An Iterative Approach to User-Centered Design of Smart Home Systems

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Abstract. Recent technological advances have brought smart homes to the forefront of innovation, transforming the home into a platform that can support residents' connectivity and care. Smart home systems promise a more convenient and comfortable lifestyle for people across ages and of different living arrangements, for example improving older adults' ability to safely age in place. The present study aims to illustrate how an iterative design process with user involvement and evaluation in real-world settings could be used to inform and facilitate the development of an integrated, remotely-deployed smart home technology system. An experimental smart home prototype was developed to demonstrate a secure, scalable service model addressing future home service needs. The process was informed by user-centered design methods and iteratively refined based on feedback from target users. This study demonstrates key considerations for design researchers and practitioners in designing user studies that can provide a comprehensive, holistic understanding of the user experience and, in turn, most effectively inform future design decisions.

Keywords: Iterative Design · User-Centered Design · Smart Home Systems · Aging in Place · Field Study

1 Introduction

Recent technological advances have brought smart homes to the forefront of innovation, transforming the home into a platform that can support residents. As of 2020, the smart home market was expected to reach USD 317 billion by 2026, up 5% from pre-COVID-19 forecasts [1].

User-centered design is a framework for a design process that optimizes the usability and acceptance of a system by involving users in the development of a product [2, 3]. According to Gulliksen et al. [4] and Buurman [5], when using a user-centered design approach, products should be developed based on an interdisciplinary design team; knowledge of users' needs, abilities, attitudes, and characteristics; and an iterative approach to design with active user involvement. Iterative design is defined by the World Design Organization [6] as "a design methodology based on a cyclic process of

Q. Gao and J. Zhou (Eds.): HCII 2023, LNCS 14043, pp. 3–16, 2023.
https://doi.org/10.1007/978-3-031-34917-1_1

prototyping, testing, analyzing, and refining a product or process. Based on the results of testing the most recent iteration of a design, changes and refinements are made."

Another important factor in user-centered design is the involvement of a diverse range of users in the iterative design and evaluation process. Some demographic groups, such as older adults, have historically been underrepresented in user research. Older adults can benefit greatly from adopting smart home technologies [7]. Various smart home technologies have the potential to fulfill common needs of older adults including everyday tasks such as personal care and housework, social connectedness and companionship, health monitoring, home security and maintenance, and more [8]. Technology-enabled support for these tasks can facilitate aging in place, allowing older adults to remain independently in their homes for longer [9]. Thus, older adults have the potential to be key users of smart home technologies, but their exclusion from user research results in products that may not meet their unique needs and abilities.

Past research has explored the benefits and challenges of user-centered design, demonstrating the value of participatory and iterative approaches to designing smart home systems for older adults [10–12]. Wilson et al. [13] evaluated the usability of a robot system designed to provide in-home support for individuals requiring assistance with basic and instrumental activities of daily living (ADLs) in the smart home environment. The system was tested with target users in a smart home testbed environment and then collecting and analyzing feedback. Other research has explored the co-creation approach, e.g., leveraging additional stakeholders; Ghods et al. [14] described the iterative design of an interactive graphical interface for remote in-home monitoring of aging patients, as informed by feedback from an experienced set of health professionals who used the system in a real-world setting. Results indicated that this approach resulted in improved usability over iterations.

In order to most effectively assess products, user feedback is most valuable when research takes place in real-world environments. For example, in Wilson et al. [13], the system was tested in a testbed environment and the procedure was reliant on "scripted activities." Although participants provided valuable feedback that informed a better understanding of target user needs, researchers outlined the needs to test smart home systems in more realistic settings (e.g., the home) over longer periods of time such that the aptitude of the system to meet real-world user needs could be more accurately assessed.

Smart home research involving user testing in in-home settings has traditionally required researchers to make in-person visits for installation, participant training, ongoing support and maintenance, data collection, and study closure [15]. However, the COVID-19 pandemic has rendered these in-person visits less feasible. Thus, new approaches to system deployment for user testing that allow for self-installation and remote deployment have been required. Although potentially complicated in a technical sense, the need for new approaches presents an opportunity to design procedures that more closely reflect a realistic smart home experience.

The present study aims to illustrate how an iterative design process with user involvement and evaluation in real-world settings could be used to inform and facilitate the development of an integrated, remotely-deployed smart home technology system.

