Reviewing and Reflecting on Smart Home Research from the Human-Centered Perspective

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ABSTRACT

While there has been rapid growth in smart home research from a technical perspective – focusing on home automation, devices, software, and protocols – few review papers examine the human-centered perspective. A human-centered focus is crucial for achieving the goals of providing natural, convenient, comfortable, friendly, and safe user experiences in the smart home. To understand key innovations in human-centered smart home research, we analyzed keyword changes over time via 19,091 papers from 2000 to 2022, then selected 55 papers from high-impact venues in the last five years, and summarized them through a combination of qualitative and quantitative methods. Our analysis revealed five research trends with unique characteristics and interdependence. Drawing on this review, we elaborate on the future of smart home design research with respect to multidisciplinary development, stakeholder involvement, and the shift of design implications.

CCS CONCEPTS

• **Human-centered computing** → *HCI theory, concepts and models.*

KEYWORDS

smart home, human-centered design, literature analysis, research trends

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1 INTRODUCTION

A smart home[1] is a residential system equipped with various interactive automation technologies [14, 102], allowing residents to control lighting, temperature, multimedia set-ups, security monitoring, door and window operations, and other aspects of the home. All these functions are designed to provide a more convenient, comfortable, and safe living experience. While the term "smart home" was coined by the American Home Builders Association in 1984 [52], electronic technologies such as vacuum cleaners, food processors and washing machines appeared in the early 20th century [14], increasing convenience and comfort. Throughout the 20th century, these technologies slowly advanced, but now with the rise of the Internet of Things (IoT) and Artificial Intelligence (AI) in the 21st century, the field of smart home research and application has entered the rapid development stage. On the industry side, large technology companies such as Google, Amazon, Apple, Huawei and Xiaomi have all released a variety of smart devices and home automation systems. Meanwhile, in academia, several institutions have launched smart home research projects, such as Georgia Institute of Technology's Aware Home [1], MIT's PlaceLab [3], Indiana University's R-House [4], Microsoft Research's Easy Living [22], Imperial College UKDRI Smart Home [6], and Japan's Keio The Smart Space of Uiku University [5]. As of July 2022, the Digital Library of the American Association for Computing Machinery (ACM) contains more than 19,000 papers related to smart home

[1]In both academia and industry, the term "smart home" can sometimes be used interchangeably with "intelligent home", "aware home", and "living lab". Since "Smart Home" appears the most frequently, in this study we consistently use it as the key term for literature search, analysis and discussion.

technologies, of which about 8,000 were published in the past five years.

As an interdisciplinary field, research on smart home technologies is mainly carried out in several main directions [52, 77]. The first focuses on using Bluetooth [15], Wi-Fi [25], machine learning (ML) [57], IoT [10] and other technologies to build home automation systems. The second examines configuring smart devices to monitor the home environment [34] and designing efficient protocols [78, 87, 119] and software platforms to further improve residential security [41]. A third area looks at protecting user privacy and exploring how to design smart devices and how to formulate relevant policies and regulations to prevent the leakage of private data [112, 130]. The fourth explores using data-driven and machine learning methods to optimize household daily energy consumption and efficiency [75] with the help of remote monitoring and device management functions [39, 43, 51, 131]. And a fifth direction within smart home research engages with the medical field; using sensors, wearable devices, cloud computing and other technologies to build home-based nursing platforms [33, 80, 92, 100] where users (especially patients and elderly residents) can be provided with daily care and assisted in medical decision-making; investigating factors that hinder smart home adoption and developing plans to remove the obstacles [33, 80, 92, 100]. These research areas reveal the interdisciplinarity of smart home research, drawing not only on engineering domains, but also psychology, medicine, cognitive science, security and privacy, design, and many others.

At present, researchers in several fields have conducted literature reviews that summarize the diverse, interdisciplinary research work in the smart home field [11, 34, 70, 73, 109, 131]. These review articles summarize and analyze existing smart home studies in a specific research direction, such as safety and privacy issue, sensor technology, user interface and etc. Additionally, there have been efforts to systematically review the field. Analysing about 17,000 relevant papers, Li *et al.* presented a timeline of smart home research over the past 20 years, explored the latest technologies, discussed existing research directions, and deduced the emerging trends [71].

Despite these thorough reviews, few works summarized smart home research from a human-centered perspective. At the time of this writing, there are only two literature reviews of smart home research to be found via Google Scholar. Cho *et al.* (2014) focused on the user interface design to support elderly living in smart home [32]; while Kim *et al.* (2015) focused on users' emotional states when they interacted with smart home devices [64]. Few smart home design-related review studies have been published since then. Figure 1 highlight the research perspectives and analysis methods of our work and prior work.

Two closely related research directions are required to achieve a smart home environment that is natural, convenient, comfortable, friendly and secure: 1) technological innovation and 2) human-centered HCI research [14, 102]. Human-centered research in this domain includes understanding the human experience of using technologies, developing effective and applicable interactions, designing satisfactory interaction interfaces, analyzing potential risks to smart home security and privacy, and proposing potential solutions. In addition, work in this area should recognize the diversity of user roles and the importance of user involvement in smart home design. At the same time, human-centered design is not only

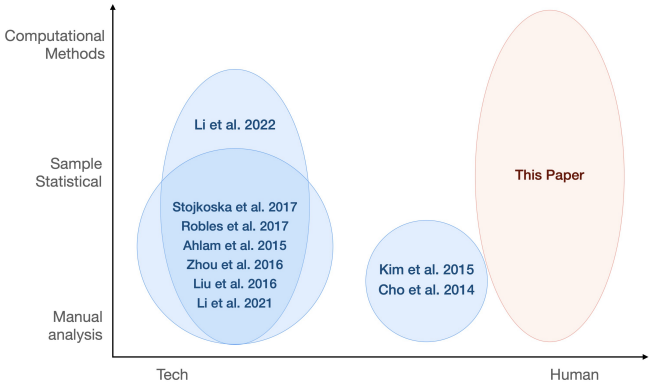

Figure 1: Research perspectives and analysis methods of related work, x-axis is the research perspective; y-axis is the different analysis methods.

advocating that computers should show decent manners when interacting with people, we also call for people should respect and tolerate computers in order to develop sustainable smart home research.

To better understand the role of human-centered design in the domain of smart home research, we conducted a keyword frequency analysis with 19,091 smart home papers over the past 20 years. We noted an increasing number of human-centered design papers in the data corpus over the last five years. This suggests a need for a review of the research from the human-centered perspective, to better understand the direction of the field.

We then selected 55 related publications (i.e., human-centered design articles) in the past five years from high-impact HCI venues, systematically analyzed their research findings, and conducted multiple rounds of analyses to summarize the main trends in human-centered smart home design. The main contributions of the paper are as follows:

(1) A comprehensive presentation of human-centered design in the smart home domain over the past five years, including whether users can be the core "experts"; how researcher roles are differentiated; and what the research actions or content are.

(2) A summary of five research trends (Interaction Design, User Behaviour, Data, Privacy and Security, Smart Devices, Design Exploration) related to human-centered design in smart home scenarios, with detailed analysis and description of their characteristics.

(3) A series of reflections about facilitating future research on smart space from the disciplinary integration, the transformation of participant identities, and the cultural advocacy of technology.

(4) A proposed set of efficient, systematic and reproducible literature analysis approaches, encompassing exploratory reading, literature encoding, topic extraction and classification, manual analysis of encodings, research trend induction, and correlation analysis.

2 RELATED WORK

Over the past decade, there have been many literature reviews on smart home research, most of them focusing on the technological innovation perspective.

For example, Stojkoska *et al.* reviewed various cutting-edge IoT technologies and discussed which technologies have been (or have the potential to be) applied in smart home scenarios [109]. The authors proposed a smart home operation framework that comprehensively covered components of IoT as a technical basis for the future development of IoT-based smart home solutions.

Robles *et al.* summarized three types of technologies for ensuring smart home security: 1) perception technologies of sound, vision and environment, 2) home and resident state detection as well as detection of abnormal behaviors, 3) related technologies to inform and alert residents and grant access to devices [34].

Meanwhile, Ahlam *et al.* evaluated existing state-of-the-art smart home privacy protection technologies based on five evaluation criteria (that is, accuracy, delay, cost, topology, and effectiveness) for data transmission in Wireless Sensor Networks (WSNs) [11].

Zhou *et al.* outlined the architecture and functional modules of smart home energy management systems, introduced related infrastructure and household appliances, demonstrated the possibilities of renewable energy (including solar, wind, biomass and geothermal energy) in smart homes, and finally analyzed the strategies of using various household appliances to reduce residential electricity costs and improve energy efficiency of power generation facilities [131].

Liu *et al.* explored home-based healthcare technologies mainly for monitoring activities of daily living, cognitive decline, mental health, and cardiac conditions in the elderly. They pointed out that, for the elderly with complex needs, the completeness of health monitoring technologies is still at a relatively low level [73].

Li *et al.* summarized the main factors hindering the widespread adoption of smart home, such as the limited awareness of the industry in most potential users or stakeholder groups, the distrust and resistance of smart home technologies, concerns about financial issues, privacy and security threats, technological anxiety, and negative social impacts [70]. Other than these review papers that focus on particular aspects of smart home technologies, there are also some comprehensive review papers that cover the research area as a whole. For example, Li *et al.* analysed 17,000 smart home-related research papers published in the last two decades to examine current trends in the field and deduce future directions [71]. Figure 1 presents the differences in research perspectives and analytical approaches among these discussions of smart home technologies.

Despite the extensive literature surveys of smart home research, few researchers have focused on reviewing work from the human-centered perspective. The literature reviews published by Cho and Kim *et al.* mentioned above provide us with references from human-centered design [32, 64]. However, they were published in 2014 and 2015, respectively, with limited focus on this area in the smart home domain since. Thus, we believe that the research efforts of multi- and interdisciplinary researchers in this area deserve more attention, as they have proposed many cases, methods, tools, and reflections for furthering the field. In this paper, we aim to address this gap in systematic reviews and provide an overview of the human–centered perspecctive in smart home research.

3 SYSTEMATIC ANALYSIS

3.1 Selection of Papers

We selected the ACM Digital Library (DL) as the source database for literature collection since it contains the largest proportion of smart home-related publications (We searched Elsevier, ACM DL and IEEE Xplore for "smart home" on December 12, 2022, with 128,860 records for ACMDL, 79,283 for Elsevier and 15,206 for IEEE Xplore). We defined the search criteria in the ACM DL database as *[all: smart] and [all: home] and [publication date: (01/01/2000 to 12/31/2022)]*, requiring that all returned articles contained both "smart" and "home" and were published within the period of 2000~2022. The database housed 19,091 relevant papers, from which we extracted all the keywords and performed keyword frequency analysis [91].

To obtain a timely summary of smart home research trends, we filtered the 19,091 papers to focus on the time span of 2018~2022 in journals/conferences relevant to HCI and ubiquitous computing for in-depth analysis. This returned 71 relevant papers from the TOCHI journal and eight conferences: CHI, UbiComp, CSCW, MobileHCI, DIS, AVI, IUI, and ICMI[2]. To ensure the high relevance to the topic of smart home interaction design, we matched the term "smart home" with the abstract, introduction and conclusion of these 71 papers. Of the 71, 34 of them had all three sections containing the term. For each of the remaining 37 papers, we carefully read through the three sections, discussed the scope, and identified 21 articles with a significant connection to the review topic, resulting in 55 articles in total for literature review and analysis [9, 19, 26, 27, 29–31, 38, 40, 42, 44–50, 56, 58–61, 67, 69, 72, 74, 79, 81, 86, 90, 93, 94, 98, 103, 104, 108, 110, 113, 115, 120–122, 124, 125, 127–129]. All of them were in line with the research theme of smart home interaction design and could convey the advances and trends of state-of-the-art smart home design research. The search and selection procedure strictly followed Webster *et al.*'s systematic literature review criteria, which ensured the comprehensiveness and reproducibility of the results [120]. Meanwhile, in these 55 papers, there are other fields besides smart home that have been discussed. We checked the abstracts, keywords, introductions, and conclusions of all papers, and found that 29 papers mentioned IoT and 11 papers mentioned ubiquitous computing.

Focusing on each paper in the literature review and corpus, while being inspired by DiSalvo *et al.*'s research on sustainable HCI [35]. Their paper discussed the disciplines used, the users included as additional experts, the role of researchers involved, and their actions taken in sustainable design. This work further offers a comprehensive perspective on interpretation of sustainable HCI and, importantly, inspired us to formulate the research questions in this study. We developed several questions to ask about each paper, looking for themes that appeared to recur or that would illuminate

[2]TOCHI- ACM Transactions on Computer-Human Interaction;
CHI- ACM Conference on Human Factors in Computing Systems;
UbiComp- ACM International Conference on Ubiquitous Computing;
CSCW- ACM Conference on Computer Supported Cooperative Work and Social Computing;
MobileHCI- International Conference on Human Computer Interaction with Mobile Devices and Services ;
DIS-ACM Conference on Designing Interactive Systems;
AVI- International Working Conference on Advanced Visual Interfaces;
IUI- ACM International Conference on Intelligent User Interfaces;
ICMI- ACM International Conference on Multimodal Interaction.

differences between diverse human-centered smart home studies. The research questions are as follows:

(1) What domain do we talk about when we talk about the smart home?

(2) What disciplinary orientations are involved?

(3) Who is considered the "expert", and who is at the core of smart home research?

(4) How is the role of the researcher framed?

(5) Who takes action and what actions are they supposed to take?

(6) From a human-centered perspective, what sparks or reflections can this paper provide, which can contribute to the sustainable development of smart home?

The six questions reflected thoughtful inquiries into the relevant disciplines, the versatile roles of users, and the significance of their participation in smart home research. We also want to categorize the researchers so that the various analysis results and conclusions can be specifically used, referred to, or leveraged by targeted researcher groups.

3.2 Literature Analysis Method

The literature analysis pipeline in this study began with preliminary reading the full text of the 55 selected articles to gain a general understanding of the research content, which resulted in the following three findings:

(1) Each review might answer one or more research questions; there were multiple articles with completely different sets of research topics; meanwhile, some articles might use different wordings to express similar concepts.

(2) The 55 literature reviews tended to exhibit multiple research trends in smart homes that differed in research directions, workload, and problem spaces.

(3) A certain interdependence existed between research objectives of the 55 papers and the research trends of smart home.

To grasp the research objectives and trends of the selected articles, uncover the objective-trend relationships, and explore characteristics of the trends, we propose an efficient, comprehensive and reproducible literature analysis pipeline. Figure 2 presents an overview of the process.

In this process, we combined manual and computing analyses to improve the efficiency of literature review and ensure the reliability of analytical results [7, 12, 17, 21, 76, 84]. Our subsequent analyses procedure also followed the systematic literature review standard [120]. We followed the stage-wise review methodology [97]; each step is introduced as follows.

