RESEARCH ARTICLES

ARena of Privacy: Exploring Augmented Reality in Enhancing Smart Home Privacy Awareness and Control

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ABSTRACT
The rapid emergence of smart homes offers convenience but also raises significant privacy concerns, such as challenges in comprehending privacy-related statuses, information, and settings. This study aims to mitigate these concerns by leveraging augmented reality technology to enhance privacy protection user experiences. Through interviews with experienced users, we systematically identify and categorize three primary aspects of concerns encountered during smart home usage: sensor range and status, data transmission directions, and transparency of mode settings. Drawing on these insights, we design and implement a streamlined AR system for interacting with smart home devices. Our user studies demonstrate that our AR system offers significant advantages over traditional 2D smart home applications in terms of information representation, workload reduction, and enhanced privacy awareness. This research presents a notable step forward in privacy protection while suggesting pathways for AR-enhanced smart home systems.

KEYWORDS
Privacy, Augmented Reality, Smart Environments / Connected Home, Interaction Design

1. Introduction

Smart home technology has revolutionized how we interact with our living spaces, offering unprecedented levels of convenience, automation, and control [23, 40]. Through the integration of various computing and communication technologies, smart homes provide unparalleled automation, convenience, and control. The proliferation of voice-activated assistants and intelligent sensors, coupled with advancements in artificial intelligence and ubiquitous connectivity, has paved the way for a new era of interconnected homes that seamlessly blend technology and everyday living [50]. The potential benefits of smart homes are vast, ranging from increased comfort and convenience to enhanced energy efficiency and security. However, as the number of interconnected devices and sensors within smart homes continues to grow, concerns about privacy become paramount. Privacy issues such as the collection and misuse of personal data

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can potentially infringe upon individual privacy rights. The continuous monitoring and data collection capabilities of smart home devices raise questions about data ownership, consent, and potential leakage.

As these technologies become more integrated into our daily lives, understanding the human factors and implications associated with their use is crucial. Currently, mainstream smart home systems primarily rely on separate applications to control and configure individual devices [25]. Even when integrated into one application, the complex interaction logic and difficulty in finding relevant information pose challenges for users in terms of locating privacy-related information and configuring privacy modes [24]. Users require more innovative solutions to maintain a sense of privacy and control over their personal information while enjoying the benefits of smart home technology. Augmented reality (AR) has emerged as a promising technology that can address these disadvantages and enhance the overall user experience in smart homes [43]. By overlaying virtual elements onto the physical world, AR provides users with new ways to visualize and interact with their smart home environments.

In this study, we explore ARena (Augmented Reality-enabled) privacy to enhance related experiences in smart homes, focusing on potential benefits, challenges, and design implications of AR glasses. We first collected perspectives from experienced users on privacy issues related to smart home devices through user interviews. These interviews revealed common concerns regarding privacy in current smart home systems, such as visualizing sensor statuses, managing data sharing permissions between devices and the cloud, and providing simple privacy protection modes. Our survey led to an important conclusion: users are primarily concerned with privacy issues in smart homes, most importantly needing a system that can easily and accurately display the privacy-related status of smart home devices and configure them through simple and understandable interactions.

To respond to this need, we utilized HoloLens AR glasses to create an intuitive and user-friendly smart home system. We seamlessly integrate device information into the user's physical environment, creating a unified and intuitive interaction paradigm that transcends the limitations of traditional smart home interfaces confined to smartphone or tablet screens. We then conducted user studies to compare the AR system with traditional tablet applications. The results demonstrated that AR interaction technology can enhance users' perceptions of sensor coverage and angles, improve task completion success rates, and increase operational efficiency. Furthermore, in a semi-structured task, AR users demonstrated greater accuracy in selecting appropriate privacy protection settings based on imaginary scenarios. By examining human factors, privacy concerns, usability, and the challenges of traditional privacy-preservation applications, we gained insights into the opportunities and challenges associated with adopting AR technology in smart home systems. Our findings are crucial for designing user-centered systems that prioritize the well-being, privacy, and inclusivity of individuals and families in the era of smart homes. The three key contributions of this research can be summarized as follows:

- Systematically identify and categorize primary privacy concerns encountered by smart home users, as well as their longing for missing privacy-related features for visualization of sensor range and status, data transition, and transparent mode settings.
- Design and implement an all-in-one comprehensive AR system that integrates the mentioned features and effectively addresses the identified issues. Adopt innovative information visualization solutions to provide a better user experience

and enhance privacy protection.
- Conduct user studies to compare the proposed system with a traditional 2D tablet application, focusing on two key aspects: device effectiveness and the influence of scene settings. Real user data demonstrates the advantages of AR techniques in privacy-related information perception and system interaction transparency.

2. Prior Work

2.1. User Experience in Smart Homes

A smart home refers to a residential environment equipped with various interconnected devices and systems, such as sensors, actuators, appliances, and communication networks [27]. These technologies enable the automation, control, and monitoring of various aspects of the home environment, ranging from lighting and temperature to security and entertainment [19]. Smart homes have emerged as a prominent domain within the field of human-computer interaction (HCI), focusing on the interaction between users and the technology that permeates their living spaces. The user experience (UX) in the context of smart homes encompasses the holistic perception of users' interactions, emotions, and overall satisfaction with the smart home environment [40]. It involves understanding and addressing users' needs, goals, preferences, and challenges to design intuitive, efficient, and enjoyable interactions [51]. The goal of smart home UX is to create seamless and meaningful experiences that enhance users' quality of life, promote well-being, and support their daily activities [23].

Designing for the smart home user experience poses unique challenges. Smart home systems are often complex and involve multiple devices, interfaces, and technologies that need to work together seamlessly [24]. Users must interact with diverse control mechanisms, such as mobile apps, voice assistants, physical switches, or gesture-based interfaces [9, 53], which require careful consideration of usability, learnability, and accessibility.

To overcome the multifaceted challenges of smart home, researchers have investigated various aspects, including interface design, automation algorithms, context-awareness, energy efficiency, and user acceptance [5, 10, 19, 20, 26, 33, 34, 41, 45, 46]. They have explored different methodologies, such as user studies, prototyping, and iterative design, to understand user needs, evaluate designs, and address usability issues [39, 47, 54]. Researchers are exploring novel interaction paradigms, such as natural language processing, gesture recognition, and context awareness, to enhance user experiences in smart homes [1, 11, 31]. Understanding smart homeowners' needs will be crucial for advancing smart home research and unlocking the full potential of this technology in improving users' daily lives. Advanced interactive technologies can enable users to quickly recognize and instantly interact with a device, conveniently accessing the device's features and services and bringing more possibilities to the user experience of a smart home system, such as the use of augmented reality for IoT device recognition and interaction [12]. For example, one work implemented an AR browser that uses mobile phones to recognize nearby devices and access associated web interfaces [56]. Our work innovatively designs an integrated AR solution that uses AR technology to enhance the visualization and interaction of private information and better support privacy protection than tablets.

While prior research has explored the use of advanced interactive technologies, there is a lack of understanding regarding how well users perceive and interact with these novel interaction paradigms in the context of smart homes. Unlike previous work, this study proposes using AR glasses as an all-in-one smart home control device, projecting the control interface of all devices into the user's field of view. By recognizing smart devices through the camera and integrating virtual information with the actual environment, users can monitor and control devices in real-time, resulting in an intuitive and immersive experience. This approach enables collaboration among multiple devices, interfaces, and technologies while applying multiple control mechanisms.

2.2. Privacy Concerns in Smart Home Systems

Smart home technologies offer convenience, efficiency, and an enhanced quality of life; however, critics have raised concerns about the potential misuse of personal data [29]. Moreover, privacy and security issues are paramount in smart homes, necessitating the development of user-centered approaches that empower individuals to maintain control over their data and ensure trust in the technology. Research on the privacy concerns of smart home systems has gained significant attention in recent years [21, 58]. Studies have focused on understanding the privacy risks and challenges associated with the collection, storage, and sharing of personal data within smart home environments [52]. Researchers have examined user perceptions, attitudes, and awareness regarding privacy in smart homes, uncovering concerns related to data security, unauthorized access, and the potential misuse of personal information [48]. They have also investigated the privacy implications of various smart home devices and technologies, including voice assistants, cameras, and IoT sensors. These devices have the potential to collect a vast amount of user data, ranging from personal preferences and habits to sensitive information like daily routines and even audio or video recordings [30]. Research has even suggested that valuable privacy information can be obtained by analyzing network-layer traffic without direct access to the device's sensor data [59]. Researchers have focused on understanding the various ways in which sensitive user information can be unintentionally disclosed or accessed by unauthorized parties within the context of smart homes [15, 42]. As new devices and capabilities emerge [25], maintaining privacy in smart home systems remains a critical research domain due to the rapid advancement of smart home technology.

While considerable research has been conducted in this field, there are still several areas that require further exploration and attention. One key knowledge gap lies in the effectiveness and practicality of existing privacy-preserving mechanisms. Many of the current solutions focus on encryption, access control, and anonymization techniques. However, the complexity of these systems, coupled with inconsistent and fragmented user interfaces, still contributes to user frustration and confusion. To address the problem of smart home privacy, there is a gap between current approaches and an advanced system capable of visualizing the states of multiple smart devices to address privacy concerns. By providing real-time information on permission granting, sensor distance, and data communication relationships, users can gain control over device operations. This visualization would allow users to monitor and adjust device settings, detect abnormal behaviors, and take timely actions to protect their privacy.