2 The Iterative Design Process

To inform the selection of components and the design of features, implementation, and development for a first prototype, key user needs were identified based on a review of past literature, user interviews, and a large-scale online survey [16]. The initial prototype was built with these user needs in mind then refined based on user feedback from an in-home pilot study. With the refined version 1 prototype, an in-home field study was completed to collect insights to inform future design. A second version of the prototype implemented new design considerations based on feedback from the main field study and researcher learnings. In the future, the second version will be piloted and fielded.

The overall design process, which can be conceptualized as an ongoing cycle of human-centered and iterative design principles, extends upon the design thinking approach described by IDEO [3] and Nielsen Norman Group [17]. The process is depicted in Fig. 1.

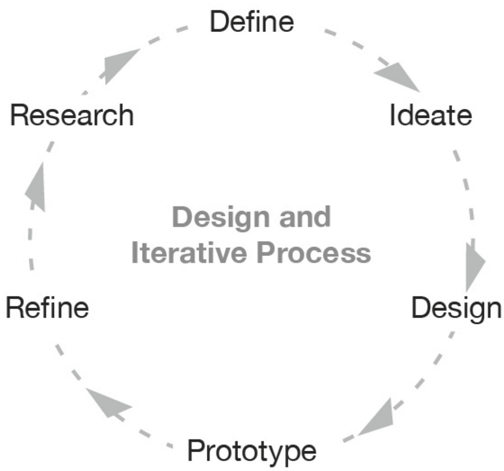

Fig. 1. Overall depiction of the cyclical design and iterative process.

2.1 Development of the First Prototype

Initial Ideation and Concept Development

The prototype was built with the goal of providing users with useful information about themselves and their home, as well as companionship. Logistically, the system would be low-cost and efficient, with advanced data analytics capabilities. It would also be scalable for future research and possible to deploy remotely.

In addition to considerations regarding remote deployment, one key goal was to achieve system versatility for supporting various smart home use cases. Due to the vastness of possible use cases and user needs, a targeted set of use cases and related user needs was required. A large set of use cases was identified based upon a set of user interviews, a large-scale online survey [16, 18], and a review of past studies [15]. Then, eleven diverse participants were interviewed about their routines, pain points, and expectations for smart homes. Ten key needs and concerns related to safety, convenience, self-care, and family care were identified and analyzed alongside the earlier findings. Finally, with feedback from industry experts, three of the most practical and feasible use cases were selected. The final set of use cases was safety and security, caregiving needs, and home energy and environment control. The overall process of identifying user needs is depicted in Fig. 2.

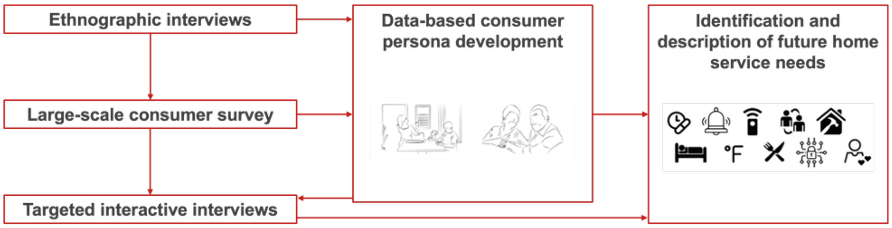

Fig. 2. Process of identifying user needs before condensing to a set of three.

The initial physical prototype consisted of a set of low-cost, off-the-shelf hardware components that could facilitate awareness of and provide data about the home environment. An internet-connected power strip was selected to collect information about power usage. Sensors addressing motion, light, sound, air quality, temperature, and humidity were affixed on a wooden frame, creating a centralized "sensor module" for easy shipping and installation. The power strip and sensor module are shown in Fig. 3. An Android tablet was chosen to house the internally-developed dashboard application and serve as the user interface. The hardware components were integrated with the dashboard application using the IFTTT[1] platform.

The user interface was designed to provide information that allows users to understand in-home activity and to support the final set of use cases. Six features were selected and developed for the dashboard application: Today, Climate, Activity, Energy Use, Alerts, and Wellness. As depicted in Fig. 4, these features leverage data from the hardware (e.g., sensor module and power strip) in addition to user input on the dashboard.

