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ORIGINAL ARTICLE

Smart homes and their users: a systematic analysis and key challenges

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Abstract Published research on smart homes and their users is growing exponentially, yet a clear understanding of who these users are and how they might use smart home technologies is missing from a field being overwhelmingly pushed by technology developers. Through a systematic analysis of peer-reviewed literature on smart homes and their users, this paper takes stock of the dominant research themes and the linkages and disconnects between them. Key findings within each of nine themes are analysed, grouped into three: (1) views of the smart home—functional, instrumental, socio-technical; (2) users and the use of the smart home—prospective users, interactions and decisions, using technologies in the home; and (3) challenges for realising the smart home—hardware and software, design, domestication. These themes are integrated into an organising framework for future research that identifies the presence or absence of cross-cutting relationships between different understandings of smart homes and their users. The usefulness of the organising framework is illustrated in relation to two major concerns—privacy and control—that have been narrowly interpreted to date, precluding deeper insights and potential solutions. Future research on smart homes and their users can benefit by exploring and developing cross-cutting relationships between the research themes identified.

Keywords Smart homes · Users · Technologies · Households · Energy · Assisted living

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1 Introduction

Smart technologies are pervasive. Embedding information and communication technologies in consumer appliances such as phones and TVs and in infrastructures such as cities and grids promises enhanced functionality, connectivity and manageability. Major technology developers, service providers and energy utilities are now lining up to extend smartness beyond specific devices to the home as a whole and link these smart homes into the meters, wires and pipes of the utility networks. The market for smart home appliances alone is projected to grow from \$40 m in 2012 to \$26bn in 2019 [46, p. 78]. The advent of smart homes may ensure smart technologies become a commonplace feature of people's lives, whether they are wanted or not [36, p. 358].

Scientific and technological research on smart homes is burgeoning alongside this wave of applied technology development. Behind both the technology developers and researchers, advancing applied knowledge in this field is a clear sense of purpose. Smart homes, it is argued, will "undoubtedly make our lives much more comfortable than ever" [51, p. 110]. But will they?

A smaller, but growing, number of social science researchers are asking: Who are the users of smart homes, and why do they want or need them? Will the technological promise of "customized, automated support that is so gracefully integrated with our lives that it 'disappears'" [20, p. 1579] be fulfilled? Might there be unexpected or perverse consequences? Are smart homes an inevitability or a choice?

The essence of a smart home is information and communication technologies (ICTs) distributed throughout rooms, devices and systems (lighting, heating, ventilation) relaying information to users and feeding back user or automated commands to manage the domestic environment

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[31]. Irrespective of the particular technological configuration of a smart home, its purpose—according to technology developers—is "to improve the living experience" in some way [35, 54]. This may be through new functionality such as remote control and automation of appliances, through enhancement of existing functionality such as heating management, through improved security or through the provision of assisted living services by monitoring, alerting and detecting health incidents [56]. Smart homes are also the end-use node of the smart energy system that allows utilities to respond to real-time flows of information on energy demand fed back by smart meters from millions of homes [23].

Despite this broad range of potential and assumed benefits, a clear user-centric vision of smart homes is currently missing from a field being overwhelmingly "pushed" by technology developers [65, 70]. This is a critical oversight given that the overall success of smart homes, whatever eventual form they may take, hinges fundamentally on their adoption and use by real people in the context of their normal everyday lives. This article takes stock of what is understood to date about smart homes and their users.

We conducted a systematic literature review and thematic analysis of 150 peer-reviewed academic publications that explicitly address "smart homes" and "users" (Sect. 2). We identified nine inter-related lines of enquiry and the key findings within each. We organised these themes in three groups: view and visions for the smart home (Sect. 3); understandings of users and the use of smart homes (Sect. 4); and challenges to the realisation of smart homes (Sect. 5). We use this analysis to develop an organising framework for further research on smart home users designed to bring coherence and comprehensiveness to an important and growing field (Sect. 6). We illustrate how the organising framework helps to identify cross-cutting linkages as well as disconnects by applying it to explore two key issues—privacy and control. We conclude by calling for future research to build on the organising framework to develop more comprehensive understandings of the relationships between smart homes and their users (Sect. 7). In so doing, we contend that the central user-related challenge for smart home development is not as simple as improving their reliability and functionality, or designing out concerns around trust, privacy or user-friendliness. Rather, the challenge is to recognise these issues as parts of a broader effort to redefine the notion of "smart" itself, seeing it as emerging within users' everyday lives and in the ways technologies are used in the home, not as something that resides in technologies themselves.

This contribution is timely as the number of research publications on smart home users is growing exponentially (Fig. 1), but has largely followed rather than led a strongly technology push field [36]. A recent review of the barriers to smart home adoption found users lacked a clear sense of smart home benefits [8]. Meanwhile, large-scale national smart meter rollouts are underway [19] and off-the-shelf smart home technologies are becoming more widely available around the world [46]. It is important, therefore, to synthesise smart homes and user research so far, and set out markers for ongoing and future research.

