Control in Context: How Smart Home Users Navigate Proxy-based Schemes

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Abstract

A homeowner controls their smart home devices along a spectrum of approaches, ranging from physical device control to various proxy-based control modalities. This paper studies *how and why* users move along this spectrum in their day-to-day lives, building upon existing research that focused only on specific interactions. We surveyed smart home owners ($N = 43$ users), and conducted follow-up interviews with a subset of the survey participants ($N = 8$). Our studies allow us to both distill specific contexts and experiences of smart home owners as they navigate the control spectrum, as well as to describe how their experiences (both positive and negative) shape their tendencies to control devices in a particular way. These insights lead us to propose practical implications for designers and researchers of smart home management systems, including the need to support flexible control scheme transitions, reduce switching costs, and account for temporal and spatial heterogeneity in the evaluation and design of control systems.

CCS Concepts

• **Human-centered computing → User studies**; *Empirical studies in collaborative and social computing*; **Collaborative and social computing design and evaluation methods**; **User studies**; *Interaction design.*

Keywords

Smart homes, Smart home control, User studies, Qualitative study

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1 Introduction

The adoption of over 10 billion Internet of Things (IoT) devices has reshaped homes, workplaces, and industries [77, 99, 100, 126, 135]. Vendors of smart devices—e.g., Philips Hue, Ecobee, Apple HomeKit, Siemens, Samsung SmartThings, GE Cync, Honeywell, and others [3, 7, 21, 61, 73, 116, 122]—have traditionally provided their own software for users to control their devices (through *vendor-specific* interfaces), building on top of existing physical controls like buttons or switches [82, 85]. Yet, as smart homes scale, controlling each vendor's devices separately becomes less desirable for homeowners.

To combat the overhead of controlling each device or product individually [80], some vendors introduced new modalities of control, layering additional control options on top of traditional vendor-specific interfaces. This allows users to control both vendor-specific and cross-vendor devices through a single interface, potentially reducing overhead. For example, hubs or apps like Google Home [4], Apple HomeKit [2], or Amazon Alexa [1], enable users to control many devices (e.g., lights, thermostats, door locks) through both individual commands and automations (i.e., routines) from a single dashboard [41, 74, 106]. Using such a hub, a smart home user can leverage proxy-based control to create a "good-night" routine that turns off their porch lights and locks their door with a voice command, even when these devices come from different vendors, without operating each device individually [123].

Previous research has established that vendor-specific and cross-vendor control are on opposite sides of a smart device control spectrum [147, 155]. However, these control schemes may refer to *how* users issue commands [62, 105], *which* apps or ecosystems they use [14], or *where* the configuration logic resides (per-device rules or shared routines) [39]. In this paper, we focus on the *locus of execution* of control logic, namely whether device configuration is initiated directly on the device, or through proxies. Rather than treating one side of the spectrum as vendor-specific and the other as cross-vendor, we observe that these points are parts of an extended spectrum from **physical control**, i.e., interacting with the target device's physical controls, to *varying levels* of **proxy-based control**, where user commands are routed through one or more intermediaries, such as hub apps, voice assistants, cloud services, etc., before reaching the target device [111, 155]. For example, centralized control is one form of proxy-based control: a single proxy (or a tightly coupled set of proxies) orchestrates many devices and brands from a unified configuration layer [115].

This control spectrum (Figure 1), with physical control to proxy-based[1] central control as the two ends, is widely used in practice, as many homeowners rely on intermediate points on this spectrum rather than its endpoints. Smart home device vendors offer control interfaces that can access either a single device, multiple devices from the same brand, or devices across various brands. People routinely blend proxy-based and physical device control, moving across the locus of execution spectrum based on convenience, reliability, and their understanding of how the system works. These movements become especially visible during troubleshooting. When routines misfire, devices fail, or connectivity is unstable, users abandon usual cross-vendor proxies, fall back to device-local physical interfaces, or switch among apps and platforms [15, 55]. Troubleshooting exposes users' understandings of the smart home infrastructure, including how they choose to reveal or hide connections between devices, apps, and services. These user actions are often referred as *seam practices* [88]. Triage of device errors is a core part of living with smart homes and strongly shapes trust, preferences, and long-term configuration strategies [131].

Despite the known existence of this control spectrum, much of the research on building operating systems (OSs) for smart homes still *assumes* proxy-based control is the primary way for users to interact with and control their home [13, 52, 118]. This assumption of "always proxy-based control" echos how smart home OSs have traditionally been designed for machines [5, 6, 64, 114, 132, 133, 145], datacenters [117, 134, 138], and networks [72, 89], domains where end-users rarely interact directly with individual devices. Empirical studies supported this disconnect by highlighting users experiencing difficulties when managing multiple dashboards for the same task [80]. In occupied homes, however, different loci of execution offer distinct capabilities and trade-offs for users, making the "always proxy-based control" approach incomplete. In addition, much prior smart home control research focused on specific devices or interaction styles instead of empirical user studies [29, 59, 137, 143].

User studies are critical for designing usable and technologically sound systems, complementing prior work that focused mainly on system proposals [12, 13, 103, 107]. Moreover, existing research often abstracts away the messiness of real-world use, where devices are added gradually, apps and platforms overlap, cloud services change, and users inherit configurations set up by others. As a result, we know far less about how existing systems actually behaved in occupied homes and how people patch around misalignments across different control schemes.

This paper seeks to rectify this mismatch by understanding: *How do users make decisions of which control mode(s) to use across different scenarios?* We investigate real-world workflows for interacting with smart home devices with and without proxies, giving particular attention to troubleshooting and recovery. We conducted a survey and follow-up interviews to understand how people combine direct device control and proxy-based control (including centralized hubs), and how breakdowns and uncertainties shape these choices. First, we examine how people navigate and combine different control schemes in everyday use: when and why they prefer proxy-based hubs, per-brand apps, or device-local control in different contexts. Second, we focus on troubleshooting as a critical moment within that broader experience. During troubleshooting, users' understandings of the system surface more clearly and they often reconsider which control loci they trust and are willing to invest in.

[1]Our use of this term in this paper is inspired by literature in the systems and networking space, which establishes the use of the "OSI Model" as an abstraction that encapsulates seven layers ranging from physical to application [45].

By investigating real-world workflows for interacting with smart home devices, we answer the following research questions:

- **RQ1:** *How do smart home users navigate and combine different control schemes in their homes?*
- **RQ1a:** *What factors drive users to move between, and combine, control methods within their homes?*

We also examine how device and interface breakdowns or errors affect the above choices:

- **RQ2:** *When smart home interactions do not go as expected, how do user perceptions of control schemes shape their responses?*

Sub-questions arise about how these experiences affect perceptions:

- **RQ2a:** *How do troubleshooting experiences affect users' perceptions and trust of/in their preferred smart home control methods?*
- **RQ2b:** *How does user uncertainty around functionality affect their strategies for engaging with different control methods and their seam practices?*

In summary, this paper makes the following contributions:

- We evaluate how smart home control affects a user's ability to meet their smart home goals, and find that ***the spectrum of smart device control plays a major role*** in user preferences and experiences in managing and using their smart home devices.
- We reveal how and why users decide to control their devices at different points along the proxy-based to direct device control spectrum, exposing the different seams within their smart homes, understanding that ***users move freely along the spectrum, guided by situational factors such as convenience, task, and perceived reliability***.
- We characterize troubleshooting workflows and seam practices across control schemes, and detail how breakdowns and uncertainties prompt users to ***reconfigure control arrangements, fall back to direct device control, and strategically reveal or hide infrastructural seams when troubleshooting.***
- We identify and understand the factors that guide smart home control preferences and suggest ways for future research and design to incorporate these perspectives, namely ***accounting for spatial and temporal heterogeneity*** in smart homes, as well as ***supporting movement through varying seam hiding/revealing practices along the smart home control spectrum***.

2 Related Work

We build upon prior literature on user experiences within smart homes and associated control modalities.