An iterative process was used to design the dashboard interface, during which mockups were drawn (see Fig. 5) and evaluated based on the identified user needs. The finalized dashboard application interface, as shown in Fig. 6, summarizes information about each of the features and relevant data. A menu bar is static on the left side of the interface, and users can use these buttons to seek more information about each of the features and navigate between pages at any time.

As depicted in Fig. 7, back-end dashboard support was implemented via AWS EC2 server optimization and stabilization for concurrent data transactions, and HTTPS-based secure data transmission.

[1] If This Then That – An online digital automation platform for integration of devices, apps, and services using conditional statements. https://ifttt.com/.

Fig. 3. The power strip on the left and finalized sensor module on the right.

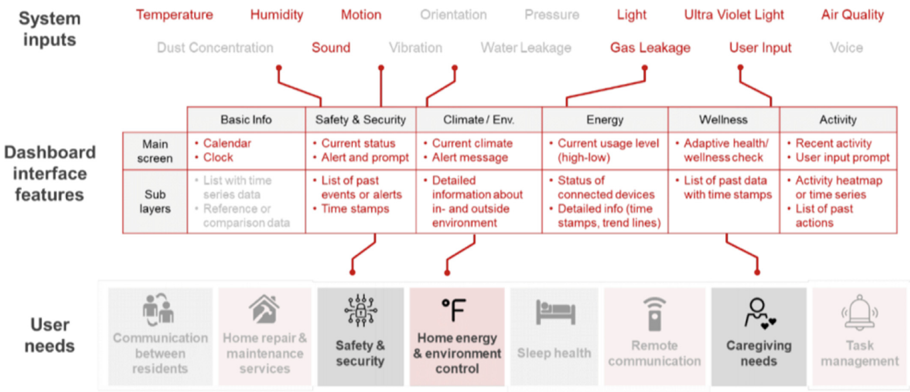

Fig. 4. Depiction of relationships between user needs, system inputs, and interface features.

The prototypes were accompanied by a comprehensive user instruction document to guide participants through the installation and usage of the prototype in an accessible, user-friendly manner. The document consisted of plain-language, step-by-step instructions and troubleshooting advice for potential obstacles, as well as helpful illustrations and screenshots. The document was designed based on a full walkthrough of the installation process and relevant user preferences as identified in earlier interviews and surveys.

Refining the First Prototype based on User Feedback

The first prototype was refined based on feedback from two small pilot studies. The main intent of the first pilot study was to gather insights and feedback that could inform modifications to the installation and operation processes before piloting the larger-scale field study. The prototypes were packaged and delivered directly to a convenience sample of 8 participants' homes. The goal was to determine whether participants were able to install the kit themselves without onsite support from researchers. After some minor

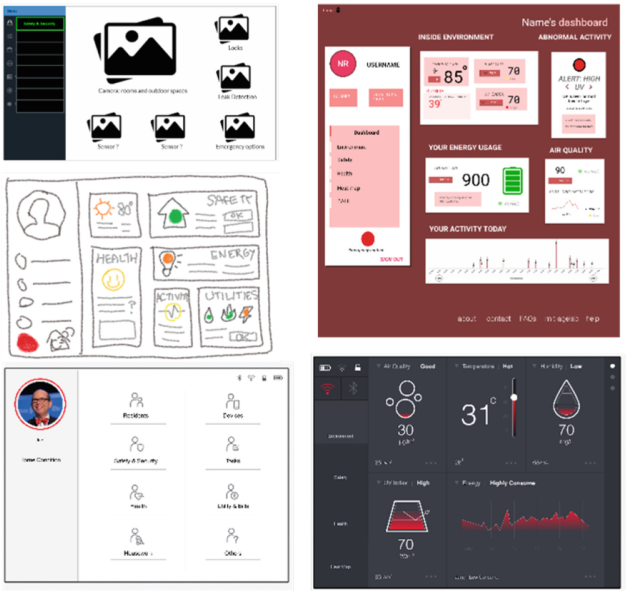

Fig. 5. Various mockups for the dashboard application interface.