2.3. Privacy-Preserving Technologies in Smart Home Systems

To address these concerns, researchers from the human-computer interaction domain have proposed various privacy-preserving mechanisms and solutions [1, 3, 4, 6, 7, 18, 21, 36, 38, 49, 58]. These researchers aim to inform the design of privacy-friendly technologies and policies, fostering user trust and ensuring the responsible use of personal data in these increasingly connected environments. Additionally, studies have examined user perceptions, attitudes, and concerns related to data handling in smart homes, informing the design of user interfaces that empower individuals to understand and control the data collected by their devices [2, 8, 9, 44]. Often, users lack knowledge about the specific methods and purposes of collecting, using, and sharing personal data when utilizing smart home devices. Research by Cruz et al. has improved users' understanding of data processing and privacy disclosures in smart home devices through visualization, indicating the potential of augmented reality technology in enhancing users' visualization and understanding of data flows in smart devices [16]. Instead of focusing on traffic changes, our research focuses on data flow relationships with devices and how these relationships can be mapped and displayed through augmented reality technology, allowing users to intuitively understand the data exchange process between different devices and the potential privacy risks. This approach not only deepens users' understanding of data flows in the home network but also provides a more direct way to identify and manage critical data nodes that could lead to information breaches. Similar to Coppers et al. [14], our work focuses on privacy issues in intelligent environments and aims to improve users' understanding of system behavior. Leveraging configurable audit logging mechanisms, both approaches explore capturing runtime data to facilitate transparency. However, while Coppers et al. focus on anticipating rules' near future triggers through predictions, we emphasize understanding current and historical behavior. Additionally, given mobile constraints, our work investigates embedded limitations and solutions. Some suggest that manual restrictions should be imposed on what devices are allowed to do [32]. In a multi-user environment, due to varying privacy requirements among different users, corresponding mechanisms should be employed to protect the privacy of different identity members [57]. By utilizing IoT devices and sensors, personalized privacy notifications can also be sent based on individual users' preferences [55]. Changes in scenarios are also a focal point for users, as privacy settings tend to vary significantly depending on different stages such as being at home, away from home, or returning home [37]. AR and VR (Virtual Reality) have also demonstrated potential applications in smart home privacy preservation, for instance, facilitating indoor positioning [43] or authentication [22]. Despite the extensive research conducted, there is a gap in investigating the impact of varying scenarios on privacy settings and the use of AR technology as an all-in-one solution to enhance data transparency.

In summary, significant advancements have been made in the field of smart homes and human-computer interaction. However, the challenge of privacy preservation remains unresolved. Furthermore, there is limited research on the reasons behind the subpar performance of current smart home systems. The current privacy-related information visualization in smart home systems is inadequate in effectively conveying information and providing meaningful feedback to users. Existing solutions have not identified an optimal approach to fully integrate the smart home control system with physical devices. Thus, there is an urgent need for further exploration and development from the HCI perspective to ensure privacy protection and enhance user experiences within smart home environments.

3. Study 1: Exploring Experienced Smart Home Users' Perspectives on Privacy Concerns

In the first study, we employed a qualitative user interview experimental design. The primary objective of the interview was to gather opinions and identify issues related to privacy protection during the usage of smart home systems, as well as to extract users' missing features and inquire about their preferences for privacy preservation in smart home systems. Adopting a semi-structured interview approach allowed us to gain a deeper understanding of the user experience, perceive their perspectives on privacy protection, and provide more detailed data and context from the experienced users' point of view. The experimental methods from both Study 1 and Study 2 were approved by the ethics commission of the university.

3.1. Study Overview

Participants Since finding participants with smart home experience in daily life is relatively difficult, participants were recruited online through various social media platforms. The selection criteria included users with prior experience in utilizing smart home technology and ownership of multiple smart home devices (e.g., smart speakers, smart lights, smart TVs), excluding general smart digital devices like PCs, tablets, and smartphones. The aim was to ensure that the participants possessed profound perspectives related to privacy issues in smart home systems. In total, 10 participants (6 males and 4 females, with an average age of 28 years) were recruited. These participants had an average of 4 years of experience in using smart home technology and had used an average of 5 different types of smart home devices. The interviews were conducted online at a mutually convenient time and place and lasted approximately 30 minutes. Participants read and approved the consent form before the interview and were compensated with a monetary reward afterward.

Procedure The interviews were designed to obtain users' authentic perspectives on privacy issues in smart home devices through a series of dialogues. After a brief introduction and providing background information on the experiment's purpose, the conversations focused on five main areas: participants' experiences with smart home technologies, perspectives regarding sensors and data collection in smart home devices, suggestions for enhancing privacy-related features, and overall recommendations. All interview questions were open-ended, encouraging participants to freely share any privacy-related issues, concerns, experiences, and suggestions they encountered while using smart home systems.

Design Interviews were audio-recorded and transcribed by the research team. The interview transcripts were then analyzed using an open coding method. Initially, two researchers independently prepared the transcriptions, followed by discussions to align and consolidate the codes. The results were incorporated into a shared codebook accessible to the entire team only when a mutual agreement was reached among the researchers. Throughout the discussion phase, we meticulously reexamined the raw data to ensure the accuracy of our final qualitative findings.

3.2. Data Collection by Smart Home Devices

The interviews revealed a consistent theme among all participants (*P*): concerns about the privacy of data collection in smart home systems. While participants expressed varying levels of apprehension, data privacy was a primary concern for smart home users (*P2-10*). Notably, participants expressed worries about the potential for privacy breaches during intimate moments through the cameras (*P2, P4, P5, P6, P7, P8, P9, P10*).

"...I do worry about the camera." (P2)

Individuals expressed concerns about their lack of control over privacy with always-on surveillance devices like smart home cameras, leading to fears of data misuse, unauthorized access, and hacking incidents. To address these concerns, some interviewees took control measures such as physically blocking, turning away, or disconnecting the cameras to achieve a greater sense of security (*P4, P5*) compared to digital methods of disabling them.

"...Our television actually has a camera, but I try my best to prevent it from capturing the appearance, daily routines, and schedules of our family members. For example, if I usually come home around 7 or 8 in the evening, I set a timer to turn off its power during that time to ensure the camera is not functioning." (P4)

While some participants perceived the risk of privacy infringement in smart homes as low (*P1, P10*), there were varied perspectives on the balance between convenience and privacy. Participants acknowledged the benefits of smart home systems but emphasized the need for privacy safeguards (*P6*). They recognized that convenience and privacy may not always coexist and were willing to trade some privacy for enhanced features and improved functionality in their smart homes.

"...Besides the verbal promises, it seems there's no way to provide substantial reassurances through certain promises or measures." (P10)

"...Actually, what I'm more concerned about is that everyone's voice is different, right? I don't know if the backend data of this speaker will have annotations or labels for each family member." (P9) "...It's possible that it might use my personal information to push advertisements or something like that, which I find quite worrisome." (P3)

Interviewees strongly demanded localized control and management of their data, highlighting concerns about risks associated with data transmission to the cloud (*P3, P4, P5, P8, P9*). Robust device control, integrated privacy switches, and reversible permission management are deemed essential (*P5*). Participants also value personalized control over their smart devices and emphasize the importance of perceiving and accessing data-related functions (*P7*). Proactive reminders, post-usage notifications, and transparent visibility into uploaded data are desired, along with regular deletion of both cloud-based and local records to maintain privacy and data security. Overall, the findings highlight participants' widespread concern about privacy in smart homes and the importance of balancing convenience and privacy. While some perceived the risk as low, they still emphasized the need for robust privacy protection measures. These insights deepen our understanding of privacy concerns in smart homes and offer valuable implications for designing privacy-enhancing features and guidelines in this domain.

3.3. Sensor Status of Smart Home Devices

Another widely discussed topic during the interviews is the sensing range and status of sensors, which raises significant concerns among users regarding their limited control and understanding of data collection and scope on smart devices. While users are generally aware that smart devices gather information during usage, they express frustration over the passive collection of large amounts of irrelevant data, perceiving it as unnecessary (*P1, P3, P6, P7, P9*). Compounding the issue, device manufacturers have failed to provide adequate functionality for users to effectively control and comprehend the data collection and scope of their devices. As a result, users are left with minimal options, restricted to simply toggling the device's on/off status without access to specific, relevant information.

> *"...If I'm not an industry professional and I have such devices installed in my home, then I wouldn't have any idea about where to find information regarding the scope of data collection by these devices." (P3)*

Interviewees express concerns about the types of data collected in smart devices, including sensitive information like image data, voice data, home layout information, device usage frequency, and personal lifestyle habits. The implications of data collection on privacy, security, and personal autonomy are paramount. Improved user agency, transparency, and control over data collection practices are needed to address these concerns, empowering users to make informed decisions and fostering trust and engagement in smart technology adoption.

3.4. System Configuration for Smart Home Devices

When asked about the current shortcomings and areas for improvement regarding privacy-related features, the majority of users stated that the existing privacy-related system settings are not intuitive and user-friendly (*P2, P3, P6, P7, P8, P9, P10*). The current methods of permission control often prove obscure, requiring complex processes to indirectly manage or navigate through default settings. Users yearn for a comprehensive, all-in-one application (*P1*) or voice control via mobile phones (*P4*) to effectively manage their devices. They desire diverse visualization and interaction options for device status. They prefer visual access to device data and sensor information to enhance personal privacy. For instance, a red dot indicator during data collection could offer privacy protection. However, concerns exist about the usability of such features, particularly for non-IT professionals configuring settings. Similarly, regarding privacy control over devices, most individuals express a desire for simple and convenient settings for all devices in their homes (*P1, P3, P6, P8, P9*). They want the ability to switch to a mode that avoids disturbances and protects personal privacy when needed (*P1*). However, concerns exist about the potential impact of one-click setting modes on normal device usage.