2 Method: systematic literature review

We conducted a systematic search of the peer-reviewed literature using key words denoting "user" as well as "smart home". Specifically, in July 2012, we searched the Scopus database using the search string "Smart" AND "Home" AND "User" AND "Technology" and included a total of 23 synonyms and variants (e.g. "Residen*" and "Hous*" in lieu of "Home", with the *capturing different possible word endings, e.g. "House", "Housing"). For further details on the search protocol, see [39].

This initial search yielded 12,310 articles. In two initial sifts, we reduced the sample to 538 articles by reviewing titles, and then titles and abstracts, and excluding all spurious or otherwise irrelevant hits. We then used a final sift to exclude articles which mentioned or referenced users but on closer examination did not focus on users either directly or indirectly in the research and analysis. The final sample was 150 articles that either explicitly investigated prospective users of smart homes or implicitly considered users through inferences on the usability, design or attractiveness of smart home technologies. Using the Scopus disciplinary classifications, this set of 150 articles was dominated by engineering and technical sciences (61 %) with the remainder split evenly between health-related disciplines (19 %) and the social sciences (20 %) (see Fig. 1 for details).

From our review of this set of 150 articles, we identified an initial set of themes which were iteratively revised, expanded and organised hierarchically, noting the key findings and references within each theme. For further details of the thematic coding method, see [39]. An annotated bibliography of over 70 articles is freely available for download at http://www.refitsmarthomes.org/?attachment_id=725.

The final set of nine themes, organised in three sets of three, are as follows:

1. Views of the smart home

   i. functional
   ii. instrumental
   iii. socio-technical

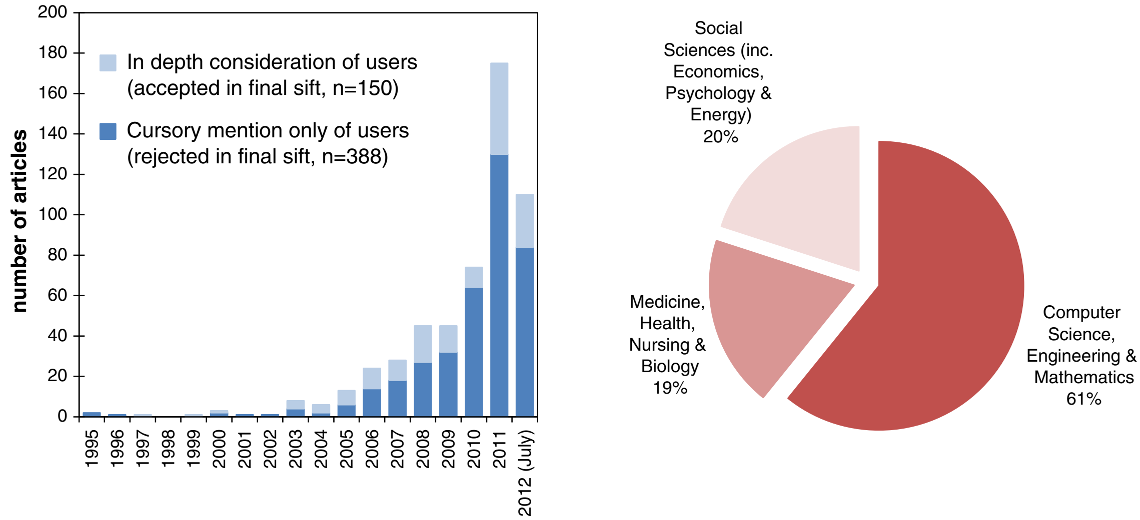

Fig. 1 Peer-reviewed research on smart home users. *Notes: Left panel* shows exponential growth in published articles using search terms "smart homes" and "users" (and variants thereof—see text for details). *Right panel* shows broad non-exclusive disciplinary groupings for $n = 150$ publications reviewed

2. Users and the use of the smart home

    i. prospective users
    ii. interactions and decisions
    iii. technology in the home

3. Challenges for realising the smart home

    i. hardware and software
    ii. design
    iii. domestication

The first set of themes describes three views of the smart home. These views provide the context and underlying rationale for industry activity and scientific research, offering different and at times competing visions or interpretations of what smart homes are and what they are for. The second set of themes relate specifically to the users and use of smart homes. They begin with basic questions about who smart home users are and what specific characteristics they have. They then extend to different views of the form, frequency and function of user interactions with smart technologies in the home. The final set of themes turns to the principal challenges for realising the smart home in the near-term future, distinguishing hardware and software development issues from design and usability challenges. More fundamental questions are also asked about the users of smart technologies amidst the complex and irregular rhythms and patterns of everyday life in the home.

3 Why the smart home?

Why is the smart home a growing and potentially important field of research and development? Three broad views are evident in the literature: a functional view; an instrumental view; and a socio-technical view. The *functional* view sees smart homes as a way of better managing the demands of daily living through technology. The *instrumental* view emphasises smart homes' potential for managing and reducing energy demand in households as part of a wider transition to a low-carbon future. The *socio-technical* view sees the smart home as the next wave of development in the ongoing electrification and digitalisation of everyday life.

3.1 The functional view

Proponents of the functional view contend that extending and integrating the functionality already provided in homes by a range of information and communication technologies (ICTs) will contribute to "better living" (e.g. [32, 59]). Much of the technologically oriented literature on smart homes presents their benefits for end-users as both obvious and manifold: comfort, security, scheduling tasks, convenience through automation, energy management and efficiency; and for specific end-users, health and assisted living [20, 63]. Balta-Ozkan et al. [8] group these benefits in three categories: lifestyle support, energy management and safety.