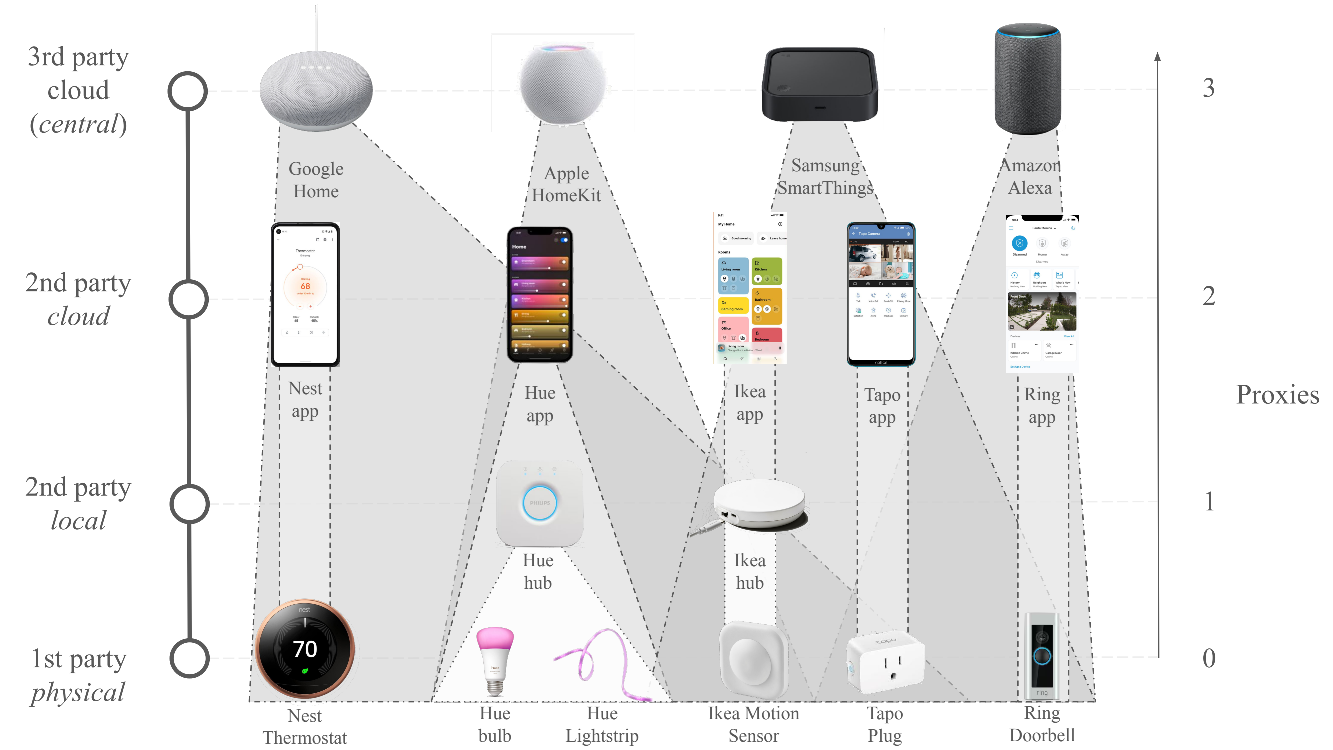


Figure 1: Proxy-based Control Spectrum. Control schemes vary along two related axes. (1) Locus of execution: controls may be first-party/*physical* (direct, on-device), second-party/*local* (vendor hubs or LAN apps), second-party/*cloud* (vendor-operated cloud services), or third-party/*central* cloud ecosystems (cross-vendor platforms such as Google Home or Apple HomeKit). (2) Proxy depth: shown vertically, this indicates how many intermediary layers–hubs, vendor clouds, or central platforms–sit between the user and the device in the control path. Each control scheme has a different reach; the higher the number of proxies, the higher the degree of control centralization (breadth).

2.1 Smart Homes, Devices, and Control

We define *smart home devices* as *"sensors, monitors, interfaces, appliances, and devices networked together to enable automation as well as localized and remote control"* [68]. These include but are not limited to smart lights, smart home security systems, smart thermostats, smart TVs, and smart speakers [31]. We use the term *smart home ecosystem* to describe the interconnected set of devices, platforms, applications, cloud services, data flows, and household members that together provide and control smart functionality in a home. An ecosystem can span multiple brands and control loci (e.g., hubs, vendor apps, device-local interfaces), and changes as devices are added, removed, or reconfigured over time.

As smart devices become integrated into homes, user interaction and control over these systems emerge as key areas of study. Integrating smart devices into households is a domestication process involving pilot users to drive the setup and passenger users adopting these devices, sometimes even without understanding them [86]. Household members gradually adapt their routines around these devices, exercising control over how smart devices fit into their daily lives [37]. Research highlights that users can have different expectations of smart device behaviors when two routines run simultaneously because they have different values [149]. These devices, marketed for convenience, inherently come with user expectations regarding ease of use and seamless integration [40, 87]. Additionally, studies revealed that stakeholders like cohabitants, bystanders, and non-users could not control how they interact with smart home devices placed in different locations in households [101]. Users tend to group their devices based on their location, functionality, and/or use contexts to expedite control [143]. A common thread among this prior research is the central role of control in shaping individual experiences with smart home devices [43]. Despite the growing variety of smart home devices and control methods, there is limited literature examining *how* users navigate control schemes for individual devices or groups of devices within their homes. In this paper, we identify key factors that shape device control workflows and explore how users' experiences, including troubleshooting, influence their perceptions of these control schemes.

2.2 Smart Home Control Schemes

Smart home control schemes refer to the guiding paradigm for categorizing mechanisms to control smart home devices. In this paper, we focus on the spectrum of *proxy-based control*, visualized in Figure 1. The spectrum represents the levels of centralization or indirection in smart device control. Essentially, *proxy-based control*

Papers	Focus	Contribution
[62, 143]	Central, limited Physical	Empirical
[52, 57]	Central	Empirical
[13, 17, 20, 25, 51, 103, 112, 119, 130, 141]	Central	System
[66, 150]	Central	Literature Review
[22]	Cloud, Local, Physical	Evaluation
[136]	Central	Evaluation
[12, 107]	Second party	System
[152]	–	Empirical

Table 1: Prior work mostly assumes one control scheme of the spectrum exclusively. It does not study the relationship between the two, even when both are discussed in the same work.

refers to how user commands are sent to devices through a proxy, such as an application, voice assistant, routine/automation, etc. On one end of the spectrum sits *physical device control*, which refers to the direct interaction between the user and target device (first party), without any intermediaries or indirection (i.e., zero proxies), regardless of the interface modality, i.e., touch, voice, etc. On the other end of the spectrum, *central control* (or *third-party cloud control*), represents the highest level of centralization, with multiple layers or proxies of control systems between the user and the target device. *Central control* is an extreme type of proxy-based control, where a single interface allows users to control multiple smart home devices, possibly of different brands, directly or indirectly. The points in between the two extremes refer to vendor-specific (second-party) interfaces, or per-brand control, that execute locally in the same network as the target device through Zigbee, Bluetooth, etc., or in the cloud, adding one or two network hops to the control path, respectively.

Our focus on this spectrum of control builds upon existing theoretical HCI models. In this paper, we focus on the information ecology model in smart homes. Information ecology theory envisions smart homes as continuously evolving technologies that must interact with existing human and technical processes [65, 75, 139]. Our control spectrum refines this view by specifying *where* actions are executed in the ecology (the locus of execution) and *how* seams in infrastructure are hidden or revealed during everyday use and troubleshooting. The control spectrum also reinforces concepts introduced in other models used often in user-centered smart home research, such as the Technology Acceptance Model (TAM) [44, 121, 129, 154] and Activity Theory (AT) [47, 79, 96].

Smart devices can be controlled through varying levels of these two types of control, which users must understand and navigate to build their desired smart home setup [143]. These reflect common methods of controlling smart devices, including smartphone applications, voice assistants, smart hubs, routines/automation, and physical controllers in the market today. We detail part of the landscape of existing research surrounding smart home control in Table 1.

Such an abstraction reduces complexity for smart home device users and provides a single, cohesive user experience. Apple Home[2], Google Home[3], and Samsung SmartThings[4] are examples of central control schemes. Across systems, security and HCI, research focuses on centralized control, such as surfacing the need for finer-grained access control within households [123], designing more transparent and privacy-focused data processing for centralized smart home control [78] or proposing a unified interface where applications, commonly known as routines, interact with different smart home devices [52]. In contrast, physical control allows users to maintain coarse-grained control over their device even in the face of network failures [62]. A downside is that users must maintain multiple applications in their smartphone if their smart devices come from different brands, which quickly becomes exhausting [143].