> *"...Having easily adjustable settings is indeed essential because I need to have control over my own preferences and not solely rely on external control." (P8); "...It would be ideal for the majority of users to have a single app, an application, to control all their devices." (P1)*

Smart Home System Privacy Feature	Pain Points Identified During the Interviews (Study 1)	AR Countermeasures (Study 2)
Data collection	Lack of straightforward data visualization	Augmented user interface for device and data configuration (Func 1, 2)
Sensor status	Hard to identify sensor status	Project information onto physical objects (Func 3)
System configuration	Lack of easy setup configuration for every device	Global all-in-one application (Func 4)

Table 1. Comparisons between the pain points for current smart home systems and the countermeasures for each of them with AR technology.

3.5. Summary of the Interviews

According to the interviews, we can summarize that smart home users face several typical pain points, primarily caused by the fragmented relationship between the current smart home configuration interface and devices. Three key privacy-related pain points were identified: (1) Lack of straightforward visualization for data transition and status; (2) Difficulty in identifying sensor status and range; and (3) Lack of an easy setup function for various devices (see Table 1). Our findings diverge from previous studies as we discovered that the fragmented relationship between the smart home configuration interface and devices, along with the lack of an intuitive connection between the interface systems and the physical world, contributed to usability issues and pain points for users, highlighting the necessity for innovative approaches that address these concerns and enhance the user experience in smart home privacy protection.

4. Study 2: Exploring the Potential of Augmented Reality for Smart Home Privacy Preservation

Building on the findings from Study 1, it is evident that smart home users encounter several challenges, primarily due to the disjointed relationship between smart home systems and devices. Although users can physically see their devices, accessing relevant information directly from these devices remains difficult, especially for smaller sensors like motion sensors and cameras. Moreover, these devices are typically managed through mobile apps, yet there is a noticeable lack of intuitive linkage between these apps and the physical devices. The system's usability is also hindered by integration issues from multiple manufacturers.

Alternative interfaces for smart home system control, such as indicator lights and conversational agents, exist but have limitations in preserving privacy. For example, indicator lights display device status but lack detail about the data scope and transmission. Conversational agents, while convenient, could inadvertently expose sensitive information in shared spaces. Previous research suggests that visualizing potential privacy breaches in smart home systems enhances user awareness about privacy and security [38]. We aim to explore an all-in-one solution that provides comprehensive device information and enhances user interaction through augmented reality, given the rapid development of AR technology [43]. By integrating different ways of visualizing and controlling device information, we hope to build on previous efforts to increase user awareness of smart home privacy violations and enhance the smart home experience. Implementing novel solutions through AR not only promotes user engagement, but also maintains strong privacy measures by utilizing the immersive and interactive features of AR. We aim to present a holistic perspective on the future of smart homes that balances technological advancements with user privacy considerations. The pain points, their countermeasures extracted from the interviews, and the advantages of applying AR technology are summarized in Table 1.

4.1. System design

We developed three smart home systems for comparative analysis within our proposed framework. The first approach, the Augmented Reality (**AR System**), allows users to visualize and interact with virtual elements overlaid in the real-world environment, enabling them to see how different smart devices and configurations would look and fit within their physical space. It offers intuitive interaction methods, such as gesture-based controls or voice commands, simplifying the configuration process. Users can manipulate virtual objects directly, making it easier to set up and configure smart devices. AR can simulate scenarios and demonstrate the outcomes of different configurations, allowing users to view the effects of their actions directly. Unlike existing research [12, 56], our AR system integrates the system into a unified whole, enabling the localization and configuration of multiple devices.

To make the AR system work, we developed a prototype using the Unity engine and Microsoft HoloLens 2 glasses. The Mixed Reality Toolkit provides fundamental building blocks for Unity development, including manual tracking and 3D user interface controls for interaction, offering features for 3D object recognition, tracking, and interaction. Once the scene data and system settings are configured, the system enhances perception and interaction through various modes. Users wear HoloLens glasses to access the AR scene. For scene perception and smart home device localization, we utilized the Vuforia framework, which recognizes real-world objects and overlays digital information onto them, allowing accurate identification and localization of physical devices. When a real-world object is recognized, virtual content is bound to it, and users can interact through touch, rotation, tilting, or other gestures. The scanning function utilizes image recognition to identify specific images, logos, objects, or scenes from the real world using the mobile device's camera. Visual feature points are extracted from recognized images, building a feature database for matching virtual content to physical objects. By continuously matching the real-time image against the feature points in the database, it tracks the position and orientation of the user's device in real-time.

To examine the effect of the AR system, control conditions must be established for comparison. This allows us to determine whether these different smart home systems have distinct effects on users' perceptions and decisions. The second system, an interactive UI (**Pad System**), achieves the same functionality as the AR interface. Its design and interaction logic were inspired by popular smart home systems available on the Apple and Android stores, such as Apple HomeKit and MIJIA, with suitable adaptations made as needed.

Expanding upon the Pad System's capabilities, we developed the enhanced Pad system (**EPad System**), which introduces visualization features in a 2D format. The

EPad group ensures compatibility with existing smart home control paradigms while leveraging visualization to improve user experience and decision-making. This "intermediate group" can help to isolate the effects of AR on user experience and task performance.

To ensure fairness and impartiality, each system—AR, Pad, and EPad—offers identical functionalities, enabling participants to complete tasks with equal proficiency across all platforms, maintaining the integrity and validity of the experimental results and ensuring that any observed effects are attributable to the differences in the systems themselves rather than any experimental bias. By comparing the results across these three groups, we can better understand the incremental benefits of each aspect of our system and make more informed design decisions for future iterations.

Within the scope of this discourse, we present several conceptual frameworks for the engineering realization of the aforementioned system.A pivotal challenge encountered in the architectural blueprint of this system pertains to the interoperability between smart home appliances and wearable technology. The deployment of a multi-protocol gateway, proficient in assimilating Zigbee and Bluetooth Mesh protocols, in conjunction with a localized hardware apparatus furnished with software analogous to Home Assistant, could potentially surmount this barrier to a notable degree. Furthermore, concerning the paradigm of data cloudification, the attainment of a cohesive control schema among the intricate commercial frameworks, namely HomeKit and Mijia, necessitates an advanced approach. It is postulated that the construction of a bespoke MQTT-protocol-based cloud server by the end-user may facilitate the requisite privacy processing by local devices prior to the data being escalated to the remote repositories of iCloud and Mijia's servers, thereby ensuring a heightened level of data security and privacy preservation.

4.1.1. Function Design

Based on the above findings, combined with the need to improve home comfort, energy efficiency, and privacy security in the smart home system, we propose the following four smart home functions: 1. Device status and control; 2. Data transmission visualization; 3. Sensor range visualization; 4. Global mode setup.

1. Device status and control This function facilitates the presentation of operational status, data readings, and control interfaces of smart devices to users via a graphical interface. It enables users to monitor and view the current status of various smart devices, including detailed permission settings, through a control panel. Integrated control allows users to manage all their smart devices through a unified interface, eliminating the need for separate applications or control panels for each device. Fine-grained permission management empowers users to restrict access to sensitive devices, safeguarding household members' privacy. The system can offer a clear interface that visualizes and tracks permission settings, ensuring proper configuration. In the **AR system**, users can activate a quick access panel by extending their palm upwards, containing control modules for smart devices. When a device is selected, a blue arrow appears, aiding in locating the designated device. The device's control panel then appears, enabling remote configuration of settings such as power, sensors, and cloud upload. Changes made through the interface are seamlessly transmitted to the respective device for remote configuration (see Figure 1a). The **Pad system** can display the status information of all connected devices through a graphical interface, using icons to represent different devices and colors to differentiate states. Users can click on

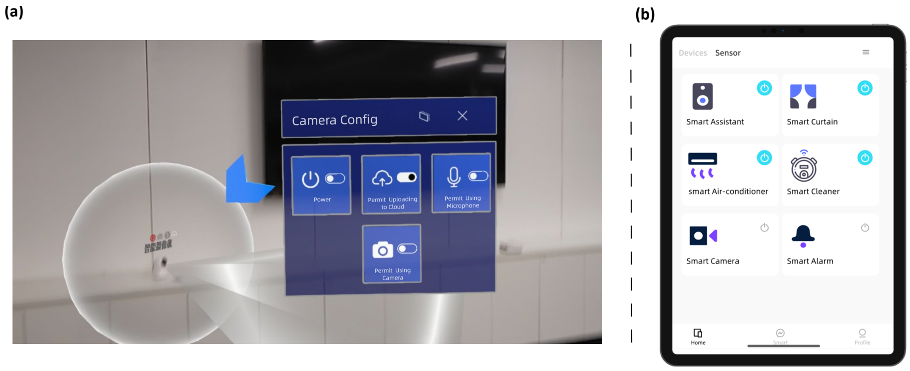

Figure 1. Device status and control functions system implementation. (a) The schematic of the AR system user interface menu is depicted, featuring a blue arrow indicating the device's location. A camera control panel with switches for power, cloud upload, audio recording, and video recording permissions is displayed. (b) The main menu of the Pad system is displayed, featuring a navigation menu and switch buttons that allow users to select devices and configure their settings.