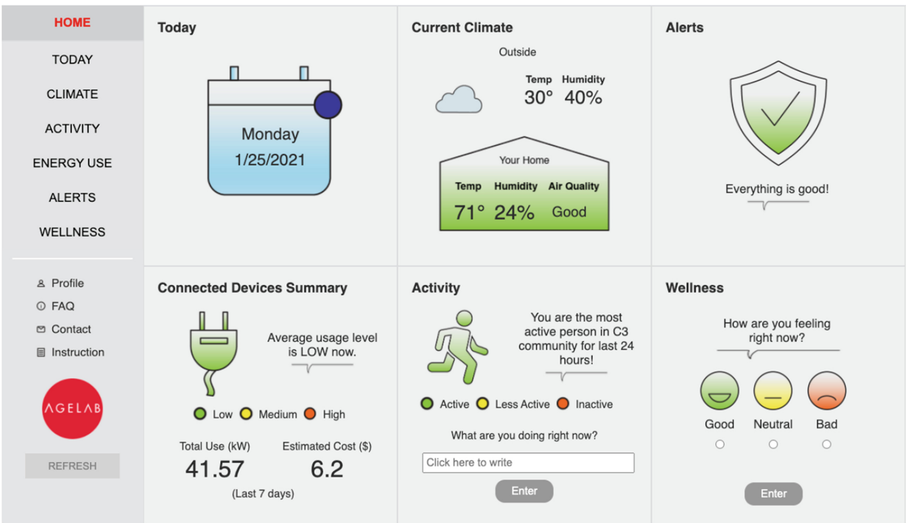

Fig. 6. The finalized Homepage for the dashboard application interface.

refinements to the self-installation process based on the initial feedback, 5 externally recruited participants completed the second pilot study in accordance with the field study procedure as depicted in Fig. 8. These pilot study participants' characteristics are described in Table 1.

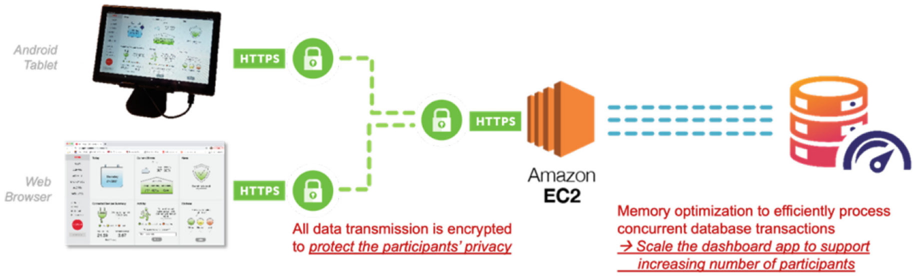

Fig. 7. Back-end implementation.

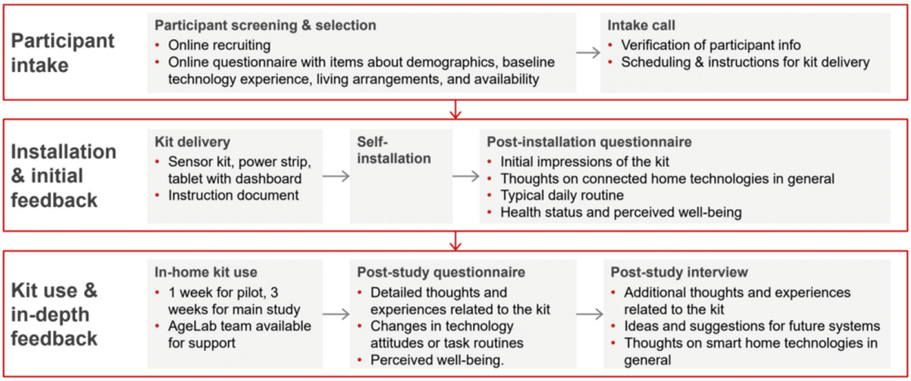

Fig. 8. Field study procedure.

Survey results indicated that, although participants found the self-installation process to be quite easy, older participants found the self-installation process to be more challenging than younger participants did. Many participants cited particular issues with installing the sensor module. Because the camera on the included Android tablet was low-resolution, the participants who used the tablet reported challenges with the QR-code-based pairing of the sensor module. As a result of this unforeseen challenge, researchers made the decision to complete this pairing prior to shipping to participants such that participants would only need to reconnect the paired system to their WiFi upon its arrival. Nonetheless, ongoing challenges and failures with this portion of the process resulted in frustration and made the overall installation process considerably more time-consuming, indicating a need for more detailed instructions and troubleshooting guidance in the instruction manual.