(1) Exploratory reading: To summarize the trends in smart home research, five researchers evenly split the 55 articles into batches, each article in the batch was read and analyzed independently by one of the researchers; and each article was then described by a set of tags. Then, we, the research team, discussed, exchanged and refined the descriptive tags, recording the final tags in a spreadsheet for subsequent analysis.

(2) Literature coding: The first step of coding was categorization of the literature tags summarized in exploratory reading. The quality of coding is determined by precision and extensiveness [97], thus the literature tags summarized by researchers should accurately describe the attributes of the corresponding smart home study in each article and cover all main points each review seeks to deliver. We identified 11 categories of tags to comprehensively cover the content of each article for further manual and computer analysis.

Second, one-hot encoding [54] was performed on the 11 types of tags for the 55 selected articles to yield a 55×171 dimensional tag matrix D (see A1) [53], where $F_{i,k}$indicated whether the ith article was described by the kth tag type or not (1 for yes and 0 for no), and these were used as data material for the quantitative analysis.

For example, the tag vector F only has a value of 1 for "parsing security risk" and "evaluating interaction expectation", while the values for all other tags are 0, as shown in Table 1. Similar operations were performed on all 11 types of tags for the 55 articles, resulting in a total of 171-dimensional features.

Table 1: Exemplar rows and columns of the literature label matrix

Literature number	…	Modelling predictive behaviour	Dissecting security risks	Preventing privacy breaches	Assessing interaction expectations
…	…	…	…	…	…
Literature *i-1*	…	0	1	0	1
Literature *i*	…	0	0	0	0
…	…	…	…	…	…

The final part of literature coding is to extract and combine each article's abstract, introduction and conclusion into a shorter textual corpus for topic analysis in the next step.

(3) Refinement and analysis of research objectives: in this study, we combined manual coding and computational methods. While frequency and count-based findings can be obtained via manual analysis, regarding refinement of research objectives and trends, computational tools of Agglomerative Hierarchical Clustering (AHC) [76] and Latent Dirichlet Allocation (LDA) [21] can be used to complement researchers' manual analysis and decision-making on the number and content of research objectives and trends. Based on these AHC and LDA results, we can further depend on our knowledge and reading of the articles to refine the number and content research objectives and trends, and determine which articles belong to which objective/trends. These results form the basis for delving into the current state of the field and summarizing the research trends of human-centered design in smart home scenarios. The approach of firstly leveraging computational tools for preliminary exploration and then using researchers' domain expertise to refine results can increase the efficiency of literature analysis and help obtain precise findings with the aid of computational methods. This can be viewed as an example of mixed machine-human intelligence.

(4) Manual analysis of encoding labels: researchers manually explored multivariate information with respect to target user groups, associated researchers and research methods and preliminarily analyzed correlation between the articles in preparation for the next analysis stage.

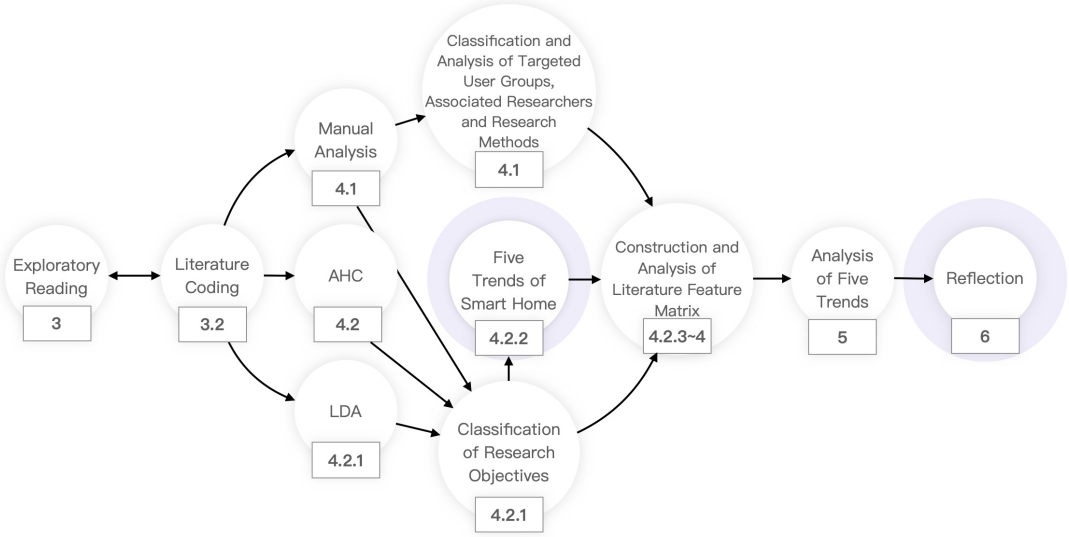

Figure 2: The literature analysis pipeline with corresponding sections in this paper.

(5) Research trend induction and correlation analysis: researchers summarized a set of smart home research trends based on the research objectives and the aforementioned timeline analysis. Combining the trends, research objectives, target user groups, associated researchers and research methods yielded an all-encompassing literature feature matrix. We then analyzed this matrix by dimensionality reduction, visualization and feature correlation analysis to clarify the similarities and differences between the selected articles, illustrate the research trends to which each article belongs, and analyzed the correlations between the literature features and the trends.

(6) Analysis of research trend characteristics: according to the correlations discovered in the previous analytical step, the characteristics of each research trend are formulated and explained with concrete examples from the selected articles.

Finally, consolidating all analytical results attained in the pipeline inspired the researchers to reflect on smart home studies from the human-centered perspective and to speculate on the possible future research opportunities and challenges.

4 LITERATURE ANALYSIS PROCESS AND RESULTS

In our examination of the data corpus publication dates (2000~2022), there is an increasing trend of the number of papers in the past two decades, accelerating after 2015. Therefore, we divided the former period into larger time spans as 2000~2005, 2006~2010, 2011~2015 and split the former into narrow spans as 2016~2018 and 2019~2022. This division ensures a relatively uniform distribution of literature count across different time spans. The purpose is to more clearly observe the trend of article keywords over the years.

Then, we used the Natural Language Toolkit (NLTK) to identify synonyms of each keywords of the papers being counted and merge them (with "smart home" removed from the keyword collection [20]). In each time span, we counted the keyword frequencies and visually presented the top 100 keywords in Figure 3 to depict how smart home research topics evolved during the past 22 years. Specifically, the following findings can be observed:

(1) The volume of smart home studies has been constantly increasing.

(2) Early articles related to smart home research mainly focused on technology and engineering fields, such as ubiquitous computing and the smart grid.

(3) Over time, keywords related to design, humanities, and psychology in smart home scenarios (represented by purple bars) began to emerge and gradually rise.

(4) From 2016 to 2022, the frequency ranking of keywords related to design, humanities, and psychology has been notably increasing.

(5) The keywords span of 2000~2010 was dominated by entertainment, industrial design, aesthetics, visual and interdisciplinary design. Since 2010, the content and types of smart home design have become more diversified. After 2016, keywords representing more interdisciplinary and forward-thinking, such as co-design, design fiction, research through design, and sustainable HCI appeared.

These findings highlight the need of a review of the recent years' smart home interaction design research. In the rest of the section, we focus on the 55 papers that we selected in Sec. 3.1.

4.1 Classification and Analysis of Targeted User Groups, Associated Researchers and Research Methods

This study not only investigated the focal content of the 55 articles by means of bibliometrics, but also covered each article's ethnographic research part (if available), which may contain both quantitative and qualitative analytical processes. The analysis results are, however, difficult to be precisely coded by computers. Through manual reading, we categorized the research subjects involved in the articles, and the results were: 14 articles were analyzed using only smart device data, and the remaining 31 papers involved

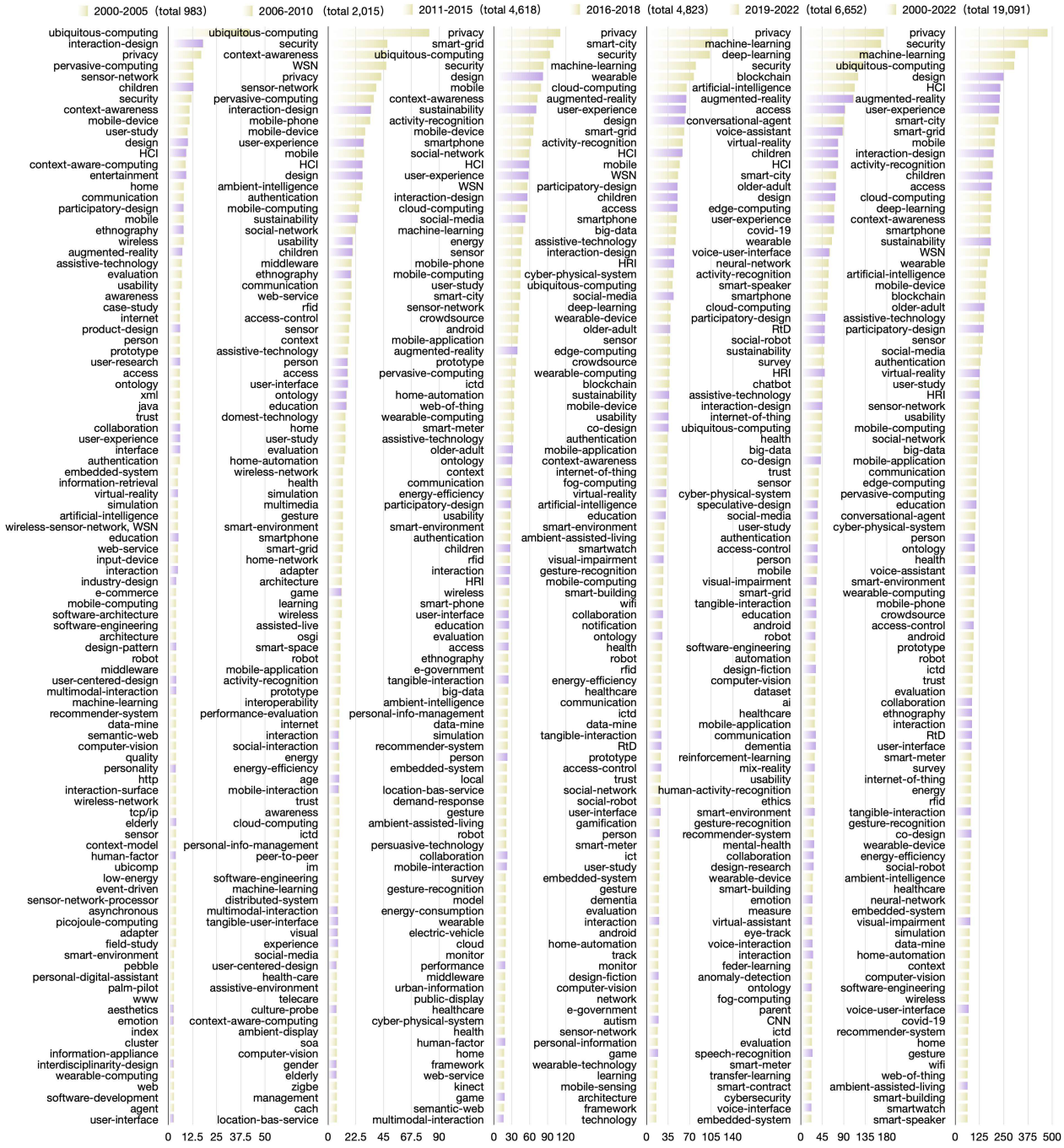

Figure 3: Changes of keyword frequencies rankings in the smart home research field from 2000 to 2022 (Purple bars represent keywords related to human-centered design).

the analysis of the users themselves. The results to as many as 34 articles analyzing user opinions and behaviors, 19 articles mixing device data, user opinions, and behaviors, and 2 articles analyzing multi-stakeholders.

Based on our findings, it seems that smart home researchers have started to break through the limitation of device data and further understand the design intentions of smart homes from the perspective of users and other stakeholders. Therefore, we proposed to analyze the data based on three categories: targeted user groups, associated researchers, and research methods. The purpose was to further infer the research motivations, development paths and potential research key points related to smart home research. It

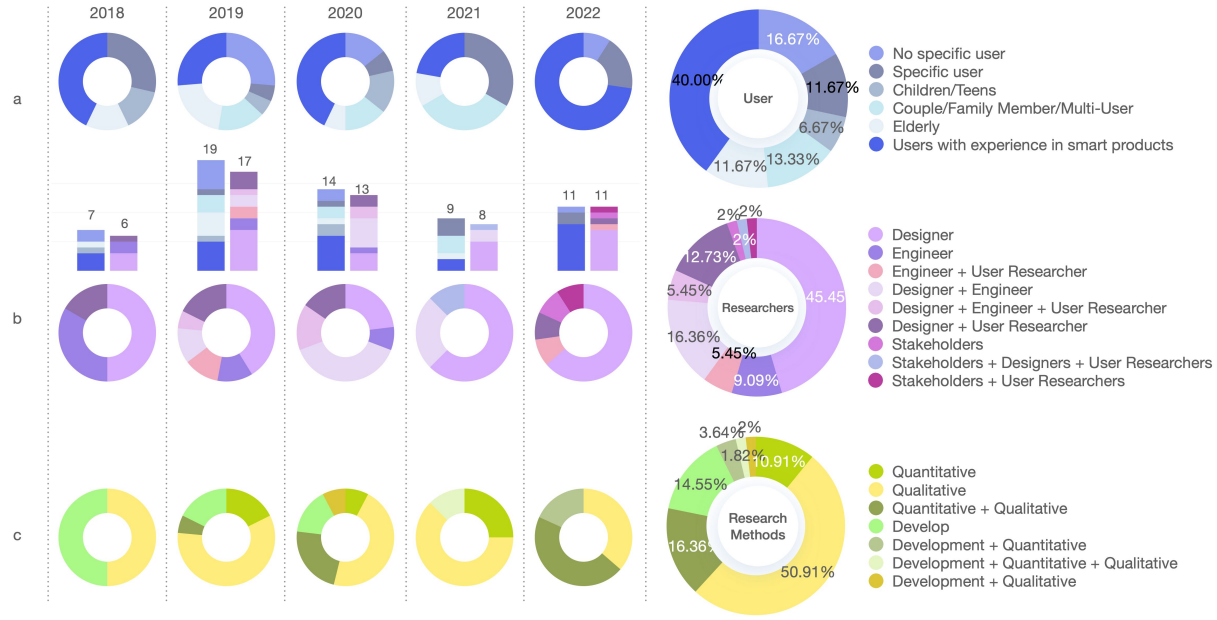

Figure 4: From top to bottom (a) the first row shows the targeted user groups, (b) the second row shows the associated researchers, and (c) the third row shows the adopted research methods, and between (a) (b) is a comparison of the targeted user groups and associated researchers. From left to right, are the statistics and distribution from 2018 to 2022 and the total number.

is worth noting that each article may target multiple user groups, causing the total number of identified user groups greater than 55.