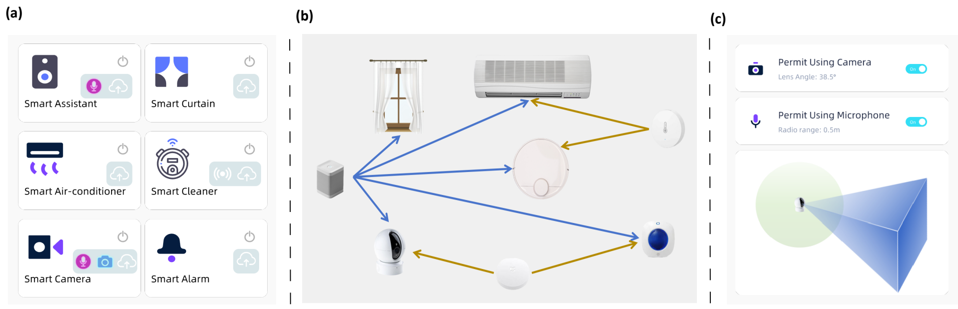

Figure 2. Visualization features of EPad system implementation. (a) Schematic diagram of device status information display. (b) Schematic diagram of data transmission display in the EPad system (displayed in the main menu). (c) Schematic diagram of the visualization of the sensing range of the EPad system (using a smart camera as an example).

devices to enter the device information interface for further control and management (see Figure 1b). The **EPad system** adds device permission status visualization to the Pad system, allowing users to observe more information about the device on the home page without going to the Settings screen (see Figure 2a).

2. Data Transmission Visualization AR implementation of network visualization has demonstrated its applicability in device effectiveness and other aspects [13]. Visualizing data transmission enables users to observe the flow and processing of data, enhancing their understanding of how personal data is handled and shared. By controlling these connections, users can effectively manage privacy settings, prevent unnecessary data sharing, and ensure that data is solely utilized for authorized and essential purposes. In the **AR system**, users can view power, sensor, and data status atop the device. Data transmission directions are represented by a cloud icon and cross-device links, with colors indicating whether the transmission involves control or sensing information. The direction and number of arrows provide information about the current

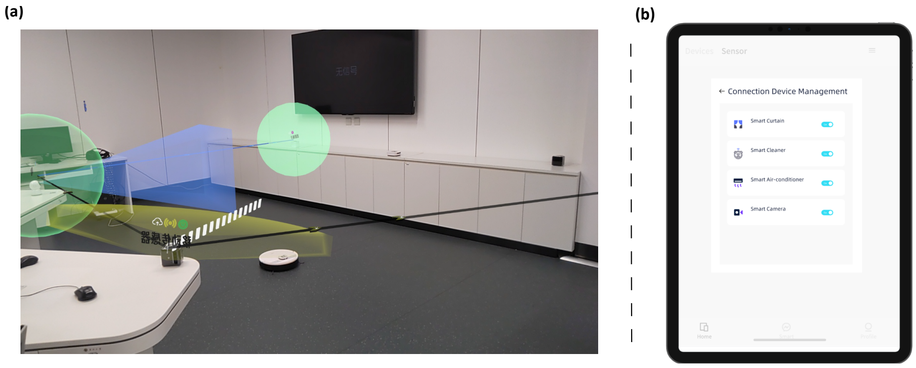

Figure 3. Data transmission visualization functions system implementation. (a) Cross-device communication visualization of the AR system. Different devices are connected by lines to depict communication relationships. Additionally, semi-transparent three-dimensional shapes in various colors represent different permission ranges. (b) Cross-device communication setup menu of the Pad system. Device connections are displayed and can be configured in an itemized list format.

direction and volume of traffic (see Figure 3a). The **Pad system** displays a list of data connection relationships in the device information section (see Figure 3b). The **EPad system** provides an overview of the device's data connection relationships on the home page, using colors to distinguish data types and arrows to indicate data flow (see Figure 2b).

3. Sensor Range Visualization By intuitively displaying the working ranges of sensors, users can easily understand the performance and limitations of the devices. This reduces the learning difficulty for users and improves product usability. Users can adjust the direction or settings of devices based on visual feedback, such as the angle of a camera or the volume of a speaker, to achieve optimal results. For the **AR system**, the data collection range for each sensor is visually represented using colored cones and semicircle scanning effects. The visualization dynamically changes based on the sensor's state: it appears gray when permission is not granted, colored but static when sensing permission is granted but the power is off, and dynamic when the power is on, indicating the active data collection range of the sensor (see Figure 4a). For the **Pad system**, users can use a graphical list to display the permissions and their range information for devices and provide simple buttons to modify the permission settings in the settings or user management sections (see Figure 4b). For the **EPad system**, it provides a pictorial representation of the sensor range based on the Pad system, similar to the AR system, but it is two-dimensional and static (see Figure 2c).In order to enhance the system's usability and to define the privacy features of sensors more accurately, we have designed definitions regarding the detection range of sensors for reference. For optical devices such as cameras, their detection range is a sector-shaped area determined by the field of view, with the angle of the sector area being determined by the camera's focal length; generally, lenses with shorter focal lengths have a larger field of view, and the radius of the sector area is determined by the camera's pixel count, with higher pixel sensors corresponding to a larger sector radius. For audio devices such as microphones, their detection range is a circular area, with the radius of the area being determined by the dynamic range of the microphone equipment, that is, the range between the maximum and minimum sounds it can capture.

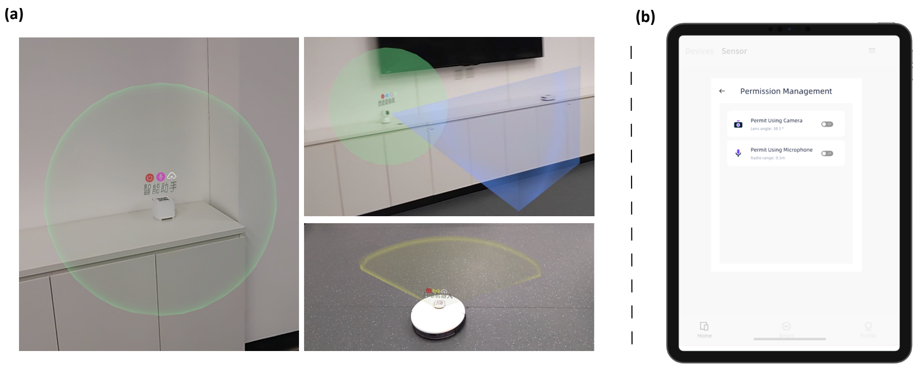

Figure 4. Sensor range visualization functions system implementation. (a) Sensor range visualization of the AR system. A green, semi-transparent sphere represents the audio recording range of the smart assistant on the left. A blue, semi-transparent pyramid represents the video recording range starting from the camera position on the top right. A yellow, semi-transparent fan-shaped cylinder on the bottom right represents the motion detection range of the floor cleaning robot, with the direction of motion as the positive direction. (b) Permission management menu for the Pad system with sensor ranges descriptions. Detailed range information can be accessed and viewed within the configuration interface.

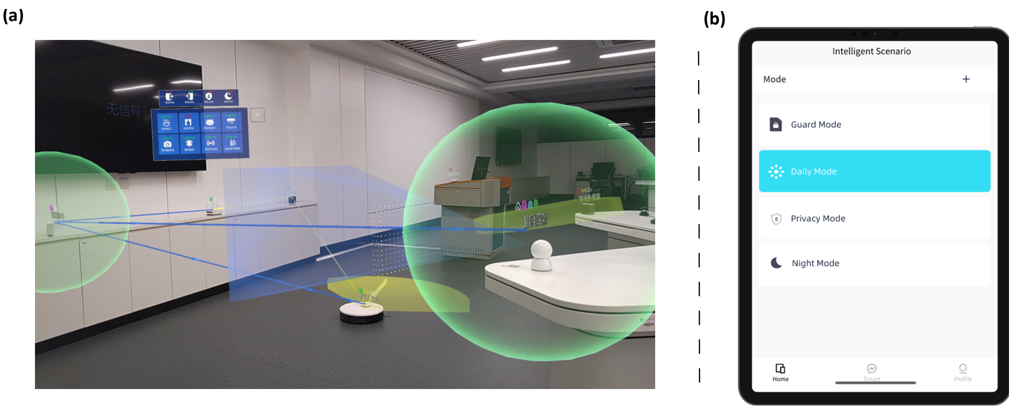

Figure 5. Global mode setup functions system implementation. (a) Illustration of the scene switching interface menu and scene change display of the AR system. (b) The Pad system features a switch mode menu that allows users to choose and activate four different global modes.

4. Global Mode Setup Global mode setup allows users to define a set of predefined device actions based on specific activities or times. For example, users can create a "Leaving Home" mode that automatically turns off lights and appliances, adjusts the thermostat, and activates the security system upon their departure. Users can create and customize different scenes based on their lifestyle habits, enabling automation and intelligent living experiences. Moreover, users can automatically adjust device settings, such as disabling cameras and microphones, in situations where confidentiality is necessary, thereby enhancing privacy protection. For the **AR system**, the quick access panel includes a global mode module, which indicates the currently selected mode with different colored text. There are four available global modes: night mode, home mode, privacy mode, and away mode. Users can easily switch between these modes with a single click. The change effect is immediately visible within the augmented reality glasses, providing real-time feedback to the user (see Figure 5a). For the **Pad system** and **EPad system**, it provides an interface for users to select and activate/deactivate the global modes with switch buttons (see Figure 5b).

