first explored how the households heated their homes and the social patterns of their everyday living. After the introduction of Squid, we followed the same households for a period of three weeks. Taking an ethnographically-inspired methodology, we used a mix of methods originating from social science research and HCI home fieldwork (home walkthrough, interviews, fieldnotes, technology logs) to gain access to participants' everyday practices and document user interactions with Squid.

2. Background

2.1. Rational and temporal design considerations for AI-enabled SHHT

Supporting users to negotiate their thermal comfort against other factors over time has been a prominent consideration in AI-enabled SHHT design and related HCI field studies. Yang and Newman (2013a) researched Google Nest's automated temperature scheduling feature, finding that many occupants were frustrated when using this feature as they could not always understand the temperature decisions made by the algorithm or discern their own influence over it. The same study also reported a range of motivations underpinning the use of the scheduling feature, from seeking efficiency to optimising cost savings. Home occupants wishing to save costs sometimes opted for temperature inputs that prioritised 'thermal comfort over cost', raising questions as to whether they had trained the algorithm to conserve the energy they desired. These findings underscored the challenges involved in designing SHHTs that can support users' understanding of AI and are thus intelligible. User understanding was also affected by the limited time home occupants could devote to engage with, and configure, the Nest. Lack of time to engage with this technology has also been identified in adoption studies of smart home technologies where home occupants' engagements was severely affected by the perceived complexity of technology, with many reducing their engagement with its features over time, or constraining the use of smart home technologies to a subset of basic functions (Hargreaves et al., 2018).

In other work, Alan et al. (2016) studied the use of two smart thermostats (with one that allowed users to temporarily override the AI with manual temperature selections to ease them into the automation) and a manual thermostat. The smart thermostats were designed to optimize thermal comfort and cost in relation to the UK's dynamic energy tariffs which changed every 30 min. Whilst this study also reported user misconceptions about the AI, most participants were guided by the dynamic tariff information available and set lower temperatures in their thermostats when prices were higher. Though the smart thermostats were found to stimulate users to make rational economic decisions about their heating, it was also shown that users at times overrode the AI in favour of maintaining their thermal comfort. In contrast to the Nest, the smart thermostat features were intelligible and persuasive to some extent in prompting household occupants to change their heating decisions. Of particular interest to users of this study was the daily and monthly estimated cost information feature, which enabled them to understand the cost consequences of different temperature settings. Connecting users' actions (i.e., their preferred temperatures under different price conditions) to real-world consequences (i.e., estimated costs) was a useful feature to sustain user engagement with the rational SHHT.

Despite the limited HCI research on visualising algorithms within AI-enabled SHHT, visualisation has been a central aspect of smart home technology more broadly. Chalal et al. (2022) identified that statistical visualisations were the most prominent type of visualisation in smart home energy technologies. Whilst the primary focus has been on visualising households' use in "resource management units" (e.g., p/kWh), other approaches have included data on the estimated resource costs and/or the environmental footprint of occupants' consumption. Notwithstanding their prominence, however, these visualisations have come with challenges, as Strengers' (Strengers, 2011a) seminal study of smart home visualisations for resource consumption showed. Some participants in this study could not understand and relate the meaning of the resource management units employed in the graphs to their everyday lives. Peaks introduced in the visualisation due to the use of certain appliances (e.g., kettle) were misinterpreted by occupants, who believed these appliances to use more electricity compared to those that were in constant use (e.g., fridge). The same study also revealed the limitations of researching smart home technologies outside an understanding of how everyday life shapes their use, an issue which is at the centre of our research, as explored in the next section.

2.2. SHHT in the everyday temporality of the home

The importance of an everyday lens in HCI has emerged in recognition that cost-efficient actions are not just a matter of understanding and interpreting information. As Strengers asserts, there is a continued need of accounting for "the complex ways in which people actually consume energy and water—which do not often respond to theories of rational action or consumer choice". Everyday practices, therefore, may challenge the assumption that "when provided with the 'right' information about the costs and benefits of consumption, individuals will make rational and autonomous choices that result in more efficient resource use" (Strengers, 2011b).

A key concept for approaching everyday practices is temporality, which has been identified as a central consideration in the research, design, and use of technology, such as SHHT (Wiberg and Stolterman, 2021), and it is crucial in understanding the home. Home occupants' present practices are connected to their past experiences and are often anticipatory of future changes (Pink et al., 2017), with Pink et al. (2017) proposing that the "home can be seen as a project which is continually ongoing". Similarly, Gram-Hanseen and Darby (2018) discuss the relevance of change and continuity in the home: "home is a temporal process, changing over time but also relating back to what was before". Whilst technical systems can order time in different ways (Jalas and Rinkinen, 2016; Rapp et al., 2022; Wiberg and Stolterman, 2021), home temporalities are also contingent to manifold factors that affect how we do heating, such as the changing seasons, the organisation of time into monthly energy bills, and most importantly, daily routines (Jalas and Rinkinen, 2016; Pink et al., 2017).

To our current interest, social practices are organised in time and space (Shove and Walker, 2014). As evidenced in one SHHT adoption study (Larsen and Gram-Hanssen, 2020), many householders had developed sensory expectations on what is an adequate temperature in the different rooms of their home shaped by the activities they carried out in those spaces (also Tuomela et al., 2020), informing the use of SHHTs to establish ``zonal controls''. In the context of another SHHT intervention that offered automated small temperature reductions over time alongside a user-controlled feature to boost the temperature for higher thermal comfort, it was shown that temperature was but one aspect of the sensory experience of home comfort, and it gained meaning in combination with social activities, such as gathering around the TV in the evening (Pink et al., 2013). Further elaborating on the social dimension of home heating, other research showed that occupants often choose to adapt their own preferences for thermal comfort when sensory differences exist within the household to ensure the comfort of others (Gram-Hanssen and Darby, 2018; Larsen and Gram-Hanssen, 2020; Tuomela et al., 2020).

Moreover, the social practices in which energy use is a part of are inseparable to material arrangements (Shove and Walker, 2014). As Jalas and Rinkinen (2016) illustrated, when using wood-burners for home heating, occupants engaged in cutting, storing, carrying wood, wearing warm clothes and so on. In other research, Royston (2014) showed how occupants using gas heating managed the heat flows in their homes by drawing on a range of materials whose qualities and relationships to heating they had learned over time. In the context of SHHT, Larsen and Gram-Hanssen (2020) reported similar findings proposing there were "competencies" for maintaining thermal comfort at home. These competencies rely on embodied knowledge and skills in using these different materials such as donning warmer clothing, adjusting windows, or strategically allowing heat to flow from the ground floor upward.

2.3. Motivation and RQs

In summary, previous literature indicates that the home is not a stable and fixed unit. Households' heating practices are co-shaped by the interplay of ever-changing routines and temporalities, materiality (objects, tools, infrastructures), meanings (cultural conventions, expectations, socially shared meanings), and competencies (knowledge and practical skills). In response to this, Strengers has argued for bringing HCI research in conversation with "social, cultural and anthropological research", reflective of the perspectives we presented under Section 2.2 (Strengers, 2011a). Introducing an everyday lens into HCI SHHT-centred research offers the potential to explain some of the tensions raised in relation to specific SHHT design features within past research. For example, AI-enabled SHHTs require regular user input (Chen et al., 2017; Gram-Hanssen and Darby, 2018; Jensen et al., 2018; Yang and Newman, 2013b), whilst the often-complex design of smart home technologies (Hargreaves et al., 2018) or their perceived lack of fit with users' lifestyle or goals (Mennicken et al., 2014) introduce new time demands. In disrupting the rhythm of the work involved in heating (Jalas and Rinkinen, 2016), past research shows that some occupants embrace the new rhythm introduced by the SHHT whilst many others reject it or seek passive roles, such as adopting embedded pre-configurations (Hargreaves et al., 2018; Larsen and Gram-Hanssen, 2020) or allowing SHHTs to work in the background without their direct input (Hargreaves et al., 2018). Crucially, attention to the material arrangements and social practices involved in heating can help explain the tensions between SHHT design and everyday life, such as the everyday factors that continue to propel households to discard SHHT information and engage in energy-intensive activities and appliances (e.g. laundry machine) during peak times (Strengers, 2011a).

