What Do We Design for When We Design "Smart Buildings"? - A Scoping Review of Human Experience Design Research in Buildings

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Abstract

Built environments increasingly incorporate new forms of intelligence, creating opportunities for enhancing human interactive experiences with and within building spaces. This scoping review examines design interventions and discourses within the domain of "Smart Buildings". The goal is to identify and characterise the type of human experiences that research in this domain aims to address. Using a hybrid deductive-inductive coding approach, we analysed 192 papers related to human experiences and smart buildings from ACM Digital Library and Scopus published between 1996 and 2024. Our analysis revealed 11 distinct "targeted human experiences", 20 commonly used "design mechanisms" to achieve those design goals, as well as two typologies of "technological interventions". Our findings create a foundation for understanding building design research and the range of human experience they entail.

CCS Concepts

• **Human-centered computing → Human computer interaction (HCI)**; **Interaction design**; • **Applied computing → Architecture (buildings)**.

Keywords

scoping review, smart building, human experience, user experience, interaction design, interactive technologies

ACM Reference Format:
Shruti Rao, Katja Rogers, Judith Good, and Hamed Alavi. 2025. What Do We Design for When We Design "Smart Buildings"? - A Scoping Review of Human Experience Design Research in Buildings. In *CHI Conference on Human Factors in Computing Systems (CHI '25), April 26–May 01, 2025, Yokohama, Japan.* ACM, New York, NY, USA, 23 pages. https://doi.org/10.1145/3706598.3713903

CHI '25, Yokohama, Japan

ACM ISBN 979-8-4007-1394-1/25/04
https://doi.org/10.1145/3706598.3713903

1 Introduction

The convergence of research and design endeavours in architecture and interaction design (IxD) has brought forward new ways of thinking about the relationship between humans and the built environment. Historically, research in the domains of architecture and building performance engineering has focused on human experiences through an objective lens [98], often using environmental sensing and metrics such as thermal comfort and indoor air quality to assess and improve building design [39]. In human-computer interaction (HCI), questions around architectural spaces began to emerge, notably in the foundational paper on *places* and *spaces* by Harrison and Dourish [78] in 1996, which explored how people interact with physical spaces through a digital lens [78]. Across various domains, researchers have since developed a deeper understanding of how technology shapes human experiences within built environments, moving beyond objective assessments of the environment to recognise individual differences and subjective experiences. In recent years, researchers and designers have sought to re-imagine the role of interactive technologies embedded in our built environments [2, 173]. This has been complemented by new visions that interface HCI with the domains of architecture and urban design to delineate a new area of design research under the banner of human-building interaction (HBI) [3]. HBI delves into the relationships between digital technologies, physical spaces, and the human experiences they shape [3, 19], considering the subjectivity and individuality of human experiences.

Furthermore, HBI acknowledges that technologies impact human experiences in smart building environments in various ways. Designers and developers who create and shape smart buildings inherently embed both explicit and implicit values, assumptions, and expectations from their respective disciplines into the experiences they envision or the technologies they create [173]. For example, they might focus primarily on enhancing human comfort (across its four classic dimensions: thermal, visual, acoustic, respiratory) [5], or on human agency and control [27]. They might promote supporting individual needs [17], or collaborative, community-centred interactions [91]. They might frame the role of the built environment in people's lives purely as functional spaces [177], or as immersive, responsive environments that contribute to emotions [115], sustainability [106], and social engagement [150]. Furthermore, with the rapid and pervasive deployment of interactive technology, smart building environments are increasing in complexity, and the factors involved in shaping human experiences are also increasingly multifaceted. By and large, smart building research consists of a rich but fragmented body of work encompassing diverse perspectives, methodologies, and disciplines. This highlights the necessity to conduct a comprehensive mapping of the literature in order to understand the full scope of what we design for when we design smart buildings. Our review studies human experiences in smart buildings through this central question: *what do we envision and research when we design for human experiences in future smart buildings?*

The answers to this question not only shape how smart building experiences are created, but also how people interact with, value, and experience the spaces they inhabit. Smart buildings, in this perspective, are not just passive infrastructures; they are active "shapers" of individual, cultural, and societal attitudes toward the built environment. We seek to uncover these visions through a scoping review, addressing the following research questions:

- ***RQ1.*** What are the different types of *human experiences* that research in the broad domain of smart buildings aims to improve or introduce?
- ***RQ2.*** What are the *design methods and approaches* employed in smart building research to shape human experiences?
- ***RQ3.*** What types of *technological interventions* are developed or conceptualised to enhance interactive experiences in smart buildings?

To address these questions, we analysed 192 papers that contribute to the research and design of human experiences in smart buildings, sourced from the ACM Digital Library and Scopus. Using a hybrid latent coding approach [30], our scoping review provides a comprehensive descriptive analysis of how smart building research has explored human experiences in relation to digital technology. Specifically, we offer: (a)*a classification of 11 distinct human experiences* that smart building research aims to improve or introduce, (b) *a classification of 20 commonly used design mechanisms* employed to enhance or create these human experiences, and (c) *a typology of the technological interventions* used to impact these human experiences.

Our contributions help in understanding and describing the current and future of smart building design research, while incorporating a broad, diverse range of human experience in these spaces.

2 Background and Related Work

In this section, we first clarify key terms used in our scoping review. We then review existing secondary research on human experiences in smart buildings, identifying gaps that motivate our research.

2.1 Clarifying Relevant Terminology Pertaining to the Scoping Review

Our scoping review is built around the terms discussed below:

"Smart" Buildings: Previous works use terms like "smart buildings" and"intelligent buildings", often interchangeably with the term "built environment" [32, 104]. Irrespective of the term used, the goal is to create a responsive environment where users interact with buildings through automated systems that optimise functions like lighting, heating, and ventilation, using data-driven approaches to adapt to occupants' needs [147]. Smart buildings also emphasise human-centred design, aiming to create environments that foster occupants' satisfaction or agency [120, 122]. In our review, we do not distinguish between these terms, collectively referring to them as "smart buildings" throughout the paper.

"Interactions" (with)in Smart Buildings: We view interaction in smart buildings as a dynamic relationship in which humans and buildings influence and determine each other's behaviour. We believe this relationship can encompass all forms of interaction described by Hornbæk and Oulasvirta [86]: the interaction between occupants and the embedded technologies within a building can be understood as a continuous dialogue, a transmission of information, as tool use, as an adaptation towards optimal behaviour, and a controlled move towards a target state, but also as embodiment and experience (and likely other concepts as well). Using "interaction" as another search keyword in our review, we do not discriminate against a specific understanding of interaction. With this view of interaction, in which "[u]sers, with their goals and pursuits, are the ultimate metric of interaction" [86], human experiences can similarly be viewed holistically.

"Human Experiences" in Buildings: There are different conceptualisations of experience, e.g. Wright et al. [176]'s compositional, sensual, emotional, and spatio-temporal "threads" or Wright and McCarthy [175]'s lens of empathy. However, we do not employ a specific existing framework of user experience to constrain the type of human experiences that we extract from the literature. Instead, our review includes diverse and emergent aspects of human experiences in smart buildings, without imposing any predefined structure. We consider the experience of occupants in smart buildings as context-dependent, influenced by embodied cognition, emotions, sensory inputs, and ongoing interactions with their environment.

"Comfort": In this paper, we frequently refer to "comfort" as a technical term that has been meticulously studied in architecture and building performance engineering, and which comprises four dimensions: "thermal", "visual", "acoustic", and "respiratory". These dimensions have also emerged in HBI research. For example, thermal comfort has examined personalised heating, ventilation, and air conditioning (HVAC) systems [41, 97], addressing social dynamics like shared control [114, 169] and the impact of data displays with environmental information [47]. Visual comfort studies have explored the importance of lighting design [21, 25, 182]. Research on indoor air quality has focused on raising awareness [183] and encouraging behavioural changes, often using playful systems [72, 155], and acoustic comfort studies examined noise preferences and control mechanisms through surveys [113, 133] and sound awareness systems [131, 174]. These dimensions collectively contribute to the understanding of comfort as a key experience in the built environment. For the rest of this paper, when referring to comfort, we refer to these four dimensions.

2.2 Secondary Research on Experiences in the Built Environment

Several works have reviewed literature on human comfort in built environments. For example, Frontczak and Wargocki [65] surveyed

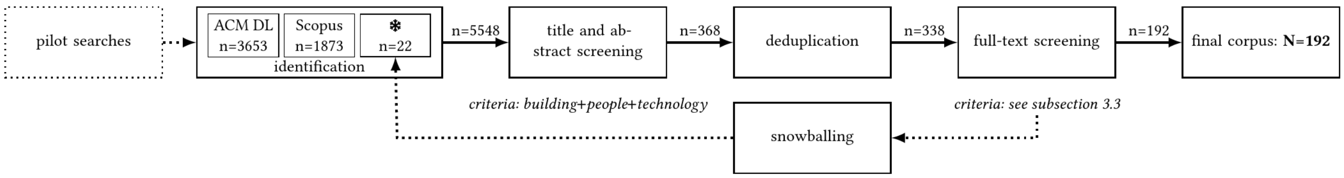

Figure 1: This flowchart demonstrates the scoping review process and the number of papers considered in each stage.

how lighting and temperature influence human comfort. Similarly, Zhang and Barrett [180] discuss occupant satisfaction with comfort dimensions in the context of green office buildings. Few works explore human experiences beyond comfort in smart buildings through secondary research (i.e. scoping or systematic reviews). For example, a review by Pourzolfaghar and Helfert [137] identifies design challenges in creating smart environments but only addresses user experience in broad terms. Aliero et al. [9] explore trends in control over automated buildings and smart technologies while considering user experience in the context of privacy in automation systems. Work by Saputra and Ramadhan [147] highlights the key components that make up smart buildings, emphasising energy management and building information modelling, while viewing occupant comfort in the context of improving quality of life. Similarly, Latifah et al. [104] connect smart building features with smart city frameworks to enhance comfort and transparency in meeting digital society's needs [104].

Other reviews focus on specific environments. For example, Bäcklund et al. [13] examined campus buildings to explore the relationship between occupant behaviour, building systems, and energy use, proposing a framework for assessing the impact of occupant behaviour on energy consumption. Ji et al. [96] reviewed sensing technologies across six areas—occupancy status, physiological indicators, building components, environment, consumption, and multi-sensor fusion—to identify concerns related to privacy and data concealment from building occupants. Smart home reviews have focused on how users view benefits arising from technology in these spaces [112], and the complexity of domestic spaces and opportunities around human-home collaboration [117]. Further secondary research has examined smart technology adoption by ageing populations [110] and communication challenges within smart homes for vulnerable groups [94]. To the best of our knowledge, our scoping review is the first of its kind to encompass all types of smart environments and consider the full spectrum of human experiences beyond traditional notions of comfort.

3 Methodology

This work seeks to investigate smart building research to understand what researchers envision and design for. The goal is not to provide an exhaustive summary of existing research findings but to focus on identifying the human experiences that research in this domain aims to improve or introduce. In addition, we identified *how* the field aims to shape those human experiences through design mechanisms and technological interventions. This was accomplished by conducting a scoping review based on the five-stage framework outlined by Arksey and O'Malley [12]. We chose a scoping review as this method suits broad research questions that map key characteristics rather than a targeted study of a specific effect [126, 143]. The review was planned with pre-defined research questions and a search strategy, rather than following a formal protocol, allowing the specifics of the analysis to be shaped by the first author's growing familiarity with the literature by reading the selected corpus papers. The process is documented in the rest of this section. To ensure comprehensive reporting, this paper broadly follows the Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) checklist where applicable[1]. Figure 1 provides an overview of the search and screening stages to reach the final review corpus.