4.2. System Usability Study

4.2.1. Participants

Participants were recruited through social networks and student organizations at the university. A total of 80 participants were randomly assigned to the AR group, the Pad group, and the EPad group. It is important to note that these participants were different from those mentioned earlier in the study. Five participants were excluded because they did not complete some tasks or parts of the study due to technical problems, interruptions, or personal reasons, resulting in incomplete or low-quality data. The final sample consisted of 75 participants (42 males, 33 females) aged from 18 to 24 years old (*mean=21.01, sd=1.98*), with 25 participants in each of the AR, Pad, and EPad experimental groups.

4.2.2. Materials

For our experimental analysis within the smart home framework, three distinct systems were developed and utilized. Each system offers similar functionalities but differs in the mode of user interaction and visual presentation. **AR system**: Utilizes Microsoft HoloLens 2 and augmented reality technologies to allow users to interact with and configure smart devices directly within their physical environment using gesture and voice controls, enhancing realism and immersion. **Pad system**: Employs a traditional tablet-based interface with a touch-based graphical user interface, inspired by popular systems like Apple HomeKit and MIJIA, for straightforward manipulation of smart home settings. **EPad system**: Enhances the traditional Pad System by integrating advanced 2D visual representations of devices and configurations, providing deeper insights while maintaining the familiarity of a conventional pad interface.

The main experiment consisted of two modules, with Task 1 consisting of 5 sub-tasks (Task 1-1 to 1-5), and Task 2 consisting of 3 sub-tasks (Task 2-1 to 2-3). Throughout the experiment, each task was accompanied by a written text description that included task requirements as well as prompts. Participants were notified by the experimenter to move on to the next task after completing the previous task. After each sub-task in Task 1, participants were asked to complete a questionnaire before proceeding to the next one. After completing both Task 1 and Task 2, the experimenter invited

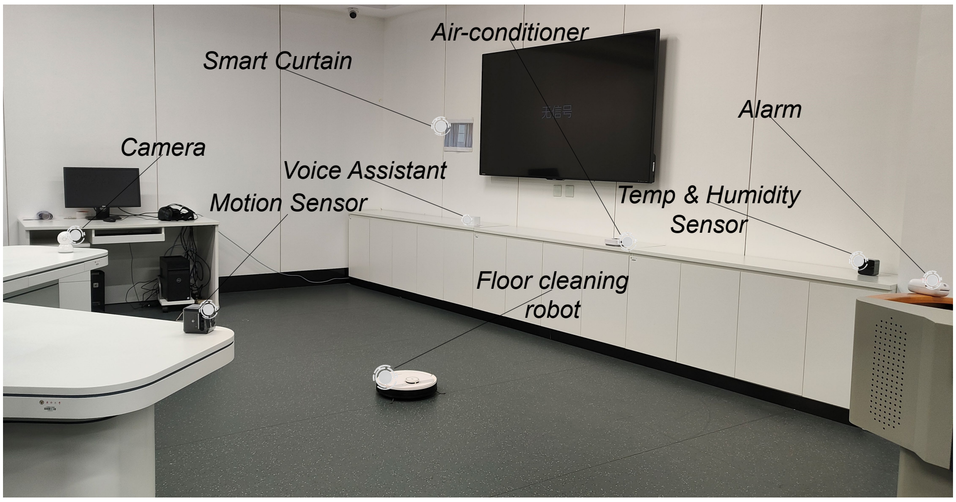

Figure 6. Experiment environment and smart devices overview.

participants to conduct a short interview about the system usage experience. The detailed content of each task is listed below:

Task 1-1 Sensor Range Task In the sensor range awareness task, participants are asked to view and estimate the coverage of the data collection area based on prompts, and then minimally move physical objects out of the smart devices' detection range in the physical world. This task includes three sub-tasks, involving the recording range of the voice assistant (distance), the recording range of the camera (angle), and the movement sensing range of the cleaning robot (both distance and angle). After completing the task, participants are required to answer questions about the sensor range status they have just observed and evaluate this feature.

Task 1-2 Device Status Control and Awareness The objective of this task is to assess the control functions for the power switch and permission settings of smart devices. Participants are instructed to manipulate the power and permissions as directed. This task includes three sub-tasks, involving toggling the power and cloud storage permissions of the smart curtains, changing the movement sensing permissions of the mobile sensor, and adjusting the recording and video recording permissions of the smart camera. Upon completion, participants must complete a questionnaire to address questions about the current status of the devices observed during the task and evaluate the control mechanism.

Task 1-3 Cross-device Communication Awareness This task requires participants to monitor the communication links between devices and disable data transmission for specific devices. It is structured into three sub-tasks, with the complexity of device linkage increasing from two to five devices as the task progresses. After finishing the task, participants need to complete a questionnaire to respond to questions about the cross-device communication relationships they observed and assess this functionality.

Task 1-4 Scene Switch and Awareness In this task, participants are tasked with switching between four modes and noting their differences. The task is divided into four sub-tasks, including Night mode, Home mode, Privacy mode, and Away mode. When switching scenes, participants are to observe the effects of the scene transition and monitor the power and permission status of various devices within each scene. After each sub-task, participants must answer questions about device status and cross-device communication in different scenes and complete a questionnaire to evaluate this feature.

Task 1-5 Permission Turn Off Task At the conclusion of Task 1, participants are required to disable the data collection permissions of all devices.

Task 2 Unlike the fixed task descriptions in Task 1, Task 2 employs a semi-open task design. To investigate the effects of AR and Pad systems on users' privacy decisions, participants are required to configure the smart devices according to various scenario descriptions and prompts, tailored to their personal preferences. For task 2, each scenario and hint is designed with corresponding score points, and users can get the corresponding score by configuring accordingly. Below are the three scenarios in Task 2:

Task 2-1 Leaving Home for Work Scenario **Scenario:** It's 8:00 in the morning, and you are preparing to leave for work. **Prompts:** 1. Turn off the air conditioner and other power-consuming devices when the house is empty. 2. It's preferable to schedule household cleaning when the house is empty. 3. Ensure that unexpected guests cannot enter the home during your absence.

Task 2-2 Welcoming Guests Scenario **Scenario:** You have just returned from work, and friends are coming over to chat at your home. **Prompts:** 1. Consider playing some background music to enhance the ambiance. 2. The room may become warm; adjust the temperature accordingly. 3. Ensure that the conversation remains private. Could it be overheard?

Task 2-3 Night Scenario **Scenario:** Night has fallen, and you are getting ready for bed. **Prompts:** 1. Create a quiet and dark environment to facilitate sleep. 2. Consider whether sleeping postures or conversations during sleep could be monitored.

The experiment includes two types of questionnaires: Perception tasks and Post-task evaluation. In **Perception tasks**, we designed a series of questions to test participants' retention of information post-task. For the sensor range task, we provided images depicting real-world objects and smart devices at varying angles and distances, and participants were asked to select the option where the real-world object is within the detection range of the smart device. For device status perception, participants were asked to identify changes in device status before and after the task through multiple-choice questions. For the cross-device communication perception task, participants were instructed to select the accurate communication relationship from multiple diagrams illustrating device linkages. In **Post-task evaluation**, participants are to rate the ease of learning, convenience, and usability of each function of AR and Pad systems after completing each task. Ease of learning is assessed on a scale from 1 to 10, where 1 means very unclear and 10 means very clear. Convenience is evaluated on a scale from 1 to 10, where 1 means very inconvenient and 10 means very convenient. Usability is rated on a scale from 1 to 10, where 1 means very dissatisfied and 10 means very satisfied.

4.2.3. Design

This study employed a between-subjects design, randomly assigning participants to one of three conditions: AR, Pad, and EPad. The independent variable was the interface design of the three smart home systems. Dependent variables included task-related actions, number of clicks, time spent on tasks, and questionnaire responses. Clicks and time were recorded only for Task 1. For Tasks 1-1 and 1-2, the deviation angle and distance of the moved object were calculated. In Task 2, the final settings of the user's smart devices were recorded, and scores were calculated by matching the correct answers derived from the specific configurations required for different scenarios. Each Perception task was scored based on the questionnaire responses, with the total score being the sum of the scores for each item. The post-task evaluation score was calculated as the average score for each item. Except for the success rate, which was analyzed using a z-test, all other variables were analyzed using ANOVA to compare differences between the three groups, with multiple comparisons corrected using Tukey's HSD (Honestly Significant Difference) and FDR (False Discovery Rate), at a significance level of 0.05.

4.2.4. Procedure

Participants were individually tested and randomly assigned to the AR, Pad, or EPad group prior to the experiment. Upon entering the lab, participants read and signed the consent form, and the experimenter provided an oral presentation of the study background. Participants in the AR group then performed calibration of the AR glasses and were instructed in the basic operations. Most participants in the AR group had not previously used AR glasses, necessitating a basic operations tutorial that included viewing the control panel, clicking, and dragging. This tutorial did not contain information related to the main experiment. The Pad group received an oral briefing on the device and its application to ensure familiarity with tablet operations, which posed no difficulty for nearly all participants. Following this, participants completed both Task 1 and Task 2 and took part in an open-ended interview session. Participants were compensated with a fixed cash reward upon completion of the experiment.