Against this backdrop our paper aims to contribute with a situated understanding of how people use rational SHHT in the everyday with a focus on temporality. By connecting people's initial practices involving heating in time and space with those triggered after the introduction of this technology, we seek to identify emergent mis/alignments with SHHT. Furthermore, as presented throughout Section 2, it is established that the design of SHHT itself (e.g., requiring regular input to personalise) introduces new labour that can clash with existing routines. Our study extends this finding through a fine-grained focus of how households interact with AI, how they fit technology-triggered temporal changes in their everyday life, and how AI-human agency consequently co-evolve. To this end, we ask two research questions:

1. How do households engage with and adapt to the rational design of SHHT in the context of their daily heating practices?
2. How do households incorporate SHHT's AI capabilities into the temporal aspects of home life to manage their heating?

3. Smart home technology for heating: the squid technology probe

Technology probes are functional renditions of technology that can inform theories of how people use technology and advance their interaction design. They can thus generate new social science insights, allow for testing the technology, and provide new design openings (Hutchinson et al., 2003). Probes incorporate few key functions and are made to be simple as well as flexible, allowing users to interpret them in different ways. Some probes can also lack functionality to trigger user reflections. Our aim was to understand and contrast the situated heating practices of the home with how households make meaning, interpret, and appropriate SHHT in relation to their rational underpinnings (RQ1) and the temporal engagements they invite with their AI (RQ2). The probe's features were designed to invoke these notions of rationality and temporality in its design: a rational economic model to how people heat their homes underpinned Squid's AI and design features, whilst its functionalities allowed the user to input to the AI model and inspect their understanding of its decisions as it learned from them over time. On the whole, the simplicity advocated by probes allowed us to deepen our understanding of rationality and temporality since smart home technology design has often been complex, leading to its abandonment and contributing to users experiencing lack of control (Hargreaves et al., 2018). The remainder of this section provides a description of Squid as a probe.

3.1. Squid's economic and rational underpinnings

Squid is a smart heating probe that uses AI to regulate heating. It was inspired from previous research by Alan and colleagues (Alan et al., 2016; Shann et al., 2017), who relied on a rational economic model of how people consume energy using AI to develop a smart thermostat supporting home users to automate their heating based on dynamic tariffs, which are increasingly introduced into the context of domestic energy use—e.g. the energy provider Octopus Energy in the UK. Drawing from this past research, Squid's AI is premised on the assumption that people have sensory preferences that inform their ideal room temperature, but also have a preference as to how much they are willing to pay for energy. Thus, Squid's automation allows for frequently adjusting the temperature settings throughout the day in response to the varying price conditions removing the need for time-consuming manual interventions.

Squid's AI thus addresses the challenges of manually adjusting temperature settings throughout the day under varying price conditions, highlighting the value of automation. Additionally, in using dynamic pricing where energy prices fluctuate every 30 min, an economic way of reasoning about energy is amplified. Due to the automation, a household acting rationally could save money by lowering the room temperature at times when the price is high and increase the temperature when the price is low.

3.2. Squid app and its ecosystem

- For the purposes of this research, Squid was designed to operate in one room regulating the heating of a single radiator when the boiler or central heating was on. It included three components (see Fig. 1)—two were physical components from the commercially-available Netatmo smart radiator valve kit (used without modifications) with the third, a web app, developed as part of the research:

  The physical **smart valve** is installed on a radiator. It is fitted to the pipework at the bottom of the radiator replacing any existing thermostatic radiator valve (TRV). The valve includes an embedded thermostat that regulates the flow of hot water into the radiator by adjusting (opening or closing) the valve. It contains a physical display that shows the current temperature as measured by the valve, as well as the target temperature requested by Squid's web app at a given point in time.
- The **relay** is plugged to an electrical socket, and connects both to the internet and the **cube**, which is the Netatmo physical interface with users. It includes a reading of the temperature at the valve and the ability to change the thermostat. The functions of the cube were hidden to our participants by a sticker, and they were only told that it manages connectivity and should be placed in the same room at the valve.

The Squid **web application** was developed to allow AI control of the smart valve, which the user trains using the app.

3.3. AI in squid

Squid uses AI to automate heating. As introduced under 3.1, this is underpinned by a rational economic model of how people consume energy (Alan et al., 2016) but Squid does not assume that households share similar priorities when it comes to energy-saving practices and considers users' changing preferences for cost × temperature in different times of the day. In the initial period of using Squid, users are required to make deliberate choices on the SHHT on how to balance the energy price at a given time with their *preferred temperature*, i.e., the temperature that matches their thermal comfort preference. Based on their temperature inputs, Squid's algorithm extracts each user's sensitivity to price and preferred temperature for each of five time slots in a day, differentiating between weekends and weekdays. For this, Bayesian linear regression is used, which is an easily interpretable (or glass box) machine learning algorithm method that can provide both characteristics after only a few uses of Squid; in our pilot experiments, this was 4–5 temperature inputs at different price points in each time slot which had to be made once (i. e., a total of 25 for the five heating profiles). Thus, from the first or second day of use, the algorithm can start to regulate the temperature in alignment with what the households' decisions reveal about their preferred temperature and price sensitivity. If a user inputs roughly the same temperature regardless of the price, the price sensitivity will be low, and the preferred temperature will be close to the one input. Conversely, for a user who sets a low temperature when the price is high, the sensitivity will be high, and the preferred temperature will be higher than the one input. We note here that, by default, Squid's AI reflects a starting preferred temperature of 22 °C and moderate price sensitivity, which changes gradually as the users begin to change their temperatures. As such, at any given time, the target temperature of the SHHT is set by the AI to negotiate between cost and the household's preferred temperature, within the boundaries of the household's previous inputs—or is overridden by direct users' direct temperature input.

3.4. Squid's features

Squid was designed to offer the key customisation and visualisation features that would support its main goal to inform and automate heating.

Smart valve Web application Cube Relay

Fig. 1. Squid ecosystem.

When first setting up Squid, users are required to create an individual schedule of available heating profiles that allows them to reflect their heating practices throughout the week. The **schedule** (Fig. 2: Top Left) presents five pre-populated heating profiles and their timeslots the user can adjust for any day of the week. Through its **side panel**, which is always visible, Squid displays the current temperature, as measured by the smart valve's thermostat, and the target temperature designated by the AI. Using the temperature dial on the side panel, the user updates the temperature which allows the algorithm to learn. The side panel also presents the dynamic tariff, i.e., the energy prices for the current 30-min slot, alongside estimates for daily/weekly/monthly prices. At the time of the study, there was a global energy crisis and energy costs had plateaued to a flat rate (Guardian, 2023). Due to this reason, historical (not simulated) prices were used in Squid, reflected in the 2019 dataset published by Octopus Energy, one of the first energy providers to introduce dynamic pricing to households. The prices are presented in the sector's standard pricing format of pence per kilowatt hour (p/kWh), as used in households' energy bills. In addition to this key information, the side panel displays when the smart valve is open and which heating profile is active.

The Squid app also includes four separate visualisations and logs showing how the algorithm works, which we review. For the visualisations, we drew inspiration from Chalal et al. (2022) systematic review of energy visualisation types designing two statistical visualisations and a gauge, intended to encourage users' interpretations of the AI.

- Under the **schedule** tab, users can click on any heating profile. This triggers the **AI temperature schedule visualisation** that displays how the AI changes the smart valve's target temperature, whilst the price changes during the profile's time slot. As Fig. 2 (Top Right) displays, when the price (in orange) goes up, the temperature (in teal) decreases.
- Squid also displays a summary of the AI model for each heating profile under the profile tab (Fig. 2: Bottom Left). When the **gauge visualisation** on the top part of the page points to right red quadrant, it indicates that the household is very sensitive to price. In contrast, when the gauge points to the left red quadrant, this indicates that the household is choosing to increase the target temperature when the price is at the highest. Underneath the gauge, there is an **AI summary visualisation** that summarises the AI model and the relationship between target temperature and price based on the user's inputs.
- Finally, by accessing the **notifications** tab (Fig. 2: Bottom Right), the user can view their own temperature inputs and the decisions the AI has taken for each thirty-minute slot based on the price applying to that slot. Specifically, for each AI decision, the notification provides a summary of the decision that includes the preferred and target temperatures (in degrees °C), the price sensitivity (displayed as "very low" to "very high", mapping to the quadrants of the gauge), and the energy price that was considered.