Aside from challenges with the sensor module, survey ratings and interview feedback suggested that the manual was successful in facilitating a seamless installation process. One participant said: "My compliments on the instructions. Nicely done, step by step, clear and photos were awesome. Nice touch putting the email login info at the top right corner. This is all thinking out loud, but it may reflect some elements of what the public might be thinking too." Minor improvements were suggested to indicate where components should most ideally be placed in the home. In addition, survey results showed that older participants had difficulties in using small hardware components, suggesting the need to improve the design and interface of the sensor module.

Table 1. Demographic information for participants of the field study; both the pilot study and the main study.

Study category	Birth year	Gender	Location[a]	Household size	Residential environment	Technology savviness[b]
Pilot study	1997	Female	MA	2	Urban	High
	1953	Female	MA	1	Suburban	Med-high
	1995	Female	IN	1	Suburban	High
	1966	Female	MA	2	Suburban	Med-high
	1959	Female	MA	3	Suburban	Low-med
Main study	1994	Female	MA	3	Urban	Low-med
	1953	Female	MA	1	Urban	High
	1977	Male	MA	5	Suburban	High
	1986	Male	MA	4	Suburban	Med-high
	1934	Male	AZ	1	Urban	Med-high
	1940	Male	NY	2	Suburban	Med-high
	1995	Female	MA	2	Urban	High
	1952	Female	MA	1	Urban	Low
	1990	Female	CA	3	Suburban	High
	1974	Female	OH	2	Suburban	Med
	1977	Female	GA	3	Suburban	Med-high
	1934	Male	WA	2	Urban	High
	1950	Male	FL	2	Urban	Med-high
	1984	Female	NC	5	Suburban	Med-high

[a] State name abbreviation. All participants lived in the United States
[b] Assessed using three questions regarding technology experience and attitudes: 1) How would you rate your overall level of trust in technology? (Answer options ranging from "very low trust" to "very high trust"); 2) How interested are you in learning about new technologies? (Answer options ranging from "not interested at all" to "very interested"); and 3) In general, how would you rate yourself as being an avoider or an early adopter of new technology? (Answer options ranging from "avoid as long as possible" to "try as soon as possible")

Finalizing the Prototype and Gathering User Evaluations

Based on user feedback received during the pilot, various changes were made to finalize the prototype before beginning the field study. The sensor module frame was modified to add a plastic covering over the sensors. This alleviated some of the dexterity-related challenges experienced by older participants and added a layer of physical protection to the individual sensors, some of which had been damaged in shipment. To address the possibility of future changes to data privacy-related requirements, the architecture of the prototype was refined to more easily accommodate new changes. The Google Home voice assistant was excluded; first, it was solely an extra mode of interaction without supporting any use cases, and second, it presented some privacy concerns. The instruction document was updated to provide more examples and clarity, with specific attention to the section focused on installing the sensor module. The dashboard features remained the same.

A total of 14 technologically- and demographically-diverse participants received the newly-updated prototype and went through the field study procedure (as depicted in Fig. 8). Participants provided feedback via surveys and an interview.

Although the exposure to the kit resulted in significantly greater willingness to adopt new technologies, the dashboard features did not offer high practical value to participants [19]. Participants rated the climate, energy use, and menu bar features as most useful; they rated participant support, alerts, and wellness the least useful. Participants rated the kit highly for ease-of-use and the self-installation process was generally successful for most participants.

2.2 Making Revisions for the Second Prototype

Design Implications and Recommendations Identified from the Previous Version In designing the second version of the prototype, design implications were largely informed by participant feedback from the field study as well as limitations identified by researchers throughout fielding. Some general qualities of the prototype were demonstrated with version 1, but desired to be improved for version 2. These qualities included interactivity, privacy, scalability in development and deployment, and ease of use. New priorities for version 2 included customizability in features and interface, additional convenience and information features for health and housework support, and additional security features.