4.3. Results

4.3.1. Basic Interaction

The basic interaction involved measuring the number of clicks and time consumption across various sub-tasks in Task 1. We conducted an ANOVA and Tukey's HSD test to examine the effects of group assignment on touch frequency, with FDR correction applied. The results (see Table 2) indicated that the total touch frequency for the AR group (*mean=68.4, sd=20.01*) was significantly lower than that for the Pad group (*mean=228.16, sd=36.3, p¡.001*) and the EPad group (*mean=116.04, sd=47.23, p¡.01*). This suggests that the AR group required fewer interactions to complete the tasks. Notably, significant differences in total touch frequency among the three groups were observed in Tasks 1-2, 1-3, and 1-4 (*F=16.51, p¡.001; F=108.8, p¡.001; F=144.4,*

Task	AR	Pad	EPad	F value	P value
1-2	15.84±5.66	27.24±9.35	19.20±6.08	16.51	¡.001
1-3	11.92±5.22	87.76±20.29	47.92±23.53	108.8	¡.001
1-4	6.56±5.30	76.36±16.15	19.80±20.61	144.4	¡.001
1-5	34.08±17.04	36.8±25.59	29.12±16.68	0.93	=.40
Total	68.40±20.01	228.16±36.30	116.04±47.23	76.33	¡.001

Table 2. Total number of clicks during the experiments for the AR, Pad, and EPad groups.

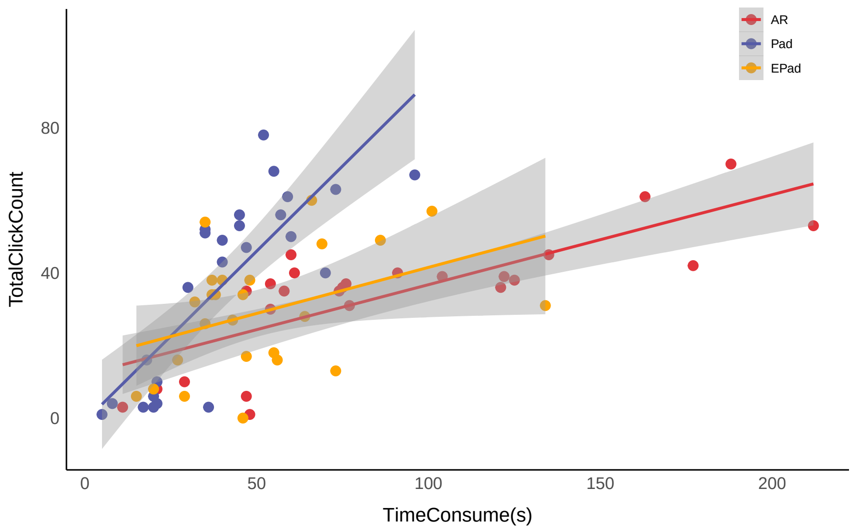

Figure 7. Scatter plot of the distribution of clicks and time. Each point represents a participant, with different colors distinguishing between the groups. It displays the distribution of the total time consumed and click counts during the task for all users in the AR, Pad, and EPad groups, with fitted trend lines and 95% confidence intervals for reliability assessment. The AR group exhibits a trend of fewer clicks but longer time durations.

p¡.001), while no significant difference was found in Task 1-5 (*F=.93, p=.40*).

We also measured the total time consumption of participants in the three groups during the experiment. The results showed that the total time consumption for the AR group (*mean=258.48, sd=102.37*) was significantly higher than that of the Pad group (*mean=177.16, sd=74.47, p¡.01*) and the EPad group (*mean=144.76, sd=57.98, p¡.001*), suggesting that AR may be more challenging or immersive to manipulate. The scatter plot depicting the distribution of total clicks and time is illustrated in Figure 7.

4.3.2. Task completion

Task Success Rate Figure 8 shows the success rates in Task 1. We used one-proportion Z-tests to test the effect of the group on task success rate. The results showed that the task success rate of the AR group was significantly higher than that of the Pad group (*z=-5.89, p¡0.001*) and EPad group (*z=4.89, p¡0.001*). In detail, there was a significant difference in the success rate of Task 1-1 **Sensor Range Task** (*z=-3.06, p¡0.01*), Task 1-2 **Device Status Control and Awareness** (*z=-3.06, p¡0.01*), and Task 1-5 **Permission Turn Off Task** (*z=-4.98, p¡0.001*), where the

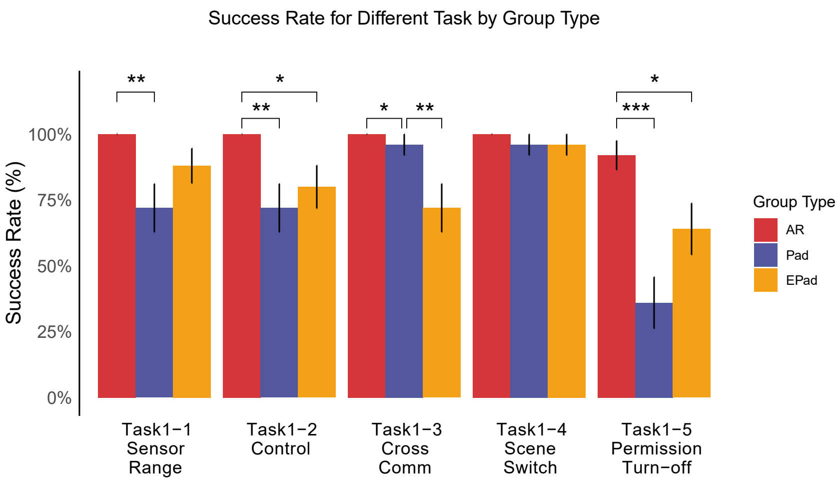

Figure 8. Grouped bar chart of success rates for different sub-tasks in Task 1 for the AR, Pad and EPad groups. It compares the success rates of the AR group, Pad group and EPad group in each sub-task of Task 1. Overall, the AR group demonstrates higher success rates than the Pad group and EPad group, particularly for Task 1-2 and Task 1-5. This suggests that AR has more advantages in range sensing of sensors, state sensing of devices, and sensing changes in scene switching. The X-axis represents the five sub-tasks focusing on various aspects of the system, and the Y-axis represents the task finish success rate. The error bars represent the standard deviation. The asterisks '*' denote a significant effect: ** = p¡.05; ** = p ¡.01; *** = p¡0.001*. These apply to the rest of the figures.

success rates of the Pad group were lower than that of the AR group. There was no significant difference in the success rate of Task 1-3 **Cross-device Communication Awareness** (z=-1, p=0.32) and Task 1-4 **Scene Switch and Awareness** (z=-1, p=0.32) between the AR group and Pad group. The EPad group's success rate at Task 1-2 (z=2.45, p¡.05), Task 1-3 (z=3.06, p¡.01), and Task 1-5 (z=2.49, p¡.05) was much lower than that of the AR group, and was also significantly different from that of the Pad group (z=2.4, p¡.05) at Task 1-3. There was no significant difference between the EPad group and the AR group in Task 1-1 ($z = 1.81$, $p = .11$) and Task 1-4 ($z = 1$, $p = .48$). Additionally, in Task 1-1 ($z = -1.41$, $p = .47$), Task 1-2 ($z = -0.65$, $p = .51$), Task 1-4 ($z = 0$, $p = 1$), and Task 1-5 ($z = -2.02$, $p = .13$), no statistically significant difference was found between the EPad group and Pad group.

Sensor Range Task In Task 1-1, we asked users to move physical objects out of the recording or video range with the smallest possible distance and angle. We measured the deviation between the physical distance or angle moved by users and the standard answer. Figure 9 shows the deviated distances and angles of users in different tasks. Significant differences were observed in the angle data (Camera: F=20.54, p¡.001; Robot: F=10.43, p¡.001) and distance data (Speaker: F=39.52, p¡.001; Robot: F=13.68, p¡.001) among the three groups in the sensor range tasks. In the different subtasks, the AR group differed significantly from the Pad group (Angle: Camera p¡.001, r=-.16 and Robot p¡.001, r=.08; Distance: Speaker p¡.001, r=.05 and Robot p¡.001, r=.14) and the EPad group (Angle: Camera p¡.001, r=-.11 and Robot p¡.001, r=-.02; Distance: Speaker p¡.001, r=-.11 and Robot p¡.001, r=-.16) in terms of both angle and distance, with the AR group demonstrating significantly better performance with smaller errors. Meanwhile, no significant differences were found in angle errors

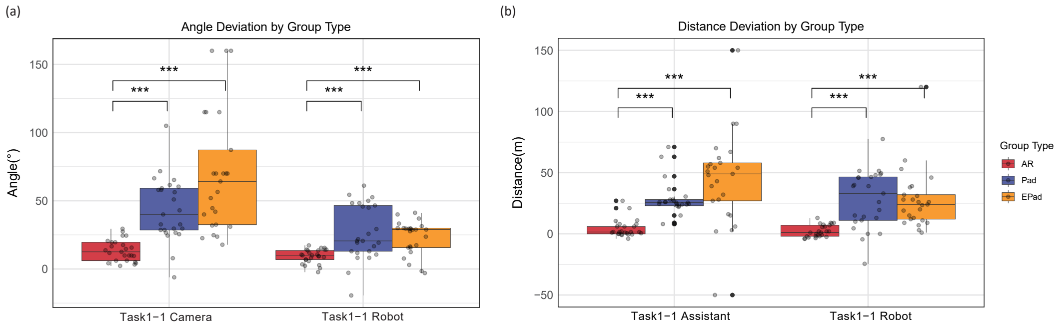

Figure 9. Sensor range task results. (a) Box plot and the distribution of deviated angles for different tasks. (b) Box plot and the distribution of deviated distances for different tasks. Measurement results indicate that both angle errors and distance errors are significantly smaller in the AR group compared to the Pad group and the EPad group. This further highlights the advantage of AR in the sensor range task.