4. Methodology

4.1. Households

The research took place between January and March 2023 with households in England. At the time of the study, the weather ranged from 13 °C at the warmest to 2 °C at the coldest.[1] It is important to note that the study coincided with a surge in energy prices and increases in the cost of living more broadly (Guardian, 2023). While this circumstance underscored the relevance of Squid's AI, the team was mindful that many households faced added vulnerabilities during winter. Combined with the level of commitment the study required and the level of digital and data literacy needed to use Squid, we took care not to include any household that could be negatively impacted by the project.

The study was advertised through community centres, social media, and snowball sampling using our existing networks. As an incentive, the project offered compensation in vouchers that amounted to 100 pounds. Households were recruited based on two criteria. First, we wished to reflect a range of living arrangements and household compositions. Second, we wanted to identify participants with a mix of professional backgrounds. This sampling approach was deemed important for us to capture heterogenous heating practices and different ways of interacting with AI and technology in general. From thirty-six households that initially expressed interest, eleven (20 participants) were selected to take part in the study. There were a range of reasons for not involving households such as their lack of flexibility for the research visits, unsuitable heating set up, or potential participants withdrawing their interest due to lack of time.

Except for one household, all others were recruited through the research team's extended social and professional networks. Within these constraints, we managed to gather a diverse cohort of participants in terms of professional background, household composition and living arrangements. From the eleven households involved, five were in London and six in the Southwest of England. Participants had multiple nationalities, coming from ten different countries (UK, Turkey, Hong Kong, Taiwan, France, Germany, India, Spain, Slovakia, Greece, Brazil). As Table 1 indicates, most households consisted of nuclear families and couples. Participants' dwellings were balanced between single occupancy houses and flats. Only one couple lived in shared accommodation and seven of the households owned their home. Participants' age ranged from 25 to 64 years old, and two were in mature working age (55–64). Except for one participant, all others had a high level of education, with six continuing to post-graduate studies. All participants used digital technology as part of their everyday lives and reported being confident in using technology to participate in professional and social activities. Except for one household (Sam & Mara), the rest used at least one smart technology. Three households (Isaad, Barış & Maya, Hayford & Tina) owned between three-four smart technologies and considered themselves technology enthusiasts.

From the nine households with two adult occupants, only in one case Squid was equally used by both participants (Barış & Maya). In the rest, one of the occupants acted as a 'lead user', engaging more prominently with Squid during the field study. In total, there were 12 lead users in the study. In five of the households this was due to pragmatic factors related to presence and temporality (e.g., relative presence of the occupants in their home or the smart-valve room and their ability to allocate time to the task). In the remaining four, Squid's primary user emerged out of the relations the occupants had already formed with digital technology (Ernesto, and Ender) or energy (Debora). To some extent, this mirrored past work that has shown gendered roles in technology (Ehrenberg and Keinonen, 2021a; Strengers, 2014), whilst revealing the wider range of reasons underpinning who takes the lead with technology in the context of field research.

4.2. Field study procedure and data collection

The study received ethical approval from the University ethics committee. Following initial contact, participants were invited to an introductory conversation about the research. The purpose of this conversation was to share the aims of the research and ensure participants were aware of and able to commit to the proposed tasks. Once they registered interest, an information sheet and consent form were provided. All adults in each household completed the informed consent and participated in the data collection. In one household (Kevin and Ria), whose flatmates did not take part in the study, we collected informed consent from the couple and made sure the flatmates were aware of but

[1] Data taken from metoffice with Heathrow's station data used: https://www.metoffice.gov.uk/pub/data/weather/uk/climate/stationdata/heathrowdata.txt .

Fig. 2. Squid. Top left: Heating profile scheduler; Top right: AI temperature schedule visualisation; Bottom left: AI summary and gauge visualisation. Bottom right: Notifications log.

not affected by the project. In houses with families, children were not involved in the research. Table 2 below summarises the field study approach, which we describe in detail.

4.2.1. First visit

The study commenced between the second and third week of January 2023, when the research team visited each household to install the smart valve. To ensure the smart valve would have an impact on how people experienced their heating, we asked participants to select a radiator in a room they frequently used. Since the technology set-up consisted of a single smart valve, we wished to install it in a room that had one radiator. If there was a second radiator, we consulted participants if they were happy to switch it off for the duration of the study, which two households did. We discussed room options at the start of our visit while asking participants for a brief home tour (Larsen and Gram-Hanssen, 2020; Pink et al., 2017; Tuomela et al., 2020). The tour had a twofold objective: (i) to gather informal insights into participants' home life and (ii) make a joint decision on the smart valve installation, considering how and when they used each room. Participants were given an 8-inch tablet hosting the Squid app. This ensured that all households experienced Squid at the same screen resolution.

Following the installation of the smart valve, a semi-structured entry interview was held with the adult members of the household. The interview explored participants' general attitudes and practices related to heating, technology (including AI), and domestic routines. We opened with a playful activity about households' everyday routines and task divisions. For those who lived with others, we proposed a "who does what" game: with their eyes closed, participants were asked to point to the person whom they considered to be most in charge of eleven types of tasks. These ranged from topics around technology and heating to everyday household tasks, such as washing the dishes and finding products in the cupboards, as a prompt to home management. The game worked as an icebreaker and offered an overview of how heating, energy consumption and technology were embedded in a broader set of daily practices that make up domestic spaces and family life. Following the game, participants were asked to talk about their household's routines around the clock. To aid in this activity, they were given a paper with the image of a large clock and worked together to describe what they did the day before the interview, from the time they woke up until they went to bed. This served as a conversation starter about home temporalities, the use of different spaces at home, and how technology is embedded in their everyday routines. The following interview questions examined in greater detail participants' approaches to technology, notions about smart technology, heating patterns and considerations about energy consumption.

Following the interview, participants received a 30-min training session on how to use Squid, with a focus on supporting households' understanding of energy tariffs/dynamic pricing, the AI algorithm, and Squid's features. The topics presented in Table 3 were covered through hands-on interactions with Squid in which the participants used or evaluated the app's features. To ensure participants' understanding of Squid, the same topics were reinforced through four 1-min info videos sent to the households over the course of two weeks via email (two videos per week).

4.2.2. Using squid

We aimed for each household to use Squid for a period of three weeks. This was possible except for two instances (Simon & Theo, Hayford & Tina) where we had to limit the period to two weeks due to the household's scheduling constraints. Participants were encouraged to calibrate the AI during this period and use the features introduced in the training as they saw fit. To gather ongoing insights about participants' engagement and ensure there were no technical issues, the research team held weekly 15-min online check-ins with each household, documented in fieldnotes. In contrast to the interviews that required the participation of all adult members, the check-ins were mostly held with one household member to maintain a flexible approach.

4.2.3. Second visit

The aim of the second visit was to gauge how the households had interacted with Squid, their understanding of AI, and their experience with heating using this new technology. This semi-structured exit interview explored the times of day participants used Squid and, if the household included more than one adult, we identified who used Squid the most and why (see 4.1). Following this, we focused on participants' understanding of the AI and its relevance to how they made heating decisions, drawing links with the practices they had shared in the entry interview. In the remainder of the interview, we carried out a walk-through of the key features of Squid prompting participants to explain how they used them, the reasons why they did not use some of them, and whether they would want improvements to how the features were designed. Participants were also shown the Squid features in a visual

Table 1
Descriptions of participating households (participants' names have been pseudonymised). The lead user is indicated with an *. Households who had already experienced one winter in their dwelling are indicated with *a* ±.

