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Article

Challenges of Integrating Assistive Technologies and Robots with Embodied Intelligence in the Homes of Older People Living with Frailty

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Abstract

The rapid increase in the global population of older adults presents a significant challenge, but also a unique opportunity to leverage technological advancements for promoting independent living and well-being. This study introduces the CIREI framework, which is a comprehensive model designed to enhance the integration of smart home and assistive technologies specifically for pre-frail older adults. Developed through a systematic literature review and innovative and comprehensive co-design activities, the CIREI framework captures the nuanced needs, preferences, and challenges faced by older adults, caregivers, and experts. Key findings from the co-design workshop highlight critical factors such as usability, privacy, and personalised learning preferences, which directly influence technology adoption. These insights informed the creation of an intelligent middleware prototype named WISE-WARE, which seamlessly integrates commercial off-the-shelf (COTS) devices to support health management and improve the quality of life for older adults. The CIREI framework's adaptability ensures it can be extended and refined to meet the ever-changing needs of the ageing population, providing a robust foundation for future research and development in user-centred technology design. All workshop materials, including tools and methodologies, are made available to encourage the further exploration and adaptation of the CIREI framework, ensuring its relevance and effectiveness in the dynamic landscape of ageing and technology. This research contributes significantly to the discourse on ageing in place, digital inclusion, and the role of technology in empowering older adults to maintain independence.

Keywords: gerontology; smart homes; geriatrics; assistive technologies; middleware; innovation management; user-centred design; digital transformation; technology-enabled care

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1. Introduction

The proportion of the older adult population is experiencing a marked increase, a trend underscored by comprehensive data from the United Nations World Population Prospects (UNWPP) [1]. As demographics shift towards an ageing population, understanding and addressing the challenges associated with ageing becomes paramount for ensuring the well-being and independence of older adults. One significant aspect of ageing is the phenomenon of frailty, where various faculties tend to deteriorate, impacting overall health and resilience [2,3].

Frailty is a multifaceted and dynamic condition marked by declines in reserve and function across various physiological systems, making it difficult to cope with both every day and acute stressors [4]. Frailty significantly impacts daily life by increasing vulnerability to various health issues such as hospitalisation, infections, disability, and falls, leading to a reduced quality of life due to physical and cognitive decline. It also results in higher healthcare costs and can cause loneliness, further exacerbating the condition by contributing to issues such as a more sedentary lifestyle [5] and persistent loneliness [6,7]. Overall, frailty diminishes functional capacity and independence, making everyday tasks more challenging for those affected [8].

Pre-frailty refers to a state where individuals show one or two signs of physical decline, such as unintentional weight loss or reduced muscle strength, but are not yet fully classified as frail due to the absence of additional deficits [9]. Unlike frailty, which is characterised by multiple accumulated losses in physical function and often leads to significant disability or even death, pre-frailty represents an earlier stage where interventions may be more effective at slowing down or reversing further deterioration. While pre-frail individuals are still generally able to perform daily activities independently, they face a higher risk of becoming frail if no preventative measures are taken. This makes it crucial for public health campaigns and early intervention strategies to target this phase, as it offers an opportunity to improve outcomes before the condition progresses further [10].

The prevalence of pre-frailty is substantial within the older adult population, generally ranging from 35% to 50% among community-dwelling individuals aged 65 or older [10]. In Germany, a systematic review found the pooled prevalence of pre-frailty to be 40.2% (95% CI: 28.3% to 52.1%), a prevalence that increased with age [11]. Notably, among older caregivers of older adults, the prevalence of pre-frailty was found to be as high as 58.8% [12]. Working with individuals living with pre-frailty is critical because it offers a significant opportunity for timely interventions that can improve health outcomes, reduce hospitalisations, and potentially delay or even reverse progression to full frailty and disability.

Frailty not only poses challenges to individual health but also places stress on care systems, conflicting with the prevailing desire of older adults to live independently for as long as possible [13]. Recognising the implications of frailty on independent living, this paper explores the intersection of frailty mitigation and the potential of smart and assistive living environments in supporting well-being. By leveraging smart home and assistive technologies, a unified framework can be established to align resident needs with connected, intelligent systems within the home, as both a physical and lived environment [14], thereby supporting greater independence and enhancing overall well-being [15].