Early research on smart home devices shows that direct and unmediated interactions with devices are often perceived more positively than interactions mediated by a single source of indirect response [90]. This suggests that users' preferences may vary depending on whether they interact with devices through a highly centralized *proxy-based* interface or use control schemes with fewer proxies involved, yielding more direct feedback. Matter [151] has been introduced in an effort to bring central control to the local network and reduce the intermediaries, yet vendors still expose only certain APIs through that integration, making little to no difference from the interface perspective. Few studies have examined the dynamics between these control schemes. As shown in Table 1, prior work primarily focuses on a particular end of the spectrum. Prior work has examined reasons why users may interconnect or purposefully separate their smart devices [120, 143]. However, such research focused on specific tasks in a controlled environment, limiting its ability to capture the challenges users face in real-world scenarios, for example, when devices fail. These troubleshooting experiences play a crucial role in shaping users' perceptions of control schemes along the spectrum, which we explore in detail in the next section.

2.3 Troubleshooting Smart Home Devices

Troubleshooting, the process where smart device users try to identify and resolve errors within smart devices, is a common part of the smart home device management experience [131]. It contains several different steps and involves working with both software, i.e., device applications, and hardware, i.e., the physical device [32].

[2]https://www.apple.com/home-app/

[3]https://home.google.com/welcome/

[4]https://www.samsung.com/us/smartthings/

Device failures erode expectations and trust among smart device owners, as they have high expectations of how the device will improve their lives at home when they initially purchase it [9, 131].

A seamless troubleshooting experience, where users can easily isolate and address issues, can increase positive perceptions of the device [69]. However, it is often during the troubleshooting process that the boundaries and imperfections, i.e., the seams, of smart home devices are exposed to the user. Research has identified seams as both something that must be hidden from the user [19, 84], as well as an opportunity to support enhanced user understanding of their devices [60, 92, 93]. We do not assume that either perspective on seams is correct; instead, we investigate how smart home device control schemes affect the seam hiding and revealing practices of devices and users.

Schemes along the control spectrum can offer drastically different troubleshooting experiences and seam-hiding practices, affecting user perceptions of these control schemes differently [23]. While it may offer increased convenience, central control can be especially challenging due to only a single point of failure [97]. When an error or exception occurs in the central controller, all devices controlled via central control are at risk of failing. In addition, when a single device connected to the central controller fails, the user must look not only at the failing device but also at the central controller to find the source of the issue. Direct device control provides a more localized approach to troubleshooting, allowing users to examine only one device at a time. However, in large-scale home failures, such as power outages or network failures, such control schemes require the user to troubleshoot each device individually. Control schemes involving very few proxies, such as second-party proxy-based control, or *per-brand control*, often offer more fine-grained functionality than other schemes, making troubleshooting more efficient and intuitive. When a Roomba stops mid-clean, the iRobot Home app shows the exact error code[5]; a central controller like Alexa/Google typically only starts/stops the vacuum or reports 'device not responding'[6].

While previous work has focused solely on the technical aspects of troubleshooting [18, 102], this paper investigates how users' choice of control schemes in smart homes affects their troubleshooting experiences. We extract generalized troubleshooting workflows grounded in real-world user experiences. Additionally, we discuss with users how these troubleshooting experiences have affected their perceptions of their devices and the ways they control them. This perspective allows us to connect concrete troubleshooting workflows to broader theories of seams and infrastructure, and to derive design implications for how future systems might better support these transitions.

3 Methods

We conducted a survey and follow-up interview study to understand the perceptions of smart home device users and their control schemes. We collected $N = 60$ survey responses through Prolific, a commonly used crowdsourcing platform for collecting data for online human-subjects research [54, 56, 108] (Table 2). We conducted follow-up interviews with a subset of $N = 8$ survey respondents to extract specific insights between September 2023 and March 2024. Our study's methodology is grounded in previous user-centered smart home research, which focuses more on eliciting high-level themes rather than drawing statistically significant conclusions [48, 71, 81]. All study procedures were piloted internally and approved by our institution's Institutional Review Board (IRB).

3.1 Survey Methodology

Participants first completed a brief screening survey (median completion time: 65 seconds), which required them to provide their Prolific ID and indicate the number of smart home devices they owned.

Our goal was to study people with active smart home setups rather than casual single-device owners. We therefore restricted survey participation to adults who (1) were registered on Prolific and reported owning at least one internet-enabled device in Prolific's prescreening questions [109], and (2) reported owning at least four smart home devices (e.g., smart lights, plugs, thermostats, cameras, speakers) in our screening survey. Participants were not limited to central-hub households, and those only using per-brand apps or direct device control were eligible. 60 participants completed this survey.

Participants were paid $0.40 USD (hourly rate of $24 USD) for completing the screening survey and $4.00 USD (hourly rate of $16 USD) for completing the main survey. We did not specifically recruit or target professional smart home installers or technicians. A small number of participants described installing devices themselves (e.g., DIY setups), but they still participated in the study as end users of those systems rather than in a professional capacity.

We had 43 valid survey responses from the 60 participants, excluding those who failed any of the arithmetic-based attention-check questions we included at random points in our survey (e.g., "What is 2 + 7") [8] or had inconsistent responses, such as differences in the number of or types of smart devices owned. All 60 survey participants were compensated for their time.

3.2 Survey details

The survey aimed to elicit participant preferences and perceptions related to smart home device control, as well as existing troubleshooting workflows and how device control preferences influence them. For the full survey, refer to the Supplementary materials.

3.2.1 General Smart Home Setup. The survey began by collecting information regarding each participant's general smart home setup. Participants listed smart home devices they currently use, where they lived, where each device was located, and what smart home device-related applications they currently have on their phones.

Participants reported what, when, and why they purchased their most recent smart home devices, then rated how well these devices met their goals and explained their ratings. We asked participants to focus on this single device to reduce survey cognitive load [91] and provide detailed context.

[5] https://homesupport.irobot.com/s/article/21044
[6] https://www.amazon.com/gp/help/customer/display.html?nodeId=GJRYAWXYCQKQF28E

Age	18-24 (2%), 25-34 (28%), 35-44 (23%), 45-54 (31%), 55-64 (7%), 65+ (9%)
Education	High School or GED (16%), Some College (22%), Associate's Degree (7%), Bachelor's Degree (42%), Post-Graduate Degree (11%), Some High School (2%)
Gender	Male (40%), Female (60%)
Race	Black/African American (4%), White (92%), Asian (2%), Hispanic or Latino (2%)
Living Situation	House (88%), Apartment (10%), Town Home (2%)
Number of Smart Devices Owned	0-5 (16%), 6-10 (19%), 11-15 (31%), 16-20 (21%), 21-25 (7%), 26-30 (2%), 31-35 (2%), 36-40 (2%)

Table 2: Summary of Survey Participant Demographics.

3.2.2 Current Methods for Device Control. The survey then asked participants how they *controlled* the various smart devices in their home. Participants selected their control schemes for a specific device in their home from the following: routines, central control, per-device control, voice commands, and content streaming/casting. Participants were asked more broadly about their smart home control patterns, such as how they choose to control a device in a specific way when it could be controlled in multiple ways. This section concluded with participants reporting their awareness of home management systems, such as Amazon Alexa, and how they were made aware of these systems' existence.

3.2.3 Device Failures and Troubleshooting Methods. To understand device troubleshooting experiences (RQ2), the survey asked participants to describe issues they encountered with their smart devices. Participants recalled when their smart devices did not work as planned and their perceptions of the devices during the failure. They also indicated whether they had ever returned a smart device because it stopped working as intended. Participants then provided a step-by-step account of how they troubleshot the device's failure. They continued to report whether they had ever given up on getting a smart home device to work in their home, identifying the device if so.

3.2.4 Survey Wrap-Up and Interview Interest. Finally, the survey asked whether the participant was the primary user of any homes other than their primary residence. If they were, participants were asked if there were any significant differences in how they controlled these devices compared to their primary residence. Then, participants were invited to provide their email if they were interested in participating in a follow-up interview with research team members.