Participants and their professions	Household composition	Dwelling type	Smart technology used
*Simone, primary school teacher (French) Theo, medical writer (British)	Parents, two children	Semi-detached house±	Smart watch, smart meter
*Isaad, head of service delivery (British/ Moroccan)	Father, two children	Detached house	Smart meter, personal assistant, smart doorbell
Wiola, academic university staff in health (German) *Naadir, town planning consultant (Indian)	Parents, two children	Semi-detached house	Smart watch, smart meter, personal assistant
*Ernesto, research manager (Spanish) Klara, medical trainee (Slovakian)	Parents, one child	Semi-detached house±	Smart meter
*Carrie, Communications manager (British)	Single occupant	Three-bedroom terraced house±	Smart meter
*Maya, post-graduate student (Turkish) *Barış, Civil engineer (Turkish)	Couple	One-bedroom flat ±	Smart watch, smart meter, smart doorbell
*Hayford, not employed (Taiwanese) Tina, Graphic designer (Taiwanese)	Couple	Two-bedroom flat ±	Smart watch, smart meter, smart doorbell, personal assistant
*Sam, event worker (British/Greek) Mara, academic university staff in education (Greek)	Mother and adult son	Two-bedroom flat ±	
*Kevin, marketing (Hong Kong) Ria, sales (Taiwanese)	Couple flat sharing with three flat mates	Four-bedroom flat share±	Smart vacuum cleaner
Açelya, CEO of a start-up in education (Turkish) *Ender, CEO of a start-up in accessibility (Turkish)	Couple	Two-bedroom flat	Smart watch
*Debora, head of bioprocess and optimisation (Brazilian) Aris, academic university staff in Microbiology (Greek)	Parents, two children	Semi-detached house	Personal assistant

Table 2
Summary of field study.

	Activities and tasks
Engagement with household	One house visit (install technology) Training on how to use Squid to heat the focal room Weekly online check-ins
Data collection	Entry and exit interviews Weekly fieldnotes Squid interaction logs

sheet and asked to rank the frequency of their use during this period. This provided a better understanding of participants' specific engagement with Squid's features prior to commencing the walkthrough of the web-app.

Table 3
Training aims and tasks.

Training aims	Interaction with Squid feature(s)	Training outcome
Setting up heating profiles for weekdays and weekends	Visiting the schedule tab	Set up of new profiles
Setting the preferred temperature across Squid's profiles	Accessing the side panel	Setting the temperature by consulting the current energy tariff price to train the AI
Evaluating how the AI adjusted the temperature in relation to price	Accessing the AI temperature schedule visualisation by clicking on a profile under the schedule tab. Visiting the notifications tab	Evaluating the graph relationships and log content
Evaluating the AI model's price sensitivity based on each household's temperature inputs	Visiting the profiles tab to review the gauge and AI summary visualisations	Evaluating the gauge and the slope of the graph

4.2.4. *Data collection and analysis*

A total of 22 interviews were carried out across the two visits, in addition to fieldnotes. The first interview lasted between 30 and 63 min with an average of 47 min. The second interview was an average of 56 min (between 41 and 68 min). Both interviews were audio-recorded, anonymised, and transcribed. During the weekly check-ins, we kept detailed fieldnotes of our conversations with the participants. In addition to this qualitative data, logs of participants' temperature selections in Squid were collected.

The qualitative data was thematically analysed with NVivo by the first author. Following Braun and Clarke (Braun and Clarke, 2006), an inductive coding approach was followed that yielded insights aligning with our RQs, describing prior heating practices in the everyday (5.1), approaches to setting temperatures within Squid in the context of existing routines (5.2), controlling the AI and human-AI agency (5.3), and relations with Squid's rational design (5.4). Here we note that whilst heating practices were analysed on a household level, owing to the emergence of a lead-user in many households, the remaining themes were generated based on the lead-user's practices with Squid. Since the data was collected by a team of five researchers, the analytic approach taken reflected the need to ensure the interpretations generated aligned with the data and researchers' contextual insights. A collaborative approach had been already established during the data collection with the research team meeting regularly to share insights generated with the households they supported. To coordinate the analytic effort, the lead author read all the text transcripts initially to familiarise themselves with the data and used bottom-up coding to develop an initial set of descriptive codes. An inclusive approach was taken to the coding that aimed to capture all the interesting themes in the data. Using these codes as a basis, the same researcher created mini summaries for each household. This was followed by a collaborative coding session in which the team of five discussed and refined the mini summaries ensuring any interpretations were grounded in the primary data to establish the credibility of the coding process. This step was used by the lead author to thematise the codes into latent themes, which were shared with the team to corroborate. In addition to the primarily qualitative analysis, the daily temporal patterns in the logs were visualised using Tableau to triangulate interpretations drawn from the qualitative findings. This involved plotting participants' total temperature changes by hour, as well as their chosen temperature set-points by hour averaged over the study duration.

5. Findings

5.1. Contextualising the households

Consistent with our research objectives, which aim to establish connections between the use of Squid and households' existing practices and temporalities, we provide below short summaries of their general heating routines, with a specific focus on the room where Squid was installed. These summaries incorporate several factors, including cost considerations and concerns over energy conservation, the physical and external environment, as well as the knowledge and skills occupants possessed to practice energy conservation. They also incorporate aspects relating to time and space that impact how heating is managed, such as seasonal sensitivities and multiple uses of the same room (e.g., family relaxation and work). Additionally, we indicate the range of preferred temperatures at which participants set their existing home thermostat, serving as an indicator of their sensory preferences and cost considerations. Relatedly, it is noted that out of the eleven households two (Kevin & Ria, and Ernesto & Klara) did not have a thermostat and used the TRV directly to regulate the heating. The rest of the households had thermostats that controlled the boiler and thus hot water flowed into the radiators when the boiler was on. Unless indicated in the table below, participants paid their bill monthly through a contract with an energy provider. Throughout our findings, we will refer to these summaries to contextualise participants' interactions with Squid. While not the primary focus of our current research, we acknowledge the influence of participants' cultural backgrounds and relational dynamics when they impact their heating practices, aiming to represent the diversity of home heating experiences.

5.2. Fitting AI training and heating profiles into home life

Eight of Squid's lead-users embedded Squid in existing routines by identifying activities, or transition moments in the day, that would allow them to easily interact with it. Examples included Carrie and Sam, who worked from home and reported to effortlessly interact with Squid whenever taking coffee/lunch breaks away from work, or Kevin who used Squid at pre-determined times of the day before work, at lunch, and at the start of the evening. Fig. 3 illustrates how these routines shaped interactions with Squid (e.g., Carrie's temperature changes occurred during lunchtime, alongside mornings and afternoons like Sam and Kevin).

Nonetheless, maintaining this regularity of engagement was challenging for those with children, particularly for Ernesto and Simone. Simone addressed this challenge by engaging with Squid the most on her non-workdays, whereas Ernesto carved time to interact with it very early in the morning or in the late evening when his son was asleep, also corroborated in Fig. 3. As he explained: *"You go down here* [the living room], *you get on with sorting things that we need to do. And then when he* [son] *is already in bed, you say, 'Actually, I forgot about this* [Squid]*'."* To minimise these demands, lead-users took into consideration when their heating was active. Ernesto and Simone, whose boilers were switched off for part of the day, focused their use of Squid to the timeslots that intersected with the boiler being switched on. Ender, whose flat retained heating during the day, mostly interacted with Squid in the early morning and in the evening when the thermostat was likely to activate the boiler (see Fig. 3).

In the process of temporally embedding Squid in their routines, several lead-users experienced a tension between the predetermined heating profiles (each requiring preferred temperature input) and their presence in the home required to train their AI models. Having set the 'morning profile' during the morning school run, by the time Ernesto was able to interact with Squid the profile was no longer active. Similarly, Hayford voiced concern about his 'night profile' given that he was not awake when he had scheduled it to activate. The same challenge was pre-empted by Carrie by tinkering with the profile scheduling times. In anticipation of her two workdays at the office, she ensured her 'weekday profile' began before she left for work: "*Because the AI updates so often I changed the morning so it actually ends mornings, before I leave the house in the morning at 6:45, so I can actually start the weekday and do a weekday update before I leave the house, if I am going to work*." To this end, many participants shared that Squid's schedule, albeit customisable, did not align with the existing and emergent routines of their home life:

> *I am surprised that in some ways it doesn't really fit around your life. I set it up to be thinking that I am going to be three days in the office, two days working at home and two days weekend. But then actually last week I had a cold and worked at home for a couple of days. And rather than actually resetting the whole profile for those days- Well, I could have reset the profile for those days, but it would be quite a bit of faff, so I didn't. It just*