The accessibility of technology plays a significant role in enhancing the quality of life for older adults. This is evident through the application of various technologies, including humanoid robots, mental stimulation robots, virtual reality, wearable bladder scanners, and smart health video consultations. These advancements can demonstrably improve the well-being of older adults residing in independent living environments, nursing homes, daycare centres, and public hospitals, while also offering considerable benefits to their caregivers [16].

For instance, during the COVID-19 pandemic, digital technology played a crucial role in mitigating the negative consequences of social isolation and limited access to routine health and social care services for older adults [17]. Bridging the digital divide through digital inclusion initiatives directly impacts the quality of life for older adults. These initiatives promote social integration and contribute to an overall improvement in their well-being [18]. However, the progress of assistive technology, particularly smart home tech, is impeded by cost pressure, lack of interoperability, vendor lock-in, accessibility challenges, complexity in usage and maintenance, and limited functionalities [19].

Several factors shape how readily older adults embrace new technologies, including sociodemographic characteristics (age, education, income), cognitive abilities (memory, processing speed), attitudinal aspects (beliefs about technology's usefulness), emotional responses (comfort level, anxiety), and environmental considerations (accessibility features, home layout, and technology adoption by landlords who own and rent independent environments) [20–22]. Overcoming these limitations requires a comprehensive approach that also addresses the fragmented nature of existing commercial off-the-shelf (COTS) devices [23]. Furthermore, the data generated by these devices hold immense potential for monitoring and supporting individuals that are vulnerable to frailty [24]. However, while middleware solutions exist in larger-scale contexts, their applicability to home users remains limited [25].

This paper draws on demographic trends, frailty research, and technological challenges to propose a comprehensive framework for leveraging smart home technologies. This framework aims to mitigate frailty and enhance independent living among older adults. By exploring the integration of smart and assistive technologies, we contribute to the discussion on optimising living environments for the well-being and independence of the ageing population.

Building on a review of existing literature on assistive technology adoption by older adults, the study utilises co-design activities to understand their needs and concerns. These activities engage older adults in articulating their preferences and apprehensions regarding the use of assistive and robotic devices in their homes. Insights from these sessions are to inform the development of a more comprehensive model that addresses the key themes and concerns identified by participants.

The presented systematic literature review provides a foundational theoretical understanding by identifying existing factors influencing technology acceptance, while the co-design activities gather rich, nuanced and user-oriented data to fill the gaps left by generic models. Ultimately, this research strives to create a middleware solution that seamlessly integrates COTS devices, enhancing health management capabilities and facilitating the prediction and prevention of health issues.

The following research questions delve into the perceptions of older adults, caregivers, and technicians regarding the challenges of integrating smart home assistive technology, addressing design and implementation decisions, and understanding the learning preferences of older adults for technology adoption.

R1a: How do older adults, along with caregivers and technicians in independent living communities, perceive the challenges associated with integrating COTS smart home assistive technology and robotics into their homes to enhance quality of life and mitigate frailty?

R1b: Considering the challenges identified in R1a, how can we design and implement assistive technology that can be easily retrofitted into existing homes to better suit the needs of older adults, caregivers, and technicians who work in independent living communities?

R2a: What are the learning preferences of older adults in independent living communities for becoming comfortable with new (smart) technology, especially smart home assistive technology and robotics?

R2b: How do these preferences impact the design and implementation of assistive technologies, including educational mechanisms like chatbots, to enhance technology adoption and ultimately improve quality of life?

To answer these research questions, we designed several qualitative and quantitative instruments, followed by thematic analysis to identify recurring themes in their perceptions, allowing us to understand the key barriers to adoption and how their preferences would impact the design and implementation of assistive technologies.

To ensure the robustness of our findings, we conducted this research using a diverse sample primarily consisting of individuals aged 55 years or older who have been identified by their caregivers as "managing well" on the Rockwood Frailty Scale and as requiring assistive technology support due to age-related health conditions. The participants were recruited from Johnnie Johnson (JJ) schemes in the South Yorkshire area over six months.