3.1 Stage 1: Identifying Research Questions

During the first stage in our scoping review work, key research questions were identified. The first question, established from the outset of the project, focuses on the different targeted human experiences in smart buildings:

- ***RQ1.*** What are the different types of *human experiences* that research in the broad domain of smart buildings aims to improve or introduce?

The other two research questions underwent iterations but focused on the technologies and mechanisms that the field adopts from interaction design, architecture, and other areas to improve human experiences in smart buildings:

- ***RQ2.*** What are the *design methods and approaches* employed in smart building research to shape human experiences?
- ***RQ3.*** What types of *technological interventions* are developed or conceptualised to enhance human interactive experiences in smart buildings?

3.2 Stage 2: Identifying Relevant Studies

To ensure that our scoping review investigates disciplines beyond the HCI domain, we queried for works in two established databases. The ACM Digital Library (DL) primarily features computer science and engineering research (including HCI). Scopus offers multidisciplinary coverage, with frequent indexing of architecture works, making it a valuable resource for architecture studies on smart building research[2].

3.2.1 Pilot Searches. We first conducted pilot searches on *smart buildings* and *experiences*, which resulted in some 9000 references in Scopus alone. We reviewed the first 20%, finding many irrelevant

[1]As conventions in HCI do not always accommodate the PRISMA-ScR items, we provide a table in the supplementary materials to detail the manner by which we adhere to the reporting checklist.
[2]List of architecture-based sources available here when filtered by subject area: https://www.scopus.com/sources.uri

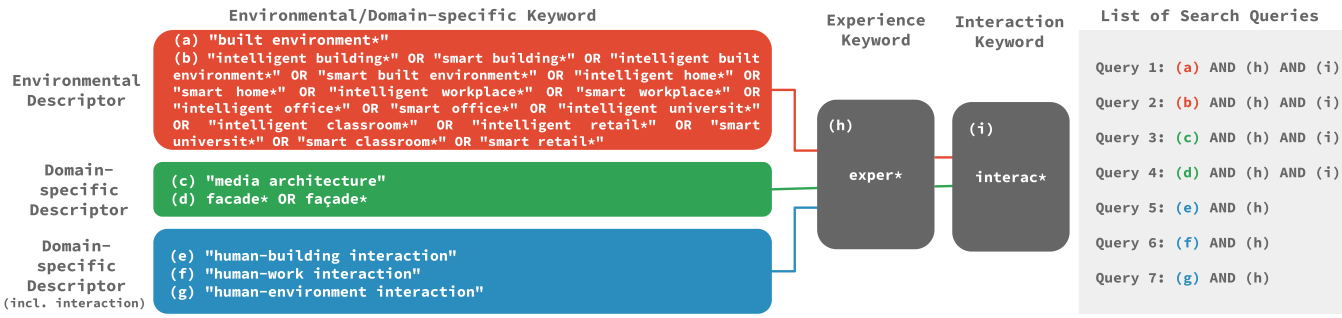

Figure 2: The search comprised seven queries (Query 1 – Query 7), combining nine components ((a)–(i)). The nine components were either 1) environment/domain-specific descriptors (first column), 2) a keyword for experience (second column), or 3) a keyword for interaction (third column). We conducted the searches using combinations of these—query list on the right. Thus, environmental descriptors were combined with experience and interaction keywords (red line). This was implemented for "Built environment" separately—(a) in red box—as this yielded many results, while more specific terms were combined in a second search—(b) in red box. Domain-specific descriptors were handled separately again—(c) and (d) in green box; green line. When the domain-specific descriptor already included the word interaction (e.g. 'human-building interaction'), the query was only accompanied by the experience keyword—(e), (f), and (g) in blue box; blue line.

studies that did not involve human experiences, such as Internet of Things (IoT) and civil and computational engineering. Based on this, we decided to include *interaction* (`interac*`) in our search strategy to refer to interactive human experiences in smart buildings.

3.2.2 Employed Search Queries. Our search queries are explained in Figure 2. The search involved seven queries (Query 1–Query 7), structured around three keyword categories: 1) environment/domain-specific descriptors, 2) experience, and 3) interaction keywords. We conducted the searches using a combination of the keyword groups. A combination with "built environment" was searched separately due to the large volume of results, while more specific environmental descriptors—(b) in Figure 2—were combined in a second search. Domain-specific descriptors were handled individually, and when these already included interaction (e.g. "human-building interaction"), only experience keywords were added. An example of a search query (applied to Scopus) is: `"BUILT ENVIRONMENT*" AND EXPERIEN* AND INTERAC*`. The complete list of queries we used are included in the supplementary materials.

We conducted the searches based on papers' keywords, abstract, and title across both databases[3]. This generated **5,526 references** across both sources, collected during April – May 2024 (later increased by 22 papers through snowballing [14], see Figure 1).

3.3 Stage 3: Study Selection

During our pilot search, we developed initial inclusion-exclusion (I/E) criteria for the first (title and abstract) screening stage, refining them as we grew familiar with the literature. Broadly, references were included if they: (1) were set within the context of a smart building, (2) discussed human experiences, and (3) explored the use or potential use of technologies. References solely focused on engineering, algorithms, or building design without addressing human interaction or the use of technology were excluded. In addition, we excluded papers that were not in English and secondary research (e.g. meta-reviews). The first author applied the I/E criteria to the 5,548 citations, reading all associated abstracts, keywords, and titles. If the relevance of a study was unclear from the abstract, the study was retained for a full article review. This process resulted in 368 shortlisted abstracts. After a review by the last author and the removal of duplicate studies, 338 abstracts were shortlisted for full-paper screening. For the latter, the criteria established for inclusion and exclusion were specified and expanded:

(1) We included studies around *human interaction* within smart buildings using *any form of technology* for occupants. Conversely, we excluded studies that focused on technology development without clear relevance to user interaction or experience, such as works on theoretical models, architectural frameworks, or technical optimisations.
(2) Our research focuses on *real-world environments*, however, we incorporated papers that utilise Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR) to augment existing spaces, enhancing spatial experiences and smart building capacities [7, 99]. However, we excluded research focused on designing purely virtual environments or those centred on gaming realism and virtual worlds without connection to physical space.
(3) We included papers that examined human experiences *within smart buildings and building façades*. However, we excluded papers focused on outdoor experiences like hiking, cycling, and city walks. Additionally, automotive contexts were excluded as they fall outside the scope of smart buildings.
(4) We excluded papers on domotics, mobile apps, and Conversational User Interfaces (CUIs) that lacked a focus on spatial factors of human experience or interaction within a smart building. Studies on human-robot interaction without connection to physical space were also excluded.

[3]Scopus supports a combined search of titles, abstracts, and keywords. In contrast, the ACM DL requires these parameters to be searched separately. To ensure consistency and comparability, we conducted separate searches within the ACM DL: first by titles, then by abstracts, and finally by keywords, before collating the results.

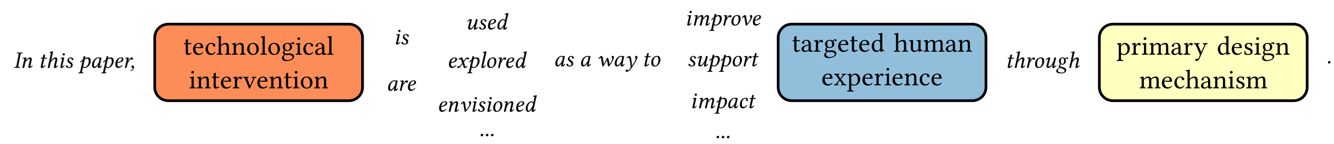

Figure 3: To examine the suitability and the terminology of the targeted human experiences, primary design mechanisms, and technological interventions, we structured them in a sentence, illustrated in this diagram. For example, a paper might be described in the form of "In this paper, Environmental Sensing is used as a way to support Comfort through Personalisation".

The first and last authors held discussions to resolve any points of confusion throughout the study selection. After reading the articles in full and cross-checking references cited by the selected papers that may have been accidentally left out, a total of **192 articles** were selected for inclusion in the scoping review.

3.4 Stage 4: Charting the Data

The next stage involved charting key items from the selected papers. Our charting approach was akin to a "descriptive-analytical narrative review" [12], where a common analytical framework was applied to the papers, enabling us to systematically collect and analyse standard information from each study. The first and last authors collaboratively developed a charting table template to capture information related to the research questions. This process involved categorisation (labelling) and extraction of relevant sentences for later analysis. While some papers were straightforward to chart, others involved multiple discussions to satisfactorily capture the research perspectives.

Our template recorded *title*, *author(s)*, *publication year*, *publication source/venue*, *publication type* and *type of smart building* addressed. We structured our template to record items directly related to our research questions. We documented *research motivations*, and *methodologies* including research and design methodologies to infer whether the research was qualitative, quantitative, or mixed-methods. We recorded the *interactive technologies* and any *instruments* used to assess the environments or their users. Central to our research, we noted the *aspects of human experience* discussed. *Key findings* and the papers' *visions* for future were also recorded (in case we needed to examine evidence supporting claims made by the studies), but were considered out of scope for this paper. The charting template with an example entry is included in Table 4. Throughout this iterative process, the research team met regularly to discuss the scope of the review, refine definitions, and ensure consistency in the categorisation of information.

3.5 Stage 5: Collating, Summarising, and Reporting

After charting the study data, we analysed it in two main stages: a descriptive summary followed by an interpretive analysis (semantic and latent approaches) [36]. First, we examined the characteristics of the literature such as the venues they were published at. Next, we adopted a hybrid latent coding approach, based on thematic analysis [30], to analyse the charting table. This approach was hybrid because while we employed an inductive process to create new codes and themes, we also incorporated deductive coding for the four dimensions of comfort that we adopted from existing literature [5] as well as Brand [28]'s shearing layers (details described below). The coding was highly iterative and completed over multiple rounds by the first author, with intermittent discussions with the full research team, eventually resulting in overarching themes for the targeted human experiences. Though targeted human experiences are the resulting themes, the other core categories (design mechanisms and technological interventions) were iterated on as well. Our method borrows from reflexive thematic analysis in the organic, flexible nature of the rounds of iteration of codes and themes, but overall is better aligned with a codebook approach [29].

In line with our research questions, we identified key themes around human experiences in smart buildings by coding papers based on the *primary* experiences they targeted. After identifying the targeted experiences, we recognised that the papers could be analysed for the design measure or approach (hereafter referred to as design mechanism) used to achieve that experience. We developed RQ2 and conducted a second round of this analysis where we coded each paper for the *primary* design mechanisms employed to achieve the targeted human experiences. For our third research question, we categorised the technology data by type, iteratively grouping them based on observed commonalities and patterns. We also coded the papers based on their technologies' positioning in Brand [28]'s shearing layers which describe distinct layers of a building based on its temporal lifespan [28]. Finally, the full research team finalised the resulting themes of targeted human experiences, design mechanisms, and types of technological interventions over two meetings. These discussions considered the suitability and terminology of these themes in the form of the example sentences presented in Figure 3. The full list of corpus papers and the analysis process are documented in the supplementary materials.