3.3 Follow-up Interviews

40 survey participants expressed interest in the semi-structured follow-up interview in exchange for an extra $20 USD in compensation. We prioritized invitation to respondents with the largest reported smart home devices they owned, with the aim of capturing rich experiences across the control spectrum in multi-device ecosystems. Although later waves extended invitations to all participants eventually, only a subset responded, and we conducted 8 interviews. Interview participants had a variety of devices in their homes, allowing us to elicit a range of perspectives (Table 3). We used interviewees' survey responses to personalize specific questions during the study. For example, if a participant reported owning smart lights, we asked how they controlled them and why. Each of the 8 interviews we conducted lasted around 30 minutes and was structured into the following sections (the full interview protocol can be seen in the supplementary materials):

- *Smart Home Setup*: Participants were asked to describe their most recent smart device purchase, their motivation for purchasing it, how they set it up, and whether it met their intended goal.
- *Smart Home Device Control*: Participants discussed how they controlled their smart home devices. Devices they mentioned in the survey were brought up to contextualize the discussion (Section 3.2.2). Participants then described their ideal control scheme for their smart home devices. Participants could mention any control method and scheme that may or may not exist on the market. Participants described whether they controlled smart home devices in a way that allowed them to work together, i.e., through routines. Participants discussed how this setup was beneficial to them, if they did, and how they managed it, i.e., what method they used for central control. Finally, participants reflected on how their existing setup and preferences for smart home control methods affected their willingness to purchase new types of smart home devices.
- *Smart Home Errors and Exceptions*: Participants described specific experiences when their smart home devices did not work as planned. This section asked participants to elaborate on experiences they had briefly described in the survey and to describe any errors or exceptions not included in the survey. In particular, we asked participants to explain any errors they had when integrating devices into their smart home infrastructure.
- *Smart Home Troubleshooting*: The interview concluded with participants describing their troubleshooting workflow in detail and providing examples of when it was successful and when it was not. The detailed troubleshooting workflows and the impact of troubleshooting experiences on their perception of smart home devices and the corresponding control scheme were augmented by the participants' survey responses.

3.4 Data Analysis

We conducted descriptive statistical analysis of the survey data, calculating mean and median ratings for Likert scale-based questions. For qualitative responses and interviews, we performed in-depth qualitative analysis using thematic analysis and open coding [50, 83]. Two members of the research team independently coded four interviews, followed by cross-coding two interviews to assess inter-rater reliability (IRR) [67], resulting in a Fleiss' Kappa of 0.44, indicating moderate agreement [58]. Codes were consolidated and discussed through team discussions, yielding codes and themes directly related to the research questions, as well as a concrete set

	Smart Plug(s)	Smart Light(s)	Smart Thermostat(s)	Smart Door/Window Sensor(s)	Motion Sensor(s)	Smart Smoke Alarm(s)	Smart Camera(s)	Smart Security System(s)	Smart TV/Casting Device(s)	Smart Speaker(s)	Smart Tag(s)	Smart Health Device(s)	Smart Washing Machine/Dryer(s)	Smart Dishwasher(s)
P1	x	x	x				x	x	x	x		x		
P2	x	x	x			x			x	x		x		
P3		x	x	x		x	x	x	x				x	
P4			x	x	x		x	x	x		x			x
P5	x	x	x		x		x		x			x	x	
P6	x	x					x		x					
P7	x	x	x		x					x		x		
P8			x				x			x		x		

Table 3: Smart device ownership of our 8 interview participants. For each smart device, an ‘x’ indicates that the participant owns that device in their home.

Theme	**Codes**	**Meaning**
Control Scheme Perspective	Central control: viewed positively or negatively Central control: viewed as useless of convenient Per-device control: viewed positively or negatively Per-device control: viewed as useless of convenient	Participant describes how they view the described control scheme
Awareness Mechanism	Advertisement Online research Social media Word of mouth	How participant became aware of smart home device control scheme
Usage Pattern	Safety Convenience Cleaning Communication Entertainment	The described reasons for why participant uses a smart home device
Usage Frequency	Daily Weekly As needed	How often the participant uses the device
User Type	Primary user Partner/Spouse Child Pet Secondary/Passenger user	The type of user in participant’s home that benefits from the described smart home device
Perception-driven Behavior	Increased device usage due to positive perception Decreased device usage due to negative perception Avoiding device type/brand for future purchases Seeking out device type/brand for future purchases Considering integration for future purchases	How the participant’s perception of the device affects their behavior
Device Control Factors	Convenience Increased functionality Trust Device types	Participant reasons for using a particular device control scheme
Troubleshooting Steps	Check and reconnect physical device Check home management system Check application Contact IT support or conduct online research Check and restart home Wi-Fi Modify device commands or routines Give up	How participants troubleshoot their devices
Troubleshooting-based Perception	Positive experience improving device perception Negative experience worsening device perception Troubleshooting experience reduces trust Troubleshooting experience improves trust	Effects of troubleshooting experience

Table 4: Codebook generated from qualitative analysis.

of user workflows for troubleshooting smart home devices. These results provided high-level insights into user perceptions, user behavior, and control workflows for smart home devices (Table 4).

While our interview and survey samples are not designed to support statistical inference, our findings should be interpreted as analytic generalizations about how smart home users navigate proxy-based and physical device control, not as precise estimates of how common each behavior is in the broader population. Our work sits among other qualitative smart home behavior research, providing in-depth insights into user experiences, privacy concerns, and adoption barriers [49, 153].

4 Results

Our analysis of survey and interview data focuses on how users navigate the spectrum between proxy-based and physical device control in everyday smart home use. We structure our findings around three core themes: (1) user strategies for navigating this spectrum (RQ1), (2) the tradeoffs they perceive when doing so (RQ1a), (3) how navigation strategies, perspectives, and trust shift when users encounter device errors or failures (RQ2, RQ2a), and (4) how users commonly struggle to realize their goals across the control spectrum (RQ2b).

4.1 Control spectrum navigation strategies (RQ1)

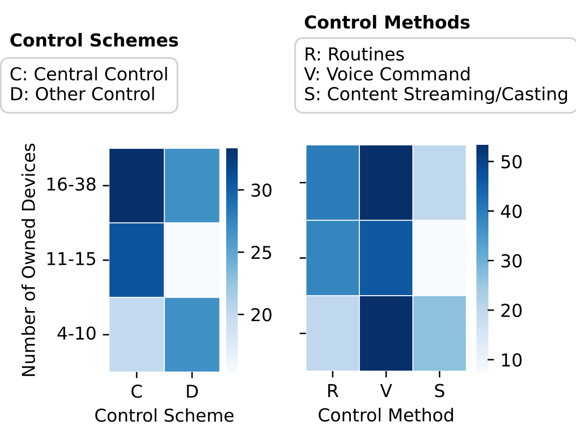


Figure 2: Percentage of survey participants using central or other control schemes and several control methods vs. number of owned devices. Each cell's color shows the percentage of participants falling into it who choose the respective control scheme or method. The percentages for the different options of control schemes and methods do not add up to 100% since the participants could provide multiple answers.

Survey and interview responses showed that participants rarely commit to a single point on the control spectrum. About half of the survey participants (51%) controlled their devices using voice commands, which can be used across the proxy-based control spectrum. Additionally, 33% of participants reported using routines to control their devices, which allowed them to control groups of devices simultaneously. Furthermore, 18% of participants reported using 'content streaming or casting' to control single devices, which is common for media devices such as smart TVs. Both user preferences and device constraints influenced participants' choice of control methods; for instance, participants using Amazon Alexa often relied on voice control due to physical device functionality limitations, while others with broader device ecosystems could select among multiple control methods.

As smart home ecosystems became more complex, participants increasingly shifted toward centralized control by purchasing and using smart home third-party hubs and adopting routines. Figure 2 shows that the use of centralized schemes rises alongside the number of devices owned among the survey participants.

Interview participants who manage many devices reinforced this result, as they reported turning to centralized hubs or voice assistants to reduce the cognitive load of juggling multiple interfaces. In particular, interview participant P7, who owned nearly 50 devices, said they relied heavily on central control but acknowledged its limitations: "*It's not easy to remember [what each device is named].*" Still, this strategy helped them operate a large-scale setup more efficiently.