4.1.1 Targeted User Groups. The main user group of smart home technologies in the research was residential users. Our findings identify six user groups from 55 papers (see Figure 4a): 40.0% of the papers focus on people with experience in smart products; 16.67% of outcomes no user group is specified; 13.33% focus on couples, large families, and many user groups; 11.67% focus on older persons/the elderly; 11.67% focus on specific user groups, such as different countries, different gender groups; 6.6% focus on young people.

40.0% of the papers focus on users of smart gadgets,

According to the research, 40.0% of the papers focus on people with experience in smart products. This type of literature tends to analyze generalized problems in smart home scenarios, including user behavior perception analysis [30, 60], user identity prediction [56], privacy data analysis [8, 16, 29, 48, 60, 81, 94, 104, 108], and multi-device connection or setup issues [90, 94]. 16.67% of the literature does not place much emphasis on the targeted user group, meaning that it could generalized to any group. Eight papers in the corpus concentrate on user information privacy issues and sensitive data [31, 44, 61, 72, 86, 93, 124, 125], while two papers focus on smart home design methods and design tools [19, 58]. The findings of these two largest areas demonstrate that the current academic research on smart home has been increasingly carried out in more diversified areas.

13.33% of the papers focused on multi-user smart home systems. Although the percentage of this finding is not as large, the issues it highlights are important to consider. Some works focus on the spatial layout design or home design under multi-member activities [37, 46], while others are concerned with the privacy issues of multi-users [24, 69]. Several publications also address the evolution of multi-user relationships in the context of smart homes [121, 123]. For example, Williams *et al.* proposed design rules by analyzing changes in family multi-member relationships. The goal was to integrate various household appliances into the IoT system or to make recommendations for further refining the design of smart homes to support many users [121]. Some researchers have also shown that updating smart home devices and improving remote connectivity can strengthen family ties [123]. These papers demonstrate the connection between smart homes and multiple user groups. The literature in related domains also discusses multi-user conundrums. For instance, the work of Sunjeong Park *et al.* demonstrated the supportive role of AI voice assistants in social competence and privacy protection, and illustrated the problem of co-ownership of AI voice assistants among family members [88].

The target user group as elderly persons makes up 11.67% of the articles in our data set. This type of literature focuses on elder-oriented design, including behavior analysis in older people [127], behavior prediction [128], interactive control, and device development [47, 50]. Some works, such as home monitoring and privacy information mechanism design, focus on the user demands of stakeholders who are concerned with the health and well-being of the elderly [50].

Along with the aforementioned, 6.67% of the papers specifically look at smart home technologies for children and adolescents. The material is mostly centered on design that is acceptable for a

given age group, for example, co-designing interactive interfaces with teenagers [42, 103], creating smart bedrooms that meet their needs [38], keeping an eye out for potentially harmful circumstances at home [9], etc. Despite the small number of pertinent studies, we are encouraged by the research trends. Perhaps inviting young people to participate in the design can encourage them to increase their understanding of the information and communication system of the IoT and promote awareness of information privacy and security.

We learned that the field of HCI, not just smart home, has begun to call for the well-being of different populations with practical actions. Among them, there are not only advocates for how smart home technologies can better support the lives of older adults[65], but also other populations. Sultana *et al.* call for design technologies to support rural women[111], Bennett *et al.* supported reimagining empathy as guided by the lived experiences of people with disabilities[18], and Resnick *et al.* encouraged designing new technologies for kids, giving kids what they want, not what they ask for[96]. We hope that these findings also provide some opportunities for researchers to use the smart home as a scenario or building block, calling on researchers to focus on the diverse needs of different user group.

Finally, 11.67% of the literature is targeted toward certain specific user groups. A portion of them focuses on the regional design of smart houses, for example, discussing user privacy concerns in smart homes in the Middle East and East Africa [13]; incorporating local culture into smart devices [28]; gender performance design in the smart home [110]; and adaptive design for people with motor disabilities [79]. Numerous studies concentrate on certain user groups and underrepresented user groups, such as Tayyaba Shahzadi *et al.* who introduced wearable devices for smart home to assist visual impairments for navigation [114]. This is a good sign that the field of smart home research is becoming more inclusive, and we hope that interactive technology and interface design will assist specialized groups and minority groups.

4.1.2 Associated Researchers. We also examined the makeup of the smart home researcher teams in addition to investigating the user groups. One of our research goals is understanding how the professional knowledge and abilities needed for smart homes have changed over time, while the second is to examine recent changes in the identities of smart home researchers. We aim to provide a resource for upcoming smart home researchers to undertake their research activities based on own expertise and needs. These identities were investigated by examining the keywords, key content, future work, and discussions of the 55 papers: we inferred and interpreted from the technical problems addressed, the design considerations formulated, and the design implications offered in each paper, concluding with four refined categories of identities, namely, engineers, user researchers, designers, and stakeholders.

Engineers primarily comprise test engineers, statisticians, and data scientists as well as hardware and software engineers. Development, data collection, user behavior model establishment, and testing are their main duties.

Human factors engineering, psychology, and behavioral science are the key fields from which user researchers appear. Their main responsibilities include analyzing user cognition, administering psychometric tests, planning user experiments.

The designer's responsibilities are now more varied and adaptable than in previous decades. In addition to the basic product and interface aesthetic design, interaction design, and user experience design, the designer also needs to play an inclusive role and interact with other researchers in a multidisciplinary research team. In addition, the design discipline is also adept in incorporating some unconstrained research aspects into the research process and enhancing the research findings. The unconstrained research aspects refer to variables that are often difficult to quantify but important in the design process, such as some user self-reported opinions. Therefore, designers need to undertake a variety of "invisible" tasks such as organization, coordination, aggregation, and reflection [132].

Stakeholders include industry stakeholders and scenario stakeholders, and typically draw from their own experience to advance more qualified opinions during the design process for users or researchers to consult and discuss.

However, smart home field is a typical multidisciplinary research endeavor, and the analysis revealed a variety of combined researcher types, including Engineers + Designers, Engineers + User Researchers, Designers + User Researchers, Stakeholders + User Researcher, Designer + Engineer + User Researcher, Designer + Stakeholder + User Researcher. After extracting the types of researchers, we subsequently draw the types of researchers for each year from 2018-2022 (see Figure 4b).

The 2018 results indicate that most smart home research requires engineering disciplines. Since 2019, there has been a marked increase in multidisciplinary research teams. Very recently, since 2021, stakeholders' insights will be incorporated as research variables or materials to promote more professional research support for smart homes. From a multidisciplinary standpoint, professional skills and expertise are invested in the smart home, but on the other hand, researchers' talents have also been broadened and incorporated.

4.1.3 Research Methods. Based on our analysis of the 55 papers, the research methods of the data set were mainly divided into quantitative, qualitative, and development. Quantitative research methods mainly included A/B testing, questionnaire, statistical analysis, and other techniques. Qualitative research methods included semi-structured interviews, context awareness, co-design, participatory design, speculative design, etc. We categorized development as the creation of user behavior prediction models and the development of software and hardware.

Comparing the targeted researcher identities in the previous section, we discovered that the research methods used in the 55 papers strongly correlate with the researcher identities. In some independent development projects, engineers make up the majority of the workforce. Meanwhile, he majority of the work that uses qualitative research techniques is done by designers or user researchers. Cross-team cooperation is used in mixed methods projects. Most stakeholders lack experience with HCI research methods, due to their diverse experiences and backgrounds. Therefore, the work involving stakeholder participation is mostly carried out with the assistance of other designers or user researchers, mainly using mixed methods approaches [79, 86, 116].

According to our analysis of the literature from 2018 to 2022, we see a decrease in development-only papers (see Figure 4c). An increasing percentage of work now uses multiple methodologies. Firstly, smart home research usually involves multiple methods and phases. Secondly, the research team's professional makeup is becoming increasingly interdisciplinary, and new methods are emerging. Additionally, as research into smart homes develops, researchers are uncovering more tensions and gaps in the space, encouraging the development of more human-centered methods that prioritize the user. At the same time, it is also challenging to assess user skill levels, motivating further research into tools and techniques for this purpose. The complexity of assessing users may be part of the reason qualitative approaches are heavily used in these papers. Researchers can make flexible decisions by using qualitative approaches to gather a wide range of unconstrained data sources and ideas and include them into the research process.

4.2 Literature Trends Induction and Correlation Analysis

4.2.1 Refinement of research objectives. Appendices Figure 10 shows the computational clustering of the 55 articles based on the literature tags summarized by the researchers. This can allow us to preview similarity among articles as well as the possible optimal number of clusters, as depicted by the red horizontal lines, which respectively inspire the decision on the number of research objectives (18) and trends (5). Additionally, Supplementary Figure 11 illustrates computational extraction of the 55 articles' topic distributions via LDAvis [106], where each article may be generated by multiple topics and each topic contains a number of key words. The parameters of LDA, alpha and beta, are both set to the default value of 1.0 divided by the number of topics; the number of topics is determined according to two measures, namely, coherence score [107] and perplexity [117] of the extracted topics given various possible topic numbers ranging from 7 to 20. Coherence score is considered a more effective measure for topic modelling than the commonly-used perplexity [107] and thus prioritized to evaluate the LDA results in our study. As shown in Appendices Table 1, it is apparent that when coherence score peaks with the topic number of 12, 17 or 18; among the three, 18 yields the least perplexity.

Therefore, we decided to set the number of topics to 18 (corresponding to 18 research objectives). Figure 5 shows the number of smart home-related papers per research objective and year of publication.

4.2.2 Summary of five research trends. Based on the above 18 research objectives, we present five eminent research trends ("Focus on interaction design", "Focus on user behaviors", "Focus on smart devices", "Data, privacy and security", "Design exploration") found in the 55 articles, demonstrating the distribution and correlation of research hotspots in the field of smart home research. We can infer the characteristics of different research trends by following the distribution of coding tags for the various literature reviews. In order to ensure every paper can be uniquely identified by only one research trend, we created specific explanations for trends to make them clear and distinct from each other.

As the analysis moved forward, we found that the five trends might be interconnected. Therefore, we decided to conduct further data analysis to examine the relationships between research trends rather than specific clusters, thereby obtaining the relationship between research trends and literature coding tags.

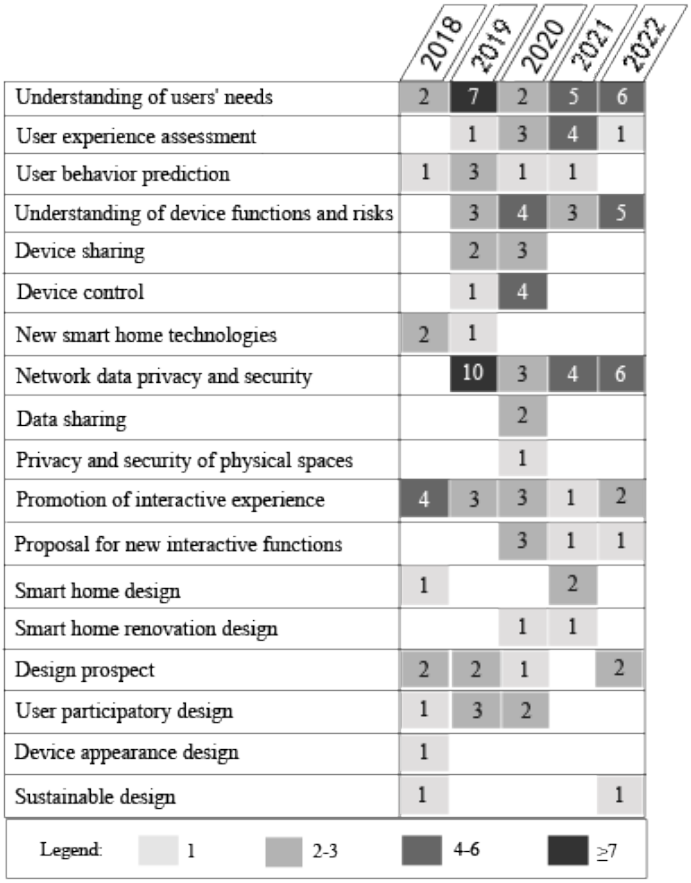

Figure 5: Count of research objectives for the 55 selected articles sorted by year of publication.

4.2.3 Construction and Analysis of Literature Feature Matrix. To identify the relationships and interdependencies as well search for evidence supporting the aforementioned hypothesis, we carried out the following steps:

(1) The 18 research objectives (listed in Table 2), the targeted user groups, the types of associated researchers and the research methods (to be presented in Section 4.2) were utilized as literature coding labels to comprehensively describe the characteristics of each paper; one-hot encoding was then conducted on all labels to form a feature matrix that contained 31 dimensional article features: namely, 18 research objectives, 6 targeted user groups, 4 associated and 3 adopted research methods.

The final dimension of the feature matrix M (see A2) consisted of 32 columns (representing the 31 dimensional article features and an additional trend type feature, used to identify the trend to which each piece of literature belongs) 55 rows (representing the selected articles). $A_{i,k}$ was a binary value indicating whether feature k appeared in paper i or not. S_i denoted a value between

one to five and indicated the type of trend in paper *i*. Next, matrix M would be used as input for data analysis.

(2) One of the well-known techniques for identifying and visualizing interdependence in multivariate data is principal component analysis (PCA), which is a good fit for our goal of analyzing the interdependence between trends in the coded data [7]. PCA took all features $A_{i,k}$ in matrix M as the original variables, and performed zero averaging (i.e.,$A_{i,k}$ subtracting the mean value of A_i) on each row of the original variables to obtain a new matrix V with 31 columns (here only article features were used) and 55 rows. Then we determined the covariance matrix of V, calculated as the eigenvalue and eigenvector of the covariance matrix, and used the first two rows with the largest eigenvalue, meaning that the original data was reduced to two dimensions. Here, it should be noted that, following Alavi et al's approach [12], PCA is not performed on the research trends but on the 31-dimensional article features. The latter are reduced to lower dimensional representations to facilitate visualization; the former serve as the labels of the articles so that on the plot each article can be colored differently based on its trend. Then, it becomes feasible to visually analyze the distributions of both articles and research trends regarding smart home.

Percentages of variance explained by each of the selected components of PCA are as follows: component0: 0.98639659, component1: 0.00227631. The amount of variance explained by the selected components is high. The sum of all components should be 1, which means that the higher the variance explained by a component, the more this component reflects the distribution of the original data. After dimension reduction, PCA can preserve the original data features and make the data features independent of each other. Additionally, we assigned each trend a different color so that Figure 6 can show how the research trends relate to one another.