User-centric research clearly emphasises the enhancement of existing services not the provision of new ones: "the point of technology is not to replace experiences that we already enjoy today with our families… [but to] support or enhance experiences you already enjoy… but in new ways" [40, p. 258]. As examples, smart homes can deliver better-connected workspaces [15], enhance existing televisions through interactivity [11] and even help overcome digital divides by including elderly and other households currently marginalised from the information society [54].

The functional view points to a wide variety of tasks and activities that smart homes could help people achieve: remotely controlling specific appliances, improving memory and recall through automated reminders, enhancing security through simulated occupancy when homes are empty, and so on [14, 56, 59]. These correspond in broad terms with users' perceived needs for improved comfort, convenience, security and entertainment [3]. Improved security, in particular, is of clear value to users [49].

The most clearly resolved functional view of "better living" is articulated by researchers in the health and social care domain. Here, smart homes can "contribute to the support of the elderly, people with chronic illness and disabled people living alone at home… (by improving the quality and variety of information transmitted to the clinician" [16, p. 93]). This decision support functionality is centred on monitoring through wearable, implantable and sensing devices to facilitate preventative care and detect adverse health incidents [17]. Other health researchers examine specific vulnerabilities, such as individuals living with serious mental illness, emphasising that caregivers rather than individuals are often the direct beneficiaries [34].

3.2 The instrumental view

A more clearly instrumental or goal-oriented view of smart homes emphasises their potential to help achieve energy demand reduction goals, with associated benefits for households, utilities and policymakers. The aims of households trying to save money and energy align with the efforts of utilities improving energy system management and the objectives of policymakers pursuing greenhouse gas emission reduction and a secure and reliable energy supply. The instrumental view thus sees the smart home as an important technological solution in delivering an affordable low-carbon energy transition (e.g. [50, 53] or sustainability more generally [18]. This builds on existing research in the commercial and institutional sectors on "intelligent" buildings with automated energy management systems [13, 77].

In the instrumental view, core components of the smart home are smart meters, smart energy-using appliances and energy management functionality to enable user-control and programmed optimisation of appliance use and microgeneration [57]. Energy smart homes thus encourage a transformation of passive end-users into "micro-resource managers" [71, p. 227; see also 33]. Personalised, tailored and real-time information and feedback on energy use (and tariffs) via smart meters and in-home displays help to "make energy visible" [37, 76]. Smart technologies also open up a suite of options for household energy management that were not possible under previous "dumb" systems of monthly feedback via energy bills. Smart homes, this view suggests, will enable energy to be cut, trimmed, switched, upgraded or shifted [62].

However, demonstrated energy savings from the use of smart home technologies in studies or field trials are relatively small, although potential savings (or "shaving") during peak times can be more pronounced [22, 26, 78]. Large-scale trials of smart meters and in-home displays in the UK demonstrated around 3 % energy reductions on average [1]. Households' appetite or capacity for reducing energy bills in response to information feedback and price incentives appears limited, and interest in information and price signals rapidly wears off [38, 74].

Energy utilities are key proponents of the instrumental view but are interested less in household-level energy savings and more on the rollout of smart meters. These will provide utilities with real-time information on both supply and demand distributed across the millions of nodes of the distribution network [58]. Linked in-home displays communicating usage and cost information to end-users enable utilities to charge for electricity at its marginal cost, providing a price signal to shift or curtail demand when supply is expensive or in short supply [4, 42]. Individual homes are thus integrated into wider "smart grids", with considerably improved energy management functionality for utilities, and potential efficiency gains with associated financial and environmental benefits [57]. This utility-driven instrumental view is already strong in the USA (e.g. [26, 30]) and is increasingly receiving attention in Europe as the rationale behind smart meter rollouts and smart grid development (e.g. [19, 23].

3.3 The socio-technical view

The functional and instrumental views dominated the literature reviewed, but a third "socio-technical" perspective on smart homes is also evident. Rather than focussing on the specific functions smart homes can offer or seeing smart homes as useful tools to realise broader energy objectives, the socio-technical view sees smart homes as simply the latest (or perhaps the next) episode in the coevolving relationship between technology and society. The socio-technical view emphasises how the use and meaning of technologies will be socially constructed and iteratively negotiated, rather than being the inevitable outcome of assumed functional benefits [5].

Røpke and colleagues contextualise “the pervasive integration of ICT into everyday practices” [66, p. 1771] as part of what they call the “third round of household electrification”. Building on Schwartz-Cowan’s [68] seminal work on the “industrialisation of the home”, they see the electrification and digitalisation of the home as the latest round of socio-technical change. Previous rounds involved lighting (early 1890s) and power and heating (1940s–1970s). The core technology of the current round is the micro-chip, which has enabled the creeping digitalisation of almost all aspects of everyday life.