4 Findings

This section presents a descriptive overview of the literature, the thematic analysis of targeted human experiences (RQ1), design mechanisms (RQ2), and technological interventions (RQ3). These are also summarised in Table 1.

4.1 Characteristics of the Literature

In line with general publication increases, the distribution of the 192 papers in our corpus by publication year shows a growing trend that peaked in 2019, coinciding with the ACM ToCHI special issue on human-building interaction (HBI) [3] (Figure 7a in the appendix). The reviewed papers predominantly explored smart homes (24%) or smart buildings (20%). Smart offices (17%) and educational spaces (15%) also received attention, along with specific locations like places of worship, historical sites, children's play areas (19%),

Table 1: An overview of our analysis with a count of the number of occurrences of the paper - (a) The 11 targeted human experiences in smart buildings, (b) The first 10 out of 20 design mechanisms towards enabling human experiences in smart buildings, and (c) The seven types of technological interventions developed or used by research in smart buildings.

(a)

Targeted Human Experience	No.
Aesthetic Experience	18
Bodily Experience	23
Comfort	47
Democratic Experience	16
Explorative and/or Future and Speculative	48
Emotional Experience	38
Experience of Relatedness	21
Inclusion Experience	13
Learning and Teaching Experience	9
Sense of Orientation	8
Sense of Place-making	23

(b)

Design Mechanisms	No.
Community and Social Connection	40
Spatial Design	34
Technological Immersion	22
Playful Design	22
Environmental and Social Information	21
Participation and Co-Design	17
Somaesthetic Design	17
Personalisation	16
N.A.	12
Biophilic Design	9
...	

(c)

Type of Technological Intervention	No.
Audio and Lighting Technologies	27
Augmented and Virtual Reality	17
Environmental Sensing	23
Feedback Systems	11
Interactive Displays	45
Physiological Sensing	10
Shape-Changing and Kinetic Interfaces	22

and interactive installations (7%) (Figure 7b). Publications resulted primarily from conferences (56%) followed by journal articles (19%), as shown in Figure 7c. Within conference publications, 22% of works were published at ACM CHI, otherwise appearing in a variety of HCI and HCI-adjacent conferences as well as architecture and built environments conferences (Figure 7d).

4.2 The Targeted Human Experiences in Smart Buildings

We identified 11 key themes corresponding to distinct human experiences within smart buildings, presented in Table 1(a). While we aimed to identify the primary and overarching human experience targeted in each paper, it was not always possible to assign works to a single experience. In those cases, papers were assigned to multiple themes. Specifically, six papers addressed three different human experiences (e.g. [162]), 90 targeted two (e.g. [185]), and the remaining 96 focused on a single experience. We provide a high-level overview of the experiences below. Detailed descriptions, including the number of papers addressing each experience and prototypical examples, can be found in Table 2. For readability, all targeted human experiences are in bold for the rest of this paper.

Perhaps unsurprisingly, the established concept of **Comfort** was one of the most targeted human experiences. **Emotional Experiences** and **Explorative** and/or Future and Speculative Experiences were similarly common. In the former, spaces aimed to elicit affective states, sentiments, and moods In **Explorative** and/or Future and Speculative Experiences, papers did not target a specific experience. These works often use design probes to test speculative ideas, presenting novel concepts to explore their impact on human experiences [58, 173]. One work captures the essence of this: *"The interpretation of that situation is left to the people who encounter the [system]"* [70], illustrating the open-ended nature of these explorations. Works also focused on **Bodily Experiences**, exploring how technology can create environments that adapt to and reflect users' physical presence and/or enhance their sense of bodily awareness.

Other experiences included users' **Sense of Place-making**. Here, technology was designed to encourage occupants' to create *places out of spaces* [78]. **Experiences of Relatedness** emphasise building a connection between people in a space, e.g. social presence or intimacy. **Democratic Experiences** were shaped by recent discussions in HCI about preserving and fostering democratic values within smart buildings [53]—this work amplifies inhabitant voices and highlights a shared impact on the space. **Inclusion Experiences** focus on environments in which users with diverse needs are taken care of; it is the outcome of accessible and inclusive design [141]. **Aesthetic Experiences** target sensory perception through manipulation of (largely) audiovisual features.

Fewer works explored **Learning and Teaching Experiences** which involves creating educational interactions, such as enhancing student-teacher engagement. Similarly, **Sense of Orientation** refers to experiences related to navigating and understanding one's position within the environment, including wayfinding. Figure 4 highlights a resurgence in comfort-focused research from 2017, influenced by HBI's introduction of comfort through a human-centred lens [5]. Figure 8 in the appendix provides an overview of research trends, beginning with Harrison and Dourish [78]'s work on *the roles of place and space.*

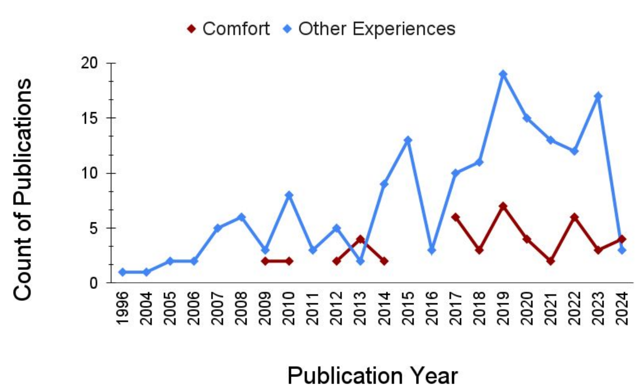

Figure 4: Research trends shows publications on comfort versus all other targeted human experiences.

Table 2: The 11 human experiences in smart buildings following the analysis of our charting table. We provide a name for the targeted experience and explain what we mean. We share the number of papers that were identified as targeting the experience with a few prototypical examples for each.

The Targeted Experience	Description	N	Prototypical Examples
Aesthetic Experience	Technological and aesthetic considerations transform atmospheres within smart built environments, resulting in specific experiences of their aesthetics. Departing from classical notions of beauty [37], this research emphasises the creation of sensory experiential qualities through the manipulation of sound, light, and space.	18	*InBloom* introduces a playful ambience using breathing elements and light-based interactions [101]. *Synesthesia* attempts to replicate the perceptual phenomenon of the same name, utilising touch and visual stimuli to create cross-sensory experiences to evoke a perception of body as one with the object [8].
Bodily Experience	The physical body's role in creating and sustaining experiences is fostered or enabled through the integration of technology. This research explores how physical movements and gestures such as touching, moving, or manipulating artifacts, as well as the body's presence, can both influence and be influenced by the surrounding environment [84].	23	The *SKIN* bodysuit translates wireless signals from the environment into vibro-tactile responses to change the perception of space around the body [167]. In the *Dress Room*, a responsive cube moves towards or away from the dancer's body to create intimacy as well as encourage the dancer to reflect on their motions and movement. [165].
Comfort	Occupant comfort, in its traditional sense, is defined by human perception across four environmental dimensions: thermal, visual, air quality, and acoustic [2]. In HCI, comfort is understood through users' decisions to adjust these dimensions—including the type of adjustment (e.g. increasing or decreasing) or choosing not to adjust—as well as the absence of discomfort [19].	47	The *ActuAir* Room Divider Display visualises real-time air quality data, raising occupant awareness of their surrounding environment [111]. The *PrisMe* tangible user interface aids users in understanding and managing surrounding sounds, enhancing their control over auditory experiences in the space [131].
Democratic Experience	Technology fosters a sense of community and democratic engagement by empowering users to shape their smart building environment [53]. Through physical and digital actions, users contribute to civic inclusivity, occupant privacy, and resilience by making decisions and engaging with those of others. This extends to building activism, where actions like comfort management allow users to collectively shape their surroundings in alignment with shared values.	16	*ThermoKiosk*'s voting device creates a sense of community by allowing users to voice concerns in automated workspaces and facilitating participation in building decision-making [47]. The *Exo Building* creates a similar experience through privacy and data control via an adaptive smart façades [149].
Explorative and/or Future and Speculative Experiences	Exploratory works that push the boundaries of what is possible in smart building environments. It is characterised by uncertainty and openness, where researchers and designers do not have predefined expectations of the experience but seek to discover how users engage with novel ideas, technologies, or spaces. For this, works employ speculative or futuring concepts or design probes, observing how they adapt, react, interact, and experience in unforeseen ways. Leveraging open-ended experimentation, this theme encourages users to explore and co-create future possibilities, revealing insights into how they might live in and experience smart environments yet to be fully imagined.	48	*WindowWall* examines users' future experiences of adaptive and smart windows as ubiquitous displays at home through speculative sessions followed by low-fidelity design probes [15]. The *Pendaphonics* project explores futuristic ways for using architecture for urban revitalisation, public engagement, expression, and performance [77]. By integrating a physical-digital-sonic pendulum into a public space, it invites visitors to interact with an installation that blends movement, sound, and digital interaction.
Emotional Experience	Exploring how spaces can support the emotional aspects of human experiences in smart buildings. Following Picard [136]'s definition of affect in HCI, emotion encompasses emotional states (e.g. valence and arousal), sentiments (e.g. positivity), and moods (e.g. discontentment). It includes bodily states when measured as physiological responses.	38	*LiveNature* integrates living walls and blooming mechanical flowers to evoke calming and restorative experiences [61]. The *Arup Sentiment Cocoon* displays collective emotions in workspaces for shared experiences to foster collective emotional responses [20].
Experience of Relatedness	Creating a sense of connection and belonging between individuals, whether co-located or remote, through technology [172]. For this, works try to support development of deeper emotional bonds, mutual understanding, and social support between occupants in the built environment.	21	*Ghosting* captures multi-modal social presence and casual interactions via lights and audio to create connectedness between remote users [77]. The *Hide and Seek Wallpaper* invites adults and children to build social bonds through play [83].
Inclusion Experience	Environments that are experienced as catering to the diverse cognitive, sensory, and physical needs of users, for example with particular attention to neuro-diversity (e.g. autism or ADHD) and sensory (mainly auditory and visual) impairments.	13	*NavTiles* explores tactile guiding surfaces for non-visual navigation for blind travellers [157]. *PLAYSCAPE* [1] and the *Magic Room* [69] create responsive environments that support therapeutic and social play for children with autism, to improve motor planning and social function.
Learning and Teaching Experience	The experiences resulting from interactions, activities, and environments that contribute to the educational and learning process within a smart building.	9	*The EvoRoom* is a rain-forest simulation utilising large-scale displays to foster collective inquiry among students and enhance teacher-student engagement [108].
Sense of Place-making	How smart building users experience places as meaningful through cultural, social, and sensory engagement. These experiences are facilitated by embodied experiences between people and their environment through technology [78].	23	The *Robotic Wall* changes spatial configurations based on users needs to instil a sense of meaning in the spatial arrangement [129]. *Within the Walls of York Gaol* utilised AR to connect visitors with the prison by experiencing stories of prisoners lives [18].
Sense of Orientation	Technology-enhanced methods that influence how people experience spatial orientation as part of navigation, including identifying landmarks, detecting surface-level changes, and wayfinding.	8	*Footsteps* uses projection-based displays to visualise peoples' historical presence to influence navigation in unfamiliar environments [6].