4.2.4 Analysis Results. There is some degree of overlap in the trends, as displayed by the data distribution of the five trends in the figure 6. In particular, we observed the following traits in the distribution of trends: "Data, privacy and security" stands out from other trends and is primarily present in the fourth quadrant. In stark contrast to other trends, "Focus on interaction design" is mostly found in the first quadrant. The distribution of "Focus on user behaviors" and "Focus on smart devices" is more dispersed. In addition, "Design exploration" has an intersection with the other four trends.

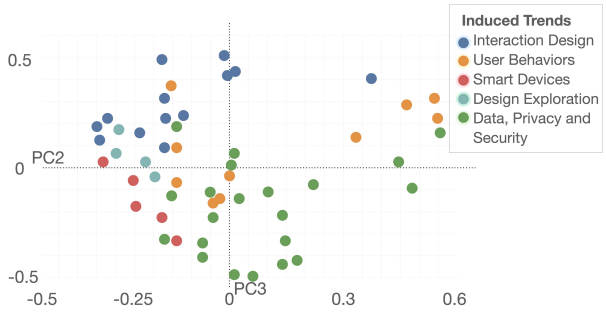

Figure 6: Distribution of the 55 selected articles based on feature dimension reduction, with colors representing their corresponding research trends.

Further analysis of this distribution according to the research content of the 55 selected articles reveals:

a) "Data, privacy and security" is relatively independent. In contrast to other publications, the majority of the articles under this trend focus solely on issues related to data security, equipment security, and other difficulties.

b) In the interaction design field, "Interaction Design" aimed to enhance user experience. Furthermore, the trend "Focus on interaction design" has numerous interconnected components that are all user-centered.

Table 2: Five trends induced from the research objectives of the 55 selected articles

Research Trend	Explanation	Research Objective
Focus on interaction design	Focus on the interaction design defects, problems and solutions in smart homes to improve smart home interaction experience.	Proposal for new interactive functions Promotion of interactive experience Smart home design Smart home renovation design
Focus on user behaviors	Pay attention to the user's behavior, needs and interaction experience in smart home use environment, and conduct evaluation at different levels.	User behavior prediction User experience assessment Understanding of users' needs
Focus on smart devices	Describe the functions and use methods of smart devices, and evaluate the advantages and disadvantages of them.	Understanding of device functions and risks Device sharing Device control New smart home technologies
Data, privacy and security	Involve data leakage, privacy security and physical security of smart homes, and propose solutions or optimization methods.	Data sharing Network data privacy and security Privacy and security of physical spaces
Design exploration	Cooperate with relevant designers or users to explore new design forms and future design trends.	Design prospect User participatory design Sustainable design Device appearance design

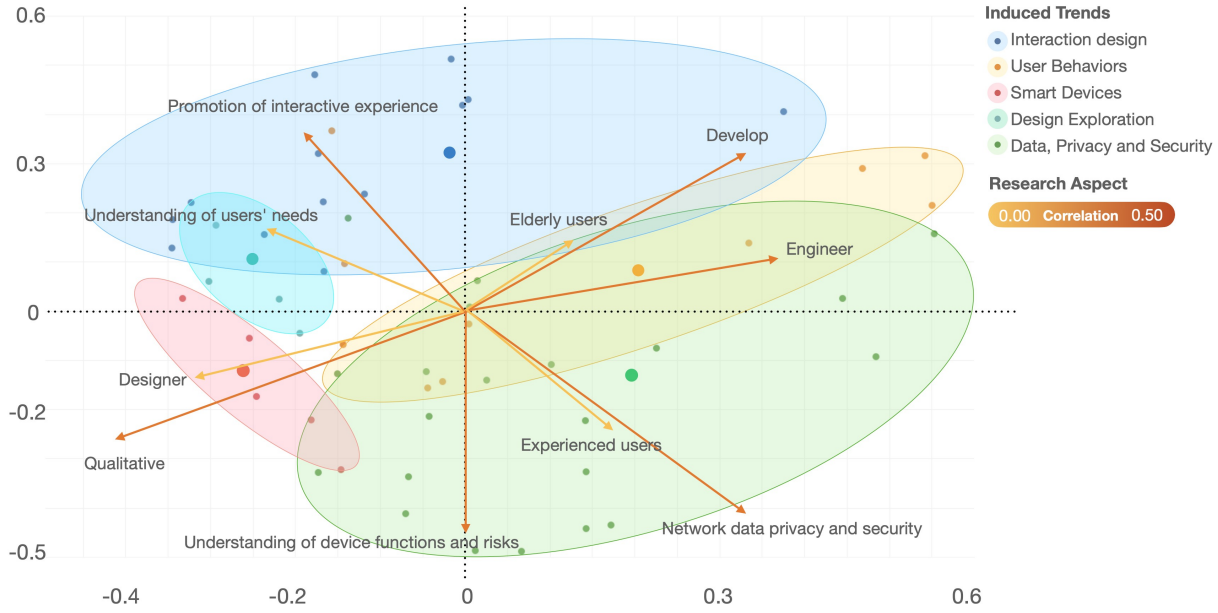

Figure 7: Distribution regions of the five trends: small dots represent the individual articles, while larger dots represent the centers of each trend region; the arrows represent distribution of the most significant ten research aspects.

c) Because "Design exploration" is a rather open trend that involves all design-related topics, it is clear that there are intersections with all types, with the exception of "Data, privacy, and security".

d) "Focus on smart devices" may not aim to address design problems, so it has less overlap with "Design exploration" and "Focus on interaction design".

e) Because users interact with devices through interaction behaviors, "Focus on user behaviors" is closely related to "Focus on interaction design" and "Focus on smart devices."

Each trend has obvious characteristics, thus, we further designated the distribution region of each trend in accordance with the PCA results so that the distribution relationship can become more visible (See in Figure 7).

The variance and correlation of all coded labels in the matrix M were also calculated when PCA was performed, and the results are displayed in the figure as vectors. The characteristics' variance shows its statistical significance. The stronger directionality of the characteristic is indicated by a larger variance, resulting in a longer length for the vector. The arrow directions show how there is a correlation. The correlation between the corresponding characteristic and the cosine value of the angle between the vectors can be determined. The two traits are independent if two vectors make a 90-degree angle, and associated or negatively correlated if the two form an angle of 0 or 180 degrees. According to the calculation results, we drew the most significant 10 characteristics in Figure 7.

In addition to the ten research aspects shown in Figure 7 that are strongly correlated with different research trends, there are still many research aspects concentrated near the origin that have not been visually presented. While they seem not strongly correlated with any trends; this does not necessarily suggest that they all exhibit weak correlation. We identified research aspects with broad correlations and designated them as "pan-correlated" by rereading the 55 publications and performing manual analysis on them. (See Figure 8).

We discovered that the following research aspects: User Researcher, Data Sharing, Experienced Users, User Participatory Design, Quantitative, and Promotion of Interactive Experience, appear in the majority of publications; hence, the research aspects are brief and exhibit pan-correlation. Meanwhile, we discovered that numerous research aspects, such as stakeholders, sustainable design, privacy, and physical space security, did not exist in the core text of the 55 articles, but rather in subsequent work or discussions of these papers. Combined with the previous keyword frequency analysis from 2000 to 2022 (Figure 3) that indicated the keywords receiving rising interests (such as privacy and sustainable HCI), we speculate that these research aspects (or factors) may play more important roles in future smart home research.

The findings obtained through the PCA method highlight the diversity of research trends and allow each research trend to have its own unique characteristics. However, from the perspective of smart home researchers' domain expertise, these research trends do not seem to be mutually exclusive and are interdependent with each other. This is a limitation of the PCA method, so in this paper, we do not expect to obtain explicit and mutually exclusive clusters. We applied the normative method to organize and analyze the literature to obtain their characteristics in distribution. The results obtained are statistically accurate but do not accurately reflect the actual distribution characteristics of the literature, so it is also important to use the characteristics of human participation or intervention characteristics to make a reasonable interpretation or correction of

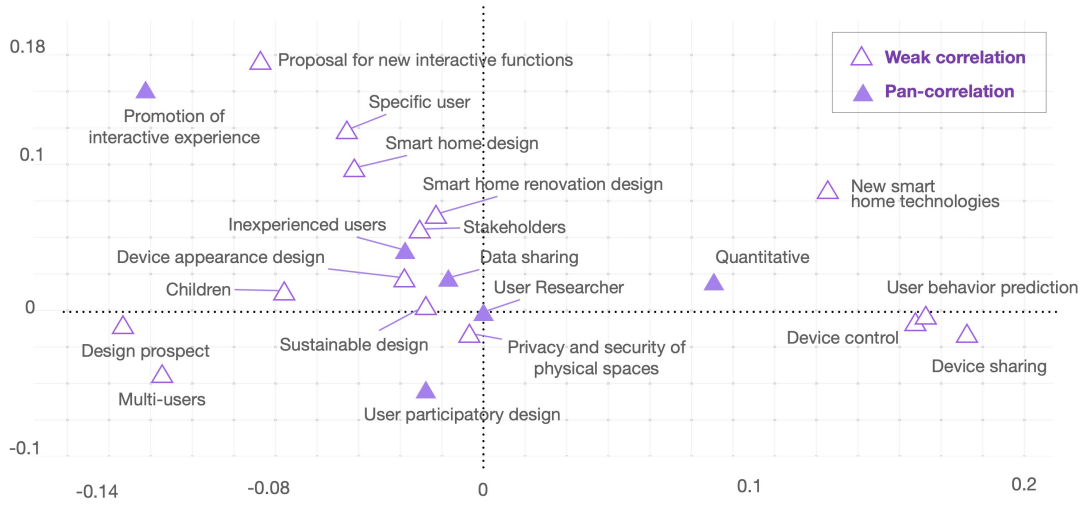

Figure 8: Demonstration of unlabeled research aspects (Hollow triangles represent weak correlations; Solid triangles represent pan-correlations).

the analysis results to facilitate a more accurate description of the characteristics of the distribution of the literature.

5 ANALYSIS OF FIVE TRENDS

5.1 Overview of Research Trends

Combining the research content, research objectives (such as Table 2) and research aspects of 55 papers that are highly correlated with trends (Figure 5), we further refined serveral characteristics to highlight and promote each direction (Figure 9).

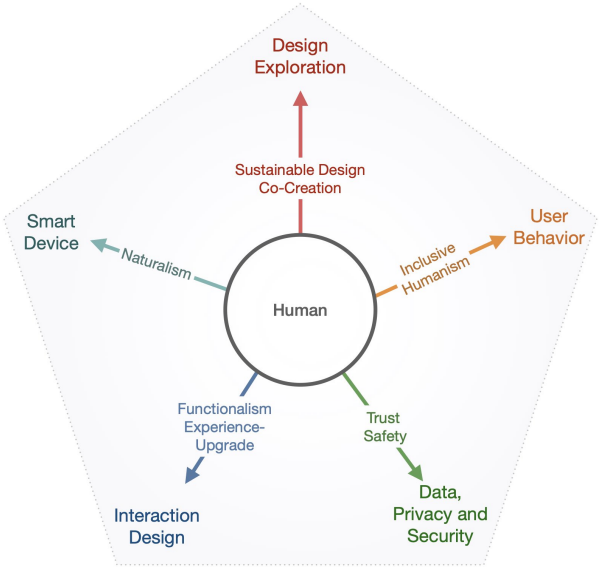

Figure 9: Characteristics of five trends from human-centered perspective.

Given that each research trend is distinct, this paper focuses on smart home research from a human-centered perspective and "Human" is the central theme of our work. Figure 9 shows the relationship between the five research trends and the key theme of "Human".

Design Exploration often starts with addressing the needs and expectations of users to explore the requirements, potential outcomes, tools, or techniques of smart homes and advocate a more sustainable design ecology in the future.

The two trends, "User Behavior" and "Data, Privacy and Security" have strong correlations with aging users and experienced users. In addition to focusing on behavior features, demands, and experience evaluation, related literature on user behavior also undertakes more in-depth study on various user kinds, demonstrating consideration, respect, and adaption for various user personalities, habits, and skills. It conveys the inclusivity that HCI strives for.

Additionally, "Data, Privacy and Security" has the most publications in recent years. We believe that this will continue to be a key focal area in the near future. Not only are there a variety of technical problems to be resolved, but also the concomitant user privacy fear and technological confidence crises are important considerations.

The papers that focus on "Interaction Design" not only emphasize the understanding of user needs and the upgrading of interaction experience, but also pay attention to the design of home device layout and device function. The attitude expressed in these publications is that smart home technology has gradually turned into a daily necessity, and "Interaction Design" can demonstrate more functionality and usefulness. Thus, the third level is where "Interaction Design" is situated in this model.

Work focused on "smart devices" relies on designers to conduct qualitative research to analyze smart devices, including sharing and controlling gadgets as well as novel interactive technologies. As smart devices proliferate, future research will need to figure out ways to lessen the expense and burden of user learning and increase the effectiveness of users' natural engagement.

In this section, each research trend will be discussed based on the trend characteristics displayed in Figure 9, the trend-related factors in Figure 5, the research objectives corresponding to the trends in Table 2, and representative works extracted from the 55 articles as examples.

5.2 Interaction Design

By comprehending user needs and/or providing new interactive functionalities (functionalism), research concentrating on interaction design tends to promote the interactive smart home experience (experience upgrading) [31, 42, 44, 56, 66, 74, 99, 121]. To gather and analyze users' voice, text, gesture, or physical interaction needs in smart home scenarios, researchers typically conduct semi-structured interviews, quantitative and qualitative user research, situational awareness experiments, and design collaboration experiments; then, targeted solutions are developed. The interactive interface and process design direct the improvement of the interactive experience.

Two representative research works are briefly summarized as follows. Cho *et al.* used Google Assistant [2] to investigate whether the differences in modality (voice or text) and device (smartphone or smart home device) would affect users' perception of Google Assistant, when they tried to retrieve private health information from the voice assistant [31]. Results show that voice interaction enhanced the Assistant's social presence more than text interaction when acquiring low-sensitivity information, while device differences did not significantly affect users' attitudes towards the Assistant. Meanwhile, Yang *et al.* explored how couples/friends in different places can accompany each other remotely through telepresence robots in a smart home to achieve the goal of maintaining a good relationship [122]. The authors conducted an autobiographical user study, describing how to use telepresence robots that can talk remotely, control actions, and share emotions to enhance the interaction and sense of belonging among multiple users. The two works paid attention to upgrading and refining the interaction experience and increasing the relationship between humans and computers rather than proposing new interaction styles.

5.3 User Behaviour

This research area focuses on user behavior and tends to explore the needs and behaviors of a specific population (such as the elderly and children, reflecting the inclusiveness and humanistic care of design) [38, 67, 127–129], thereby enhancing their home life quality [110] or security [67, 72, 127, 128]. To understand various user groups' demands and behavioral states in smart home situations, researchers frequently perform user tests, structured or semi-structured interviews, participatory design workshops, or smart device data modeling analyses.