Technology developers’ visions nourish this socio-technical interpretation. Park et al. [59], for example, sketch out working prototypes for smart pens, pillows, dressing tables, doormats, picture frames, sofas, walls, windows and so on, with a correspondingly broad array of services, from remembering, reminding, smelling, lighting, recognising, sounding, connecting and reinvigorating. Taylor et al. [73] emphasise the potential for almost all “surfaces” (doors, walls, bowls) to become “smart” digital displays in an “ecology of surfaces” with and through which users interact. Even in the health domain with its more overt surveillance and monitoring function over vulnerable household members, smart technology is to be “embedded seamlessly in the everyday objects of our lives” [45, p. 539].

The socio-technical view of smart homes is distinctive in arguing that such technological developments always, and necessarily, co-evolve with broader and longer-term societal changes that may include indirect and unintended consequences. Smart homes are important and interesting precisely because of these potentially transformative but as yet unknown effects. Social practices within everyday life at home may be combined or scheduled in new ways [55]. Differentiated identities, and particularly gender roles, associated with key household practices such as housework and leisure may be reinforced or destabilised [9, 64]. Smart home technologies may also change how householders’ understand, experience and construct meaning around their homes and domestic life more generally [6, 25].

4 Who uses smart homes and how?

Analysis of reports, studies, websites and promotional material produced by smart home technology developers and service providers reveals a notable absence of user-focused research [39]. User-oriented studies in actual smart home environments are notable exceptions rather than the rule (e.g. [57]). The resulting implicit (rather than explicit) understanding and representation of smart home users distinguishes: (1) who prospective users of smart homes might be; (2) how these users might interact with and make decisions about smart home technologies; and (3) how broader conceptualisations of the home as the adoption environment for smart home technologies conditions both users and use.

4.1 Prospective users of smart homes

There are few specific and differentiating characteristics of prospective smart home users identified in the literature. The major exception is in smart homes for assisted living which emphasise active ageing and independence, self-determination and freedom of choice, and changing and inter-dependent needs of an ageing population [32, 54]. Specific needs of elderly smart home users include easily accessible contact with emergency help, assistance with hearing or visual impairments and automatic systems to detect and prevent falls [10, 14, 43]. Vulnerable users in assisted living smart homes comprise more than just the elderly. Chan et al. [17], for example, highlight the potential for smart homes to incorporate wearable and implantable devices that can monitor various physiological parameters of patients. Giger et al. [34] focus on those with serious mental illness. Orpwood et al. [56] highlight the specific user-interface requirements of dementia sufferers.

Beyond these specific characteristics of health-related users, the identities of prospective smart home users have to be inferred. According to the instrumental view, users are information and price-responsive, and broadly rational in seeking to manage domestic energy use (e.g. [23, 50]). In the functional view, technophile users are attracted to an ICT-enhanced lifestyle, and the potential for control and automation offered by the smart home (e.g. [20, 59]). A small number of articles imply another type of user: the incremental home improver. The development of modular, affordable and accessible smart home technologies enables their incorporation into existing as well as new-build homes. Potential users may therefore include low- and middle-income households, as well as high-income technophiles (e.g. [53]). A final type of prospective user, prevalent in the more socio-technical studies reviewed, identifies women, children and families rather than unitary households or individual users [25]. Richardson [64] and Berg [9], for example, emphasise that women and children will be smart home users as well as men and therefore that distinct gender roles and identities should be recognised during technological design and development.

These types of prospective smart home user—elderly or vulnerable householders, rational energy users, technophiles, home improvers and differentiated families—are not exclusive. With the exception of health-related users, they are also inferred or assumed rather than explicitly identified in smart home user research. Arguably, this lack of focus on who the actual users of smart homes will be or on what they might want has contributed to the limited diffusion of smart homes to date: “If the history of research into this area attests to anything, it is the narrowness of the appeal of smart homes to a wider population” [73, p. 383].

4.2 User decisions and interactions with smart home technologies

Users must interact or interface with smart home technologies in some way, but these interactions can be more or less frequent and more or less passive or active (e.g. [41]). In a recent, influential depiction of the smart home, Cook reduces user interactions with smart home systems to one-off goal-setting: “computer software playing the role of an intelligent agent perceives the state of the physical environment and residents using sensors, reasons about this state using artificial intelligence techniques and then takes actions to achieve specified goals, such as maximizing comfort of the residents” [20, p. 1579]. Users are interpreted as having fixed and stable needs and preferences that homes, rather than the users themselves, can manage optimally. Smart homes as intelligent and context-aware learning systems remove the need for any active user involvement at all by automating functions according to users’ revealed habits (e.g. [24, 52, 67]).

These visions of intelligent homes are countered by the complexity, potential inflexibility and poor manageability of fully automated smart homes that are cited as key barriers to their adoption [8, 12]. A long-standing irony in human–computer interactions is that “the more advanced a control system, the more crucial may be the contribution of the human operator” [7, p. 775]. End-users rank automation as a desirable feature of smart homes, but this is qualified by calls for such automation to be strictly limited to chains of functions that users could programme or set-up themselves: “computers should not make choices for users, but the other way around” [49, p. 240]. Indeed, alongside automation, another important role of the smart home in most current visions is to provide useful information to users about various aspects of household functioning (e.g. room temperatures or occupancy, appliance conditions, energy usage) in an effort to help them make more informed choices and decisions.