(Camera: *p=.49, r=-.10*; Robot: *p=.41, r=.07*) and distance errors (Speaker: *p=.08, r=.45*; Robot: *p=.66, r=.03*) between the Pad group and the EPad group.

Perception Task Figure 10(a) shows the participants' scores in the Perception task for Task 1-1, Task 1-2, and Task 1-3. In the questionnaire for the Perception task, significant differences were observed in scores among the AR group, Pad group, and EPad group (*F=6.426, p¡.01*), whereas no significant differences were noted among the three groups in Task 1-1 (*F=.12, p=.88*) and Task 1-3 (*F=1.10, p=.34*). In Task 1-2, the AR group scored significantly higher than both the Pad group (*p¡.001, r=.02*) and the EPad group (*p¡.001, r=-.29*), indicating a superior perception of the device state by the AR group. However, there were no significant differences in scores between the Pad group and the EPad group (*p=.51, r=.08*).

4.3.3. System Function Evaluation

User evaluations of the Pad and AR systems in terms of learnability, convenience, and usability were collected via a questionnaire. As depicted in Figure 11, the results indicated high evaluations for both systems; however, there were no significant differences in learnability (*F=.48, p=.62*), convenience (*F=2.03, p=.14*), and usability (*F=1.81, p=.17*) between the two groups, suggesting that their effects are largely independent of user evaluations.

4.3.4. Privacy Scenario Settings

In Task 1, we primarily examined the effects of AR and Pad technologies on user perception. Subsequently, in Task 2, we concentrated on privacy permission settings across various scenarios. The scenario setting scores (see Figure 10b) revealed significant differences among the three groups in Scenario 2 (*F=16.42, p¡.001*) and Scenario 3 (*F=12.89, p¡.001*), though no notable differences were observed in Scenario 1 (*F=2.021, p=.14*). Specifically, in Scenario 2, the scores for the AR group (*p¡.001, r=-.16*) and the EPad group (*p¡.001, r=.10*) significantly surpassed those of the Pad group. In Scenario 3, the AR group's scores were significantly higher than those of both the Pad group (*p¡.001, r=-.32*) and the EPad group (*p¡.01, r=.16*), demonstrating the impact of visualization features on privacy settings. Regarding specific settings

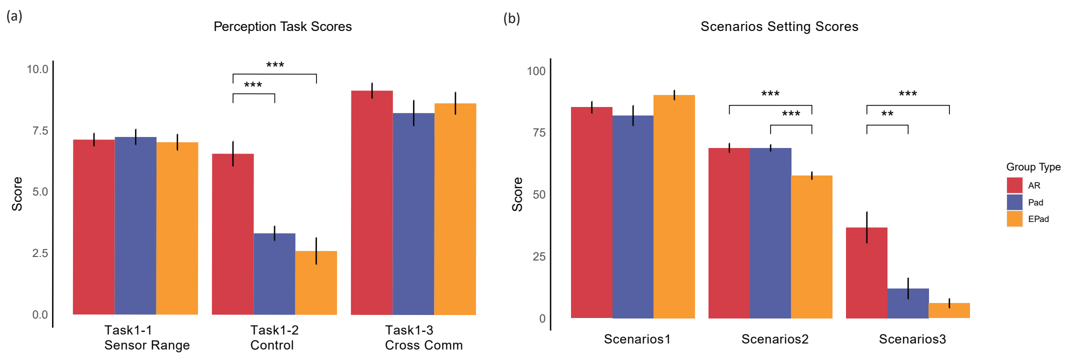

Figure 10. Grouped bar chart of Perception task and scenario setting task scores. (a) Scores for Perception Tasks in Task 1-1, Task 1-2, and Task 1-3. (b) Scenario setting scores in Task 2. Task 1 scores reflect user perceptions under different systems assessed through questionnaire responses for each subtask. Task 2 scores represent user configurations in various scenarios, scored against standard answers.

(see Figure 12), significant differences were found in the permission (*F=4.83, p¡.01*) and power (*F=15.15, p¡.001*) turn-on rates among the groups. In Scenario 1, the Pad group's permission-on rate significantly differed from that of the AR group (*p¡.001, r=-.20*) and the EPad group (*p¡.001, r=.25*). Moreover, in Scenario 1, a notable difference was observed in the power-on rate between the AR group and the EPad group (*p¡.05, r=.22*). In Scenario 3, the AR group's power-on rate was significantly different from that of both the Pad group (*p¡.001, r=.09*) and the EPad group (*p¡.001, r=.24*), indicating a preference for power settings over permissions in the Pad and EPad groups compared to the AR group.

4.3.5. Post-Experiment Interview

Brief interviews were conducted with participants, focusing on various tasks and modules within the experiment. The feedback from participants provided invaluable insights into their experiences with different interfaces.

Visualization and Control Participants in the AR group found the device status visualization intuitive, clear, easy to understand, and concise, enhancing safety and emphasizing autonomous control over permissions. Participants in the Pad group expressed mixed opinions about the visualization interface; some found the permission status clear, while others felt that permissions were too concealed. Participants in the EPad group appreciated the device status visualization features and suggested that permissions should expire upon device power-off. Some participants highlighted the need for authentication methods to prevent unauthorized use or accidental privacy breaches.

> *"...feel more secure, diminishing the feeling of being watched or listened to. (P6 in the AR group)"*

Sensor Range Participants in the AR group found the sensor range display intuitive and conducive to a clear cognitive understanding. Participants in the Pad group described the permission scope display and interaction as abstract, with issues in scope descriptions and challenges in understanding undefined data collection directions. Par-

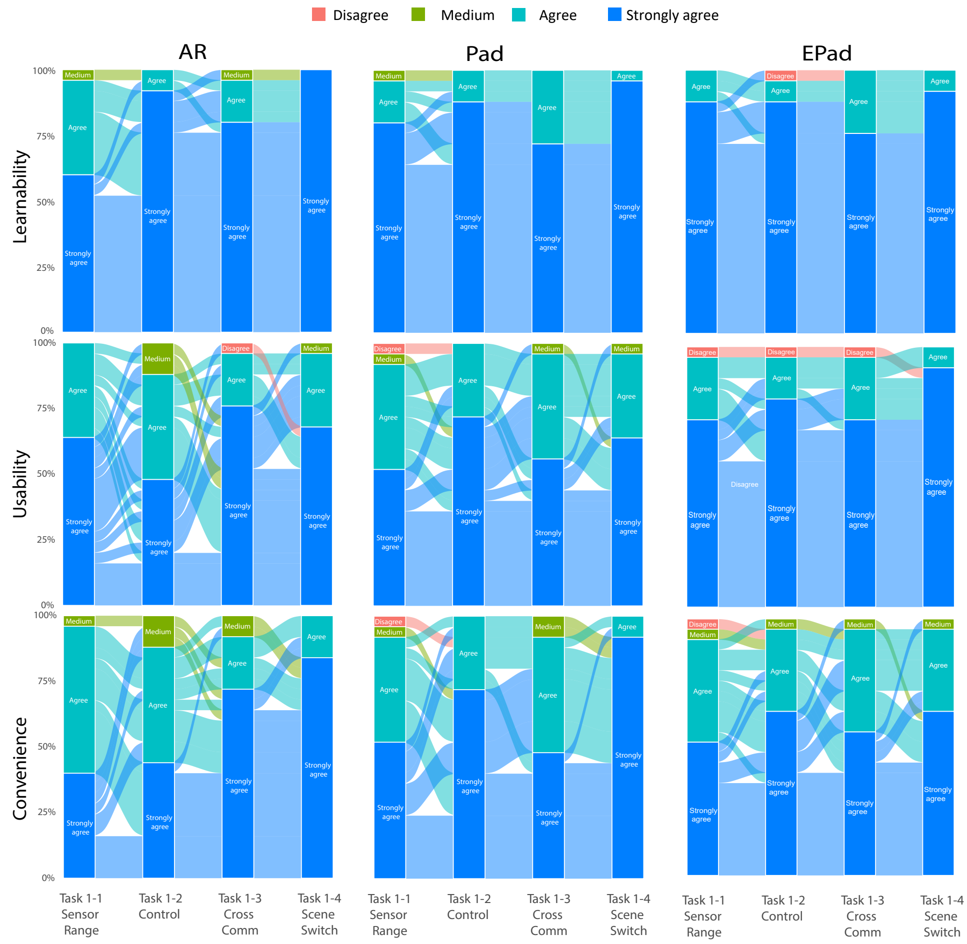

Figure 11. Alluvial plot of variations in evaluation scores for different functions from Task 1-1 to Task 1-5. Different colors represent different ratings (strongly agree, agree, neutral, and disagree) for learnability (ease of use), usability (usefulness), and convenience. The plot illustrates proportions and variations in user evaluations of the learnability, usability, and convenience of the AR system, Pad system, and EPad group during task performance. Each bar represents the percentage of user satisfaction with the current performance level, showing an overall trend of increasing satisfaction.