The following are two representative research works: Zhan *et al.* developed a deep learning model based on Long Short-Term Memory networks (LSTM) to address the health hazards that the aging population faces at home [128]. The contextual-temporal data collected by wearable devices predicted the behaviors of elderly users and facilitated health status monitoring. Erel *et al.* focused on children's bedroom areas in smart homes and conducted studies on 17 children in their bedrooms [38]. Semi-structured interviews, based on thematic coding, were used to summarize children's various needs for smart bedrooms into emotional and practical topics, so that smart home designers can design children's bedrooms in a targeted manner. The underlying motivation for these two works is to make smart home devices more responsive to different user intents, habits, and abilities.

5.4 Data, Privacy and Security

Studies related to data, privacy and security account for a large proportion of the works in this analysis, and the overall research trend is related to the understanding of device functions and risks [24, 68, 104, 113] (that can enhance users' trust in smart home technology) as well as strengthening network security [13, 29, 48, 81, 93, 94, 124]. Therefore, researchers need to draw on the opinions and insights of experienced users [8, 16, 49, 60, 69, 79, 108, 113, 115, 116, 125]; they hence generally conducted semi-structured interviews, user experiments simulating privacy/security scenarios, questionnaire surveys or collaborative design workshops to clarify how users define privacy and security, what the concerns and anxieties are, and what the needs and expectations are related to privacy and security protection. All of these methods can guide designers and engineers to build trustworthy and highly secure smart home systems.

We briefly discuss two examples of this trend. Abdi *et al.* focused on the privacy norms that smart home personal assistants (SPAs) should follow, and conducted a large-scale (more than 1,700) user questionnaire survey [8]. They identified how background circumstances and personal aspects affect privacy norms, and summarized the privacy standards that the information flow of SPA must adhere to. Kurza *et al.* proposed a "guess data" research method, which allowed users to conduct exploratory data analysis on real-time sensor data, and infer the user behaviors and intentions represented by these data together with other living users, so as to study how private information was exposed to others through sensor data and how home monitoring was facilitated based on sensor data [68]. A full understanding of these mechanisms can lead to more effective prevention of threats in privacy and security.

In addition, early research suggested that computers can be more polite when interacting with users, and that people become more forgiving and understanding when computers apologize after making a mistake [95]. Besides, gentler communication can lower users' guard when computers need to access their sensitive data and ask for permissions [126]. Such observations are closely related to the concept of etiquette-in-technology [89, 101] (which is to be elaborated upon in Section 6.3).

5.5 Smart Devices

Designers of smart devices need to qualitatively assess the device's features and their effects on users [19, 37, 46, 90, 98, 103] to make design recommendations that would lessen users' learning costs and burdens and enhance the effectiveness of their natural interaction. Researchers generally used semi-structured interviews, design collaboration workshops or user research to evaluate smart devices.

Representative research works included the following: Geeng *et al.* conducted semi-structured interviews with 18 subjects, explored the problem of intelligent device interaction conflict under multi-users, and found that the user responsible for installing the

device in a multi-person household has more dominance in accessing device features and data, and such users tend to ignore the considerations and needs of other users [46]. The author specifically provided design suggestions to reduce device interaction conflicts and mitigate device access differences between cohabitants. Sabir *et al.* paid attention to the possible ambiguity and misunderstanding of voice commands activated by the functions of Amazon Alexa smart home voice assistant, conducted interactive user experiments to evaluate whether users could accurately distinguish Alexa's own functions and third-party developed functions, and evaluated whether it was correct to judge which functions will be automatically activated through the voice interface, and finally studied how to design voice commands to improve the accuracy and effect of user interaction [98].

5.6 Design Exploration

The research trend of design exploration mainly examines the possibility of future smart home design from human-centered perspective by analyzing current user needs [28, 45], identifying emerging user needs [58, 59] (sustainable design) and co-designing with users. Compared with the other four research trends, there are fewer works in this area, and most of them are based on observations, collaborative design workshops or semi-structured interviews.

A representative research work is the collaborative design workshop carried out by Garg *et al.*, involving 18 users to explore how the operations of future smart devices could be adjusted according to the social environment, and how to design a flexible agency to enable the adjustment [45]. The authors offered design recommendations for these three problems, supporting various smart home technologies and addressing the issue of device usage that conflicted with the preferences/values/behaviors of various users.

6 REFLECTION

In this study, we have summarized 5 smart home trends using mainly a hybrid approach. At the same time, there are still many thought-provoking concepts in the 55 papers that are difficult to collect quantitatively, and these are often found in the limitations and challenges, future work, or discussions. These papers had used ethics[37, 58, 81], speculative design[19, 26, 48, 93], ethnography[72, 110], research through design[72, 81, 93], sustainability[58, 59, 121], design fiction[19, 72], design vision[59] as the tone or core of the research; probes[19, 26, 48, 59], co-design[19, 42, 45, 50, 69, 125], participatory design[67, 68], or in-the-wild studies [99] as research methods. They also actively referred to more theoretical approaches to explain complex phenomena in smart home research, such as folk theory [104], domestication theory [66], and protection motivation theory [94].

Inspired by the opinions and findings in 55 articles, we attempted to present some reflections from three perspectives: the development of the discipline, the transformation of user identity, and the advocacy of interaction etiquette.

6.1 From Multidisciplinary Integration to Sustainable Innovation

Since the 1980s, research on topics such as smart spaces and smart homes have become increasingly interdisciplinary, with accelerated expansion since the turn of the century. Alavi *et al.* used words such as "persistence", "proliferation", and "mutation" to describe the research and development of related fields in the past two decades [12]. As shown in Figure 3, we counted the keyword changes in smart home literature from 2000-2022. Earlier work in this timespan was mostly based on engineering disciplines, but since 2010, and especially since 2016, design, humanities, psychology, cognitive science and other disciplines have gained traction. Some keywords cannot be categorized into a specific discipline and take interdisciplinary approaches, such as AR, VR, sustainability, UI, health, older adult, children, etc. In addition to the 55 papers selected for this study that represents just a small portion of the overall research on smart homes, a large number of additional related studies are dispersed throughout architecture, design, engineering, humanities, communication and other disciplines. While carrying out diversified research, these works also actively explore capabilities, opportunities, and futures applicable to smart home research.

The advances in smart home research also present a good opportunity for the development and exploration of related disciplines. Not only is the smart home space suitable for ubiquitous computing, embodied interaction, and social computing [36], but it can also integrate participatory design and open innovation [23], promoting the fusion of interdisciplinary knowledge and architecture [55]. As a result of the integration of many disciplines, the field of smart home has drawn a variety of research perspectives, methods and excellent researchers, as well as encouraging the development of new disciplies and methods in the process of ongoing research, forming a sustainable research ecological trend.

On the other hand, smart space research requires long-term observation and data collection from users and living environments, which facilitates the establishment of a sustainable research process that learns user behavior in a dynamically changing environment and constantly provides appropriate feedback to users, thus forming a sustainable design ecology. For instance, Rikke *et al.* explored the sustainable design of home energy by analyzing the lighting habits of users in smart homes and established a long-term use strategy for future smart home energy [59]. Maria *et al.* expanded the smart home scene to the grocery store and developed an interactive application called EcoFriends. This app can seasonally adjust the store's products according to the user's vegetable buying habits and frequency, thereby sustainably optimizing the customer's shopping experience [85]. From the perspective of a long-term development vision, smart home research will transform from multidisciplinary integration to sustainable innovation. Furthermore, the smart home domain will also play an increasingly important role in future user-centered interaction research.

6.2 From Stakeholders to Co-Creators

In comparison to earlier studies, the reviewed 55 papers involve increasingly diverse user groups and researchers. These individuals are not only stakeholders in smart home research, but some of them also take part in the research and design process, echoing a change in the role of the user throughout HCI research. Apart from participating actively or passively in a study, they further serve as an insider, a member, and a collaborator in sharing achievements [42, 88, 103, 123]. When the users are recognized as partners, users may

feel empowered and enthusiastic about the study, which can lead to better outcomes of smart home research.

New challenges will arise when stakeholders are increasingly involved in the research. For instance, the user study places a lot of importance on trust and authorization: first, researchers need to establish data protection rules to safeguard the participants' data, which is both the prerequisite for user trust and a sufficient condition to prevent the experiment from spiraling out of control; second, establishing a more transparent and open supervision channel for data research and analysis is also necessary for gaining user trust. Meanwhile, granting users the right to access and utilize data is also crucial. However, as already mentioned, an increasing number of participants joined the study in different capacities, with different backgrounds and cognitive abilities. This sometimes resulted in their inability to reach consensus. The goal is to create a shared language for collaboration while also maintaining the necessary trust and privacy. The changing identities of stakeholders are discussed in great detail in other works. As mentioned above, Fitto *et al.* invited a group of youth to participate in the design of the voice interface, treating them as research partners [42].

Some other researchers have encouraged multi-stakeholder groups to collaborate on smart retail spaces, guided stakeholders to analyze data results, discussed design flaws, and reached design consensus through straightforward data analysis and case introduction [126]. This type of work promotes researchers to fully affirm stakeholders' expertise and match their knowledge, allowing them to quickly understand the research at hand and come to consensus. We advocate changing the role of users in smart home research from stakeholders to co-creators to increase the inclusiveness of design research, rather than lowering the standards of research and recruiting more participants.

6.3 From Functionalism to Etiquette-in-Technology

Etiquette-in-technology, commonly known as Digital etiquette or Netiquette [89, 101], is a relatively new concept to HCI. Etiquette-in-technology is not a well-recognized academic term; rather, it refers to a code of conduct that has evolved through time along with Internet technology and culture to regulate network social behavior.

Communicating without misunderstandings on the Internet can be a challenge, mainly because there are no facial expressions or body language in cyberspace to rely on. Therefore, to prevent these misunderstandings and deter unfriendly behavior, many websites regularly have rules that govern respectful and courteous behavior on social media platforms, online chat sites, web forums, and other online engagement sites.

Etiquette-in-technology is often used to restrain human behavior. However, with the increase of HCI, misunderstandings have also appeared in the case of information asymmetry. Some HCI researchers have applied etiquette to gradually anthropomorphic HCI and HRI to design the etiquette response triggered by each function or service [63, 82, 83, 118]. For example, we often observe computer-progressively-enriched voice feedback, facial appearance (cute face, dog face, etc.), emotional feedback, affecting interaction, interactivity, and so on.

> *"What are the cues that encourage people to treat a computer (or anything else) as a social actor that warrants and is expected to exhibit human speech?" [83] - Clifford Nass*

In terms of the current literature analysis, we can also see a number of design responses or expectations that elevate etiquette on smart home devices. Anthropomorphism and emotional design are the first and most expressive. Through more individualized and careful offerings, these efforts seek to provide users with flexible and welcoming services. This kind of work typically involves one-on-one interactions. However, as important components in the smart home environment, interactive computers gradually display some social attributes. We can hope that the computer will make wise decisions quickly when dealing with conflicting needs, such as in a multi-member family consisting of parents and children, husband and wife, hosts and guests, but this area is is still emerging. How can the smart device as a bystander intervene more politely to resolve the family "crisis" [62, 105]?

In addition, among the most concerned privacy and security topics in smart home, etiquette-in-technology also deserves attention because etiquette can teach the computer to respect the user's decision when obtaining the user's approved private data and etiquette also allows computers to be selective in the release of private information. Advocating etiquette-in-technology can limit potentially impolite behavior in the smart home system, avoiding a variety of risks.

Etiquette-in-technology should also be applied to research that caters to diverse user groups. First of all, it is a beneficial development because research on smart home is constantly expanding to accommodate people from different regions, ethnic groups, ages, genders, and abilities. It also brings about more challenges, as diverse social groupings have quite different standards for social behavior. Since etiquette can be compared to a habit, building a computer-friendly and sustainable etiquette-in-technology machine learning methodology may be more durable.

Future human-computer interactions and even human-invisible services embedded in intelligent environments will be more diverse and etiquette-in-technology will subtly affect more interactions in the future smart home. We not only advocate that computers should show complete etiquette but that people also treat computers with the same respect and tolerance to establish a more harmonious interaction ecology.

6.4 Limitations and Challenges

In this work we have analyzed how the field of smart home research is growing from the human-centered perspective and creating more research opportunities based on the current literature. Most the reviewed papers share similar limitations and challenges.

The first commonality is that, despite an increase in smart home users, there is still a relatively small sample size of users due to the barrier to entry and difficulty of study. As few as 10 people have participated in many papers, suggesting that it is challenging to identify the typical issues with smart homes, and the research findings are not generally applicable. The second drawback is the dearth of user scenarios and generalizable experiences. The majority of

papers are experiments and research on a specific smart home feature or service (such as user fall behavior detection, camera-based privacy data protection, voice interaction in the living room scene, etc.). Typically, the experimental conditions are harsh, making it challenging to conduct extensive experiments or expand to other scenarios. Third, most smart home studies are prospective. However, the weaker realistic foundation poses a problem that must be addressed. Many articles focused on conceptual investigations rather than real-world studies or experiments. This will force many consumers of the research to rely on their imagination or logic when providing requirements, regardless of the possibility of providing fake requirements.

A final challenge is the limitation of research methods. We noted earlier that increasingly more qualitative or mixed methods are emerging in smart home research, because it is challenging to discern the users' genuine intents from quantitative data. However, the disadvantage of qualitative methods is that they suffer from small sample sizes and are difficult to produce results with generalizability, as mentioned in the first point. Some articles pointed out that relying on qualitative methods, that is, allowing users to express their intentions through narration, may cause them to over-rely on self-report data. This can be problematic if researchers unwittingly acquire a biased interpretation.

In terms of our literature review study design, another limitation is that currently the five research trends are defined by mutually exclusive explanations and objectives (see Table 2), though Figure 7 displays overlapped regions that imply their interrelationship. Further refinement of trend definitions, together with further investigation of such overlap, can be performed to overcome this shortcoming. Lastly, quantitative methods (AHC and LDA in this study) should be adopted with caution, as researchers need to fully understand the mechanisms before combining them with manual analysis, to avoid the risk of inappropriate usage or misinterpretation of the computational results.

Notably, there are numerous potential and challenges in the field of smart homes research, which is still in a phase of rapid expansion. For the research difficulties that have emerged or may appear in the future, this work makes an effort to propose analysis methods and solutions from literature traceability to support ongoing research in the smart home field. Taken together, we see the potential for research on smart homes from a human-centered perspective. At the same time, we also hope to conduct more design explorations in the future. For instance, building a sustainable database of smart home related work that can be updated and computationally analyzed in real-time. Or developing design probes, methods, participatory design toolkits, etc. suitable for smart home scenarios to incorporate valuable suggestions from future participants. Meanwhile, we hope to see others expand on our categorization and analysis in the future to support the diversity of human life.