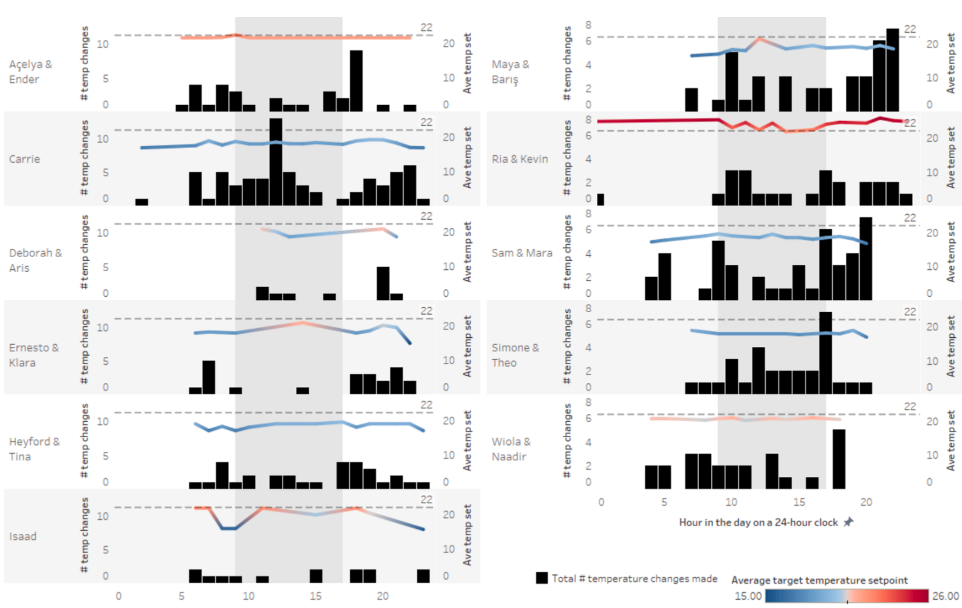

Fig. 3. Participants' total number of temperature changes (left axis) and the average temperature they set (right axis) throughout the day. Typical workday hours (9:00–17:00) are indicated in grey.

felt that little bit inflexible, and I did wonder if you actually had it how you would cope. If your routine changed for any reason how you would actually cope with that. (Carrie).

Squid's lead-users also interacted with the app whenever they felt cold. Guided by their senses when feeling cold they used Squid's side panel to increase the target temperature. Indeed, some of those who had initially engaged with Squid through temporal routines (e.g., Barış & Maya, Sam) transitioned to engaging sensorially once the AI had 'learned' their preferences. Moreover, three of the lead-users interacted with Squid in a purely sensory way in connection with their time and presence at home (Naadir & Wiola, Isaad, Debora & Aris), which Naadir explained: "*The last few weeks I've been one day a week away so I'm in the house all the time so it's- if I'm sitting here making dinner and I think, "Well, it's cold" I just go to Squid and flick it up.*" Guided by his senses, and possibly affected by his transient presence in the kitchen where Squid was installed in, Isaad reported to be happy for Squid to work with its pre-determined AI models, adding new temperatures only when he felt cold.

5.3. Human and AI agency during the use of squid

Ten lead-users took great care to align Squid to their thermal preferences, thus exhibiting a high degree of control over their sensory environment. For example, Naadir talked about his desire to 'optimise' how Squid's AI selected target temperatures, using its notifications page to establish his temperature selections had been correctly registered. Comparing the temperatures lead-users set within Squid (in Fig. 3) to those they typically selected prior to the study (in Table 4) indicates that participants tended to mirror their existing heating preferences within Squid when dynamic energy price information was not available. However, these choices restricted the AI's automation and relegated its utility as a manual control, with some participants continuing to perceive the AI as having some agency over their environment. Ernesto, for example, positioned the AI's agency as a negotiation with the human: "And it's for us to really tell the AI, 'This is too cold,' or, 'This is too hot,' at these times. You look at the price, say, 'I can afford to pay a bit more if I increase the temperature.' The AI says, this is too expensive,' let's put it down. So, it's kind of like using the data and then us, what we want to teach it, to ensure that we get an agreement we can both…" Thus, participants were not always aware of how their interaction and tight control over Squid's temperatures affected its operation. The difficulty in understanding their own influence over Squid, as well as Squid's influence over their environment (through its automation), was most vividly expressed when participants' expectations of Squid's behaviours were challenged. While "playing around" with conflicting target temperatures that trained Squid's AI (e.g., 7 °C, 18 °C), Sam was unaware of how these actions affected the algorithm reporting concerns over Squid's stability. In a different example, Hayford exercised precise control over his temperature inputs to systematically change them based on the tariff. Expecting the AI to imitate the same level of precision, he remained sceptical about Squid's benefits.

Conversely, those who recognised their own control over Squid's behaviour tended to propose specific conditions under which its AI could act more autonomously in the future to realise its financial benefits for the household. Maya and Barış envisioned Squid's cost savings when they were away from home, with Ender applying a similar logic to night-time when he was not present in the room. Considering her home's energy inefficiency (see 5.1), Debora argued that wintertime required her to exert tighter control over Squid's settings, suggesting that Squid's automation would be more beneficial during milder seasonal weather.

5.4. Interactions with squid's rational design

Thermal comfort dominated how lead-users engaged with Squid. Against this context, there were three distinct ways in which

Table 4
Households' everyday heating before Squid was introduced.

Kevin and Ria No thermostat (TRV set at the highest at 28 °C)	Squid in bedroom: Main living/sleeping area, and Kevin's daytime office as he worked from home. During the weekends, the couple tended to rest in the room. Single radiator in the bedroom with TRV, thus heating was always on. The house had no thermostat. Energy bill covered in rent; no cost concerns. Thermal comfort dictated energy usage. Originating from Asia, adapting to the English winter weather was reported as challenging particularly for Ria.
Isaad 19–20 °C	Squid in kitchen: Used periodically to cook three daily meals; dining area in separate room. Isaad prioritised thermal comfort over energy cost, which he attributed to his North African background. Temperature slightly lower at night or in less-used rooms, but generally warm for year-round comfort.
Hayford and Tina 15–17 °C	Squid in office: Used by Hayford during the day as he worked from home. Hayford and Tina were highly conservative in their energy use. Tina, who reported being influenced by her Taiwanese background, kept the thermostat low and used various conservation practices (lower heating at night, dressing warmly, delayed seasonal heating, reducing/switching off heating in rooms less used). Cost wasn't a key factor; they even increased the temperature slightly when prices rose. However, Hayford expressed some concern about rising energy expenses.
Mara and Sam 18 °C	Squid in lounge/dining area: Mara and Sam's lunch, Mara's evening workspace, yoga, and entertainment space. Sam, who worked from home, used the room periodically for meals/ coffee breaks. Mara made more use of the room during the two days she worked from home. Mara, responsible for energy bill, voiced cost concerns but was content with it. Thermostat was always set at 18 °C, perceived as modest energy use. Similar sensory preferences, though Sam showed more sensitivity to temperature fluctuations indoors and due to the weather. Mara stored heat by closing the door between the lounge and the hall. When working from home, she moved to the room with the most sunlight to keep herself warm.
Açelya and Ender 20–21.5 °C	Squid in lounge and dining area: Main living space for the couple, and Açelya's daytime office where she spent most of her workday. The couple, recently moved from Turkey, were concerned about rising prices but content with their first bill. Top floor flat facing South, often warm, heating rarely used during the day. Heating decisions guided by thermal comfort, considered moderate. Reduced thermostat by 1 degree when not at home.
Wiola and Naadir 18–20 °C	Squid in kitchen and dining area: Family cooking and meals; primary workspace of Naadir, who worked from home. Wiola and Naadir recently moved to a larger and more modern home, concerned about rising energy costs. First bill surprisingly high, emphasising thermal comfort priorities. Implemented energy conservation practices: reduced temperature when children were at school and dressed warmly.
Ernesto and Klara No thermostat (TRV set at III heating at 20 °C)	Squid in living room: Main family space, adjacent to open plan dining/kitchen area. The

(*continued on next page*)