Design implications for the second prototype were largely informed by the results of the field study. An updated set of features and functionalities for the dashboard application was required. An effort was made to maintain and improve the features from version 1 that participants liked and found useful (e.g., indoor and outdoor environment information, device use monitoring, and activity level indicator). Possible additional features suggested by participants involved needs related to task management (e.g., calendar, shopping list), device management, wellbeing monitoring, health statistics, and multi-room activity recording. Participants also expressed a desire to be able to interact with a more advanced set of data collection and analysis capabilities (e.g., to view both real-time and historical data displays). Participants also suggested implementing the ability to personalize the dashboard according to their preferences; for example, to hide a feature that is not relevant to their needs.

Researchers also identified some potential technical design changes throughout the field study. Limitations in the development of the prototype included limited and static sensing capability and data stream, reliance on a central server in the cloud, and unoptimized software implementation and hardware build. Updates to the display of information were done infrequently. There were also logistical restrictions in the deployment and management of the prototype throughout the field study. Between participants, manual code babysitting and resetting of the kit was required, which resulted in a long turnaround time (e.g., kits needed to be shipped back and manually reset before being shipped to the next participant).

Selection and Integration of Components and Features
A small collection of individual, off-the-shelf sensors were selected to replace the original sensor module. Using separate sensors allows participants to place them as desired throughout their home. The off-the-shelf sensors also reduce the need for manual technical maintenance, facilitating a more streamlined integration process from a development and installation standpoint. The same power strip and tablet were kept based on minimal issues from a user and research standpoint. The main peripherals, power strip and sensors, are shown in Fig. 9.

Fig. 9. Selected hardware for version 2 of the kit. Wifi-enabled power strip (top), Zigbee-enabled motion sensor (bottom left), and Zigbee-enabled air quality monitor (bottom right).

To address various needs identified by both users and researchers, and to test and evaluate how an alternative system may impact users' experiences, a decision was made to create a new dashboard application and implement a new system of integration for the second version of the kit. The new dashboard application was developed and integrated with the hardware using Home Assistant, an open source software for home automation, and a Raspberry Pi and Zigbee hub host the instance of Home Assistant.

The Home Assistant platform is designed for easily connecting to a large variety of off-the-shelf devices and systems and supports increased scalability compared to the previous dashboard, which was optimized to fit selected components. The change to this system may address needs identified by researchers around optimization of the software implementation, deployment, and management; for example, there is no longer a need for manual code babysitting and resetting throughout deployment. Additionally, for users, the change may reduce the complexity of and avoid problems with the setup process by allowing off-the-shelf components to be paired to the interface by researchers prior to shipment.

The system also addresses concerns expressed by many field study participants regarding privacy and data security. Some had concerns related directly to the kit, and others had concerns related to smart home technology in general. The new implementation may mitigate these user privacy concerns by utilizing a more familiar platform with an emphasis on local control and privacy, and by storing user data locally rather than on a cloud-based central server.

Updates to the dashboard addressed many of the preferences and recommendations expressed by participants during the first field study. On the new interface, summaries of each feature are displayed across four categorized columns, or "panels," on a homepage. The panels are Home Environment, which consists of blocks for externally-sourced weather, indoor humidity and temperature, light brightness, and motion; Energy Usage, which consists of blocks for powerstrip outlets, total energy consumption, and outlet-specific consumption; Health and Wellbeing, which consists of externally-sourced, widespread health data, a wellbeing index with symbols for reporting, and externally-sourced modules for leisure such as Wordle and Cute Animals; and Task Assistance, which consists of an interactive functional calendar and a shopping list. Users can efficiently view further information, such as historical data about energy consumption, by tapping on the feature. The finalized interface is shown in Fig. 10.