Table 3: The 10 primary design mechanisms in smart buildings. We provide a name for each design mechanism and explain its meaning. Additionally, we share the number of papers that employed the mechanism in their work, along with a few prototypical examples. Finally, we demonstrate the connection between the design mechanisms and the targeted human experiences by listing the top three most frequently appearing experiences for which the design mechanism was employed.

The Design Mechanism	Description	N	Prototypical Examples	Associated Targeted Experiences (n=3)
Community and Social Connection	Enhancing communal experiences in shared spaces by promoting socially motivated domestic practices (such as recalling events of the day during dinner), relationships, and collaboration among smart building occupants.	40	The Tableau Machine system was designed for spontaneous family bonding through abstract visualisations [138]. Ghosting supports distant interactions using lights and audio to enhance social presence at home [45].	Experience of Relatedness (n=18), Emotional Experiences (n=5), Comfort (n=5)
Spatial Design	The arrangement and manipulation of physical space to optimise functionality and facilitate spatial appropriation, where space becomes a medium for enabling interaction. This approach views space as a dynamic, relational entity, involving interactions between objects, bodies, and environmental elements [60].	34	Diffusive Geometries creates vapour-based walls as an alternative and flexible way of separating spaces [55]. Adaptive partitioning uses augmented reality to dynamically divide open-plan workspaces.	Explorative and/or Future and Speculative (n=13), Comfort (n=9), Sense of Place-making (n=9)
Technological Immersion	Utilising the immersive properties of technologies such as large ambient displays, VR, AR, and mixed reality (MR) to create simulated or technologically mediated experiences within the context of the smart building. These technologies envelop users in visual and/or auditory environments for simulating spaces or providing access to experiences that are otherwise unattainable in the physical building [154].	22	*The Magic Room* uses digitally enhanced physical materials and ambient embedded devices to create an interactive environment for gently stimulating primary school children [69]. *Live Building* uses virtual reality to study the design of large-scale, shape-changing interfaces [7].	Emotional Experiences (n=4), Explorative and/or Future and Speculative (n=4), Comfort (n=4)
Playful Design	The use of game-like interactions to transform everyday spaces into lively, engaging experiences, adding an element of surprise, discovery and unexpectedness to the smart building.	22	*Squeeze* and *MurMur Moderators* are chairs that enable playful re-discovery of family memories [135] or workplace communication [130].	Explorative and/or Future and Speculative (n=9), Sense of Place-making (n=7), Aesthetic Experiences (n=5)
Environmental and Social Information	Surfacing or augmenting data related to environmental conditions such as air quality and temperature or socially relevant information such as occupancy and movement. This design mechanism surfaces information that might otherwise be overlooked, helping occupants gain a deeper understanding and awareness of their surroundings.	21	*PrisMe Tangible Environment* helps users understand and manage surrounding sounds [131]. *Lumina* and *Cloud*, a kinetic canopy that responds to environmental changes [145].	Comfort (n=10), Explorative and/or Future and Speculative (n=5), Emotional Experiences (n=4)
Somaesthetic Design	The incorporation of the body and movement into the design of the smart building, where bodily interactions are both the mechanism and the ultimate experience. This approach priorities bodily awareness and sensory engagement, focusing on the body's sensations within the smart building space [85].	17	*Freequent Traveller* is a swinging hammock whose rhythmic movement inspires the notion of "wandering about" in the mind as well as physically from the motion [56]. *SonicTaiChi* promotes workplace restoration with sonic-guided bodily movements [92].	Bodily Experiences (n=14), Explorative and/or Future and Speculative (n=2), Sense of Place-making (n=1)
Participation and Co-design	Creating solutions from the users' perspective by actively involving them in shaping and influencing their environment. This mechanism covers both methods like participatory design and design elements that result in participation. This approach fosters a sense of ownership and empowerment through shared decision-making, resulting in environments that are aligned with the occupants' values.	17	*VoteBox* and *CoolDesk* are participatory devices for allowing users to voice their concerns for managing thermal environments [119]. The *Sensing Mobile App* supports comfort management by allowing users to share their preferences around comfort to building information systems [95].	Democratic Experiences (n=13), Comfort (n=3), Explorative and/or Future and Speculative (n=1)
Personalisation	Gathering and understanding the nature of users' subjective preferences and needs in (often shared and communal) indoor spaces across various contexts. The goal being that such occupants requirements and behaviours may be used to provide control over typically automated building features—such as lighting, temperature, and other environmental controls—to suit their individual preferences.	16	Interface characteristics of a shared lighting systems in office environments was evaluated for user experience in social settings [166]. Domestic energy interfaces were examined for how lower-income households personalise their environments and manage comfort [54].	Comfort (n=12), Explorative and/or Future and Speculative (n=2), Sense of Place-making (n=1)
N.A.	Works that do not explicitly apply or mention a specific design mechanism or discussed several at once, very broadly. The aim is to posit novel understandings or assess and critique current knowledge and technologies.	12	Works positing novel insights such as seminal works on Places and Spaces [78], and theoretical assessment of multi-sensory interactive space design for autistic children [151].	Explorative and/or Future and Speculative (n=6), Inclusion Experiences (n=2), Aesthetic Experiences (n=2)
Biophilic Design	This approach fosters occupants' connection with nature by integrating natural elements into the built environment, whether through direct connections, nature-inspired elements, or symbolic representations. It leverages the innate human affinity for life and living systems, incorporating them into smart buildings to enhances physical and emotional health [88].	9	*Interactive Window Display* is an intelligent screen system for viewing nature scenes in smart homes [171]. *Soft Oscillating LaLang*, *Blooming Dandelions*, and *Lotus-like Flowers* are soft robotic structures designed for capturing peoples' attention in public spaces [43].	Emotional Experiences (n=8), Bodily Experiences (n=1), Sense of Place-making (n=1)

4.3 Design Mechanisms For Smart Buildings

To understand the 11 targeted experiences, we analysed common design approaches aimed at creating them. We identified *20 design mechanisms* (italicised in the paper), listed in Figure 5. Our analysis found that that four papers addressed three different design mechanisms, 57 targeted two, and 131 focused on a single mechanism. Notably, 12 framing/vision papers did not specify any design mechanism and were marked as not applicable (*N.A.*). We focus here on the ten most frequently used design mechanisms described in detail in Table 3, with the number of associated papers, prototypical examples, and the most common associated human experience.

Our design mechanisms encompass methods, approaches, techniques, elements, and processes, individually or in combination. With no universal definition in existing literature, we inclusively categorised works across all types of design mechanisms. For example, *Biophilic Design* can include elements like vegetation [106], processes for integrating these elements into architecture [33], or innovative approaches such as organic user interfaces [127]. Papers like Chooi et al. [43] combine techniques (oscillating soft robotics), elements (flora-inspired design), and methods (symbiosis concepts)

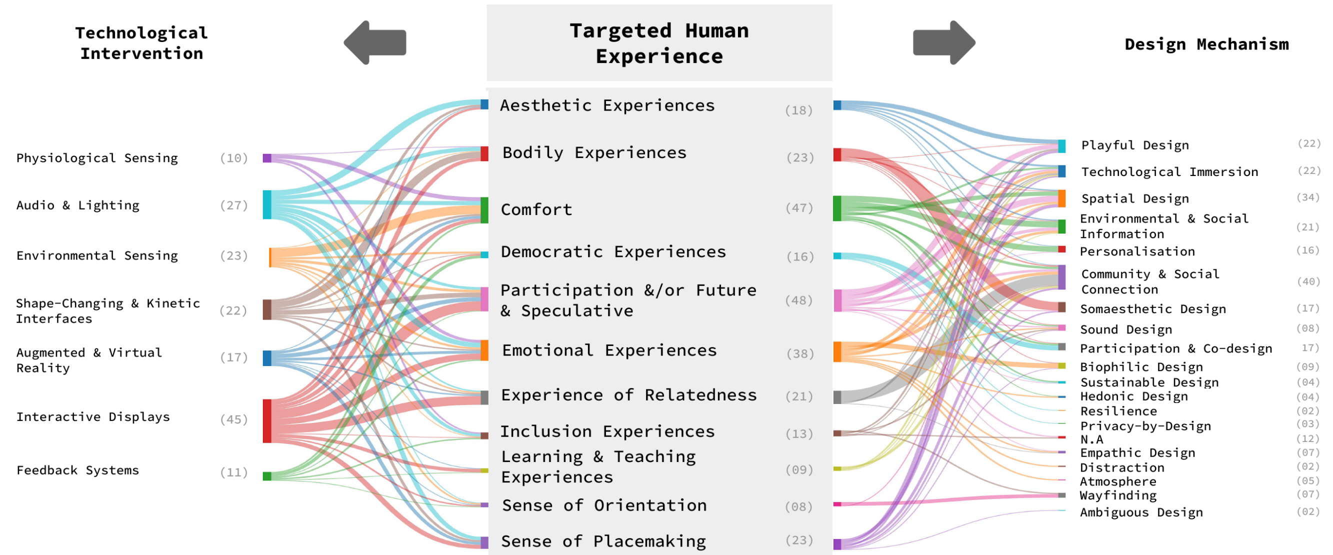

Figure 5: An overview of the targeted human experiences in smart buildings, along with their associated design mechanisms, and technological interventions. These human experiences, which are the primary focus of our scoping review, serve as the the starting point of this visualisation, linking to design mechanisms on one side and technological interventions on the other, enabled by human experiences. Figure A presents an unfolded version of this visualisation, separating the connections into two distinct plots: one illustrating the relationships between human experiences and design mechanisms, and the other between human experiences and technological interventions.

to foster nature connections. Our cataloguing promotes an inclusive understanding of how design mechanisms enhance human experiences in smart buildings[4].

A distinct pattern emerges: some mechanisms are versatile, supporting multiple experiences, while others are closely tied to specific ones. For instance, *Playful Design*, with elements like surprise [135] or storytelling [82], supports experiences such as **Explorative** and/or Future and Speculative, **Sense of Place-making**, and **Aesthetic Experiences**. Similarly, *Technological Immersion* spans diverse experiences. In contrast, mechanisms like *Community and Social Connection* focus on specific experiences, such as **Experiences of Relatedness**, fostering cultural identity [128]. *Somaesthetic Design* supports **Bodily Experiences**, emphasising human presence [178]. *Environmental and Social Information*, *Spatial Design*, and *Personalisation* enhance **Comfort** by allowing environmental adjustments [132]. *Biophilic Design* connects to **Emotional Experiences**, and *Participation and Co-design* promotes civic inclusion for **Democratic Experiences**.

The most common design mechanisms aside from *Community and Social Connection* were traditional architecture-related design mechanisms like *Spatial Design*, alongside mechanisms established and grounded in HCI such as *Technological Immersion*, *Playful Design*, the provision of *Environmental and Social Information*, and *Participation and Co-design*. This prevalence points to the position of smart building research between architecture and Interaction Design, which we discuss further in Section 5. Figure 5 illustrates the relationship between the targeted human experiences in smart buildings and the corresponding design mechanisms employed.

[4]The relationship between targeted human experiences and design mechanisms can be conceptualised similar to the distinction between "space" and "place", as articulated by Harrison and Dourish [78]. In this context, design mechanisms can be perceived as "opportunities" to create or shape the "understood reality" of targeted experiences.