Table 4 (*continued*)

	family spent time in the room when the child came home from school in the afternoon. Both had concerns about increasing energy costs. Klara activated the heat twice daily (3–4 h) when their child was home and awake. Klara's sustainability values were reportedly influenced by her Slovakian upbringing. Ernesto, from a warmer region, reported difficulties adjusting to colder home temperatures.
Debora and Aris 18–20 °C	Squid in dining room: Family meals, children's homework, couple's workspace when working from home. Debora and Aris, highly concerned about energy costs, lived in an inefficient house with poor heat retention. Like Ernesto and Klara, they only heated the house when children were present and awake. Debora attributed being more sensitive to cold to her Brazilian origin and balanced thermal comfort with perceived cost during cold winters.
Barış and Maya 17–20 °C	Squid in hallway: Connects living room, bathroom, and kitchen. The couple experienced this room when together in the evenings, or on days that Maya worked from home. The couple lived in an older, non-energy-efficient one-bedroom flat with single-glazed windows. Maya: concerned about energy costs; Barış: less concerned due to small flat size. In warmer months, heating was turned off when not at home. During the winter, they reduced heating by three degrees when away to avoid high energy consumption during reheat.
Carrie 18–20 °C	Squid in kitchen: preparing meals; frequent coffee breaks during the day. Carrie resided in a poorly insulated Victorian house that lost heat when the boiler was off. Acknowledging rising prices, her heating use reflected a minimalist and sustainable lifestyle. Embraced various energy conservation strategies, recognising their bill-reducing benefits (dressing warmly, turning off heating when not at home or asleep, heat zones for less used rooms, delayed seasonal heating) Like Debora and Aris, she turned off heating when away.
Simone and Theo 16–17 °C	Squid in lounge: Mainly children's play area in the afternoons, occasional family movie time on weekends. Both were deeply concerned about their energy bill. After the autumn, they altered heating habits, following the pattern of Ernesto and Klara, and Debora and Aris. They kept the heat on when children were awake and at home, switching off all other times. Implemented DIY changes and strategies for better energy retention, including thicker duvets and new window blinds for improved insulation while working from home.

participants dis/engaged with Squid's emphasis on dynamic energy tariffs.

Due to cultural reasons, individual preferences, and/or not being responsible for their heating bills, three lead-users (Isaad, Sam, Kevin) had initially reported a lack of concern or interest in energy costs, striving to maintain their thermal comfort when at home (see 5.1). They all adjusted the target temperatures on Squid to inform their desired comfort level without considering the price information it offered, finding that the algorithm lacked relevance to their everyday lives. Approaching Squid in this manner significantly influenced how participants perceived their own role, and both Isaad and Sam wished that Squid would automate their heating requiring minimal involvement on their part. Isaad's busy family-work routines further contributed to his desire for automation.

The remaining nine lead-users had all claimed to be aware of, and concerned about, their heating costs (see 5.1) subsequently interacting with Squid's features. Five of them reported that Squid allowed for a peripheral awareness of the energy tariff changing during the day, as reflected in Ender's testimonial: "I am looking at the price but to understand what is the general price in that period of time. So, for informative reasons I check it." Despite Squid raising their awareness on energy prices, none of these lead-users adapted their temperature decisions when the prices were at the highest. One reason for this finding may have been that these households already exercised a range of measures to conserve energy (see 5.1). In support of this, Carrie argued that Squid's impact on her heating practices was minimal given her already sustainable lifestyle. Moreover, during the entry interviews, three households (Carrie, Debora, Maya & Barış) had shared the fragile balance between making changes that would conserve energy and maintaining a level of thermal comfort in an old property affected by the cold weather (see 5.1). Initially Debora was mindful of the target temperatures she set in Squid. However, with the cold weather affecting the temperature in her home, she prioritised comfort above price: "We can say that the drive (to use Squid), when it started to get cold, was the temperature. So even if the prices were not going down, I would have increased this by one or two degrees. Because it was too cold. And this house is cold." Thus, in this example the physical environment (material), thermal comfort levels (sensory), and the weather (sensory/temporal) interacted, influencing Debora's perceived value of Squid's price model.

Finally, only three of the lead-users negotiated new alignments with Squid's rational approach to energy use (i.e., by using less energy when the price is high). During the first interview, Hayford had reported some concern over rising energy prices (even though his partner Tina, had a different view) (see 5.1). Hayford initially reproduced the household's existing energy practices, setting his preferred temperature to 17 °C throughout the day. By the second week of the study, he had begun to use Squid's AI temperature schedule visualisation to identify the most expensive periods, motivating him to lower his target temperature at those times and, thus, breaking away from current heating practice. Similarly, Ernesto used the AI temperature schedule visualisation to inform his temperature selections. Reflecting on his and Klara's ongoing practice of activating the boiler after 4pm when their child came home (see 5.1), he detected a clash with peak energy use, speculating how he could use the visualisation to guide when the boiler is kept on. Nonetheless, with the passage of time, Ernesto stabilised Squid's target temperatures to the home norm. Seeking to inform her temperature choices, Simone consulted the dynamic prices. The smart valve was installed in the home lounge, which was used primarily by her children (see 5.1). The act of changing Squid's temperature raised doubts about the importance of other factors, besides price, e.g., if the room was occupied, whether the fireplace was on, the energy efficiency of changing the temperature too often, etc. By the second week, Simone reported she was no longer 'overthinking it' and had decided to change temperatures based on who was present in the room.

During the exit-interview, the use of Squid engendered a future-orientated outlook in five households who all shared the importance of incorporating intelligent insights in SHHT. Household members wished to know the level of cost savings the SHHT's AI would generate allowing them to weight the benefits of continuing to use the AI. Ender explained: "we didn't understand what will be the total benefit, so the price is something, but I don't know if I just used the AI to control things what will it say, £1 per month, £10, £25, so it depends. If it is £1 or £2, I don't care." Theo echoed similar thoughts. Whilst recognising that micro-amounts can add up, he was disappointed to hear that a recent energy-saving session they participated in only earned them 40 pence, leading him to argue that "*at the moment it feels like you'd save more money by the big things like the whole system being switched off*." In addition to an increased understanding of energy use/cost savings, Isaad envisioned Squid to assist him with cost targets, using the AI to make suggestions for energy conservation actions: "It's like, this is my ultimate goal, in order to reach that, ideally, this is what it is. But if you can change some of your behaviours, let's say, by giving up half an hour at the right time of day, it means you can take 15% off your bill." Finally, two participants envisioned ways that Squid could benchmark their own heating costs against similar households, allowing them to make sense of their energy use and costs against the norm.

5.5. Interpretations of the gauge

Squid presented three visualisations to communicate the AI's mechanics to the user: AI temperature schedule, AI summary, and price sensitivity gauge. Whilst the first two visualised the algorithm, the gauge expressed the AI's assessment of a human quality, i.e., an occupant's sensitivity to price. For three lead-users, such as Ernesto, Barış, and Isaad, the gauge's logic remained opaque. Despite the training materials they had received, participants encountered difficulties to relate the gauge to their practices. In Isaad's view, this was due to the gauge's disconnection to an instrumental goal: "It doesn't tell me anything. That only has a meaning if there's a target, if there's a limit, if there's something you're aiming for. This is just, yes, indicative, but indicative of what I don't know, and, again, it doesn't drive me to do anything."

Lead-users who understood the underpinning logic of the gauge reacted in different ways. Most used the gauge to quickly reaffirm that their choices were 'rational', in keeping with Squid's norms. Simone explained, "Is this going down? Am I somewhere in the middle?" Similarly, Naadir shared, "Yeah. I did look at this (gauge) a couple of times, to see whether we were in the middle, middle- … 'Okay, am I sensitive or not to price?' and I stayed within the blue area I think, once we got it going, we stayed in the blue area." Compared to the "light-touch" engagement of those looking to confirm they were within the norm, when the gauge indicated high/low price sensitivity, lead-users questioned the way Squid portrayed them drawing on their lifestyles and values to challenge its assessment. In the excerpt below, Carrie, who generally set her room temperature to lower values in line with her sustainable lifestyle (see 5.1), was able to infer how the price conditions and her temperature selection at a particular time of the day changed the gauge to low price sensitivity after being startled:

> *But also, once it did go right up into the red, I thought, "Ooh, why has it done that?" And it was just because my preference was very different from what the AI was thinking it would be at that time… it was actually sometime in the last week, about three or four days ago, which surprised me. It is probably the time of day… Maybe it was actually the evening, so where the price was low, and I set the temperature lower. I think it was that, yeah.*

In Ender's case the gauge indicated low price sensitivity which directly contrasted with his broader cost saving practices in everyday life and his view of himself: "In fact I am not that less price sensitive, I am just more price sensitive, and I am just checking for offers, promotions and everything." Nonetheless, contrasting to Carrie, who was able to relate her interaction with Squid to the gauge's behaviour, it is interesting to note that, throughout the study, Ender had continued to modify his temperature selections to align with his and particularly with Açelya's comfort, thus possibly contributing to this assessment (see Fig. 3).