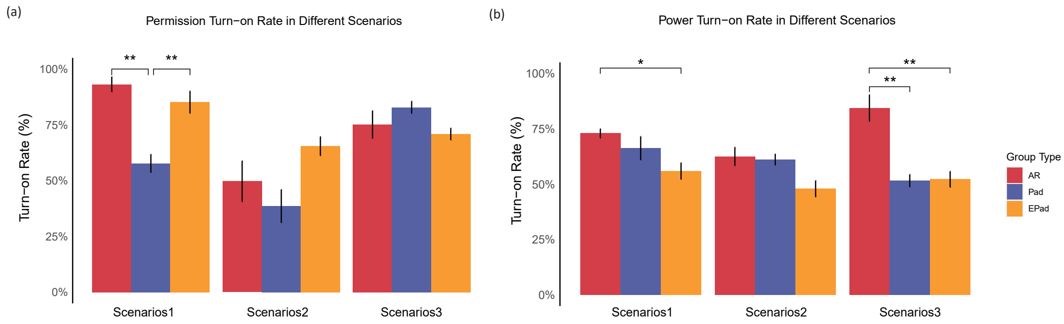

Figure 12. Results of privacy status settings in Task 2 scenarios. (a) Sensor data permission turn-on rate for smart home devices. (b) Power turn-on rate for smart home devices. Users make diverse configurations based on factors such as comfort, energy efficiency, and privacy considerations. When prioritizing energy savings, the device power-on rate tends to decline. Conversely, when focusing on privacy, users are more likely to disable specific device permissions.

ticipants in the EPad group felt that the sensor range representation was not intuitive enough. Some participants recommended maintaining a sufficient distance and angle to avoid the data collection range without the need to know the exact scope of device collection.

> *"...the app permissions are more hidden, and the range display and its interactions are more abstract. (P2 in the Pad group)"*

Data Transmission Visualization Participants in the Pad group found the data transmission method innovative yet complex, suggesting the need for auxiliary elements to aid understanding. Participants in the EPad group requested real-time updates to display data connections. Participants in the AR group found the data transmission display convenient, serving as indicators of device working status and connections.

> *"...can see if the individual devices are connected to each other and also serves as a sign that a device is available. (P17 in the AR group)"*

Scene Switch Mode All groups found the scene-switching function convenient, preferring one-click settings to more complex configurations. Participants in the AR group noted intuitive device status changes during scene switching, eliminating the need to search for permissions and switches. The Pad group mentioned that permission settings and data transmission visualization features were subtle and easily overlooked during use.

5. Discussion

5.1. Feasibility of AR in Smart Home Privacy Control

This study demonstrates that users in the AR group perceived device specifications more accurately, achieved higher task success rates, and required fewer steps compared to those using Pad or EPad systems. The in situ experience provided by AR contributed to accurate perceptions of device specifications and improved task success rates. The AR group also benefited from the spatial and environmental context information, which streamlined interactions and reduced cognitive load. Conversely, Pad and EPad users demonstrated advantages in operational simplicity, particularly in tasks requiring rapid information viewing and processing. The AR group took longer to complete tasks, suggesting a learning curve or less efficient point-and-click operation. Pad and EPad users expressed a preference for simpler configurations, underscoring the importance of considering user preferences and ease of use in smart home interface design. Despite these differences, the subjective function evaluations were similar across all groups. The subjective evaluations from users in the three groups indicated no significant difference in their perceptions of the system functions. The similarity could be attributed to the relatively high ratings given by participants in both groups. The experimenters experienced only one of the three systems, and therefore the evaluations of the different systems lacked strong contrasts. Interestingly, despite the fundamental differences in interaction design between AR and traditional touchscreen devices, participants perceived the learnability of the two systems to be comparable. This observation challenges initial expectations, as AR systems typically demand a distinct set of interactions compared to touchscreen devices. A well-designed Pad system creates a greater sense of familiarity among participants, leading to higher ratings. On the other hand, the AR system was a novel experience for most users and left a positive impression on them when they first used it. Although its users were not familiar with the AR system, similar ratings showed its strength in user-friendliness. Moreover, the analysis of user feedback over time, as depicted in the alluvial plot, revealed an intriguing trend. User evaluations progressively improved with increased usage time, indicating a learning curve and suggesting that user familiarity with the system's interaction and interface played a pivotal role in shaping their perceptions.

In this experiment, we applied AR technology to visualize privacy information related to smart home devices. The proposed visualization approach offered clear advantages, as users could intuitively observe the range and angle of the area that sensors monitor through AR glasses. With this information, they could easily make corresponding adjustments when arranging their physical homes. The findings enable future smart home system designers to focus on how to make the users easily and conveniently understand the coverage range of sensors in real-time. When there is a need to move sensitive items or positions out of the camera or sensor range, or when sensors need to be placed at angles and positions that cannot perceive sensitive areas, users can perform measurements and operations in the simplest manner with the help of AR tools. Additionally, we found that users had the best memory retention of devices' status when performing tasks using AR. This can be attributed to the greatest advantage of the augmented reality system: the ability to overlay information with actual devices in space, enabling individuals to enhance their memory to the fullest extent through visual associations. While privacy information visualization with AR offers a novel and immersive approach, it is crucial to recognize that subjective feelings of safety alone may not be sufficient for smart home privacy preservation. Objective measures, such as stringent security measures, data encryption, consent mechanisms, and transparent privacy policies, are necessary to protect user data and maintain the integrity of the smart home ecosystem, ensuring a balance between user perceptions and objective security measures for both user satisfaction and data protection.

Privacy settings with AR demonstrated significant differences in scene setups, particularly in more sensitive scenarios. The visualization capabilities enhance users' awareness and management of permissions. The AR group exhibited higher power activation rates but lower permission settings, possibly indicating a more cautious approach to permission granting facilitated by the AR interface. The higher scores for the AR group in the "Night Mode" scene, which demands high privacy, suggest that AR settings align better with the scenario's privacy requirements. AR allows real-time configuration and collaborative information presentation, enhancing privacy protection without altering the user's actual home environment and devices. These observations underscore AR's advantages in smart home privacy settings, enhancing user engagement, understanding, and alignment with privacy requirements in sensitive scenarios. Future smart home technologies should consider incorporating AR to improve the user experience and effectiveness of privacy management strategies.

5.2. Design Implications

The study results support several design implications for using AR in smart home privacy preservation. Practitioners should consider incorporating AR technologies to visualize privacy-related information, creating interactive and visually engaging experiences that enable users to perceive data flow and the impact of privacy settings in real-time. This vivid interactive mode distinguishes the system from existing systems by providing a more intuitive and dynamic configuration method [16, 28, 38]. Experiment results support the advantages of AR in providing immersive and contextually relevant representations of privacy settings, sensor permissions, and data flow, enhancing users' understanding and awareness of privacy choices.

Intuitive and user-friendly AR interfaces are crucial. The study observed that participants in the Pad group overlooked device statuses due to different menu positions, leading to lower task success rates compared to the AR group. Future AR menus should avoid the drawbacks of multi-layered redundant flat menus and present operational information in a flatter, simpler structure. Despite the relatively low prevalence of AR, it is believed that with continuous improvements in related technologies and declining costs, its application in people's daily lives will become more widespread in the near future. Future designers can consider more comprehensive AR systems and explore tangible UIs to enhance the integration of physical and AR devices, enabling information to extend from the virtual to the real world, allowing users to perceive privacy-related information more intuitively.

AR-enabled smart homes rely on interoperability, standardization [17], and encryption frameworks [35] to enable seamless communication and interaction between AR interfaces and diverse smart home components manufactured by different companies. These factors play a crucial role in establishing compatibility and ensuring effective integration within the smart home ecosystem. By addressing these aspects, designers can create more immersive, intuitive, and user-friendly interfaces that enhance privacy management and user experience in smart homes. Additionally, by combining the strengths of AR and traditional 2D approaches, designers can create user experiences that seamlessly complement each other. For example, AR can be used to provide enhanced visualizations and immersive interactions, while 2D interfaces can provide familiar and efficient controls for certain tasks. This combination can leverage the strengths of both approaches to optimize user interaction and privacy management in the smart home.

5.3. Limitations

The study has several limitations. First, the network communication between AR glasses and smart home devices focused solely on display functionality, thus cannot achieve real communication. Future research could incorporate connection modules for direct interaction between AR glasses and physical devices, providing users with a more intuitive sense of control. Second, the controlled laboratory setting might not have fully captured the complexities of a realistic home environment, potentially influencing participants' perceptions of privacy protection. To enhance ecological validity and data quality in future studies, researchers could consider conducting experiments in rented residential spaces, allowing participants to familiarize themselves with the environment through typical household tasks before engaging with the AR system. This approach would provide a more immersive and naturalistic context, leading to more accurate and generalizable findings.

6. Conclusion

The findings highlight the advantages of integrating AR into smart home systems. User interviews identified common privacy concerns related to smart home devices, including visualizing information, managing device permissions, and providing simple privacy protection modes. An intuitive smart home visualization system using HoloLens AR glasses was developed to address these concerns. Usability studies comparing the AR system with traditional tablet applications demonstrated significant improvements in privacy information perception, task completion, privacy preservation, and operational efficiency. These findings underscore the potential benefits of AR technology in enhancing privacy protection in smart homes and the importance of prioritizing user-centered design.

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A video demonstration and supplementary document can be found at https://github.com/zhthantao/ARenaSupplementary.

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