At the same time, users moved along the spectrum toward physical control when centralized systems failed to meet specific needs. This involved falling back to control methods such as physical interaction with a specific device or using a brand-specific application on their phone. Several interview participants noted that detailed settings, such as firmware updates or custom automations, were often only accessible through the device's native app. For example, P3 shared: "*There is a button in the [Hue] app to make the light bulb that you're trying to interact with, blink on and off, so that you know exactly which one it is; that doesn't exist in the Google app.*"

Some participants used strategies to stay where they were on the control spectrum rather than move along it. Half of the interview participants (4/8), in particular, expressed that they were hesitant to buy new smart home devices that required significant effort to integrate into the existing infrastructure. For example, participants often decided against purchasing devices that required them to download a new application on their phone to set up or use the device. They instead chose to purchase devices that could be controlled using applications already on their phone. P1, when discussing why they purchased a particular brand of new smart device, echoed this sentiment, saying, "*I already got a lot of apps on my phone. So when possible, I don't wanna put more apps on. So I checked that it'll work with Smart Life. I checked that it's compatible with Alexa.*" Similarly, P3 described the cost of integrating a new device into their existing smart home control scheme as a significant factor, saying "*I definitely consider that before buying a potential product, and if possible, I try to buy ones that don't require me to use a new app or ecosystem. There is a cost of switching there that I don't necessarily want to introduce to myself.*" Participants' responses reflected a desire to gain the benefits (e.g., safety, convenience, etc.) of new smart devices in their home without the potential drawbacks of needing to work outside their home's existing smart device ecosystem, forcing them to adopt mindsets of "brand loyalty" [144].

Long-term use affected user strategies as well. P3 found that as time passed, the scale of the smart home increased, and it *"no longer would be easy to control with just [their] phone,"* enhancing the need for more fine-grained control and more options through more direct control schemes. In contrast, P5 is *"using two providers, Nest and Tapo. I want to choose only from those two the new device,"* and limit the number of interfaces they are using, even if their smart device collection grows. Further, expertise grows over time for some, such as P2: *"for setup, I know now what to do. I've had problems in the past. And I've learned from those problems,"* letting them more comfortably approach new interfaces. Yet, some interfaces are still particularly hard to get used to, as P3 describes having to relearn how to find the routines setup, eroding the trust and patience that users initially have for smart features that centralize control: *"I don't rely on routines for most of the house, except for the room where our animals are."* These experiences show how temporal changes in smart home scale or expertise push users to expand or preserve their navigational limits on the control spectrum.

Overall, most participants did not adopt a fixed position on the smart home control spectrum. Instead, they moved fluidly along it, adapting to the demands of scale, task complexity, and reliability using various strategies. In the next section, we examine the specific tradeoffs users perceived and how these influenced their decisions to stay at a certain point or move within the control spectrum.

4.2 Control spectrum navigation tradeoffs (RQ1a)

While participants demonstrated flexibility in their control strategies, their decisions were shaped by tradeoffs between convenience, precision, cognitive effort, and integration. These tradeoffs were not static; instead, they shifted with the scale of the smart home, the types of devices involved, and the user's comfort with technology. Participants weighed these factors when choosing whether to lean toward centralized control (where a single proxy controls many devices) or physical individual device control at any point in their day.

Participants commonly cited convenience as the most compelling reason for adopting centralized control. This was particularly true as the number of devices in a smart home increased. For example, interview participant P8, who had a large-scale smart home setup, preferred centralized control because it streamlined routine tasks and allowed control through a single interface: "*It's just obviously the convenience.*" Survey responses supported this perspective, showing a clear increase in central control-based methods' use among participants with more than 15 devices (Figure 2). Centralized interfaces reduced the friction of opening and switching between multiple apps and offered the possibility of controlling the whole house with fewer steps. In some cases, these tradeoffs were negotiated within the household rather than by an individual. P6 explained that their partner preferred consolidating under Alexa "to keep everything easy and streamlined," while they themselves "didn't really care about the brand," reflecting how household priorities could drive ecosystem choices.

In contrast, control through second-party interfaces, or per-brand control, was often favored for its granularity, clarity, and ease of use, especially when dealing with specific device configurations or troubleshooting. P2 illustrated this distinction clearly: "*Whenever I need to adjust something specific, I go straight to the device's own app... Alexa doesn't have those settings.*" P5 echoed this sentiment, noting that certain features—like firmware updates or custom scenes—were only available in the vendor's own app: "*Google Home doesn't support [those].*" This division reveals a tradeoff between breadth and depth: centralized control enabled broad coordination across many devices, but per-brand control offered deeper access to individual brand functionality.

Participants also discussed the usability and user experience differences between central and per-brand control. P3 described centralized interfaces as confusing and overly technical, especially for less tech-savvy users: "*If you weren't very tech savvy, you would not be able to figure it out.*" Meanwhile, they described the per-brand app experience as more intuitive and better designed: "*The Hue app communicates with Hue lights, and that integration is a little bit better.*" These comparisons underscore how usability and familiarity influenced participants' willingness to rely on one scheme over another.

Not all tradeoffs were framed as strictly negative. Some participants viewed the coexistence of control schemes as beneficial, enabling fallback options or additional layers of control. For instance, participants appreciated having per-brand apps and physical control as a backup when centralized control failed, or vice versa. As P5 described, they would look at a device's specific app first for assistance, rather than the central control system app. Similarly, per-brand apps may also fail and trigger another step down to physical control, as P5 describes: "*Sometimes it shows as offline because the [brand] app is not able to connect, but the physical device is already up and running. Then I have to turn it off and turn on or do something to get it back up again.*" In these situations, control scheme redundancy offered resilience, not just complexity.

Overall, participants' experiences reveal that smart home control is shaped by ongoing negotiation. Users must continually balance ease of use with technical specificity, minimize app clutter while maximizing access, and integrate new devices without overwhelming themselves. These tradeoffs not only shaped how users controlled devices but also influenced how they structured, grew, and maintained their smart home management systems over time. In the next section, we examine how these navigation strategies and tradeoffs shift when smart home management systems encounter errors and how users respond to breakdowns that disrupt their preferred control methods.

4.3 Navigating the control spectrum when failures occur (RQ2, RQ2a)

While participants developed personalized strategies for navigating the smart home control spectrum, their routines were often disrupted by errors or device failures. These breakdowns forced users to shift control strategies, reconfigure devices, or adopt new troubleshooting behaviors—often in ways that tested the limits of their preferred schemes. Our findings show that errors were a critical moment when users' relationships to the control spectrum changed: participants re-evaluated their trust in control methods, engaged in layered troubleshooting, and sometimes abandoned devices or features altogether.

In the survey, 65% of participants reported that they had experienced at least one issue where a smart device did not work as intended, and 28% reported repeated issues. These issues ranged from connectivity failures (33%), such as devices becoming unresponsive during WiFi outages, to misinterpretation of voice commands (23%) and execution failures, where the device failed to perform the correct task (21%). For instance, one participant noted: "*When there has been an issue with WiFi in the house, the Amazon Echo tends to have issues.*" In these moments, control mechanisms that were once trusted became unreliable.

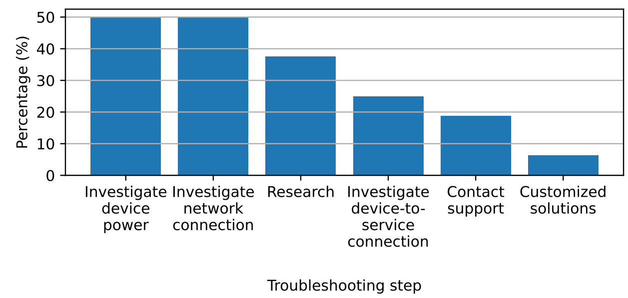
When troubleshooting, participants frequently shifted away from their preferred control methods. For users who primarily relied on central control, their first step was often to check the centralized app or voice assistant interface to confirm whether the command had been sent correctly. Interview participant P7 explained: "*I will go and look at the app straight away and make sure that the heating has activated rather than just trust it.*" However, if the centralized interface provided insufficient feedback or failed to offer detailed diagnostics, participants moved toward physical troubleshooting, such as using the vendor app or physically interacting with the device.