7 CONCLUSION

We conducted literature analysis on human-centered design in smart home scenarios, beginning with a visual summary of research keywords from 19,901 articles published between 2000 and 2022. Then, we narrowed the scope down to the past five years and selected 55 related articles from high-impact HCI venues to investigate recent advances in the field. Through systematic reading, literature encoding, feature extraction and induced trends, we transformed the literature into data materials for quantitative analysis.

We statistically analyzed several dimensions of the data in-depth, including research content, topics, target user groups, associated researchers, and research methods. From this, we extracted five research trends: 1) focus on interaction design, 2) focus on user behaviors, 3) focus on smart devices, 4) design exploration, and 5) data, privacy and security. Despite exhibiting distinctive characteristics and independence, these trends can collectively promote the diversified and multidisciplinary research on smart home. Inspired by methods in the disciplines of data science, design research, and user research, the systematic literature analysis pipeline adopted in this study is extendable, and can be utilized by researchers to perform further studies related to smart home research. We concluded this study reflections and future visions on multi- and interdisciplinary development, stakeholder involvement, and the shift of design implications in the field of smart home technologies and beyond.

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REFERENCES

[1] 2022. Aware home. https://awarehome.gatech.edu/
[2] 2022. Google Assistant. https://assistant.google.com/
[3] 2022. PlaceLab. http://alumni.media.mit.edu/~emunguia/pdf/PlaceLab.pdf
[4] 2022. R House HRI Lab. https://r-house.luddy.indiana.edu/
[5] 2022. SSLab. https://www.ht.sfc.keio.ac.jp/SSLab/research/
[6] 2022. UK Dri Care Research Technology Centre. https://www.imperial.ac.uk/uk-dri-care-research-technology
[7] Hervé Abdi and Lynne J Williams. 2010. Principal component analysis. *Wiley interdisciplinary reviews: computational statistics* 2, 4 (2010), 433–459.
[8] Noura Abdi, Xiao Zhan, Kopo M Ramokapane, and Jose Such. 2021. Privacy norms for smart home personal assistants. In *Proceedings of the 2021 CHI conference on human factors in computing systems*. 1–14. https://doi.org/10.1145/3411764.3445122
[9] Dev Agrawal, Rahul Bhagwat, Rajdeep Bandopadhyay, Vineela Kunapareddi, Eric Burden, Shane Halse, Pamela Wisniewski, and Jess Kropczynski. 2020. Enhancing smart home security using co-monitoring of iot devices. In *Companion of the 2020 ACM International Conference on Supporting Group Work*. 99–102. https://doi.org/10.1145/3323994.3369883
[10] Majid Al-Kuwari, Abdulrhman Ramadan, Yousef Ismael, Laith Al-Sughair, Adel Gastli, and Mohieddine Benammar. 2018. Smart-home automation using IoT-based sensing and monitoring platform. In *2018 IEEE 12th International Conference on Compatibility, Power Electronics and Power Engineering (CPE-POWERENG 2018)*. 1–6. https://doi.org/10.1109/CPE.2018.8372548
[11] Ahlam Alami, Laila Benhlima, and Slimane Bah. 2015. An overview of privacy preserving techniques in smart home wireless sensor networks. In *2015 10th International Conference on Intelligent Systems: Theories and Applications (SITA)*. IEEE, 1–4.
[12] Hamed S Alavi, Denis Lalanne, and Yvonne Rogers. 2020. The five strands of living lab: a literature study of the evolution of living lab concepts in HCI. *ACM Transactions on Computer-Human Interaction (TOCHI)* 27, 2 (2020), 1–26.
[13] Wael S Albayaydh and Ivan Flechais. 2022. Exploring Bystanders' Privacy Concerns with Smart Homes in Jordan. In *CHI Conference on Human Factors in Computing Systems*. 1–24. https://doi.org/10.1145/3491102.3502097
[14] Frances K Aldrich. 2003. *Smart homes: past, present and future*. Springer, 17–39.
[15] Muhammad Asadullah and Khalil Ullah. 2017. Smart home automation system using Bluetooth technology. In *2017 International Conference on Innovations in Electrical Engineering and Computational Technologies (ICIEECT)*. IEEE, 1–6.
[16] Paritosh Bahirat, Martijn Willemsen, Yangyang He, Qizhang Sun, and Bart Knijnenburg. 2021. Overlooking context: How do defaults and framing reduce deliberation in smart home privacy decision-making?. In *Proceedings of the*

2021 CHI Conference on Human Factors in Computing Systems. 1–18. https://doi.org/10.1145/3411764.3445672

[17] Maurice S Bartlett. 1950. Tests of significance in factor analysis. *British journal of psychology* (1950).

[18] Cynthia L. Bennett and Daniela K. Rosner. 2019. The Promise of Empathy: Design, Disability, and Knowing the "Other". In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems* (Glasgow, Scotland Uk) *(CHI '19)*. Association for Computing Machinery, New York, NY, USA, 1–13. https://doi.org/10.1145/3290605.3300528

[19] Arne Berger, Aloha Hufana Ambe, Alessandro Soro, Dries De Roeck, and Margot Brereton. 2019. The stories people tell about the home through IoT toolkits. In *Proceedings of the 2019 on designing interactive systems conference*. 7–19. https://doi.org/10.1145/3322276.3322308

[20] Steven Bird, Ewan Klein, and Edward Loper. 2009. *Natural language processing with Python: analyzing text with the natural language toolkit.* " O'Reilly Media, Inc.".

[21] David M Blei, Andrew Y Ng, and Michael I Jordan. 2003. Latent dirichlet allocation. *Journal of machine Learning research* 3, Jan (2003), 993–1022.

[22] Barry Brumitt, Brian Meyers, John Krumm, Amanda Kern, and Steven Shafer. 2022. EasyLiving: Technologies for Intelligent Environments. https://www.microsoft.com/en-us/research/publication/easyliving-technologies-intelligent-environments/

[23] John M Carroll and Mary Beth Rosson. 2013. Wild at home: The neighborhood as a living laboratory for HCI. *ACM Transactions on Computer-Human Interaction (TOCHI)* 20, 3 (2013), 1–28.

[24] George Chalhoub, Martin J Kraemer, Norbert Nthala, and Ivan Flechais. 2021. "It did not give me an option to decline": A Longitudinal Analysis of the User Experience of Security and Privacy in Smart Home Products. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*. 1–16. https://doi.org/10.1145/3411764.3445691

[25] J Chandramohan, R Nagarajan, K Satheeshkumar, N Ajithkumar, PA Gopinath, and S Ranjithkumar. 2017. Intelligent smart home automation and security system using Arduino and Wi-fi. *International Journal of Engineering And Computer Science (IJECS)* 6, 3 (2017), 20694–20698.

[26] Liang-Yu Chen, Ji-Hong Huang, Yu-Hao Lee, Chia-Hsu Huang, and Rung-Huei Liang. 2019. A World Following Farmer Almanac: Speculation on Lifestyle Interweaving Folk Religion and Smart Home. In *Companion Publication of the 2019 on Designing Interactive Systems Conference 2019 Companion*. 147–151. https://doi.org/10.1145/3301019.3323914

[27] Xiantao Chen, Jiaqi Mi, Menghua Jia, Yajuan Han, Moli Zhou, Tian Wu, and Daisong Guan. 2019. Chat with smart conversational agents: How to evaluate chat experience in smart home. In *Proceedings of the 21st International Conference on Human-Computer Interaction with Mobile Devices and Services*. 1–6. https://doi.org/10.1145/3338286.3344408

[28] Xing Chen, Di Xie, Qi Zhao, and Zhu-Hong You. 2019. MicroRNAs and complex diseases: from experimental results to computational models. *Briefings in bioinformatics* 20, 2 (2019), 515–539.

[29] Chola Chhetri. 2019. Towards a smart home usable privacy framework. In *Conference Companion Publication of the 2019 on Computer Supported Cooperative Work and Social Computing*. 43–46. https://doi.org/10.1145/3311957.3361849

[30] Yi-Shyuan Chiang, Ruei-Che Chang, Yi-Lin Chuang, Shih-Ya Chou, Hao-Ping Lee, I-Ju Lin, Jian-Hua Jiang Chen, and Yung-Ju Chang. 2020. Exploring the design space of user-system communication for smart-home routine assistants. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. 1–14. https://doi.org/10.1145/3313831.3376501

[31] Eugene Cho. 2019. Hey Google, can I ask you something in private?. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. 1–9. https://doi.org/10.1145/3290605.3300488

[32] Myung Eun Cho and Mi Jeong Kim. 2014. Characterizing the interaction design in healthy smart home devices for the elderly. *Indoor and Built Environment* 23, 1 (2014), 141–149.

[33] Donghyeog Choi, Hyunchul Choi, and Donghwa Shon. 2019. Future changes to smart home based on AAL healthcare service. *Journal of Asian Architecture and Building Engineering* 18, 3 (2019), 190–199.

[34] Jessamyn Dahmen, Diane J Cook, Xiaobo Wang, and Wang Honglei. 2017. Smart secure homes: a survey of smart home technologies that sense, assess, and respond to security threats. *Journal of reliable intelligent environments* 3, 2 (2017), 83–98.

[35] Carl DiSalvo, Phoebe Sengers, and Hrönn Brynjarsdóttir. 2010. Mapping the Landscape of Sustainable HCI. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Atlanta, Georgia, USA) *(CHI '10)*. Association for Computing Machinery, New York, NY, USA, 1975–1984. https://doi.org/10.1145/1753326.1753625

[36] Paul Dourish. 2001. *Where the action is: the foundations of embodied interaction*. MIT press.

[37] Nils Ehrenberg and Turkka Keinonen. 2021. The technology is enemy for me at the moment: How smart home technologies assert control beyond intent. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*. 1–11. https://doi.org/10.1145/3411764.3445058

[38] Hadas Erel, Nadav Viduchinsky, and Oren Zuckerman. 2020. Towards smart rooms for children: mapping children's needs in the context of their bedrooms in the IoT era. In *Proceedings of the 2020 ACM Interaction Design and Children Conference: Extended Abstracts*. 223–228. https://doi.org/10.1145/3397617.3397825

[39] Xiaodong Fan, Bo Qiu, Yuanyuan Liu, Haijing Zhu, and Bochong Han. 2017. Energy visualization for smart home. *Energy Procedia* 105 (2017), 2545–2548.

[40] Tom Feltwell, Gavin Wood, Phillip Brooker, Scarlett Rowland, Eric PS Baumer, Kiel Long, John Vines, Julie Barnett, and Shaun Lawson. 2020. Broadening Exposure to Socio-Political Opinions via a Pushy Smart Home Device. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. 1–14. https://doi.org/10.1145/3313831.3376774

[41] Earlence Fernandes, Jaeyeon Jung, and Atul Prakash. 2016. Security analysis of emerging smart home applications. In *2016 IEEE symposium on security and privacy (SP)*. IEEE, 636–654.

[42] Daniel Fitton, Janet C Read, Gavin Sim, and Brendan Cassidy. 2018. Co-designing voice user interfaces with teenagers in the context of smart homes. In *Proceedings of the 17th ACM Conference on Interaction Design and Children*. 55–66. https://doi.org/10.1145/3202185.3202744

[43] Rebecca Ford, Marco Pritoni, Angela Sanguinetti, and Beth Karlin. 2017. Categories and functionality of smart home technology for energy management. *Building and environment* 123 (2017), 543–554.

[44] Joep Frens, Mathias Funk, Bastiaan van Hout, and Joep Le Blanc. 2018. Designing the IoT sandbox. In *Proceedings of the 2018 designing interactive systems conference*. 341–354. https://doi.org/10.1145/3196709.3196815

[45] Radhika Garg and Hua Cui. 2022. Social contexts, agency, and conflicts: Exploring critical aspects of design for future smart home technologies. *ACM Transactions on Computer-Human Interaction* 29, 2 (2022), 1–30.

[46] Christine Geeng and Franziska Roesner. 2019. Who's in control? Interactions in multi-user smart homes. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. 1–13. https://doi.org/10.1145/3290605.3300498

[47] Stanley Goffinet, Donatien Schmitz, Igor Zavalyshyn, Axel Legay, and Etienne Riviere. 2021. Controlling security rules using natural dialogue: an application to smart home care. In *Adjunct Proceedings of the 2021 ACM International Joint Conference on Pervasive and Ubiquitous Computing and Proceedings of the 2021 ACM International Symposium on Wearable Computers*. 194–197. https://doi.org/10.1145/3460418.3479331

[48] Neilly H. Tan, Brian Kinnee, Dana Langseth, Sean A. Munson, and Audrey Desjardins. 2022. Critical-Playful Speculations with Cameras in the Home. In *CHI Conference on Human Factors in Computing Systems*. 1–22.

[49] Neilly H. Tan, Richmond Y. Wong, Audrey Desjardins, Sean A. Munson, and James Pierce. 2022. Monitoring Pets, Deterring Intruders, and Casually Spying on Neighbors: Everyday Uses of Smart Home Cameras. In *CHI Conference on Human Factors in Computing Systems*. 1–25. https://doi.org/10.1145/3491102.3517617

[50] Corentin Haidon, Hubert Kenfack Ngankam, Sylvain Giroux, and Hélène Pigot. 2020. Using augmented reality and ontologies to co-design assistive technologies in smart homes. In *Proceedings of the 25th International Conference on Intelligent User Interfaces Companion*. 126–127. https://doi.org/10.1145/3379336.3381492

[51] Dae-Man Han and Jae-Hyun Lim. 2010. Smart home energy management system using IEEE 802.15. 4 and zigbee. *IEEE Transactions on Consumer Electronics* 56, 3 (2010), 1403–1410.

[52] Richard Harper. 2003. *Inside the smart home: Ideas, possibilities and methods*. Springer, 1–13.

[53] David Harris and Sarah L Harris. 2010. *Digital design and computer architecture*. Morgan Kaufmann.

[54] Sarah L Harris and David Harris. 2015. *Digital design and computer architecture*. Morgan Kaufmann.

[55] Syed Shabih Hasan, Anja Jamrozik, Carolina Campanella, Sara Aristizabal, Rongpeng Zhang, and Nicholas Clements. 2018. Living labs: Measuring human experience in the built environment. In *Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems*. 1–8. https://doi.org/10.1145/3170427.3170627

[56] Melanie Heck, Seong Hyun Shon, and Christian Becker. 2022. Does using voice authentication in multimodal systems correlate with increased speech interaction during non-critical routine tasks?. In *27th International Conference on Intelligent User Interfaces*. 868–877. https://doi.org/10.1145/3490099.3511129

[57] John Jaihar, Neehal Lingayat, Patel Sapan Vijaybhai, Gautam Venkatesh, and KP Upla. 2020. Smart home automation using machine learning algorithms. In *2020 International Conference for Emerging Technology (INCET)*. IEEE, 1–4.