6. Discussion

This paper set out to answer two RQs: *How do households relate to and align with SHHT's potential for rational decision making in the context of their everyday practices with heating? How do households embed SHHTs AI in the temporality of home life to control their heating?* The discussion that follows focuses on how the households involved (and their lead-users) related to Squid's rational and temporal design. We situate our findings in existing literature to bolster how we understand AI-enabled SHHT in the context of the everyday, and how such technologies align and disrupt home life. Where possible, we draw implications to inform AI-enabled SHHT design, as well as to chart new design directions.

6.1. Rational SHHT in the lives of middle-class households (RQ1)

Previous research concerned with whether rational SHHT prompt quantitative behavioural changes have reported mixed findings; whereas some SHHT have not been found to trigger measurable changes in home heating, in other cases SHHT have contributed to reduced energy consumption (Tuomela et al., 2021). What is clear from qualitative research studies involving SHHT is that the maintenance of thermal comfort is balanced against a range of considerations such as cost and energy conservation, but it is ultimately a situated accomplishment (Alan et al., 2016; Pink et al., 2013; Strengers, 2011b, 2011a; Tuomela et al., 2020; Yang and Newman, 2013a). This echoes Strengers assertion that rational SHHT which rely on providing cost efficiency information will have partial impact on how heating is performed (Strengers, 2011b).

Against this context, we found that three households were not concerned about energy costs and did not perceive Squid's AI to be meaningful. Nonetheless, Squid's potential for supporting rational heating decisions appealed to the remaining eight households, aligning with their ongoing concerns about the cost of energy. These households actively engaged with Squid's features over the study period and reported an understanding of how their heating worked with respect to cost-thermal comfort. Despite their alliance with Squid's potential to support a rational approach to heating, and the study's timing coinciding with the steep rise in energy costs, thermal comfort remained the primary factor that directed participants' preferred temperature inputs within Squid.

This finding echoes past research, which found that despite some households reporting a desire to make energy savings, their interactions with the Nest prioritised thermal comfort (Yang and Newman, 2013a). Similarly, reporting on an energy shifting SHHT, other research found that participants were willing to negotiate a narrow price range in fear of risking thermal comfort (Jensen et al., 2018). Yet, it is important to also acknowledge that many of the middle-class SHHT householders involved in our study wanted Squid's design to reflect cost-efficiency goals and outcomes, and perhaps this missing feature would have triggered a more active engagement with price had it been included. This was expressed through the request to connect the gauge visualisation to the achievement of a cost target. It was also related to their proposal to incorporate summaries of the cost savings generated from the use of AI, which have been found to sustain user engagement with the rational underpinnings of SHHT design in past work (Alan et al., 2016; Shann et al., 2017). In embodying a simple rendition of technology, our probe's lack of this functionality provoked users to reflect on what was important to them (Hutchinson et al., 2003). Whilst recognising the limitations of rational SHHT design for demand flexibility, our study therefore highlights the value of incorporating goal-orientated and outcomes-based design features in rational AI-enabled SHHT. The remainder of the discussion considers Squid through the lens of temporality and the socio-material relations that are part of everyday life, providing a situated understanding to Squid's use.

6.2. Contradictions between the everyday and rational design informing new design openings (RQ1)

In support of past research, we observed that households had experiential and embodied know-how to manage heat flows within their home (Royston, 2014; van Beek and Boess, 2022) and most knew how to monitor these heat flows (e.g., knowing which rooms were warmest at what time of the day, how heat escaped a room, which room was the coldest due to the lack of insulation/radiators etc.). A range of practices were performed to maintain and balance thermal comfort with energy conservation, including:

- Keeping the thermostat to a low temperature.
- Adjusting winter heating to the weather with lower temperatures when it is milder outside.
- Reducing thermostat when occupants are not in the house.
- Switching off boiler when occupants are not in the house.
- Reducing heating at night.
- Switching off heating at night.
- Dressing warmly when cold and/or using warm covers when stationary.
- Reducing/switching off heating in rooms not used.
- Delaying heating to activate in the coldest months.
- Actioning home improvements, or energy hacks.
- Moving to a room that is warmed by the sun.
- Closing/opening the door to regulate the temperature in a cold room.

Whereas most households welcomed the prospect of using Squid to inform rational heating decisions, there was also a discord with their heating know-how. For some, Squid's potential to reduce energy use during peak times was insignificant considering they were already practicing energy conservation. However, for others, Squid's design introduced explicit conflicts with existing embodied competencies. Squid's suggestion of shifting energy use clashed with the temporal uses of materials for conserving energy in the everyday. For instance, some households were accustomed to switching off the boiler during non-peak times when children were away, which didn't align with Squid's suggestions. Also, Squid didn't account for the effect of seasonal temporalities on the physical space, such as the adverse impact of the outside weather in a non-energy efficient home. Additionally, factors like presence in the room took precedence over Squid's recommendations during peak times. It is interesting to note that participants were most frustrated by the dissonance between Squid's rational design and their energy conservation in the everyday whenever the gauge visualisation indicated extreme price sensitivity. Visualisations designed to express human qualities may thus risk provoking affective reactions if they are not perceived to be accurate.

Couched within the rational design paradigm, some research has suggested resolving such tensions through the implementation of more sophisticated algorithms, which could consider outdoor weather information, presence, and other relevant factors (Alan et al., 2016; Jensen et al., 2018; Yang and Newman, 2013b). Nonetheless, in light of the findings and the shared concerns expressed by those involved in designing and researching SHHT (as reported in Section 2), we propose the potential for reframing the current design paradigm away from rational principles and resource visualisations that remain disconnected from social practice. Our proposal draws from Jensen et al. (2018) who contrast automation, which often leads to user disengagement, with the need to actively and critically engage households in knowingly taking sustainable actions. Similarly, Royston (2014) argues that people's know-how in keeping warm is deteriorating with the advent of new technologies, which standardise temperatures in the home. We suggest that digital technologies could support household occupants in developing, sustaining, and improving their heating competencies by fostering embodied and material engagements, as observed in our study. One potential design approach involves incorporating situated sensing (e.g., measuring who is present, when, how warm a room gets etc.) with physical toolkits to prompt reflection. Physical toolkits could empower households to better understand their physical spaces, the way they use existing materials to maintain their thermal comfort, reflect on their social practices and consequently experiment with new practices and materials. Critical life transitions and events such as ageing, having a new baby, or moving home, can disrupt thermal comfort and create opportunities for new learning (Royston, 2014). In our study four households had recently relocated, potentially contributing to their efforts to acquire new competencies. We contend that such pivotal moments present opportunities for digital interventions.

6.3. Initial encounters with AI: challenges raised when technical and home temporality meet (RQ2)

Computing is temporal by design (Wiberg and Stolterman, 2021), and similar to other AI-enabled SHHTs, Squid embodied its own 'technical temporality'. First, it split the 24-h day into 'pre-defined time ranges' that could be customised by the households to align with their routines, and second, the AI updated the smart valve temperature every 30 min (reflecting temporal changes in energy prices). For the purposes of the discussion, we concentrate on the latter. User input can be vital to maintain the relevance of SHHT's automation. Accordingly, in Squid, users were prompted to register their preferred temperature 4–5 times for each of their five profiles before the profile could fully adapt to their preferences. Previous research has consistently found that the technical temporality of AI-enabled SHHT and its introduction of daily or hourly interaction requirements can clash with the temporality of heating routines, and as such, user engagement with AI remains a challenge (Jensen et al., 2018; Yang et al., 2014; Yang and Newman, 2013b). Disengagement with SHHT can be further reinforced, since the AI continues to operate without extensive user input (Jensen et al., 2018).

In line with the temporal perspective taken throughout, our study informs this known challenge by looking at the ways in which households attempted to align home temporality—particularly their routines—with the requirement to temporally interact with the AI (Hargreaves et al., 2018; Pink et al., 2017). We showed that a few householders were able to successfully achieve alignments by identifying moments that allowed for interruptions, or transition points. In contrast, for others, particularly those with children, such moments were rarely available since they juggled intense work and home routines that left little time for more. These participants chose to engage with Squid's need for training on specific days, or times of the day, that didn't compete with these routines such as late at night when the children were asleep. Whilst establishing a temporal alignment, this approach posed limitations, namely that the updated heating profile was not the one they most relied on for their thermal comfort. Even participants who identified suitable moments to interact with Squid during the day, still negotiated these new time and work commitments. For example, by using their existing heating competencies to determine when Squid's automation would be most useful (e.g., timing interactions with Squid to when the boiler would be active/most likely triggered).