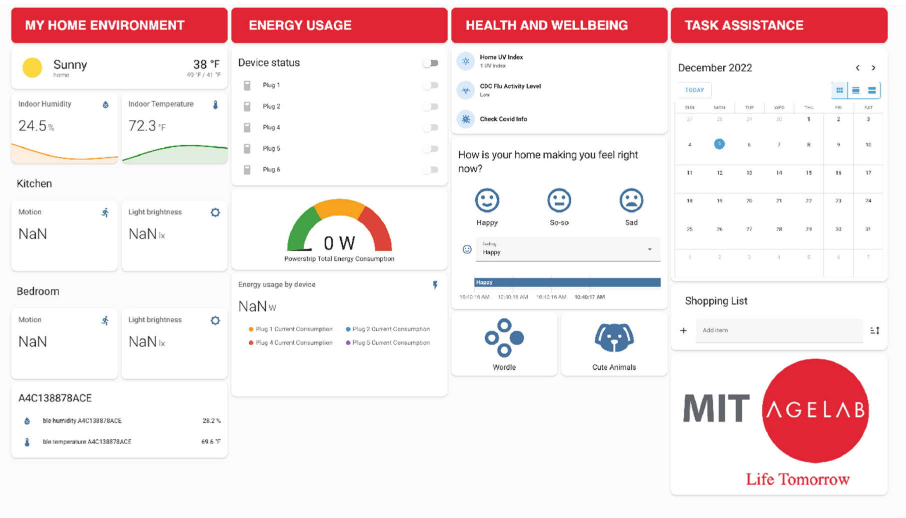

Fig. 10. The user interface for the version 2 dashboard with all features visible.

To address user feedback around a desire to personalize the system, the new dashboard application includes features that support greater user customizability. The dashboard allows users to simplify the layout of the full main interface (as shown in Fig. 10) based on their priorities; for example, users may choose to hide or minimize panels that they are not interested in or move higher-priority features to the top. Users may also personalize within panels. Labels and icons can be designated for each of the powerstrip outlets within the Energy Usage panel, and an interactive calendar—which additionally supports identified needs around task management—was added. All personalizations are optional such that there is no negative impact or change to the overall functionality for users who prefer not to customize.

Researchers identified the potential to incorporate externally-sourced information and interactivity. Thus, the updated system leverages third-party integrations offered by Home Assistant that may support the user experience and enhance engagement, such as broad public health data from the CDC and widgets for playing a word game (Wordle) and displaying uplifting photos (Cute Animals).

3 Conclusion

3.1 Implications

The pilot and field studies demonstrated key considerations for design researchers and practitioners in designing user studies that can provide a holistic understanding of the user experience and, in turn, most effectively inform future design decisions.

When recruiting participants, researchers and practitioners should make an effort to include users that represent all aspects of the target group in terms of both demographics and technology experience. For example, the field study found that evaluations of usefulness varied between participants of different demographic characteristics and technology experience. Involving a diverse group of individuals results in a better understanding of needs and experiences that people of different characteristics may have, and generates insights for addressing requirements that may vary across target user segments.

When seeking insights that will hold true in a real-world setting, a user's experience with a product should reflect their real-world experience as closely as possible. Thus, when possible, users testing a product in their natural environment (e.g., in users' own homes for smart home products) is most ideal. Field study participants were able to share valuable insights on things that would likely not be observed in a typical lab setting, such as how the prototype affected their everyday routine, usage dynamics with other members of their household, and variations in usage by housing type. In addition to the environmental dimension, a longer-term study can result in more meaningful insights than a short-term engagement. Placing the product in participants' homes for a longer period of time allows a more comprehensive observation of changes in usage behavior beyond initial interactions and the learning phase.

When evaluating and analyzing users' experiences, utilizing various methods appropriate for gathering multidimensional feedback is crucial. For example, the design process for the prototype was informed by both quantitative insights from ongoing surveys and qualitative insights from interviews. The more structured, quantitative method allowed trends to be plotted and to do comparisons, whereas the less-structured, qualitative method allowed for variation between participants and provided an opportunity to follow up and ask in-depth questions tailored to participants' individual situations and experiences. Thus, the combination of these two methods for gathering feedback resulted in a significantly more comprehensive understanding of the user experience.

3.2 Future Work

For future iterations of the prototype design and development, the cycle of iteratively refining the prototype based on feedback from real-world user testing will continue. The immediate next step will be to repeat the field study with the finalized second version of the prototype.

Through all cycles of testing and evaluation, insights from participants will be leveraged to learn about how new changes and features, such as the newly-added customizability in the second version, may impact the user experience and acceptance. In general, gathering feedback from a larger and more diverse pool of participants in future iterations of the field study could improve the validity and generalizability of findings and allow for more in-depth comparisons of preferences between users of different characteristics.

Acknowledgment. Support for this study was provided by the MIT AgeLab C3 Connected Home Logistics Consortium.

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