This paper presents a multi-phased investigation into the design of assistive technologies for older adults living independently. Section 2 details a systematic review conducted using the widely recognised Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, which informs the thematic analysis of its results, which are presented in Section 3. Building on this foundation, Section 4 describes the research instruments and methods employed in a co-design workshop. Section 5 then shares the workshop results alongside a thorough analysis. Finally, Section 6 engages in a critical discussion of how these findings can influence design decisions for assistive technologies and robotics aimed at supporting older adult independence within their homes.

2. Systematic Review Methodology

To comprehensively identify and analyse relevant literature on the barriers to acceptance and adoption of assistive technologies among older adults, a systematic review methodology guided by the PRISMA framework was employed [26]. The search strategy utilised a combination of carefully selected keywords and their synonyms to capture the key aspects of our research question. Inclusion and exclusion criteria were meticulously defined to ensure the selection of pertinent studies. Extracted data underwent a rigorous coding process using a predefined coding structure to categorise factors influencing technology acceptance in this population. Following a thematic analysis, these factors were then systematically reviewed and consolidated into a final framework.

2.1. Literature Review Search Process

To gain a comprehensive understanding of factors influencing the acceptance of robotics and assistive technologies among people living with frailty (PwF), a systematic literature review was meticulously conducted. This review employed a comprehensive search strategy utilising leading academic databases, including Scopus, PubMed, and Web of Science. The search strategy focused on peer-reviewed scholarly articles published within the five years preceding the review, including all literature available up to October 2023. This cut-off point was intentionally selected to allow sufficient time for the thorough analysis and synthesis of relevant findings prior to the co-design workshop and associated activities, which took place on 20 November 2023. Establishing this timeline ensured that the most current and influential research could inform the development of workshop materials and design decisions, while maintaining a practical window for evidence integration and preparatory planning.

To ensure a comprehensive search and capture of relevant literature, a strategic approach was employed for keyword selection. Logical operators were meticulously applied across a combination of pertinent keywords and their synonyms (detailed in Table 1). This approach aimed to maximise the identification of relevant studies. Figure 1 visually presents the bibliographic landscape of the included articles at this stage, providing a comprehensive overview of the scholarly field under investigation.

Table 1. Search terms and synonyms used in systematic literature review.

Keyword	Synonyms and Related Words
Older People	Old [er], Elder [ly], Senior, Age [ing], Geriatric
Technology	Assistive, Care, Nursing, Digital, Automation, Home Management, Smart Home, Aid, Inclusive, Support
Acceptance	Challenge, Limit, Barrier, Access, Concern, Obstacle, Issue, Inhibit, Constraint, Restriction, Adopt, Embrace, Impede, Integrate, Accept, Infuse