Control schemes with very few to no proxies played a crucial role in this context. Many participants described them as more reliable and informative when devices failed. For example, interview participant P5 said they would open the device-specific app to get a clearer view of what had gone wrong. Others, like P8, relied on physical actions like power cycling: "*And if that doesn't work, I'll just switch it off and back on again.*" These tactics were rarely described as first-choice methods but were commonly used once central or automated systems proved insufficient.

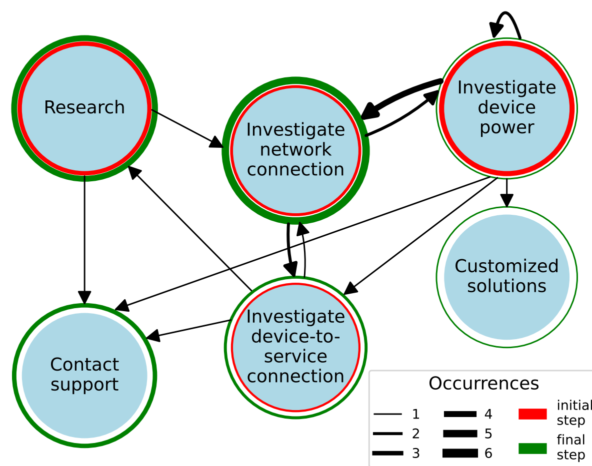
Survey data mirrored these patterns. Figure 3a shows that 50% of participants restarted the device as part of their troubleshooting process, while 36% restarted or reconnected their device to the internet. Only 12% reported contacting tech support, indicating that most participants tried to resolve issues independently using a set of well-practiced responses. Figure 3b visualizes the common sequences users followed when troubleshooting. Initial steps often included power or connectivity checks, followed by deeper exploration through brand-specific apps, web research (22%), and more.

Participants also described emotional responses to persistent failures. For some, repeated breakdowns led to troubleshooting fatigue or abandonment. Interview participant P6 shared that a voice-controlled TV consistently misunderstood commands, leading them to eventually "*give up on it for a long time*" before replacing the device entirely. While only 9% of survey participants said they returned a device after an error, and 11% said they gave up entirely on a type of device, these moments marked important shifts in how users related to control schemes and whether they were willing to continue adapting.

Notably, participants' troubleshooting practices revealed that they often understood control methods as part of the problem space. For instance, P7 mentioned researching whether thermostat failures were due to device issues or miscommunication with their central control platform. When troubleshooting failed, users sometimes restructured their systems–switching platforms, removing routines, or replacing devices that didn't integrate well with others, as P5



(a) Percentage of participants utilizing each troubleshooting step. Each participant may only contribute once towards this metric.



(b) Troubleshooting step sequence. A node has a red ring around it if it has been described as an initial step in at least one participant's troubleshooting process. A green ring around a node means it was the final step of one or more participants' troubleshooting process. An arrow links two nodes A, B if at least one participant has gone from step A to step B. The line width of each ring or arrow represents the absolute number of its occurrences across our participants' processes.

Figure 3: Troubleshooting steps results from survey responses. As many are experienced users of their smart home setups, this may subtly shape the emphasis on certain troubleshooting approaches depicted here.

said: "*[My Kasa switch] was not able to integrate correctly. I had to pair it every time with the Google Home App and every time it would disconnect. And then I had to do it again. And it was painful. So I ended up returning the device.*" Similarly, P1 described how after an extended period of troubleshooting, they had *"resigned myself to just using the app."* In these experiences, participants found themselves forced into a particular control method, rather than having autonomy over how they *wanted* to control the device.

Overall, device failures and errors forced participants to switch between control schemes, uncovering limitations and prompting changes to their routine. While many relied on layered troubleshooting strategies, persistent problems sometimes led to long-term shifts in user behavior, feature abandonment, or restructuring of control ecosystems. These findings show that the smart home control spectrum is not only navigated during setup or steady-state use but also actively re-navigated in moments of breakdown.

4.4 Discoverability Failures across the Control Spectrum

Our interviews reveal that users frequently struggle to realize their intended goals with smart home systems, not because functionality is absent, but because its integration or accessibility—whether in terms of location, when it is available, or how it is surfaced—is unclear.

We identify five recurring categories of confusion and elaborate on each below. Table 5 summarizes all these categories, including relevant quotes from interviewees.

1) Fragmented control between central and vendor apps. Participants' mental models of control schemes often assumed that central hubs (e.g., Google Home, Alexa) could fully replicate vendor apps. When this expectation was violated, users had to switch between apps, leading to uncertainty about which scheme truly "owned" a functionality. E.g., Table 5–row 1 shows that Nest and Google Home have different features.

2) Hidden or hard-to-find features. Even when functionality existed, participants' expectations of where it should reside did not align with the app design. Features like routines or shortcuts were buried in menus, clashing with the mental model that everyday actions should be easily accessible. Users who rarely engaged with a particular scheme were especially likely to misremember or misinterpret where to look, e.g., having to locate a feature all over again every time they need it (Table 5–row 2).

3) Missing or partial integrations. Participants often assumed that devices sharing a hub or assistant would integrate seamlessly. When integrations were absent or partial, like camera actuation features (Table 5–row 3), this violated their mental model of the hub as a universal coordinator, eroding confidence in central control.

4) Ecosystem lock-in and workarounds. Users expected that devices across ecosystems could be mixed and matched. When these expectations failed, e.g., accessing IKEA devices from Hue apps (Table 5–row 4), they turned to workarounds such as third-party apps. These choices reflect not just technical limitations but users' mental models of what a "smart" home should enable.

5) Multi-user household challenges. Participants assumed that central routines or device automations would be shareable within a household. When vendor apps restricted access to a single account, this clashed with their model of a shared home environment, driving them to central hubs despite their own limitations. For instance, Tapo does not allow multiple household members (Table 5–row 5).

Across all categories, confusion arose less from the outright absence of functionality than from mismatches between participants' mental models and system design. Users expected hubs to be universal, apps to be intuitive, integrations to be complete, and households to be collaborative. In practice, however, they lacked a clear taxonomy of where functionality resides, how it should be invoked, and whether it integrates with other devices. These findings show that confusion is not just an isolated annoyance but a systemic barrier that reshapes how users perceive and navigate smart home control schemes, influencing when they trust central control, fall back to vendor apps, or abandon features altogether.

5 Discussion

Our survey and interview results (Sec. 4) show that smart home owners *navigate across* layers of proxy-based control, from central, i.e., several proxies, to physical control, i.e., zero proxies. as they orchestrate intent, and that the spectrum of smart device control plays a major role in user preferences and experiences, echoing the intuition by Brush et al. [30], Davidoff et al. [43] that homes should support everyday experiences rather than mere device operation. We connect these findings to HCI and ubiquitous computing by reframing control as *transition* along two spectra (Figure 4): (1) the *locus of execution* (from centralized to local), which reflects where a device action might be initiated from, whether through a hub or on the physical device, and (2) the *exposure of the system* (from seamless to seamful), i.e., how users perceive device control, from having to set-and-forget to having fine-grained control of the devices. This *dual-spectrum* view helps explain under what conditions people keep infrastructures invisible and when they purposefully reveal seams, and it grounds actionable implications for hubs, vendor apps, and household governance.

These spectra are orthogonal: a person can operate centrally and hide seams for low-stakes routines, then shift downstream and reveal seams to accomplish a fine-grained adjustment that the hub cannot reach (e.g., voice can stream a camera feed, but pan, tilt, and zoom (PTZ) requires the vendor app). Our participants' perspectives revealed the importance of designing for these transitions, rather than a single point. We expand on this below, with examples.

5.1 From device control to orchestrating transitions

In the consumer landscape, platform marketing emphasizes *seamlessness* and *invisible* infrastructure; for example, Matter aims to make multi-brand integration routine, promising an architecture that "just works" in daily use [151]. Users move freely along the spectrum, guided by situational factors such as perceived convenience, perceived reliability, and task.