[58] Rikke Hagensby Jensen, Yolande Strengers, Jesper Kjeldskov, Larissa Nicholls, and Mikael B Skov. 2018. Designing the desirable smart home: A study of household experiences and energy consumption impacts. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. 1–14. https://doi.org/10.1145/3173574.3173578

[59] Rikke Hagensby Jensen, Yolande Strengers, Dimitrios Raptis, Larissa Nicholls, Jesper Kjeldskov, and Mikael B Skov. 2018. Exploring Hygge as a desirable design vision for the sustainable smart home. In *Proceedings of the 2018 Designing Interactive Systems Conference*. 355–360. https://doi.org/10.1145/3196709.3196804

[60] Haojian Jin, Boyuan Guo, Rituparna Roychoudhury, Yaxing Yao, Swarun Kumar, Yuvraj Agarwal, and Jason I Hong. 2022. Exploring the Needs of Users for Supporting Privacy-Protective Behaviors in Smart Homes. In *CHI Conference on Human Factors in Computing Systems*. 1–19. https://doi.org/10.1145/3491102.3517602

[61] Haojian Jin, Swarun Kumar, and Jason Hong. 2020. Providing architectural support for building privacy-sensitive smart home applications. In *Adjunct Proceedings of the 2020 ACM International Joint Conference on Pervasive and Ubiquitous Computing and Proceedings of the 2020 ACM International Symposium on Wearable Computers*. 212–217. https://doi.org/10.1145/3410530.3414328

[62] Malte F Jung, Nikolas Martelaro, and Pamela J Hinds. 2015. Using robots to moderate team conflict: the case of repairing violations. In *Proceedings of the tenth annual ACM/IEEE international conference on human-robot interaction*. 229–236.

[63] Daphne Karreman, Lex Utama, Michiel Joosse, Manja Lohse, Betsy van Dijk, and Vanessa Evers. 2014. Robot Etiquette: How to Approach a Pair of People? *(HRI '14)*. Association for Computing Machinery, New York, NY, USA, 196–197. https://doi.org/10.1145/2559636.2559839

[64] Mi Jeong Kim, Myung Eun Cho, and Jeong Tai Kim. 2015. Measures of emotion in interaction for health smart home. *International Journal of Engineering and Technology* 7, 4 (2015), 343.

[65] Bethany Kon, Alex Lam, and Jonathan Chan. 2017. Evolution of Smart Homes for the Elderly. In *Proceedings of the 26th International Conference on World Wide Web Companion* (Perth, Australia) *(WWW '17 Companion)*. International World Wide Web Conferences Steering Committee, Republic and Canton of Geneva, CHE, 1095–1101. https://doi.org/10.1145/3041021.3054928

[66] Vinay Koshy, Joon Sung Sung Park, Ti-Chung Cheng, and Karrie Karahalios. 2021. "We Just Use What They Give Us": Understanding Passenger User Perspectives in Smart Homes. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*. 1–14. https://doi.org/10.1145/3411764.3445598

[67] Sandjar Kozubaev, Fernando Rochaix, Carl DiSalvo, and Christopher A Le Dantec. 2019. Spaces and traces: Implications of smart technology in public housing. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. 1–13. https://doi.org/10.1145/3290605.3300669

[68] Albrecht Kurze, Andreas Bischof, Sören Totzauer, Michael Storz, Maximilian Eibl, Margot Brereton, and Arne Berger. 2020. Guess the data: Data work to understand how people make sense of and use simple sensor data from homes. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing systems*. 1–12. https://doi.org/10.1145/3313831.3376273

[69] Roxanne Leitão. 2019. Anticipating smart home security and privacy threats with survivors of intimate partner abuse. In *Proceedings of the 2019 on Designing Interactive Systems Conference*. 527–539. https://doi.org/10.1145/3322276.3322366

[70] Wenda Li, Tan Yigitcanlar, Isil Erol, and Aaron Liu. 2021. Motivations, barriers and risks of smart home adoption: From systematic literature review to conceptual framework. *Energy Research & Social Science* 80 (2021), 102211.

[71] Wenda Li, Tan Yigitcanlar, Aaron Liu, and Isil Erol. 2022. Mapping two decades of smart home research: A systematic scientometric analysis. *Technological Forecasting and Social Change* 179 (2022), 121676.

[72] Joseph Lindley, Adrian Gradinar, and Paul Coulton. 2020. Ghosts in the Smart Home. In *Companion Publication of the 2020 ACM Designing Interactive Systems Conference*. 465–468. https://doi.org/10.1145/3393914.3395841

[73] Lili Liu, Eleni Stroulia, Ioanis Nikolaidis, Antonio Miguel-Cruz, and Adriana Rios Rincon. 2016. Smart homes and home health monitoring technologies for older adults: A systematic review. *International journal of medical informatics* 91 (2016), 44–59.

[74] Joseph Louis and Khandakar Rashid. 2018. Utilizing building information models as operating systems for smart homes. In *Proceedings of the Workshop on Human-Habitat for Health (H3): Human-Habitat Multimodal Interaction for Promoting Health and Well-Being in the Internet of Things Era*. 1–4. https://doi.org/10.1145/3279963.3281658

[75] Isaac Machorro-Cano, Giner Alor-Hernández, Mario Andrés Paredes-Valverde, Lisbeth Rodríguez-Mazahua, José Luis Sánchez-Cervantes, and José Oscar Olmedo-Aguirre. 2020. HEMS-IoT: A big data and machine learning-based smart home system for energy saving. *Energies* 13, 5 (2020), 1097.

[76] T Soni Madhulatha. 2012. An overview on clustering methods. *arXiv preprint arXiv:1205.1117* (2012).

[77] Davit Marikyan, Savvas Papagiannidis, and Eleftherios Alamanos. 2019. A systematic review of the smart home literature: A user perspective. *Technological Forecasting and Social Change* 138 (2019), 139–154.

[78] Stefan Marksteiner, Víctor Juan Expósito Jiménez, Heribert Valiant, and Herwig Zeiner. 2017. An overview of wireless IoT protocol security in the smart home domain. *2017 Internet of Things Business Models, Users, and Networks* (2017), 1–8.

[79] Roisin McNaney, Catherine Morgan, Pranav Kulkarni, Julio Vega, Farnoosh Heidarivincheh, Ryan McConville, Alan Whone, Mickey Kim, Reuben Kirkham, and Ian Craddock. 2022. Exploring Perceptions of Cross-Sectoral Data Sharing with People with Parkinson's. In *CHI Conference on Human Factors in Computing Systems*. 1–14. https://doi.org/10.1145/3491102.3501984

[80] Hamid Medjahed, Dan Istrate, Jerome Boudy, Jean-Louis Baldinger, and Bernadette Dorizzi. 2011. A pervasive multi-sensor data fusion for smart home healthcare monitoring. In *2011 IEEE international conference on fuzzy systems (FUZZ-IEEE 2011)*. IEEE, 1466–1473.

[81] Daphne A Muller and Pierre Lévy. 2019. A design approach towards affording the trend of privacy. In *Proceedings of the 2019 on Designing Interactive Systems Conference*. 435–446. https://doi.org/10.1145/3322276.3322324

[82] Alessandro Murgia, Daan Janssens, Serge Demeyer, and Bogdan Vasilescu. 2016. Among the Machines: Human-Bot Interaction on Social Q&;A Websites. In *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems* (San Jose, California, USA) *(CHI EA '16)*. Association for Computing Machinery, New York, NY, USA, 1272–1279. https://doi.org/10.1145/2851581.2892311

[83] Clifford Nass. 2004. Etiquette Equality: Exhibitions and Expectations of Computer Politeness. *Commun. ACM* 47, 4 (apr 2004), 35–37. https://doi.org/10.1145/975817.975841

[84] Frank Nielsen. 2016. *Hierarchical clustering*. Springer, 195–211.

[85] Maria Normark and Jakob Tholander. 2014. Performativity in sustainable interaction: the case of seasonal grocery shopping in ecofriends. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. 271–280. https://doi.org/10.1145/2556288.2557318

[86] Oliver Nowak, René Schäfer, Anke Brocker, Philipp Wacker, and Jan Borchers. 2022. Shaping Textile Sliders: An Evaluation of Form Factors and Tick Marks for Textile Sliders. In *CHI Conference on Human Factors in Computing Systems*. 1–14. https://doi.org/10.1145/3491102.3517473

[87] Sharnil Pandya, Hemant Ghayvat, Ketan Kotecha, Mohammed Awais, Saeed Akbarzadeh, Prosanta Gope, Subhas Chandra Mukhopadhyay, and Wei Chen. 2018. Smart home anti-theft system: a novel approach for near real-time monitoring and smart home security for wellness protocol. *Applied System Innovation* 1, 4 (2018), 42.

[88] Sunjeong Park and Youn-kyung Lim. 2020. Investigating user expectations on the roles of family-shared AI speakers. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. 1–13. https://doi.org/10.1145/3313831.3376450

[89] Sora Park, Eun-Yeong Na, and Eun-mee Kim. 2014. The relationship between online activities, netiquette and cyberbullying. *Children and youth services review* 42 (2014), 74–81.

[90] Jeroen Peeters, Rosa van der Veen, and Ambra Trotto. 2020. Pictorial Unleashed: Into the Folds of Interactive Qualities. In *Proceedings of the 2020 ACM Designing Interactive Systems Conference*. 925–938. https://doi.org/10.1145/3357236.3395570

[91] Bryan Pesta, John Fuerst, and Emil OW Kirkegaard. 2018. Bibliometric keyword analysis across seventeen years (2000–2016) of intelligence articles. *Journal of Intelligence* 6, 4 (2018), 46.

[92] Minh Pham, Yehenew Mengistu, Ha Do, and Weihua Sheng. 2018. Delivering home healthcare through a cloud-based smart home environment (CoSHE). *Future Generation Computer Systems* 81 (2018), 129–140.

[93] James Pierce. 2019. Smart home security cameras and shifting lines of creepiness: A design-led inquiry. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. 1–14. https://doi.org/10.1145/3290605.3300275

[94] Sarah Prange, Niklas Thiem, Michael Fröhlich, and Florian Alt. 2022. "Secure settings are quick and easy!"–Motivating End-Users to Choose Secure Smart Home Configurations. In *Proceedings of the 2022 International Conference on Advanced Visual Interfaces*. 1–9. https://doi.org/10.1145/3531073.3531089

[95] Byron Reeves and Clifford Nass. 1996. The media equation: How people treat computers, television, and new media like real people. *Cambridge, UK* 10 (1996), 236605.

[96] Mitchel Resnick and Brian Silverman. 2005. Some Reflections on Designing Construction Kits for Kids. In *Proceedings of the 2005 Conference on Interaction Design and Children* (Boulder, Colorado) *(IDC '05)*. Association for Computing Machinery, New York, NY, USA, 117–122. https://doi.org/10.1145/1109540.1109556

[97] Robert Wilhelm Siegfried Ruhlandt. 2018. The governance of smart cities: A systematic literature review. *Cities* 81 (2018), 1–23.

[98] Aafaq Sabir, Evan Lafontaine, and Anupam Das. 2022. Hey Alexa, Who Am I Talking to?: Analyzing Users' Perception and Awareness Regarding Third-party Alexa Skills. In *CHI Conference on Human Factors in Computing Systems*. 1–15. https://doi.org/10.1145/3491102.3517510

[99] Antti Salovaara, Andrea Bellucci, Andrea Vianello, and Giulio Jacucci. 2021. Programmable smart home toolkits should better address households' social needs. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*. 1–14.

[100] A Hasan Sapci and H Aylin Sapci. 2019. Innovative assisted living tools, remote monitoring technologies, artificial intelligence-driven solutions, and robotic systems for aging societies: systematic review. *JMIR aging* 2, 2 (2019), e15429.

[101] Larry Scheuermann and Gary Taylor. 1997. Netiquette. *Internet Research* (1997).

[102] Michael Schiefer. 2015. Smart home definition and security threats. In *2015 ninth international conference on IT security incident management & IT forensics*.