User interactions with smart homes might therefore range from a one-off input of preferences for the domestic environment (“set and forget”) to ongoing, repeated and adaptive decision-making and control. This latter possibility leads to a small strand of research focussed on how users make decisions about smart home technologies. The instrumental view assumes users respond rationally to improved feedback, information and price signals (e.g. [78]). Alternative framings of domestic decision-making have emphasised its emotional, negotiated and pragmatic character. Friedewald et al. [32], for example, recognise users as being “emotional” and having moods, as holding cherished ideals and as valuing communication and interactions with people. Such characteristics orient decisions about the use of smart home technologies very differently from preferences for minimising energy costs. The domestic environment is also characterised by “co-presence”, meaning one individual’s goals and preferences may not be shared by others and so must be pragmatically negotiated (see also [36–38]).

4.3 Characterising the “home” in smart homes

Within much of the technologically focussed literature on smart homes, the domestic environment is simply the “taken for granted” backdrop within which technology will be used [64]. In their content analysis of smart home marketing materials, Hargreaves et al. [39] found that most images of smart homes depicted them as sterile, bland and neutral spaces that appeared unlived in. Such depictions are unsurprising given that much of the technological research and testing of smart home equipment occurs in artificially constructed test homes (e.g. [17]). These are little more than “a set of walls and enclosed *spaces*” [73, p. 383 our emphasis]. Increasingly, however, this view is giving way to a more complex understanding of homes which sees them as internally differentiated, emotionally loaded, shared and contested *places*.

Ethnographic and sociological research on the use of ICTs in domestic contexts finds homes are actively divided by their occupants into functionally and interpretively distinct spaces. Communication technologies tend to be used and stored in different places within the home for quite different purposes [21]. These places may be “ecological habitats” (where communication media is kept), “activity centres” (where media is produced, consumed and transformed) and “coordinate displays” (where media are displayed and made available to others in order to coordinate activities). All these places play significant roles in the flow and communication of information within homes. The spatial layout of specific technologies also actively divides up homes, with certain activities being undertaken in particular places (e.g. [6, 40, 75]). Technologies and objects as “clutter” can help people give meaning and order to domestic space as part of the perpetual project of organising and constructing the home [72]. This internal differentiation of the home matters for how, where, how often and by whom smart home technologies are likely to be used.

Domestic environments can also be emotionally charged. Haines et al. [36] identified the importance of memories and relationships in a study of what end-users might value in smart homes. Baillie and Benyon [6, p. 227] similarly argue that "homes are places loaded with emotion, meaning and memories". Domestic technologies will not serve solely functional purposes, but will be used and understood within broader and pre-existing household "moral economies"—the unique and normally unquestioned sets of values, routines and practices that underpin domestic life [38, 69, 76].

Moreover, although households may be a convenient unit of analysis, families are plural (e.g. [25]). Homes must be understood as shared and contested places in which different household members may have different understandings, preferences, rights, responsibilities and emotional associations. Richardson [64], for example, focuses attention on the gendered nature of technology use (see also [9]). She illustrates how technologies are often designed in ways that fail to respond sufficiently to how women as opposed to men and children use domestic spaces. Baillie and Benyon [6] further distinguish between more active users—who set and enforce the rules for technology use at home—and more passive users who comply with (and at times resist) these rules.

5 What are the user-related challenges for realising smart homes?

The smart home is yet to be realised at scale, despite the various views and propositions of the benefits it can provide to households. The technical literature that dominates smart home and user research (see Fig. 1) identifies the key technological and design challenges to be overcome. Specific issues within these two sets of challenges are in line with the social barriers to the adoption of smart homes identified in public deliberative workshops by Balta-Ozkan et al. [8]: loss of control, reliability, privacy, trust, cost and irrelevance. However, there is a third set of challenges that more explicitly situates users in the adoption environment of the home and examines how and whether smart home technologies may be effectively domesticated.

5.1 Developing technologies for smart home users

Numerous research, development, testing and trialling challenges need to be overcome before the widespread commercialisation of smart homes becomes a realistic prospect. Key technical issues include: (1) monitors and sensors that can reliably detect and sense what is going in the home, and algorithms that can accurately infer activities and patterns from the resulting abundance of data; (2) interoperability and retrospective compatibility of smart home technologies, supported by well-designed and flexible standards; and (3) functional reliability and manageability [20].

The salience of these technological challenges varies widely depending on the technologists' underlying vision for the smart home.

For Friedewald et al. [32], reliability is the central challenge as this attribute will underpin user-friendliness and empowerment. Smart homes must neither fail nor do unpredictable things. Edwards and Grinter [29] highlight several different aspects of the reliability challenge, including: debugging smart homes created "accidentally" by technologies introduced piecemeal; administering and fixing smart homes through self-healing systems that remove the need for household or third party system administrators; and inferring occupancy activity from sensor data that may be both ambiguous and unreliable. Reliability is most important in smart homes for assisted living in which failures to sense or make inaccurate inferences about the nature of occupant behaviour could have life-threatening consequences. As Orpwood et al. [56, p. 162] note with regards to dementia sufferers: "judgements made [on human behaviour] are always going to be probabilistic, and the designer has to incorporate means of dealing with errors, particularly in safety critical situations".