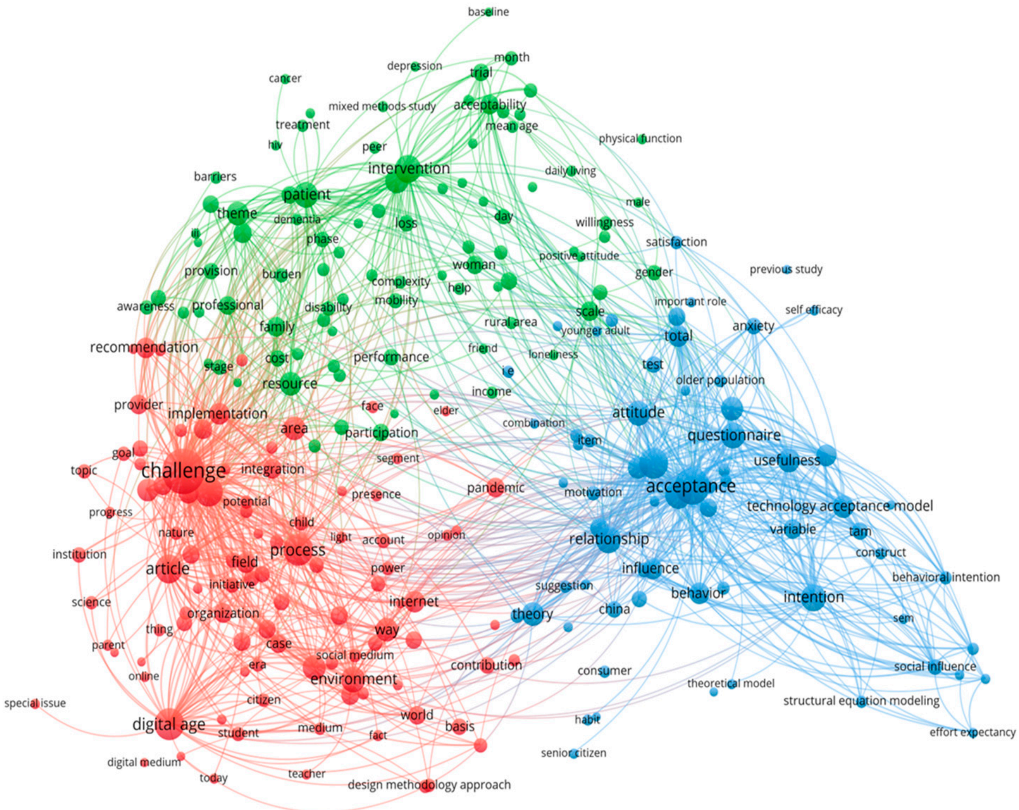


Figure 1. Bibliometric network visualisation of included literature.

Transparency and reproducibility are ensured by sharing the exact search strings used for each database in Appendix E. Searches were conducted within the title field, with syntax customised for each platform using appropriate operators, wildcards, and field-specific selectors, in accordance with the established protocol. Where necessary, additional metadata filters were either embedded within the queries or applied through the database's interface.

To analyse the thematic structure of the literature systematically, we performed a co-word analysis using VOSviewer v1.6.20, utilising the co-word analysis bibliometric method that examines term co-occurrence patterns. Titles and abstracts from the included studies formed the text corpus, with the visualisation optimised for legibility by displaying the top 25 most frequent terms and enlarging node labels. The analysis revealed three key clusters: Cluster 1 (*challenge*, *opportunity*, *digital age*) reflected contextual and structural influences on technology adoption; Cluster 2 (*intervention*, *outcome*, *patient*, *caregiver*) mapped to practical healthcare applications; and Cluster 3 (*acceptance*, *intention*, *usefulness*, *technology acceptance model*) aligned with user perception and theoretical frameworks. These clusters quantitatively validated and extended our narrative synthesis, highlighting underrepresented connections, such as the co-occurrence of caregiver and digital age, that merited deeper exploration.

The findings directly informed our co-design workshop by shaping discussion themes around the literature's dominant patterns. For instance, Cluster 1's focus on external influences prompted dialogue around systemic barriers, while Cluster 3's emphasis on behavioural drivers guided activities targeting user acceptance. By explicitly linking clusters to review themes (e.g., Cluster 2 to healthcare implementation), this method provided a data-driven perspective that complemented traditional synthesis.

Following the initial search, a rigorous three-stage screening process was implemented to refine the 1126 identified articles. Three researchers independently assessed the articles against predefined inclusion criteria (detailed in Table 2). These criteria ensured the selection of relevant studies by focusing on (1) peer-reviewed articles addressing technology acceptance among older adults, (2) empirical or theoretical studies conducted within domestic settings, and (3) studies with participants classified as pre-frail (scoring less than four on the Rockwood Frailty Scale [27]).

Table 2. Inclusion and exclusion criteria applied in systematic literature review.

	Description of the Inclusion Criterion
1	Must be peer-reviewed articles published in journals or edited collections with a rigorous editorial process.
2	Empirical studies must involve human participants, where participants are either older adults themselves or individuals directly involved in their care (e.g., family caregivers, medical professionals, gerontechnology developers).
3	Theoretical studies must focus on improving the well-being or independence of older adults.
4	Must focus on the influential factors in older adults' acceptance and usage of technology, with a specific emphasis on either technologies that support ageing in place or technologies that assist caregivers of older adults.
5	Must focus on a specific technology domain relevant to older adults, including but not limited to assistive technology and/or robotics, the Internet of Things (IoT), or eHealth services.
6	Must focus on technology adoption and usage within the context of older adults' homes, excluding studies conducted in rehabilitation centres, hospitals, nursing homes, etc.
7	Must involve participants classified as frail, with a majority (or all participants in studies with homogenous samples) scoring less than or equal to 4 on the Rockwood Frailty Scale.
8	Must be published in English or a translated version in English.