4.4 Typologies of Technological Interventions in Smart Buildings

We analysed the technological interventions across all works in our scoping review, categorising them into seven types. Out of 192 papers, 153 incorporated technological interventions in their exploration of human experiences in smart buildings. The remaining 39 papers did not directly employ technological interventions but rather presented conceptual ideas and potential theoretical solutions. While design mechanisms offer strategies for creating or enabling meaningful experiences, technological interventions refer to the tools and systems used to implement these mechanisms in practice. In this section, we share the two typologies around technology that we developed. The first typology categorises the technological interventions discussed in the papers. Similar to the previous typologies on human experiences (Table 2) and design mechanisms (Table 3), these categories are illustrated with prototypical examples and the top three associated human experiences in Table 5 in the appendix. The second typology is based on Brand [28]'s shearing layers which describes distinct layers of a building based on its temporal lifespan [28].

4.4.1 Types of Technological Interventions. Audiovisual (and sometimes haptic) modalities were common interventions. *Interactive Displays* were the most frequent intervention type. Similarly, *Audio and Lighting* technologies used sound and light as primary technologies to introduce novel interactions and experiences [10]. To address comfort, *Environmental Sensing* was frequently combined with IoT-connected sensors to monitor environmental conditions [49]. Motors and actuators were combined with everyday materials (such as neoprene fabric [59]) in *Shape-changing and Kinetic Interfaces* to introduce dynamic-physical changes that allowed spaces to respond to user presence and activities. Next, *Augmented and Virtual Reality* (AR/VR) and *Physiological Sensing* interventions were primarily used for data collection on user responses to aspects of the smart building [11, 34]. AR/VR technologies are discussed as a technological intervention but are also a component of *Technological Immersion* design mechanism (Table 3). As a technological intervention, they serve as tools for simulating future smart spaces. In contrast, as part of the *Technological Immersion* design mechanism, they are one among various technologies (e.g. large displays) that enable immersive experiences. Finally, *Feedback Systems* enabled users to exchange information with the smart building, helping them understand and personalise their environment through data collection and participatory apps [121].

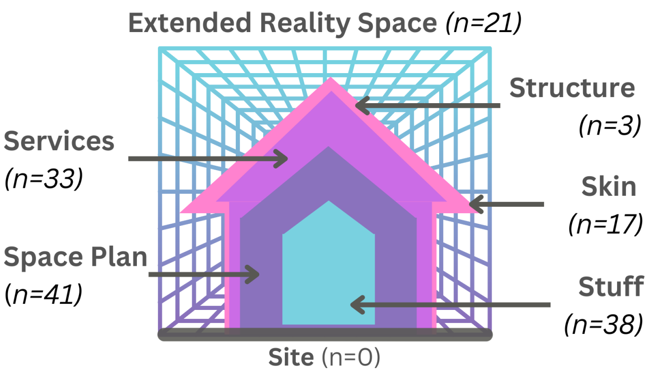

Figure 6: The smart building layers adopted from Brand [28]'s shearing layers. In our scoping review, we find the *Space Plan* to be the largest layer in contrast to the *Site* layer that has no interventions. We additionally define the *Extended Reality Space* layer to accommodate a new layer of temporality that represents the use of extended reality with smart buildings.

4.4.2 The Temporal Layers of the Smart Building. We also positioned technologies following Brand [28]'s "Shearing layers" (Figure 6). Brand describes six distinct layers of a building based on its temporal lifespan: *Site*, *Structure*, *Skin*, *Services*, *Space Plan*, and *Stuff* [28]. The majority of interventions were concentrated in the *Space Plan* (n = 41) and *Stuff* (n = 38) layers. This aligns with their transient and flexible nature, making them ideal for smart building technologies and prototypes that do not require major structural changes such as smart furniture, moving walls, and interactive floors. The *Services* layer (n = 33), traditionally encompassing HVAC, plumbing, and electrical systems, was reappropriated to include technologies related to occupant comfort: air quality, thermal conditions, lighting, and acoustics.

The *Skin* (n = 17) and *Structure* (n = 3) layers saw fewer interventions, reflecting their enduring and foundational nature. The *Skin* layer—encompassing façades and exteriors—is periodically updated, but less frequently than more adaptable layers. Interventions in the *Structure* layer, which includes foundations and load-bearing elements, are scarce due to the complexity and expense of altering these fundamental components. Unsurprisingly, smart building technologies tend to focus on layers that can be modified more easily, leaving structural changes largely to traditional architectural and engineering domains. There were no interventions categorised under the *Site* layer. This absence reflects that this layer, concerned with the building's geographical location and context, falls outside the immediate focus of smart building technologies. Urban HCI work often addresses connections to the site of the building [63], but such considerations extend beyond the scope of our review.

To accommodate works that extend physical space using augmented and virtual means, we introduced the *Extended Reality Space* (n = 21) layer. This addition reflects the growing importance of technologies that expand the physical confines of traditional building layers. Unlike traditional building layers bound by material lifespans, the *Extended Reality Space* operates independently of physical constraints. It introduces a dynamic layer to building temporality, where digital and virtual environments such as AR/VR can be updated or transformed almost instantaneously. It interacts with physical elements without altering them (apart from using devices like headsets necessary to perceive virtual content), providing temporal flexibility in which both temporary and permanent digital interventions coexist.

5 Discussion of Findings: Insights into Current Smart Building Research

We now discuss our findings to elicit higher-level understandings and implications. We wish to share messages that can inform research that seeks to design human experiences in smart buildings.

5.1 Beyond Comfort—The Diversity of Targeted Human Experiences in Smart Building Research

In our exploration of human experiences in smart buildings, we identified 11 distinct experiences around human experiences in smart building research. This reflects an evolving understanding of what it means to design a smart building and extends it substantially beyond the traditionally examined experience of comfort. For example, **Learning and Teaching Experiences** highlight the potential of smart buildings as educational tools that create interactive learning environments which support curiosity and innovation [108]. Although **Comfort** remains a major focus, it is often addressed through novel means such as *Personalisation* [139] and *Spatial Design* [129], as well as fostering *Community and Social Connections* [132] to target individual and collective well-being. This diversity of targeted human experiences beyond comfort sheds light on the major challenges and questions that need to be addressed for the development of the field. For example, what design methods must we develop or adopt to conceptualise emotionally-rich [140] or "somatic" environments [8]? How can we design for meaningful yet highly subjective **Inclusion Experiences** in smart buildings, catering to those with diverse sensory needs [1, 157]? The same question is valid for evaluation methods to assess the impact of technological interventions on these targeted human experiences.

5.2 Alignment with Trends in HCI

Our analysis reveals strong connections between human experience design in smart buildings and long-established HCI research, particularly in the use of *Community and Social Connection* as a key design measure for the **Experience of Relatedness** among occupants. Smart buildings can foster social connection between occupants through technologies like multimodal communication systems for remote users [77] and features that enhance co-located social bonding [128]. These works emphasise the potential of smart buildings to bridge physical and digital spaces, enhancing social connectedness across diverse contexts. However, several targeted experiences in smart buildings also align with some of the more recent and growing trends in HCI research and related fields, including **Bodily Experiences**, **Explorative** and/or Future and Speculative, and **Democratic Experiences**.

Bodily Experiences emphasise the role of multi-sensorial perception of the environment in shaping interactions within smart buildings, as well as mutual influences of the human body and spaces that can be studied and designed for, using methods of *Somaesthetic Design*. This builds on an architectural legacy in which the human body—its scale, directionality, proportionality, etc.—is the main source of inspiration and reference for spatial design [153]. We observe an alignment between the proliferation of works recognising the importance of bodily experiences in smart buildings with recent discourses and design instances surrounding Somaesthetic Design in HCI and IxD research.

Explorative and/or Future and Speculative Experiences captures a body of work that aims to (re-)define how people experience and re-experience home and public spaces in novel and previously un-imagined ways by deploying design probes [71] or speculative inquiry [66]. This experience is particularly relevant as it expands the concept of interaction beyond traditional interfaces, incorporating the *Spatial Design* of the smart building itself as a medium for digital engagement. It aligns with the evolving discourse on architectonic interaction, which involves "Interaction Design at the scale of architecture" and the "design of architectonic elements with interactive capabilities" [173]. As we increasingly occupy spaces with digital technologies, this concept becomes essential for exploring how these environments are created and experienced.

Finally, **Democratic Experiences** reflects recent efforts in HCI to cultivate and preserve democratic values within the context of smart buildings [53]. This work views smart buildings as civic spaces that foster dialogue between occupants and their environment, enabling greater user agency, participation, and control, while empowering users to actively shape their surroundings [53]. This theme builds on research in *Participation and co-design*, while situating itself within the relatively new domains of smart cities and civic technologies, and critical design as mechanisms in HCI for co-shaping interactive spaces through occupant involvement.

5.3 The Influences of Interaction Design and Architecture in Smart Building Research

Our findings suggest that smart building research has been shaped by both IxD and architecture, driving the field forward in three ways: (1) by re-appropriating concepts such as personalisation that draw heavily from the traditions of IxD [109], (2) by learning from space design principles rooted in the legacy of architecture [81], with a focus on the ability to "experiment" with how technology can introduce new forms of interactive experiences to our living spaces (e.g. through **Explorative** and/or Future and Speculative approaches [158]), and (3) by bringing together the two disciplines: while architecture provides the physical and cultural context, IxD enhances these spaces with interactive elements that foster connection and identity, e.g. enabling a **Sense of Placemaking** [8]. This fluidity between the two disciplines highlights the multidisciplinary nature of the smart building field which benefits from a collaborative approach to synthesising insights from multiple domains. By the same token, these observations raise important questions about what other knowledge could be transferred to smart building research. What concepts from other disciplines have yet to make their way into smart buildings? By exploring and opening new channels for interdisciplinary exchange, smart building research can continue to evolve, drawing on a broader range of ideas to shape the future of our smart buildings. For example, notions around digital rights (developed under the domain of digital philosophies [105]) in online spaces could offer opportunities to address the challenges of smart buildings, which may collect data both voluntarily and involuntarily from occupants. Specifically, data portability [105] could allow occupants to transfer their data preferences (e.g. lighting or temperature settings) between smart buildings, ensuring continuity and minimal data collection (as data gets collected once and re-used across different buildings [164]). Similarly, smart buildings could enable "guest modes" (similar to online browsing experiences) to minimise data collection, privacy zones where sensors are deactivated, or informed consent mechanisms alongside transparency dashboards to display building data usage policies [146].

5.4 The Integration of Artificial Intelligence in Human-Centred Smart Buildings

Despite the growing adoption of artificial intelligence (AI) and its emergent applications in smart building design—such as building resource management, building information modelling [52], and building security [73]—there is very limited to almost no integration of technologies like generative AI and large language models (LLMs) for designing human experiences in smart buildings. When AI is integrated with human interaction, it primarily focuses on creating responsive and personalised environments. The use of AI was noted in **Comfort** experiences [177, 181] and considered in **Emotional Experiences** [140]. Among the reviewed works, 14 utilised machine learning (ML) for example in tasks like adjusting temperature settings based on user behaviour [177] (comfort). Other examples where ML is used include Zhao et al. [181]'s *"Mediated Atmospheres"* or Andres et al. [10]'s *"System of a Sound"* transform environments by digitally controlling lighting, sound, and video projections, creating spaces that interact with human emotions.