While these narratives shape expectations, Bell and Dourish [26] argue that the seamless vision of ubiquitous computing remains less of a lived reality. In HCI, seamful design argues that exposing implementation gaps can be useful for diagnosis and adaptation [33, 34], while infrastructure studies remind us that infrastructures are ordinarily taken for granted and become visible at breakdown, adoption, or scaling [125]. Managing and constructing a smart home space requires users to constantly weigh tradeoffs between convenience and control, automation and transparency, and speed and flexibility as discussed in Section 2.1.

We mapped participants' interaction journey between physical and central control onto two orthogonal spectra that distinguished *where* individuals are operating and controlling their devices from, and *how* people are handling rough edges.

Category	Description	Example Quote
Fragmented control (central vs. vendor)	Users unsure which interface (central vs. vendor) exposes functionality.	*"In the Nest app you can see the history... but not on Google Home."* (P5)
Hidden / hard-to-find features	Poor discoverability of routines, shortcuts, or advanced options.	*"Every time I go to set a routine, I have to relearn it."* (P3)
Missing or partial integrations	Features expected to exist but absent or incomplete.	*"I can stream the camera, but I can't move it with voice."* (P5)
Ecosystem lock-in & workarounds	Vendor ecosystems discourage cross-platform setups; workarounds reduce control.	*"They assume you're Hue or IKEA exclusively."* (P7)
Multi-user household challenges	Routines or settings tied to single accounts, limiting family use.	*"If I add a routine in the Tapo app, [my wife] can't change it."* (P5)

Table 5: Taxonomy of user confusion in executing smart home functionality.

The locus of execution spectrum: Proxy-based control ↔ Physical control. The *locus of execution* refers to the level of abstraction at which smart home users control their devices [110, 113]: whether controlling them through a hub/ecosystem (central; shared scenes, routines, voice assistants) or invoking actions through the device-specific app (local; vendor app, on-device UI, physical interface). Higher-level proxy-based loci tend to provide *breadth* across devices and people; local loci provide *depth and assurance* via device-specific features, histories/logs, firmware access, and tangible fallbacks [36, 39].

Movement across loci is common. In our data, shifts toward physical control were precipitated by capability ceilings at the hub, device-specific needs (e.g., camera PTZ control or schedule histories), governance constraints (account scoping, co-editing), and lifecycle events (router/ISP swaps, device replacement). For instance, participants with larger installations described relying on a hub for routine scenes yet still opening brand apps to adjust advanced parameters or to locate firmware updates (Sec. 4.2). These participants treated proxy-based control as a default broadcast channel for tasks, but reserved physical or local controls as authoritative sources about specific device states or capabilities.

The seam practice spectrum: Seam hiding ↔ Seam revealing. In an infrastructure such as a smart home, *seams* are the imperfections and complexities of systems [95]. While the locus of execution spectrum captures *where* users act in the infrastructure, the seam practice spectrum captures *how* they choose to manage the visibility of that infrastructure as they move across layers. Rather than treating seams as a fixed property of the system, our data show seam practice as an ongoing, situated accomplishment: participants actively decide when to keep control flows invisible and when to expose the underlying infrastructure to get leverage. This everyday seam hiding reduces cognitive and social overhead (e.g., making it easier for other household members to just talk to the assistant rather than learning multiple apps), and resonates with prior critiques of frictionless interfaces [70, 76].

When smart device expectations failed, participants engaged in deliberate seam revealing processes that went beyond what prior seamful design examples [35, 88]. Participants systematically peeled back layers. They start at a high-level proxy (hub or voice), then open vendor apps to inspect device states, history, or logs, and finally manipulate device-local controls or power to test hypotheses about what was failing (Fig. 3b). By *appropriating* seams as diagnostic handles, validating prior work describing how technical exposures serve as resources for sensemaking during breakdown [27, 42]. Our dual-spectrum lens (Figure 4) frames **seam hiding as the default when proxy-based locus of execution is stable, whereas seam revealing is a manual intervention for users to regain precision, understanding, or accountability when that locus fails them.**

Transitions as design. By creating this dual spectrum, we notice that movement across control layers should be preserved rather than eliminated; this gives individuals agency to trade off convenience against fine-grained control, accountability, and recovery. Rather than arguing the control scheme for "hub vs. per-brand" claims, the agency for participants to move across the spectrum is a less explored design space where participants adopted *central + invisible* configurations for repetitive, low-stakes tasks; they shifted toward *physical + seamful* configurations for fine-grained control, accountability, or assurance. This perspective also addresses timeliness critiques: even as standards evolve, households will continue to encounter breakdowns, maintenance, mixed accounts, and perceived risk—conditions that *require* traversing axes.

5.2 Smart homes as information ecologies of control

Our work reveals that when a user considers adding or modifying devices in their home, or even interacting with their home, it is not just the devices, but the modes of control that matter. The IoT/smart home device marketplace typically frames value in terms of devices with "more" or "smarter" features [24, 104, 128]. However, our findings show that the ways those devices can be controlled are equally important for how people evaluate and live with smart home devices over time. Put more technically, smart homes are often described as a single coherent system [38, 53, 148]; however, our findings suggest a different framing, where smart homes are thought of as information ecologies of control. While traditional information ecology theory focuses broadly on human-technology configurations [94, 98], participant experiences show that the loci of execution also function as a significant part of this ecology. Households cultivate combinations of these "species," or groups of devices and associated control modalities (such as P5, who had

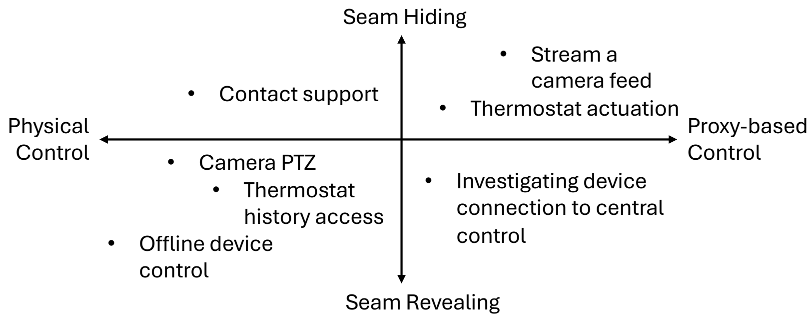


Figure 4: Dual smart home control spectrum. The proxy-based vs physical control axis refers to the locus of execution spectrum, whereas the seam hiding vs revealing axis refers to the seam practice spectrum. The user can navigate the locus spectrum based on their needs, whereas the vendors give limited navigability of the seam spectrum, almost enforcing how users will experience their control interfaces' integration.

different loci depending on the room of their house), and adjust them as their setup, routine, and environment change.

Movements along the locus of execution spectrum are less about isolated interface preferences and more about ecological preference. Adding a new device, changing homes or internet providers, experiencing repeated failures, or other external stimuli prompted participants to re-balance their control ecology. This included disabling a routine (P3), abandoning a hub/device (P5), or falling back to physical device control (P8). Furthermore, troubleshooting was revealed as a moment where not only a malfunctioning device was examined, but the entire smart home ecology.

Participants continuously evaluated their smart home ecology in terms of its usefulness and ability to integrate into their day-to-day lives. This evaluation helped participants identify which loci of execution they were willing to depend on. By framing smart homes as evolving information ecologies, which include loci of execution, we shift attention from evaluating individual products to understanding how they participate in and reshape household ecologies. Next, we translate this lens into concrete design implications and open questions for future smart home systems.

5.3 Design implications and open questions

A dual-spectrum stance shifts attention from choosing a "best" locus to *supporting transitions* to making crossings legible, low-friction, and accountable. Importantly, *control loci do not map one-to-one to physical devices*: the hardware could contain several loci (third-party app vs. second-party app vs. first-party physical control), and a routine state can be "hidden" while device state remains visible or vice versa.

Design hubs for transparency and ceilings. Centralized interfaces should disclose *capability ceilings* and provide explicit *bridges* to device-local depth. When a hub cannot reach feature/parameter-level control (e.g., camera PTZ, thermostat histories [127]), the UI should indicate this and provide a deep-link to the native panel. This reduces "hunt-the-setting" failures, lessens the mental burden of switching platforms and remembering device names, and matches observed escalations in Sec. 4.2. Designing away these transitions in pursuit of a perfectly seamless hub risks trapping users at a single, brittle locus of execution with no graceful way to regain control when expectations are violated.