A recurring theme in discussions around reliability, debugging and interoperability of smart home technologies is the importance of "future proofing" to ensure compatibility both between successive generations of smart home technologies as well as between interacting components. Modularity, flexibility and retrospective compatibility are frequently cited as necessary technological attributes (e.g. [61]). Future proofing also insulates smart home technologies from changes in regulatory frameworks, standards and policy objectives, particularly in the energy domain [53].

5.2 Designing technologies for smart home users

The acceptability of smart homes to users is closely linked to issues of security, privacy and trust as well as practical and ergonomic concerns with user-friendliness. These issues present critical design challenges that relate to the interactions between users and smart home technologies.

With respect to security, for example, Cook observes that "many individuals are reluctant to introduce sensing technologies into their home, wary of leaving digital trails that others can monitor and use to their advantage, such as to break in when the house is empty" [20, p. 1578]. In smart homes for assisted living, Demiris et al. [27] similarly note user concerns with privacy arguing that technologies that detect and monitor activity within the home risk being seen as intrusive violations in the domestic environment. For energy smart homes, concerns around both data security and the potential for utilities to monitor or even control household demand have led to consumer backlashes against smart metering [2, 23]. In the UK, a recent study on attitudes and values towards energy system change found general support for the development of smart homes, but with caveats around data sharing and a perceived loss of control through remote interference from utilities [60]. Paetz et al. [57] report similar findings from Germany.

How smart homes are designed will condition their acceptability to prospective users. Cook [20] advocates for clearly defining and guaranteeing levels of privacy and the safety and security of technologies. Paetz et al. [57] suggest the need for much greater levels of transparency and accountability on behalf of smart home developers—particularly energy utilities—and the need to make explicit exactly how all stakeholders may benefit from smart home development. Rohracher [65] argues that many of these issues might be avoided if more participatory approaches to design were employed. He suggests engaging with a wide range of different stakeholders even at the visioning stage for smart home technologies, to ensure that the widest possible range of interests and concerns are recognised and addressed.

Several other studies highlight more narrowly framed design challenges regarding the user-friendliness of smart homes. Park et al. [59, p. 189], for example, outline the immense variety of potential smart applications but caution against "overpowering" users with "complex technologies". Several studies have highlighted the difficulties of creating intuitive and easy-to-use user-interfaces given the level of complexity and number of user-control options that can potentially lie behind the interface (e.g. [28, 49, 59]).

User-centred design is widely cited as a useful response to smart home design challenges. Orpwood et al. [56] identify a number of simple design solutions that could help overcome specific difficulties faced by dementia sufferers, including wariness of new devices and forgetfulness. By working with carers, researchers could identify simple and often low-tech solutions such as making devices look familiar, concealing them from view so as to avoid causing alarm and providing prompts and reminders rather than taking control away from users. Different groups of users are likely to require different design solutions, not only just between households but also between cultures. Jeong et al. [47], for example, reveal stark differences in the understanding of and demand for control between USA and Korean smart home users.

5.3 Situating smart home technologies amid everyday life at home

"More than control of their devices, families desire more *control over their lives*" [25, p. 20 emphasis in original]. Accordingly, the central user-related challenge for the realisation of smart homes is to align and adapt technologies with the messy and differentiated nature of users' everyday lives at home [41].

New technologies are rarely used in homes in the ways their designers intend because they must always enter pre-existing environments that are contested, emotionally charged and dynamic (e.g. [40]). These apparently chaotic domestic environments possess their own "smartness" or "intelligence" in the way, for example, that households manage communications [21], make use of surfaces such as tables or fridges [73] or organise the flow of clutter and mess through the home [72]. Smart home technology development to date has assumed everyday life is made up of specific, repetitive and relatively predictable routines and schedules. But on closer examination, life at home is "organic, opportunistic and improvisational" [25, p. 19].

This generates new sets of design principles for generating technologies that align with and support users in managing everyday life. Technologies can be built "for ambiguity, instability, concealment, and disinterest, and to be treated casually" [72, p. 21]. Davidoff et al. [25] offer a set of seven principles that suggest new technologies should account for "the organic evolution of routines and plans", "periodic changes, exceptions and improvisation", "breakdowns", "multiple, overlapping and occasionally conflicting goals" and that should "participate in the construction of family identity" [25, p. 28].

Unless the smart home concept is re-thought in these ways, it is unlikely to succeed. Yet as Howard and colleagues caution, such principles would be "fiendishly difficult to apply to technology research" [44, p. 329]. The central user-related challenge for the realisation of smart homes is therefore not to improve the reliability or functionality of technologies, nor to design out concerns around trust, privacy or user-friendliness, but to re-define the notion of "smart" itself, recognising that it emerges within users' everyday lives and in the ways technologies are used in the home. As Taylor and colleagues explain: "it is people who imbue their homes with intelligence by continually weaving together things in their physical worlds with their everyday routines and distinct social arrangements" [73, p. 383].

6 Discussion

Our thematic analysis of the literature on smart homes and their users was organised under three meta-themes: (1) visions or "grand narratives" for the smart home; (2) users and their uses of smart homes; and (3) user-related challenges to realising smart homes. Within each of these meta-themes, we distinguished three distinct lines of enquiry pursued by peer-reviewed research. These are summarised in Table 1. Each line of enquiry provides its own answers to the key research questions about smart homes and their users.