In addition, some works consider (but do not implement) the role of AI in futuristic concepts (like empathic buildings [140]) that could adjust spaces to react to humans. For example, this extends to ideas like "curious agents" and "motivated agents" [118], which might support proactive problem-solving and adaptability within environments like "resilient hospitals" [161].

5.5 "Reactive" Retrofitted Design in Smart Buildings

Our analysis around the technological interventions in smart buildings (subsection 4.4) shows that the majority are concentrated in the *Space Plan* and *Stuff* layers [28], which are inherently more flexible and adaptable. The current distribution of technological interventions across the building layers thus reveals a reactive approach to interaction design in smart buildings. This late involvement raises questions about *how interaction designers can get involved earlier in the process of planning and design of future buildings?* Early involvement of designers offers the potential to integrate interactive systems directly into the building's fundamental layers, such as *Structure* and *Skin*, rather than retrofitting technology into more transient layers like *Space Plan* and *Stuff*. Designers, when included early, can employ iterative and participatory methods to ensure that the resulting smart buildings address the needs of occupants [4]. However, challenges remain in achieving the early involvement of designers. As observed by Verma et al. [168], the building design process is bound by rigid schedules and defined objectives, leaving little room for experimentation. According to Verma et al. [168], the tendency to finalise most design decisions before construction begins makes the integration of interaction design particularly challenging. Furthermore, the "siloed" nature of architecture, engineering, and technology disciplines complicates cross-disciplinary collaboration where construction timelines and budget constraints often favour established workflows, creating resistance to adopting iterative and participatory strategies [168]. While mindful of these challenges, there is potential in integrating smart building technology into the building structure from the outset, rather than being retrofitted into the more transient layers.

6 Discussion of Research Gap: What *Could* We Design for When We Design Smart Buildings

Our review identified 11 unique experiences and 20 distinct design mechanisms, reflecting the broad, experimental, and evolving nature of smart building research. While this diversity highlights a field still in its formative stages, the scattered approaches indicate an opportunity for consolidation and theory-building to provide clearer guidance. In the following, we point out research areas that we consider particularly relevant and promising for further development in the domain of smart building design.

More-Than-Human Perspectives in Smart Buildings. Our review did not find more-than-human perspectives in smart buildings. These perspectives challenge the traditional user-centred design by emphasising environments where human and non-human actors are examined collectively [51, 74, 170]. Within smart buildings, this could mean considering their environmental impact during human inhabitation as well as times of non-occupancy (e.g. during off-peak hours or after abandonment). A more-than-human perspective could guide technology to sustain relationships with non-human actors during these phases, by developing safety measures for local birds that may crash into building façades [23]. Furthermore, smart buildings could engage with local ecosystems by adopting *Biophilic Design* patterns, such as incorporating wildlife corridors to allow animal movement and reconnect fragmented habitats in urban areas [179]. *Empathic Design* mechanisms could foster a sense of ecological responsibility through the integration of "animalistically behaving" robotic components to enhance connections with local wildlife [75]. Smart building devices could actively "negotiate" climate levels in office rooms with occupants, prioritising environmental considerations [106].

Critically, more-than-human perspectives also raise ethical and practical questions. Who decides the "priorities" of non-human actors (such as the living bio-diversity in building ecosystems) in a building? How do we ensure that smart systems designed for ecological sensitivity do not inadvertently impose anthropocentric values onto non-human entities? These considerations highlight the need for interdisciplinary collaboration to integrate ecological, ethical, and technological insights into smart building design. More-than-human co-design has already become a part of smart city discourses, considering relationships between humans and non-human actors including plants, animals, insects, as well as soil, water, and other ecological features [62, 80]. Drawing inspiration from these strategies, co-design approaches could provide an opportunity to engage ecological stakeholders (e.g. conservationists, environmental scientists) alongside participants [80]. This could ensure that more-than-human perspectives are meaningfully integrated into the design and evaluation of smart buildings.

Comfort as a Bodily Experience. While somaesthetic approaches were observed in addressing **Emotional** and **Bodily Experiences**, **Comfort** continues to be predominantly defined by traditional metrics such as thermal and visual conditions, overlooking the embodied dimensions of how we experience the built environments we inhabit. The absence of *Somaesthetic Design* in **Comfort** studies indicates an opportunity to rethink comfort through the lens of "design with the body" [85]. This could involve designing smart buildings that account for not just environmental parameters, but also the ways in which bodily postures, movements, and somatic experiences contribute to a holistic well-being [40]. Incorporating somaesthetics into comfort raises questions about what it means to "live with our bodies" in smart buildings. This approach may even question the very foundations of comfort studies. For example, should building design create opportunities for (mild) discomfort—as a human natural state—to promote mindfulness through enhanced bodily awareness [163]? This would be in contrast to projects like SonicTaiChi which integrates pleasing sound and slow movement to promote restoration [92]. Instead, could we further explore smart architectural elements to intentionally induce acoustic discomfort to provoke the recognition of stress, not to alleviate stress temporarily, but to provoke awareness of its underlying causes, encouraging deeper self-reflection and the pursuit of long-term solutions? [163].

Social Justice and Activism. Beyond civic values, **Democratic Experiences** could be extended to include social justice themes such as feminism [122], racial justice [50], and activist design perspectives (such as anti-oppressive design [64]), that were notably limited. These omissions are striking, given ongoing discussions in HCI and technology design [44]. Feminist and activist lenses could be crucial for understanding how smart buildings can either reinforce or challenge power structures and inequalities [122]. For example, a feminist lens could question how personalisation features in smart buildings (e.g. temperature in shared office spaces) disproportionately impact gender relations [26]. Additionally, spatial design research highlights that **Sense of Orientation** differs across genders, i.e. a tendency to rely on mental maps and cardinal directions, as opposed to favouring route-based navigation using landmarks and sequential cues [125]. A feminist perspective could investigate how smart building features—such as adaptive wayfinding systems or customisable navigation aids—could support diverse cognitive strategies [48, 102].

Neurodiversity is another under-explored area in smart building design. Technologies could better accommodate sensory differences in individuals by incorporating features like adjustable lighting and soundscapes. For example, personalised smart lighting can benefit individuals with ADHD to retain attention and cognitive performance [16]. Similarly, adapting the design of wayfinding systems can lead individuals with autism on routes that avoid spaces with certain disturbing environmental features (e.g. sound or odours) [22]. Despite growing recognition, the effective implementation of neurodiverse considerations in smart building technologies remains an open challenge [16, 31, 103].

In the context of cultural activism, drawn from urban studies [35], smart buildings could serve as platforms for creative practices aimed at social and political change. Interactive art installations or adaptive architectural features could spotlight social injustices such as unequal access to housing or energy resources [107]. Smart buildings could also act as mediums for cultural activism by creating spaces that foster collective storytelling, resistance, or solidarity among communities. Through mechanisms such as *Playful Design* or *Community and Social Connections* [152], smart building design could support activist practices like hosting protests or interactive public events that raise awareness of societal inequities. Applying these perspectives could re-direct smart building research towards new design horizons shaped by principles of social justice [57].

Evaluating the Smart Building Experience. Through this scoping review, we observed a limited emphasis of papers on the evaluation of smart building experiences. This raises the question of whether new assessment frameworks, metrics, and methodologies are needed to be developed. Traditional metrics like objective comfort measurements do not fully capture the complexities of smart building interactions, especially as these environments become more immersive, interactive, and personalised. For instance, in the context of educational spaces, **Learning and Teaching Experiences** highlight the potential to create smart buildings that encourage collaboration, exploration, and knowledge-sharing [108]. However, evaluation of these experiences often relies on conventional measures, such as students' concentration [100]. This may overlook the impact of learning spaces on more complex experiences such as emotion [67, 68] and playfulness [38] that are recognised to affect learning. Therefore, additional metrics and new methods of evaluation are required that can account for the subjectivity and complexity of human interactive experiences in built environments.

At the same time, some of the targeted human experiences—such as **Bodily Experiences** or **Aesthetic Experiences**— require developing qualitative methods to evaluate technological interventions that are grounded in the knowledge of human psychological and physiological responses to environments (e.g. environmental psychology [24]). Currently, these experiences are captured in terms of descriptive qualities, such as the emotional resonance of a space, the sensory richness of an environment, or the harmony between occupants and their surroundings [56, 150]. While these qualitative methods can provide valuable insights into the lived and embodied aspects of smart buildings, the opportunity to combine them with physiological sensing and associated quantitative methods (e.g. [123]) has been largely overlooked. As a next step, future research should systematically review and map existing evaluation methods for assessing human experiences in smart buildings to provide a more accurate picture of existing methods and determine the need for new frameworks and approaches.

Anticipated Technological Integration in Smart Buildings. Current smart building technologies are primarily driven by sensors and actuators, with emerging technologies such as AI-enabled systems and extended reality yet to find a widespread practical application in built environments [124]. The incorporation of such technologies has however been discussed with caution and awareness around unintended consequences related to privacy, sustainability, and the risk of over-reliance on artificial environments at the expense of natural, sensory-rich experiences [124]. For example, while generative AI (genAI) offers possibilities for dynamic and adaptive environments, its substantial carbon footprint raises critical questions about sustainability [42]. With the building industry already contributing significantly to global emissions, combining these two areas requires careful consideration. While genAI may not be strictly necessary for many purposes, it is likely to be used by researchers and practitioners interested in experimenting with it. One promising avenue lies in leveraging more lightweight genAI models [116] for **Aesthetic Experiences**, which could enhance sensory engagement and atmosphere without having to hinge on data-intensive AI processes. By leveraging "scalable" environmental elements like light, sound, and spatial configurations [55, 90], lightweight genAI could support the creation of dynamic and enriching environments with a reduced ecological footprint. Adaptive lighting and soundscapes powered by such models could offer evolving atmospheres tailored to user preferences while minimising energy consumption [181]. Integrating **Aesthetic Experiences** with XR and lightweight genAI models could further enable novel forms of creative expression in smart buildings. These systems might craft immersive environments "prompted" by occupants based on their preferences to enable aspects such as creativity over purely functional or utilitarian goals in smart spaces [38].

7 Discussion of Limitations: Researcher Lens in Creation of Targeted Experiences and Design Mechanisms

We acknowledge that our work aligns with the third paradigm in HCI, making the research process interpretive and shaped by our individual and collective perspectives [79]. For instance, *Somaesthetic Design* and **Bodily Experiences** reflect the ongoing interests within the HCI community, while *Biophilic Design* might be influenced by the authors' interests in multi-sensory connections to nature in smart buildings. The creation of the **Explorative** and/or

Future and Speculative experience also draws from our background in architecture research and IxD, capturing how digital technologies transform physical spaces. Therefore, we acknowledge that our positionality as researchers in the fields of HCI and architecture influenced how we categorised and interpreted the material. Rather than offering definitive or universal insights, we present these findings as part of an ongoing discourse.