Provenance and interoperability legibility. When scenes (predefined multi-device routines) span mixed brands or partial standards support, displaying a pre-flight check with the "weakest link" highlighted and present guided degradation paths (e.g., "device offline—try local control"), along with *who executed what, where.* Provenance-forward feedback increases trust when hub-instantiated actions trigger device responses, helping smart home users construct mental models and accelerating troubleshooting paths we observed in Sec. 4.3. This approach prioritizes coverage over device-specific depth. This works well for routine, low-stakes state changes and whole-home coordination; when a capability ceiling or failure is detected, the pre-flight/provenance cues a *depth-first* pivot (e.g., open vendor app, use a physical control) to resolve the outlier. For example, centralized interfaces should be honest about what they cannot accomplish and point users to the right vendor/device-specific path when they hit those limits.

Governing households while respecting privacy. Proxy-based interfaces should treat routines and devices as shared resources with roles, co-editing, and change histories by default (Table 5). Revealing device states and last-known state offers tangible backstops for high-stakes actions, helping smart home users navigate across the two spectra. For example, prior HCI work shows users prefer simple, proactive controls in the home and benefit from tangible mechanisms for privacy and assurance [10, 46, 142]. This design echoes the delicate balance wherein tangible interfaces reveal how household members shift between central and local loci and between hiding and revealing seams. In practice, this requires deeper engagement with stakeholders in the smart home, especially those whose voices are traditionally unheard (children, secondary users, nannies, etc.), as current spectra navigating designs often hurt these users most [16, 28]. Working with such users and including them as an integral part of the design process helps establish both smart home devices and their corresponding control spectra as "sources of empowerment", which can make moving between control methods in the home a less daunting experience [146].

Open Questions: Evaluating Transition Quality. Our work opens up two further directions on transition quality. First, there is a need to characterize what information and granularity different user roles (and levels of expertise) need at the moment of crossing to be effective without overload. Second, there is a need to develop evaluation metrics for transition quality: e.g., time to successful handoff; rate of stranded actions; clarity of ceilings and provenance; and recovery burden after lifecycle events (Sec. 4.1).

6 Limitations and Future Work

Our methodology used surveys and interviews to elicit responses from participants regarding their past experiences and current perceptions.

Future research should look to expand on this work through studies that focus on clear categories of smart home owners, based on characteristics such as location (e.g., temperate zones vs. frigid vs. coastal), size of home (apartment vs. single-family home vs. mansion), and other factors. In addition, our survey respondents and interview participants likely skewed more towards a tech-savvy population, especially given that we recruited using Prolific [11]. Thus, future work can also explore perceptions and experiences of users who may be overall less aware of smart home device capabilities. In addition, surveys and interviews rely on participants to reflect on their interactions with smart home devices, rather than having the research team observe these interactions directly. Future work can utilize more observational methodologies and ethnographic studies to expand our results by providing additional context on how participants control their devices.

Our results are tied to the technology mix used during data collection. However, as technology evolves and matures, and new standards such as Matter [151] emerge, future work can incorporate our broader implications and findings into its design. Interaction patterns related to user transitions across the control spectrum will remain even as such standards develop, which will require future research to use our approach to understand *how* users' interaction patterns change with these standards in place.

Our work focused primarily on a single user in a smart home; while participants did discuss how other users in the home influenced their perceptions and preferences, our study elicited only one opinion from each smart home. Previous work has described smart homes as more sociotechnical systems, often containing multiple users with diverse experiences, desires, and perceptions [62]. Future work should more explicitly consider the sociotechnical nature by conducting studies with multiple users in the same home, examining how control schemes and methods in a single household affect different users in a smart home, and building upon the perspectives elicited in this work.

7 Conclusion

In this paper, we present an investigation into how and why smart home users navigate the spectrum of control schemes, ranging from physical device interaction to proxy-based central control, based on context, goals, and device constraints. Our survey and follow-up interviews show that users continuously adapt their smart home control strategies, as well as their smart home setups and future device procurement strategies, as they experience different levels of smart home control. Rather than treating smart home control as a static preference, our work highlights how it is a dynamic, reflective, and often labor-intensive process. Our findings suggest that users actively weigh tradeoffs between convenience, reliability, precision, and cognitive load when choosing how to control their devices. Our work emphasizes that *future systems should not only support multiple control schemes, but also actively (perhaps proactively) guide the user's movement across them.* Similarly, researchers should also reframe their evaluation metrics and system assumptions of smart home control to reflect the temporal and spatial heterogeneity of real-world usage. Via a deep dive into the user perspective of smart home control, our work is an important initial step towards moving home management systems from being device-centric towards becoming truly user-centric.

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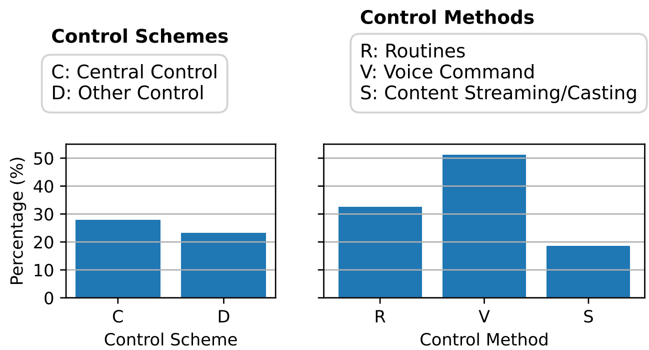
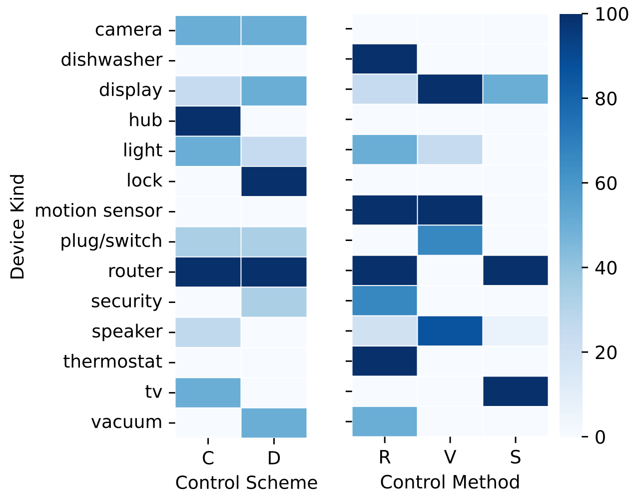
A Further Results

In this section, we present further results from our survey responses, particularly with regard to how the participant used a particular device they interacted with often[7]. Among control methods, voice commands were the most popular (Figure 5a), particularly among participants who owned less than 10 devices. The popularity is likely due to the simplicity and ease of issuing commands via voice for certain groups of devices, such as speakers and displays. Routines were the second most common control method. They were

[7]See supplementary material for the full survey. Within the survey, we used terms like central and per-device control that the participants can easily understand before the interview stage. We later analyzed the survey data from our spectrum-based lens.



(a) Percentage of participants using each control scheme/method.



(b) Percentage of participants using each control scheme/method vs. device kind. Each cell's color shows the percentage of participants falling into it who choose the respective control scheme or method. Participants may refer to a device with a different description from how they most commonly use it, leading to an occasional discrepancy between the device kind and the control method used to interact with it; for example, a participant may refer to Alexa as only a smart speaker, when it is also a Hub [63, 124, 140].

Figure 5: Percentages of participants using each control scheme/method independently and in relation to the interacting devices. The percentages for the different options of control schemes and methods do not add up to 100% since the participants could provide multiple answers.

used more consistently by participants with a moderate number of devices, typically owning more than 15 devices (Figure 2). Content streaming and casting also maintained a steady usage across participants, likely driven by the types of devices they owned, such as smart TVs or speakers, which are inherently designed for such interactions (Figure 5b).

As Figure 5b shows, control scheme preferences differ across device types. Non-central types of control remain popular among participants with devices that require more granular or custom interactions, such as security systems or vacuums, where direct control over specific features is necessary. We also observe that participants usually choose to control a device exclusively with either routines or voice commands but not both.