Table 1 Core themes in smart home user research, and how they answer key research questions

Views of the smart home	Functional	Instrumental	Socio-technical
What is the smart home?	A monitored, sensed environment that informs occupants allowing active control or automation	An optimally managed building energy system allowing information and price-responsive adjustments to behaviour	A digital, technological, networked vision confronted by the mundane realities of domestic life
What is the purpose of the smart home?	Improve quality of home life through new services and enhanced functionality	Enable energy demand reduction in the home and improved system management by utilities	No inherent purpose, functions emerge through incorporation into practices within the wider trajectory of ICT penetration into the home
Users and use of the smart home	**Prospective users**	**Interactions with technology**	**Homes as complex places**
Who uses smart homes?	Users with specific health needs or users who are price or information responsive in both existing and new-build homes	Users seeking control over the domestic environment and energy usage through flexible or schedulable behaviours	Differentiated households with negotiated roles within the distinct spaces of the home
How is technology used?	Varies according to application with assisted living smart homes emphasising passive usage and energy smart homes active usage	From continuous and active user-mediated control to passive one-off "set and forget"	A gradual and adaptive process of domestication into the existing dynamics of routines and practices
Challenges for realising the smart home	**Hardware and software**	**Design and usability**	**Situating technologies in homes**
How can smart homes be realised?	Develop and improve technologies to ensure robustness and reliability as basis for social acceptability	Design for user needs (not vice versa) and address privacy concerns through clear and transparent rights and roles, and participatory co-design	Ensure technologies are adaptable to everyday domestic contexts and allow flexibility for domestication and appropriation
What research approaches are useful?	Computer science, electrical engineering, design	User-centred design, human–computer interaction, behavioural and social psychology	Sociology, ethnography, science and technology studies, innovation studies

Although Table 1 sets out different groupings of research themes, there is clearly much overlap. Figure 2 shows the main inter-relationships between the nine themes identified. The strong links in Fig. 2 between "functional", "user-technology interactions" and "hardware and software" typify the engineering and technical scientific approach. Similarly, the strong links between "socio-technical", "home as complex places" and "domesticating technologies" characterise a critical social scientific approach. The solid vertical lines in Fig. 2, therefore, represent the concerns of different research traditions and disciplines shown in the final row of Table 1, and of the competing visions for smart homes.

The functional view gives rise to a series of technological challenges around how enhanced functionality can be efficiently and reliably delivered. This includes a detailed consideration of interactions between users and technology around issues such as control and automation. The instrumental view gives rise to a set of design challenges around how users can be made to accept and align with the energy reduction goals of the smart home based on rational responses to information and price signals. The socio-technical view gives rise to a more foundational and broadly cast set of challenges relating to the balance between users and technologies in smart homes, recognising the complex and contested nature of homes as places for technology adoption and use.

Coherence and consistency between the lines of enquiry identified in the vertical relationships of Fig. 2 have come largely at the expense of strong cross-cutting horizontal linkages between research themes. Yet as and when smart homes diffuse more widely into the fabric of everyday life at home, the functional, instrumental and socio-technical views will increasingly interact and combine, presenting more (and potentially more intractable) challenges.

The technological optimism and clarity of the functional view will confront the just-the-next-thing normality of the socio-technical view with all its ambiguities and uncertainties. Functional service enhancements in areas such as comfort and convenience will confound the energy management goals of the instrumental view amid the broader potential for smart homes to generate more resource-intensive trajectories of socio-technical change [48]. Introducing new technologies changes service expectations and use patterns, which in turn change subsequent demands, wants and needs for new technologies and the resources they consume, normalising ever more intensive ways of living [40, 55].

These disconnects between research positioned within the functional and instrumental views, and research contributing to the socio-technical view are clearly shown in Fig. 2. Efforts to develop stronger horizontal linkages provide a clear avenue for future research.

This is best illustrated by example. Two salient issues in smart home user research concern privacy and control. Table 1 and Fig. 2 show how both issues could be approached from alternative and potentially complementary angles that help expose and clarify key issues more clearly and generate wider insights.

Privacy, access to data, and issues of trust, reliability and transparency are a major concern for prospective users of smart homes [27]. In the literature reviewed, these issues are considered primarily to be design challenges affecting hardware and software developments that shape how users interact with technologies (e.g. [20, 57]). The socio-technical view of smart homes, however, sets issues of privacy within broader considerations of how the pervasive influence of ICT-enabled networks and networking are blurring the lines between the private and the social, the domestic and the public. The instrumental benefits to utilities of real-time information on energy demand and micro-generation rely on a recalculation of how much privacy (on electricity and gas usage) should be exchanged for how much potential for optimising home energy systems [33]. For users to become active "micro-resource managers" [71], privacy is further forfeit through the market trades and transactions through which preferences are revealed.