Some papers could have been understood as focused on health and care-giving (e.g. [87, 156]). We did not establish a distinct experience around this concept, recognising that these aspects are inherently embedded within the other experiences we identified. For instance, many works within **Emotional Experiences** and **Comfort** are predominantly underpinned by health and care-giving considerations [5, 183]. Mechanisms like *Community and Social Connection* and *Technological Immersion* also indirectly foster care by promoting socialisation and immersive health-related interactions. Researchers focused on these topics may choose to view our dataset through a different lens to explore care-giving more explicitly.

Our search keywords may also have impacted our overall set of works. To narrow our search, we included "interac*" to focus on human interaction. This may have inadvertently excluded studies from outside the HCI community that do not explicitly mention interaction, yet still address human experiences in smart buildings, although we found no direct evidence that this was the case. Finally, we categorised papers based on primary and overarching experiences that they targeted. Future research expanding our work to capture all experiences, i.e., including secondary and tangential ones, may uncover other targeted human experiences. Rather, this categorisation enabled us to elicit distinct features of the smart building research landscape and to conduct a deeper exploration of specific core experiences and accompanying design mechanisms.

8 Concluding Remarks and Future Direction

We were motivated to understand the key considerations and design goals that impact human experiences within smart buildings. To achieve this, we conducted a scoping review of 192 papers, adopting a hybrid inductive-deductive approach informed by thematic analysis coding techniques [30]. Through this process, we identified 11 distinct human experiences, 20 design mechanisms that shape these experiences, and a typology of the technological interventions through which they are implemented. Our research sheds light on how current smart building designs aim to address human experiences. However, this is only a partial view of the broader challenge [98]. While we have explored *what* we design for, a pressing question remains: what *should* we design for? Answering this question demands a broader conversation involving interdisciplinary collaboration, policy-making, and the inclusion of diverse voices. Moving forward, the challenge will be to create practical opportunities for smart building development underpinned by a design horizon that prioritises both the occupants and the broader societal visions.

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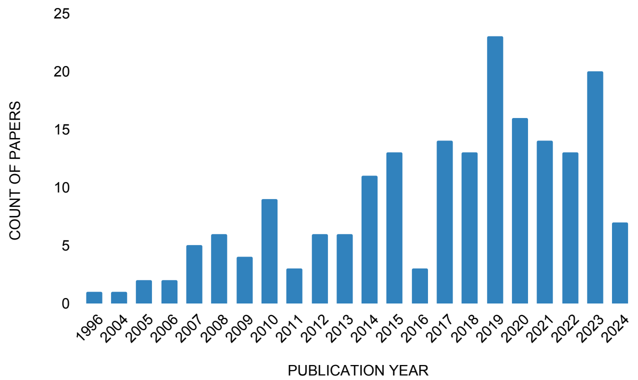
A Appendix

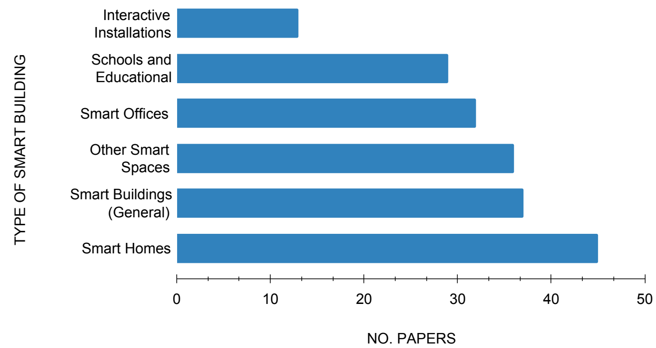
This section shows an example of our charting table with a filled example in Table 4, the general characteristics of the corpus papers in Figure 7. Table 5 provides an overview of the technological interventions, Figure 8 shows the detailed overview of the research trends, and finally Figure 9 shows the unfolded relationships between the three core findings from our scoping review.

Table 4: In addition to summary information (i.e., paper metadata), the following charting table template (column headers) shows the information that was extracted from the papers included in the analysis. An example entry shows the extracted (in quotations) and labelled information for a paper by Vallgårda [165].

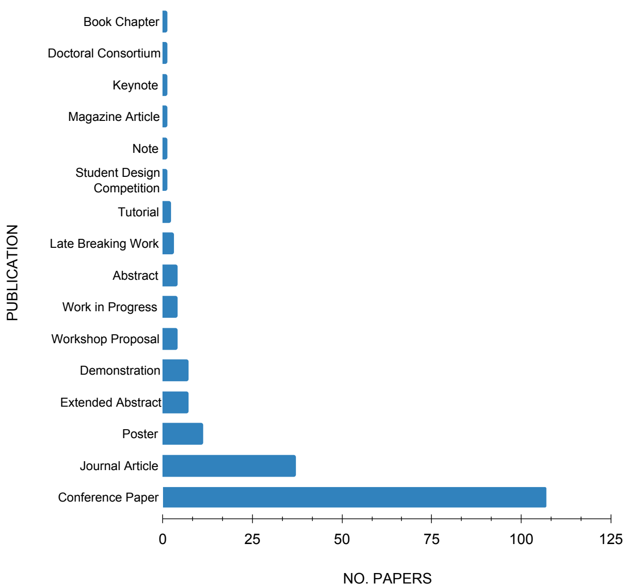
Research Motivations	Methodologies	Type of Smart Building	Interactive Technologies	Human Experience	Measures and Instruments	Visions for Future Research
“What does it entail to be embraced by a space that responds to your actions?”	Conceptual design and prototyping of a responsive space, using modern dance as a method to explore interaction qualities.	Interactive installation	The Dress Room - white cube that responds to the body movements over the floor	*“What does it entail to be embraced by a space that responds to your actions?”*	Sensors in the floor detecting body movements, Pneumatic pistons to move the walls, Arduino Mega boards for control" "White textile tent suspended within a steel frame	Future architectural spaces will incorporate responsive elements to enhance interaction and experience
“What kind of relations can we create between the active body and the active space?”				*“What kind of relations can we create between the active body and the active space?”*	*DANCE AS RESEARCH METHOD - Observations and interviews*	*“The Dress Room is a responsive space. It moves. It adapts. The floor senses where you are. The room responds. It follows you. It stops. It collapses then expands. You are enclosed. It is a dress you wear. Sometimes it fits, sometimes it misbehaves. It invites you to move. To explore. To dance. The Dress Room blurs the boundaries between architecture and clothes.”*
“What qualities does the responsivity have for creating certain experiences of a space?”				*“What qualities does the responsivity have for creating certain experiences of a space?”*		*“Thus, with the Dress Room as a simple responsive space explored through modern dance I have begun to outline some of the experiential qualities of being embraced by a space that responds to our bodily motions. My explorations have indicated that responsive spaces hold the potential to make us form a kind of symbiosis with the space they are in – that the temporal form of the space’s responsivity enables us to design for a sense of intimacy. They further indicated that our actions and the space’s responses become interchanged and while the body and the room moves together they are constantly motivated/actuated by one another. The mutual responses of the body and the space are integrated but not the same. They are in a cause-and-effect relationship that is constantly evolving.”*
“Through the Dress Room, I begin to explore the qualities of responsive spaces and embodied interaction.” *“Indeed, what I am interested in with this study is to explore the kind of relations we can create between the active body and the active space. I see explorations like this as a step towards understanding what experiences and new types of interaction these responsive spaces can foster”* *“What I want to explore here is the experience of the responsivity from a fully embodied interaction perspective. What experiential qualities does it have? What possibly new ways of inhabiting space it can encourage? What potential new types of interaction can we develop from this?”*				*“. This seems to indicate that exposing our body to an unfamiliar responsive environment may be a bit daunting at first it may be something we need to overcome.”* *“The Dress Room’s ability to motivate Nana to move towards certain areas of the space as well as to move her body in specific ways indicate that responsive spaces can have a significant qualities when it comes to motion motivation.”*		
				“Thus, with the Dress Room as a simple responsive space explored through modern dance I have begun to outline some of the experiential qualities of being embraced by a space that responds to our bodily motions. My explorations have indicated that responsive spaces hold the potential to make us form a kind of symbiosis with the space they are in – that the temporal form of the space’s responsivity enables us to design for a sense of intimacy. They further indicated that our actions and the space’s responses become interchanged and while the body and the room moves together they are constantly motivated/actuated by one another. The mutual responses of the body and the space are integrated but not the same. They are in a cause-and-effect relationship that is constantly evolving.” *“The Dress Room is a white cube that responds to the body’s movements over the floor. The walls move, the room collapses or expands.”* *“The outcome suggests that interacting with responsive environments can help create a sense of intimacy as well as motivate our motions within the space.”* *“The Dress Room is a white cube that responds to the body movements over the floor. It is made from a white square textile tent suspended within a steel frame measuring 5x5x5 meter. The suspension allows for the entire room to move more than half a meter in each direction. The sensors in the floor detect where a body is and the room responds either by moving with or away from that body depending on the setup.”* *“Through a dancer’s experiences we begin to understand what experiential qualities, and thus what possibilities for interaction design, this kind of responsiveness affords.”* *“The Dress Room was developed as an aesthetic exploration and is deliberately abstract in its expression. It has no function other than as a responsive enclosure.”* *“The Dress Room is an abstract installation made in an attempt to focus the experience around the responsivity. It is conceived as a space you take on like a dress.”* *“the Dress Room is about letting the white garment create a space in co-production with the movements of the body.”* *“First Type Responsive Form: The Room as a Dress We started out letting the room respond as a dress in the sense that the walls would follow the body within. The room follows you around. It makes you feel that you wear a room. You feel in Control. You belong together. You cannot escape – the door keeps evading you.”* *“Second Type of Responsive Form: The Vertical Response The second type of responsive form was designed to explore the vertical dimensions of the room. We had deliberately created the room with a high ceiling allowing us to collapse it without coming in contact with the person within”* *“Still, what does it mean to inhabit an abstract space like the Dress Room? It is abstract like art yet it demands more than an onlooker to be understood. It demands active participation. Thus, I have chosen a method that meets this space at its level of abstraction while still enabling active bodily engagement. I have chosen to use modern dance performed by a professional dancer whose experiences I have sought to understand through observations and interviews.”* *“Overall Nana described the Dress Room as a constant source of inspiration. She explained that even when she repeated a series of movements within the same responsive form and the response from the pistons was the same the fabric would ripple differently each time creating an overall unique expression.”* *“She explained that after a while she ceased to focus on how her actions influenced specific responses, and instead she eased into a dance where her motions became responses as well as actuators.”* *“Lastly, Nana explained while demonstrating through body language how certain responses in the Dress Room would inspire her to do certain movements.”* *“The two experiential qualities that Nana experienced in the responsive room can be articulated as intimacy and motivated motion.”* *“With the Dress Room, I sat out to explore embodied interaction with responsive spaces.”* *“Thus, with the Dress Room as a simple responsive space explored through modern dance I have begun to outline some of the experiential qualities of being embraced by a space that responds to our bodily motions. My explorations have indicated that responsive spaces hold the potential to make us form a kind of symbiosis with the space they are in – that the temporal form of the space’s responsivity enables us to design for a sense of intimacy. They further indicated that our actions and the space’s responses become interchanged and while the body and the room moves together they are constantly motivated/actuated by one another. The mutual responses of the body and the space are integrated but not the same. They are in a cause-and-effect relationship that is constantly evolving.”*		



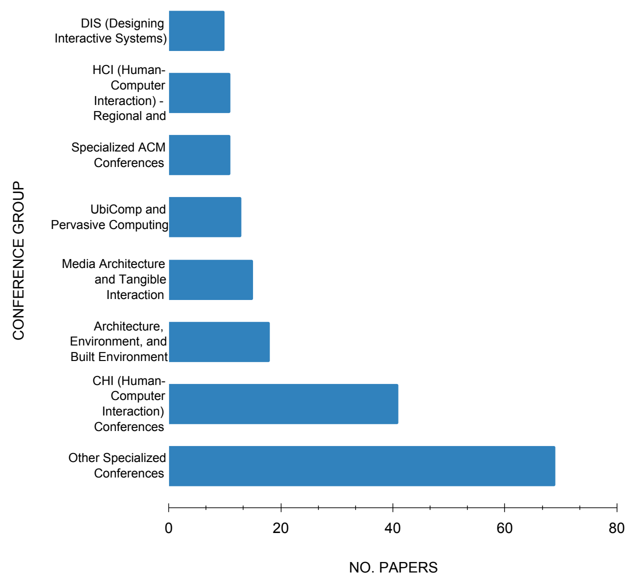
(a) Papers by Publication Years.