IEEE, 114–118.
[103] Mazyar Seraj, Cornelia S Große, Serge Autexier, and Rolf Drechsler. 2019. Smart homes programming: development and evaluation of an educational programming application for young learners. In *Proceedings of the 18th ACM International Conference on Interaction Design and Children*. 146–152. https://doi.org/10.1145/3311927.3323157
[104] William Seymour, Reuben Binns, Petr Slovak, Max Van Kleek, and Nigel Shadbolt. 2020. Strangers in the Room: Unpacking Perceptions of'Smartness' and Related Ethical Concerns in the Home. In *Proceedings of the 2020 ACM Designing Interactive Systems Conference*. 841–854.
[105] Solace Shen, Petr Slovak, and Malte F Jung. 2018. " Stop. I See a Conflict Happening." A Robot Mediator for Young Children's Interpersonal Conflict Resolution. In *Proceedings of the 2018 ACM/IEEE international conference on human-robot interaction*. 69–77.
[106] Carson Sievert and Kenneth Shirley. 2014. LDAvis: A method for visualizing and interpreting topics. In *Proceedings of the workshop on interactive language learning, visualization, and interfaces*. 63–70.
[107] Keith Stevens, Philip Kegelmeyer, David Andrzejewski, and David Buttler. 2012. Exploring topic coherence over many models and many topics. In *Proceedings of the 2012 joint conference on empirical methods in natural language processing and computational natural language learning*. 952–961.
[108] Sopicha Stirapongsasuti, Wataru Sasaki, and Keiichi Yasumoto. 2019. Decision making support for privacy data upload in smart home. In *Adjunct Proceedings of the 2019 ACM International Joint Conference on Pervasive and Ubiquitous Computing and Proceedings of the 2019 ACM International Symposium on Wearable Computers*. 214–217.
[109] Biljana L Risteska Stojkoska and Kire V Trivodaliev. 2017. A review of Internet of Things for smart home: Challenges and solutions. *Journal of cleaner production* 140 (2017), 1454–1464.
[110] Yolande Strengers, Jenny Kennedy, Paula Arcari, Larissa Nicholls, and Melissa Gregg. 2019. Protection, productivity and pleasure in the smart home: emerging expectations and gendered insights from Australian early adopters. In *Proceedings of the 2019 CHI conference on human factors in computing systems*. 1–13.
[111] Sharifa Sultana, François Guimbretière, Phoebe Sengers, and Nicola Dell. 2018. Design Within a Patriarchal Society: Opportunities and Challenges in Designing for Rural Women in Bangladesh. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems* (Montreal QC, Canada) *(CHI '18)*. Association for Computing Machinery, New York, NY, USA, 1–13. https://doi.org/10.1145/3173574.3174110
[112] Madiha Tabassum, Tomasz Kosinski, and Heather Richter Lipford. 2019. " I don't own the data": End User Perceptions of Smart Home Device Data Practices and Risks. In *Fifteenth Symposium on Usable Privacy and Security (SOUPS 2019)*. 435–450.
[113] Madiha Tabassum, Jess Kropczynski, Pamela Wisniewski, and Heather Richter Lipford. 2020. Smart home beyond the home: A case for community-based access control. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. 1–12.
[114] Shahzadi Tayyaba, Muhammad Waseem Ashraf, Thamer Alquthami, Zubair Ahmad, and Saher Manzoor. 2020. Fuzzy-based approach using IoT devices for smart home to assist blind people for navigation. *Sensors* 20, 13 (2020), 3674.
[115] Parth Kirankumar Thakkar, Shijing He, Shiyu Xu, Danny Yuxing Huang, and Yaxing Yao. 2022. "It would probably turn into a social faux-pas": Users' and Bystanders' Preferences of Privacy Awareness Mechanisms in Smart Homes. In *CHI Conference on Human Factors in Computing Systems*. 1–13.
[116] Jessica Vitak, Michael Zimmer, Anna Lenhart, Sunyup Park, Richmond Y. Wong, and Yaxing Yao. 2021. Designing for Data Awareness: Addressing Privacy and Security Concerns About "Smart" Technologies. In *Companion Publication of the 2021 Conference on Computer Supported Cooperative Work and Social Computing*. 364–367.
[117] Hanna M Wallach, Iain Murray, Ruslan Salakhutdinov, and David Mimno. 2009. Evaluation methods for topic models. In *Proceedings of the 26th annual international conference on machine learning*. 1105–1112.
[118] Michael L. Walters, Kerstin Dautenhahn, Sarah N. Woods, and Kheng Lee Koay. 2007. Robotic Etiquette: Results from User Studies Involving a Fetch and Carry Task. In *Proceedings of the ACM/IEEE International Conference on Human-Robot Interaction* (Arlington, Virginia, USA) *(HRI '07)*. Association for Computing Machinery, New York, NY, USA, 317–324. https://doi.org/10.1145/1228716.1228759
[119] Mohammad Wazid, Ashok Kumar Das, Vanga Odelu, Neeraj Kumar, and Willy Susilo. 2017. Secure remote user authenticated key establishment protocol for smart home environment. *IEEE Transactions on Dependable and Secure Computing* 17, 2 (2017), 391–406.
[120] Jane Webster and Richard T Watson. 2002. Analyzing the past to prepare for the future: Writing a literature review. *MIS quarterly* (2002), xiii–xxiii.
[121] Kristin Williams, Rajitha Pulivarthy, Scott E Hudson, and Jessica Hammer. 2020. The Upcycled Home: Removing barriers to lightweight modification of the home's everyday objects. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. 1–13.
[122] Lillian Yang and Carman Neustaedter. 2020. An autobiographical design study of a long distance relationship: When telepresence robots meet smart home tools. In *Proceedings of the 2020 ACM Designing Interactive Systems Conference*. 129–140.
[123] Lillian Yang and Carman Neustaedter. 2020. An autobiographical design study of a long distance relationship: When telepresence robots meet smart home tools. In *Proceedings of the 2020 ACM Designing Interactive Systems Conference*. 129–140.
[124] Yaxing Yao. 2019. Designing for Better Privacy Awareness in Smart Homes. In *Conference Companion Publication of the 2019 on Computer Supported Cooperative Work and Social Computing*. 98–101.
[125] Yaxing Yao, Justin Reed Basdeo, Smirity Kaushik, and Yang Wang. 2019. Defending my castle: A co-design study of privacy mechanisms for smart homes. In *Proceedings of the 2019 chi conference on human factors in computing systems*. 1–12.
[126] Yuan Yao, Junai Cai, Kexin Du, Yuxuan Hou, and Haipeng Mi. 2022. Establishing Design Consensus toward Next-Generation Retail: Data-Enabled Design Exploration and Participatory Analysis. In *CHI Conference on Human Factors in Computing Systems*. 1–22. https://doi.org/10.1145/3491102.3517637
[127] Yuting Zhan and Hamed Haddadi. 2019. Activity prediction for mapping contextual-temporal dynamics. In *Adjunct Proceedings of the 2019 ACM International Joint Conference on Pervasive and Ubiquitous Computing and Proceedings of the 2019 ACM International Symposium on Wearable Computers*. 246–249.
[128] Yuting Zhan and Hamed Haddadi. 2019. Towards automating smart homes: Contextual and temporal dynamics of activity prediction. In *Adjunct Proceedings of the 2019 ACM International Joint Conference on Pervasive and Ubiquitous Computing and Proceedings of the 2019 ACM International Symposium on Wearable Computers*. 413–417.
[129] Yue Zhang, Shijia Pan, Jonathon Fagert, Mostafa Mirshekari, Hae Young Noh, Pei Zhang, and Lin Zhang. 2018. Occupant activity level estimation using floor vibration. In *Proceedings of the 2018 ACM International Joint Conference and 2018 International Symposium on Pervasive and Ubiquitous Computing and Wearable Computers*. 1355–1363.
[130] Serena Zheng, Noah Apthorpe, Marshini Chetty, and Nick Feamster. 2018. User perceptions of smart home IoT privacy. *Proceedings of the ACM on human-computer interaction* 2, CSCW (2018), 1–20.
[131] Bin Zhou, Wentao Li, Ka Wing Chan, Yijia Cao, Yonghong Kuang, Xi Liu, and Xiong Wang. 2016. Smart home energy management systems: Concept, configurations, and scheduling strategies. *Renewable and Sustainable Energy Reviews* 61 (2016), 30–40.
[132] John Zimmerman, Jodi Forlizzi, and Shelley Evenson. 2007. Research through design as a method for interaction design research in HCI. In *Proceedings of the SIGCHI conference on Human factors in computing systems*. 493–502. https://doi.org/10.1145/1240624.1240704

APPENDIX

The tag matrix D

$$D = \begin{pmatrix} F_{1,1} & \cdots & F_{1,171} \\ \vdots & \ddots & \vdots \\ F_{55,1} & \cdots & F_{55,171} \end{pmatrix} \tag{A1}$$

The literature feature matrix M

$$M = \begin{pmatrix} A_{1,1} & \cdots & A_{1,31} & S_1 \\ \vdots & \ddots & \vdots & \vdots \\ A_{55,1} & \cdots & A_{55,31} & S_{55} \end{pmatrix} \tag{A2}$$

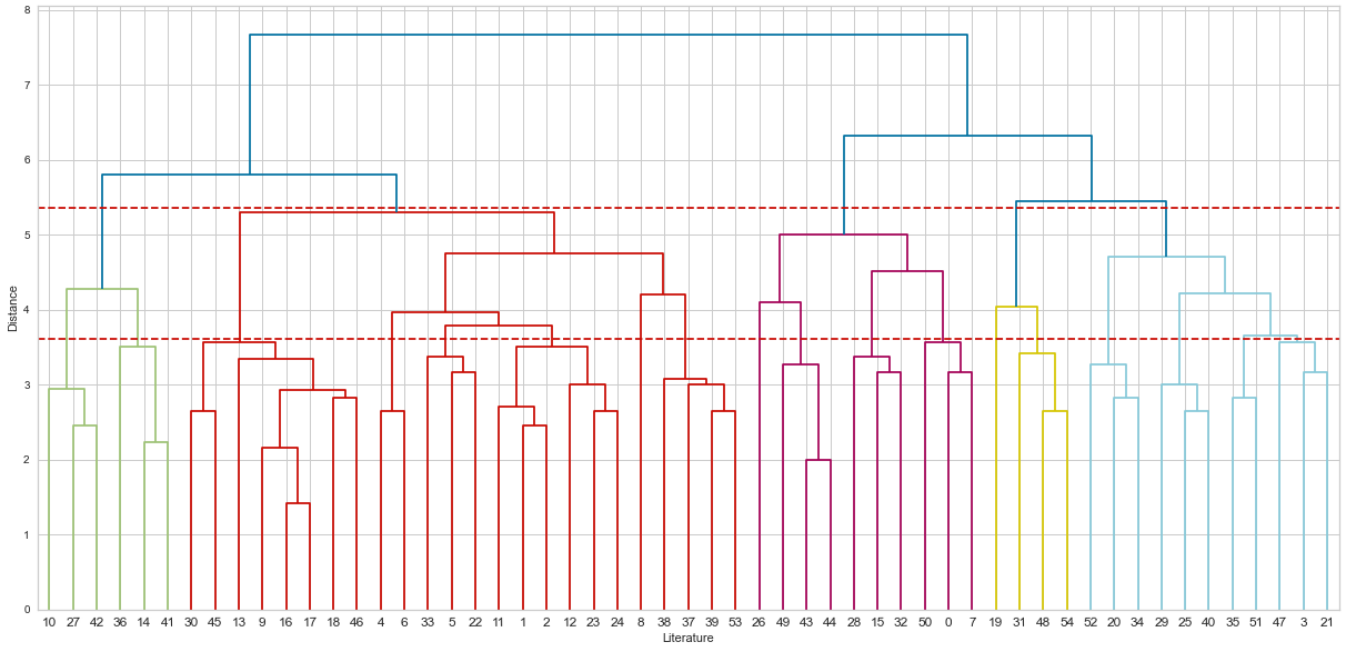

Figure 10: Result of agglomerative hierarchical clustering.

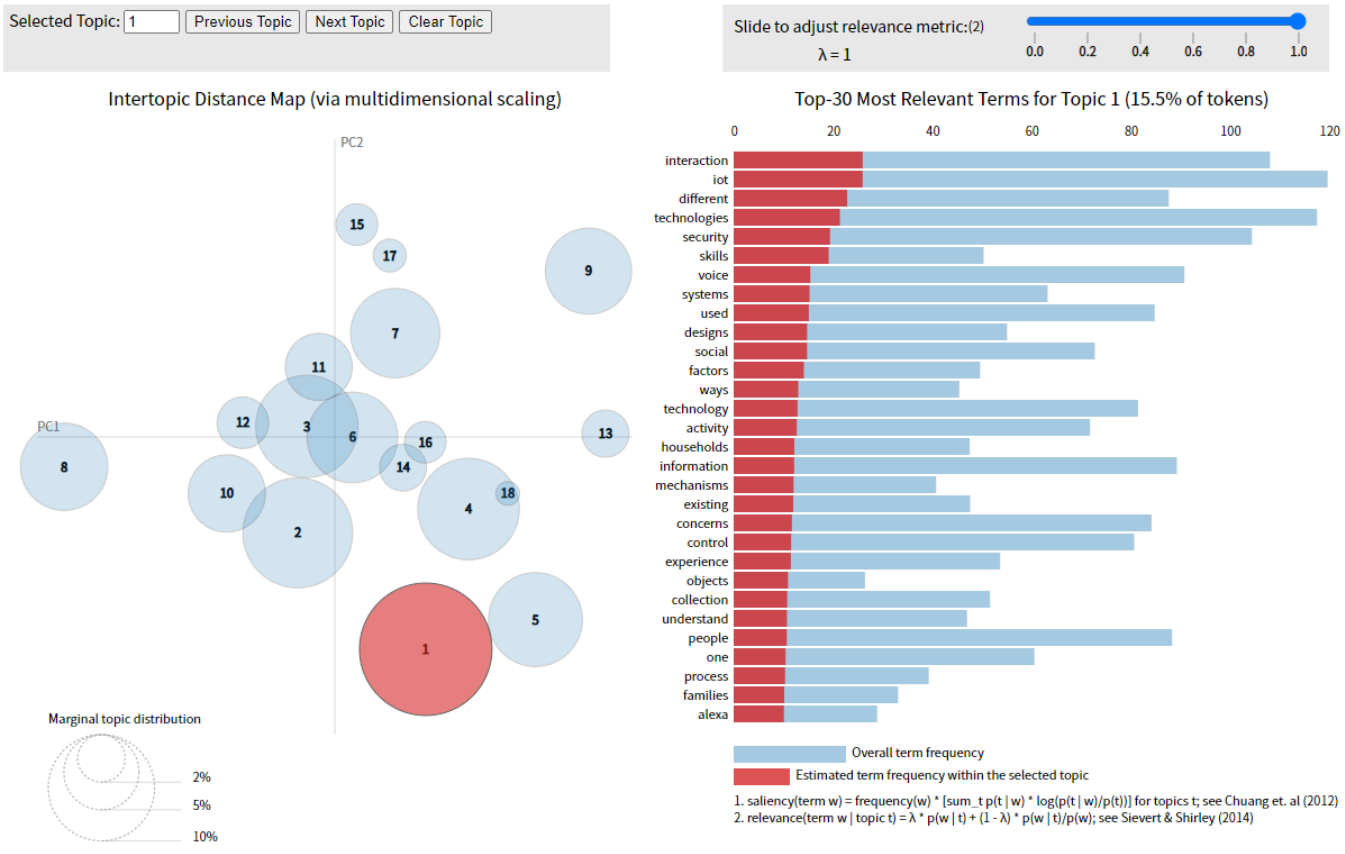

Figure 11: The 55 articles' topic distributions via LDAvis.

Table 3: Research objectives extracted from the selected 55 articles

Research objective	Explanation	Number of papers involved
Understanding of users' needs	Understand user needs and propose new design approaches and ideas.	22
User experience assessment	Assessing the user experience and the impact of the smart home on the user	9
User behavior prediction	Intelligent inference of user behaviour using algorithmic models	6
Understanding of device functions and risks	Understand the functions of smart devices and the dangers and hazards they present	15
Device sharing	Shared use of smart home	5
Device control	Cloud-based platform for smart home connectivity and monitoring	5
New smart home technologies	Propose new smart home technologies	3
Network data privacy and security	Understand privacy and security, summarise the design dimensions of future privacy mechanisms, explore smart home privacy design and avoid the risks associated with data privacy	23
Data sharing	Smart Home Shared Use and Data Sharing Discussion	2
Privacy and security of physical spaces	Monitor dangerous situations in the home	1
Promotion of interactive experience	Make research on interaction design, solve the problem of poor interaction design experience and facilitate user interaction experience	13
Proposal for new interactive functions	Propose new interactive features to inspire design thinking and improve the user experience	5
Smart home design	Design the layout of devices for the smart home	3
Smart home renovation design	Addressing issues arising from smart home retrofitting (e.g. elderly groups; family issues, etc.)	2
Design prospect	Inspire designers for more smart home design ideas	7
User participatory design	Design with users, understand their needs, anticipate their behaviour and explore user-centred smart home design	6
Device appearance design	Propose new equipment designs, incorporate culture in the design	2
Sustainable design	Sustainable design and energy savings through smart home interactive technology	1