Summarised in Table 5, our study broadly contributes to the claim that AI-enabled SHHT introduce a new rhythm of work (Jalas and Rinkinen, 2016). Our findings also highlight how households socially organise their time before they can align technical and home

Table 5
Technical and human temporal mis/alignments during the AI training phase.

Alignments	Misalignments	Negotiations
Fitting AI input in daily transition moments e.g., before lunch	Unable to input to an AI heating profile due to an absence from the room, or house	Engaging with Squid during non-workdays, or less busy hours in the evening
Fitting AI input by making alignments with existing temporal home routines during the day e.g., work breaks	AI engagement not fitting over the course of a busy day and other routines	Interacting with Squid when it has effect in relation to other home heating technologies Removing the constraints of technical temporality through sensory engagement

temporalities (Rapp et al., 2022), and consequently the hidden labour introduced by AI and automation, echoing similar arguments raised in the context of the smart home more broadly (Strengers and Nicholls, 2017). Recognising the importance of training SHHT's AI, previous work has suggested that smart home technologies be designed for their users' "intermittent engagement" (Yang and Newman, 2013a). One implication of our study is that the timing of this engagement may be as important as its frequency. However, the challenge remains that, for some households, temporal changes in the tariff costs used by SHHTs may not synchronise with their availability to engage with the AI. Decoupling users' engagement with the AI from the real time dynamic prices could be one design pathway to explore. As Table 5 further shows, some households addressed the challenges of identifying temporal alignments by purely relying on their senses to engage with Squid, and thus provided input to the AI only when feeling cold. Notwithstanding the ethical implications this strategy involves, future research could explore how to trigger user interaction with AI through sensory triggers.

6.4. AI-human agency and control in the context of heating (RQ2)

By and large, our study indicates that Squid's use engendered a sense of control for most participants. This contrasts with findings from past research where SHHT users have sometimes reported losing control, for instance when technology overruled their decisions (Hargreaves et al., 2018) or when SHHT was used by some household members to exercise power over others (Ehrenberg and Keinonen, 2021b). Our research shows that the experience of control was closely connected to the co-evolution of human and AI agency. To frame this part of the discussion, we draw on Kuijer and Giaccardi (2018) whose notion of "co-performance" reflects the recognition of human and AI agency, their respective capabilities, and the appropriateness of their co-performances over time. Accordingly, in the co-performance we observed participants initially using Squid to select target temperatures aligned with their sensory preferences, reproducing their ongoing social practices of heating and ignoring the price considerations introduced by the AI (6.1). Only once they had established their thermal comfort through temporal alignments (6.3) did they take a passive role, leaving it to the AI to set their target temperatures. Thus, AI agency was shaped by the human agency that proceeded it. The tight control users initially exerted over their target temperatures also resulted in the AI setting target temperatures with less consideration for energy prices, which reduced Squid's possibility for rational action.

Popa (2021) argues that AI agency must serve human goals and judgments, whereas Kuijer and Giaccardi (2018) discuss the appropriateness of co-performances that recognise human and AI judgments. In our study, householders and AI co-shaped the sustenance of human thermal comfort as the key judgment. However, Squid also disturbed householders' embodied competencies and human know-how in managing heating flows, raising questions of how AI-enabled SHHT may be altering these human capabilities and provoking designers to consider the future prospect of fostering these competencies with digital technology (see 6.2). Moreover, echoing the idea that appropriateness can change over time (Kuijer and Giaccardi, 2018), households identified times when the sensory discomfort caused by the AI's adjustment to a lower temperature would have minimal impact to their comfort (e.g., when away from the home or sleeping, when the weather is mild). Consequently, seasonal temporalities, along with the anticipated absence of social practices in space and time, enabled participants to envision new possibilities for AI performances that aligned with rational judgment.

Our research aligns with previous work, which has shown that AI is not always transparent to its user (Alan et al., 2016; Jensen et al., 2018, 2018; Yang and Newman, 2013b). Users' perceived control of Squid was undermined when participants were either unable to relate their own actions over the algorithm to its behaviours, or when they applied pre-existing expectations to the AI's behaviour. Crucially, our findings contribute another perspective in showing that users of SHHT can fail to fully account for the ways their own performance shapes the AI's, which in our study related to moving Squid's AI away from its initial design to exert moderate influence over their temperature based on the active energy tariff. Although participants were all aware of their comfort-driven interactions with Squid, some continued to assert that the AI acted in accordance with its original design, failing to fully appreciate its appropriateness. While co-performance provides a vocabulary to describe the types of AI-human performances observed in this study, questions remain on who is responsible for assessing appropriateness if humans struggle to understand their own performance, or that of the AI.

6.5. Limitations

We close our discussion by reflecting on our research design, ensuring our findings are interpreted within the context of our methodological decisions. This research explored temporality and rationality of AI-enabled SHHT through a technology probe. This allowed us to gain a deeper insight of these design qualities, in part because of the speculative and exploratory approach the probe introduced within the households. However, this methodological decision also excluded us from incorporating more complex features such as cost-efficiency summaries, not least since Squid's cost implications were restricted to a single room, and the use of Squid was not connected to a tangible financial outcome participants received. Whilst recognising this limitation, it is relevant to acknowledge that participants' speculations on how Squid affected their heating aligned with previous field research. More broadly, given the three-week deployment of this field study, and participants' lack of prior experience with AI-enabled SHHT, we recognise that our findings are most relevant to the beginnings of embedding this digital technology in the home.

7. Conclusion

Smart Home Heating Technologies (SHHT) aim to improve demand flexibility and energy conservation. The design of these technologies has often been informed by rational theories of energy use, with recent advancements in AI poised to automate these instrumental goals. When SHHT are introduced in the home, however, they become situated in temporal social practices that are shaped by an interplay of materiality, meanings, and competencies. To this end, previous empirical research in the social sciences has cautioned against interventions that treat energy as a resource management problem, without an understanding of the socio-material practices energy is part of Pink et al. (2017), Shove and Walker (2014). The aim of our research was to inform how the design assumptions of rational SHHT, and the temporal requirement AI in particular raises for user engagement, fit in the temporality of everyday life. We carried out a field study with eleven middle-class households in the UK who used a rational AI-enabled SHHT technology probe, Squid. Our findings make several contributions. First, in demonstrating that the households had a sensory orientation towards using the AI-enabled SHHT, we argue that for costs to be considered, it is important to include goals and savings summary features. Second, we find that rational AI-enabled SHHT disturbs other, embodied ways of heating at work in the household and we highlight an untapped opportunity for technologies to sustain and improve these competencies. Third, we show how the AI's technical temporality clashes with home routines, and propose new design avenues to engage users with the temporality of dynamic pricing. Finally, we demonstrate that despite their agency over AI, users of SHHT are not always aware of how this agency shapes AI performance. Whilst raising several design implications, the main contribution of this research is to evidence the intricate relationship between individuals and AI within the context of heating in the home through a temporal everyday perspective.

CRediT authorship contribution statement

Asimina Vasalou: Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Writing – original draft, Writing – review & editing, Conceptualization. **Andrea Gauthier:** Data curation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization, Conceptualization. **Ana Luisa Serta:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – review & editing. **Ceylan Beşevli:** Data curation, Formal analysis, Investigation, Methodology, Writing – review & editing. **Sarah Turner:** Investigation, Methodology. **Racheal Payler:** Data curation, Formal analysis, Investigation, Methodology, Writing – review & editing. **Rea Gill:** Data curation, Formal analysis, Investigation, Writing – review & editing. **Kevin McAreavey:** Software, Writing – review & editing, Data curation, Resources. **George Loukas:** Funding acquisition, Methodology, Project administration, Software, Supervision, Writing – review & editing, Conceptualization, Resources. **Weiru Liu:** Funding acquisition, Supervision. **Roser Beneito-Montagut:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no conflict of interest.

Data availability

The authors do not have permission to share data.

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