(b) Papers by Type of Smart Building.



(c) Papers by Type of Publication.



(d) Papers by Publication Venue.

Figure 7: An overview of the characteristics of the papers included in our scoping review: (a) Distribution of papers in our scoping review grouped by publication year, including partial data for 2024. We included papers that were published in 2024 until June of the same year, while we charted the data. (b) The various types of spaces addressed by papers in our scoping review. (c) Papers grouped by the type of publication. (d) Distribution of papers in our scoping review grouped by the venue they were published at.

Table 5: A typology of technological interventions in smart buildings. We provide a name and explanation for each technological intervention. Additionally, we share the number of papers that employed the intervention in their work, along with a few prototypical examples. Finally, we demonstrate the connection between the interventions and the targeted human experiences by listing the top three most frequently appearing experiences for which the intervention was employed.

Type of Intervention	Description	N	Prototypical Examples	Associated Targeted Experiences (n=3)
Audio and Lighting	Sound and light as key design materials, often synchronised to evoke emotional responses, guide behaviour, or modify spatial perception, creating multi-sensory and immersive environments.	27	Mediated Atmospheres is a modular workspace using lighting, video projection, and sound to transform the appearance of the workspace, tested with 33 participants to collect subjective and objective measures [142]. Trivet Fields uses mini-speakers to create soundscapes to aesthetically delineate space [93].	Aesthetic Experiences (n=8), Emotional Experiences (n=7), Comfort (n=6)
Augmented and Virtual Reality	Provided immersive experiences blending physical and digital spaces, enhancing spatial awareness and interaction in novel ways.	17	Weightless Walls uses user positions and noise-cancelling headphones to display virtual walls to create auditory privacy in office environments [159]. An immersive and interactive methodology using physiological indicators is developed to assess comfort and performance in work offices [148]. VR Living Rooms use virtual reality simulations of indoor environments to measure psychological responses and affective states [160].	Explorative and/or Future and Speculative (n=6), Sense of Place-making (n=4), Emotional Experiences (n=4)
Environmental Sensing	Utilises IoT-connected sensors to monitor environmental conditions-temperature, light, air quality, and noise, either adjusting parameters automatically or providing real-time information to enhance interaction with space.	23	Environmental sensors were deployed to measure temperature, humidity, and light, with data visualised for occupants and building managers [46]. Hilo-box uses CO2 sensors and machine learning to forecast indoor air quality during office meetings [184].	Comfort (n=13), Democratic Experiences (n=5), Explorative and/or Future and Speculative (n=4)
Feedback Systems	Included participatory sensing mobile apps that empowered users to design and adjust their environments through data collection and feedback, fostering personalisation and responsiveness. Also giving users cues around the building to ease tasks like navigation.	11	Follow-the-Lights uses ambient lighting, pressure mats, and abstract visualisations to influence stair and elevator usage through behavioural cues [144]. A building Twitter bot for engaging with building occupants around their preferences and experiences [120].	Emotional Experiences (n=2), Democratic Experiences (n=2), Inclusion Experiences (n=2)
Interactive Displays	Integrated with RGB and depth cameras, motion tracking, and 3D simulations, these displays adapt to user interactions, creating dynamic and responsive environments in both residential and public spaces.	45	Interactive window display uses large screens, RGB and depth cameras, and temperature sensors to display context-related scenery [171]. WaveWindow uses projectors, microphones, and cameras for users to interact with digital content on an interactive retail window display [134].	Explorative and/or Future and Speculative (n=14), Experience of Relatedness (n=13), Emotional Experiences (n=9)
Physiological Sensing	Used biofeedback devices and wearables to monitor bodily responses, with some interventions adapting environmental conditions in real-time based on physiological data.	10	Data such as Electroencephalography (EEG), heart rate, skin conductance, and pulse volume measurements were used to understand neurophysiological responses towards smart home systems [11].	Comfort (n=6), Emotional Experiences (n=4), Inclusion Experiences (n=2)
Shape-Changing and Kinetic Interfaces	Introduced dynamic physical changes in environments through adaptive furniture and walls that respond to user presence and activities, enabling real-time adaptation of spaces.	22	TidalSpace is a design concept that creates an interactive spatial boundary for work-from-home parents [89]. The Shape-changing work desk uses digital tabletops and motion tracking to enable proxemic transitions in informal meetings [76].	Bodily Experiences (n=9), Explorative and/or Future and Speculative (n=7), Sense of Place-making (n=3)

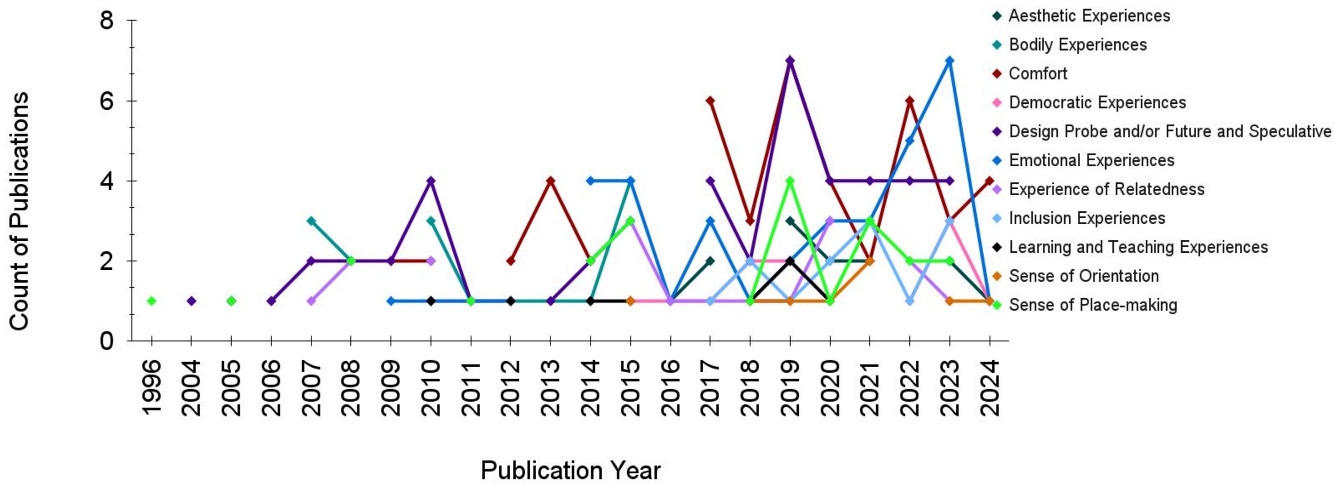
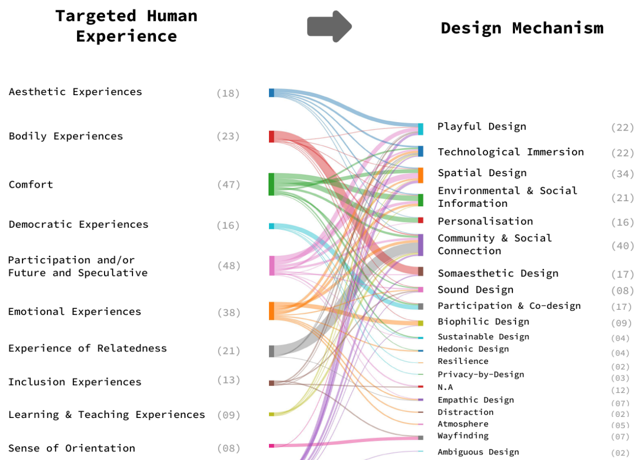
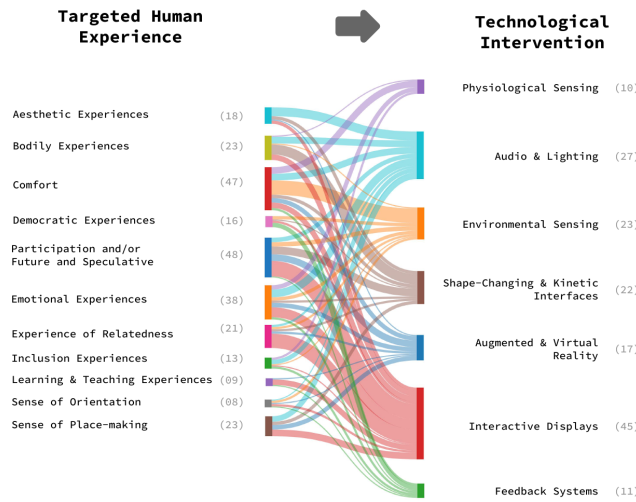


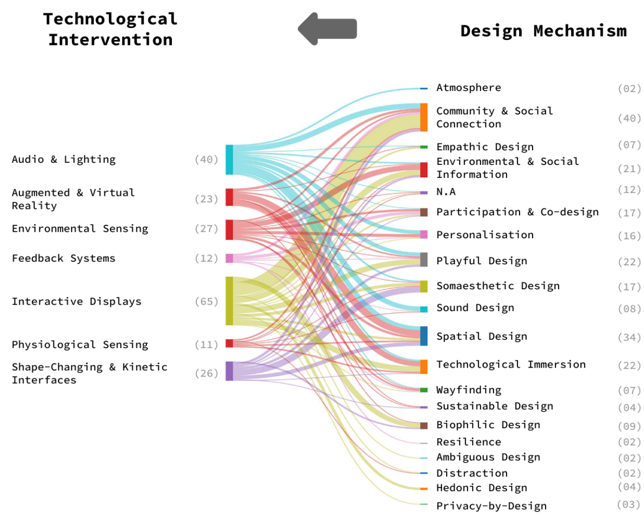
Figure 8: Research trends shows all publications targeting human experiences in smart buildings over time.



(a) Human experiences and the associated design mechanisms.



(b) Human experiences and the employed technological interventions.



(c) Technological interventions and the associated design mechanisms.

Figure 9: An unfolded representation of Figure 7 in subsection 4.3 that shows (a) the relationship between human experiences in smart buildings and the associated design mechanisms, (b) relationship between human experiences in smart buildings and the employed technological interventions, and (c) the relationship between the technological interventions designed or developed for the associated design mechanisms. The numbers in round brackets indicate the number of associated papers in this review.