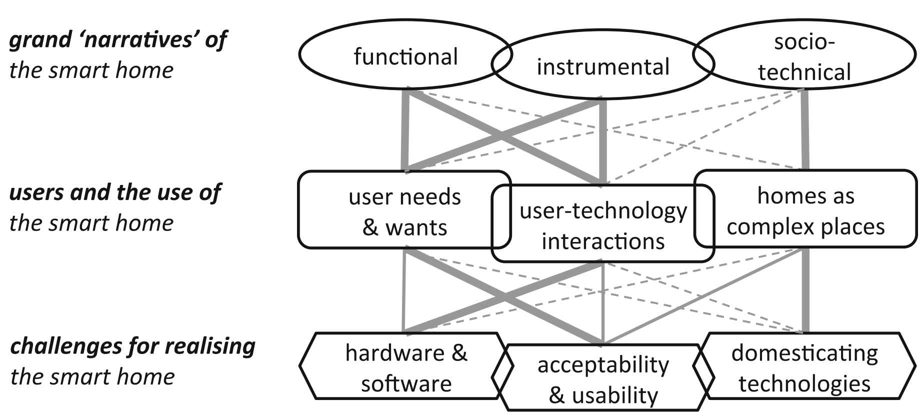

Fig. 2 Organising framework for research on smart homes and their users. *Notes: Thick solid*, *solid* and *thin dashed lines* denote strong, weak explicit and weak implicit inter-relationships, respectively, in smart home user research to date

Nor is privacy an issue simply between households (us) and utilities or smart home installers and maintenance operators (them). Seeing smart homes as complex adoption environments for new technologies reveals how enhanced functionality for one household member may imply a loss of privacy for another. Privacy may be sought within the differentiated spaces of a home that smart home technologies may inadvertently erode through communication, sharing and unitary control. Privacy is even constitutive of what a home means: any monitoring of the domestic environment challenges how occupants identify with their homes [10]. It is entirely unsurprising, therefore, that technologies designed to sense, interpret and control these uniquely emotional and memory-laden places evoke concerns over privacy [6, 72].

Alongside privacy, issues of control and automation are another of the central uncertainties in the body of research concerned with what users might want or need from smart homes. And as with privacy, there are many contrasting perspectives on control and automation shown in the organising framework in Fig. 2.

Control can be about households protecting their domestic environments from outsiders (security), or control can be about automating various functions and services [49]. Control can also be about autonomy and independence within the home (mobile and always-on maintenance and care) or about responding to information from outside the home (utility price signals). Even the technologists' vision in the functional view is unclear on the extent to which smartness should reside in the technologies—learning, inferring and pre-empting occupants' behaviour (e.g. [20])—or should reside in the users—maintaining active control or a watchful over-riding eye on automated functions [e.g. 49].

These complexities are magnified if questions are asked about the nature of the home as the arena in which issues of control and automation play out. Household members have different roles in this arena and in different spaces within this arena. Control over the interface with smart home technologies thereby translates into shifts of control within the different genders and generations in a household (e.g. [38]). By failing to recognise that users value time, roles and relationships in their domestic lives, rather than narrowly circumscribed technologies and functionalities, there are growing concerns that smart home technology is coming to dominate people, rather than the other way around [25].

Seeing smart homes as merely a small part of broader trajectories of socio-technical change dramatically shifts the framing of control again. Paradoxically, the greater individual control over the domestic environment that smart homes offer is entirely compatible with an individual's loss of control over the broader social and technological system of which the domestic environment is a microscopic part. The holy grail for users may not be control over technologies but rather control over the hectic, chaotic and demanding domestic lives into which smart homes must fit [8, 25].

Figure 2 thus shows how both control and privacy mean different things in different parts of the smart home literature. Defining issues or problems narrowly and pursuing singular lines of enquiry precludes wider insights. Future research on smart homes and their users can benefit immensely by explicitly tracing, exploring and seeking to strengthen the cross-cutting relationships between research themes highlighted in our organising framework summarised in Fig. 2.

7 Conclusions

Smart homes are an advancing wave of technological development whose success depends on a coalescence between the visions of technology developers for enhanced functionality and energy management, and the needs and demands of households in the complex places that are homes. User-focused research on smart homes is growing, dominated by engineering, technical sciences and design, but with a sizeable niche of health care-related research, and increasing attention from social scientists ranging from ethnographers and domestication theorists to economists and applied energy researchers. Yet there is a wide and growing recognition of the need to develop a better picture of who users are and how they might use smart homes (e.g. [10, 70]). Although two of the themes analysed from the literature (on "user-technology interactions" and "acceptability and usability") are most strongly informed by research on user-centred design, these themes have not typically been entry points for thinking about the purpose and use of smart homes. Rather, they have emerged as a consequence of a technological vision that is struggling to gain user acceptance. The result is that current visions of smart homes have a limited appeal to users and are perceived as failing to meet user needs [57]. This has given rise to what Nyborg and Røpke [55] term "funwashing" as smart home developers seek to broaden the appeal of smart homes because the basic functionality they offer has not proven as attractive as initially hoped.

A systematic review of published literatures on smart homes and their users reveals a wide range of research themes and lines of enquiry, often characterised by particular and partial questions (see Table 1). An integrative approach to smart home user research is neither desirable nor practical, but a comprehensive framework for positioning and interrelating research is. Our thematic analysis of the literature proposes such an organising framework (see Fig. 2). We illustrate how this framework can advance future research on smart homes and their users in relation to two major concerns: privacy and control. In so doing, we argue that it provides a valuable tool to help others navigate the existing terrain of research on smart homes and to help map out new and more fruitful avenues for future research.

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