Notably, the inclusion criteria stipulated that the studies be composed in English to ensure linguistic coherence and accessibility within the review process. Figure 2 delineates the entire flow of the systematic literature review process, meticulously adhering to PRISMA guidelines and provides a clear and structured overview of the sequential steps involved in the review.

Following the initial deduplication process using DOI (Digital Object Identifiers), the number of articles was reduced from 1126 to 920 articles. Next, a two-stage screening process was implemented. Titles and abstracts were independently screened by three researchers against the predefined inclusion criteria. Disagreements were resolved through discussion to reach a consensus on inclusion. This process yielded 138 articles for full-text review. Finally, a full-text review using the same criteria resulted in the selection of 63 articles for final inclusion in this review.

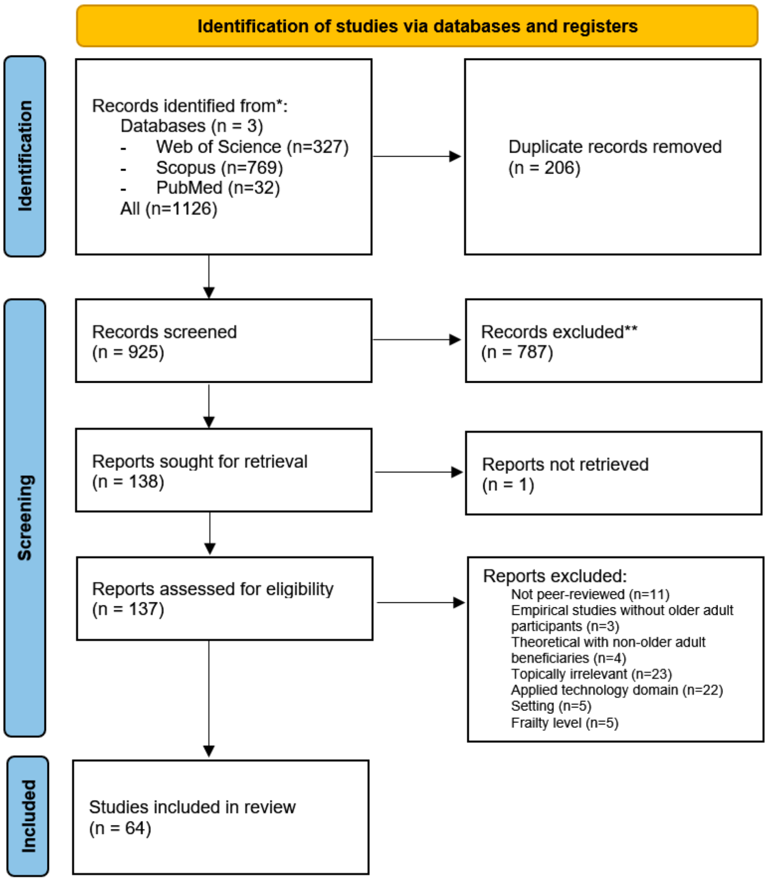


Figure 2. PRISMA flow diagram of systematic literature review process. (*) Records identified from each database are individually reported within the diagram, in addition to the total of all three. (**) As no automation tools were used in the screening process, all records were screened by human reviewers.

2.2. Coding Structure

In our systematic review, we adopted a nuanced coding structure for a meticulous dissection of the extracted data, targeting both quantitative and qualitative insights from the studies under review. This approach is centred on identifying barriers and facilitators to the adoption of assistive technologies by older adults, with a keen focus on enhancing the precision and granularity of our analysis.

The coding framework encompasses numerical features such as the Year of Publication, to monitor trends over time; Total Sample Size, to gauge the scope and potential influence of the study's findings; Gender Distribution, to assess demographic diversity and inclusiveness; and Mean Age of Sample, to ensure the study's relevance to the target population of older adults.

On the categorical front, the structure differentiates between theoretical studies, which are subdivided into reviews or conceptual analyses, and empirical research, categorised by methodology as quantitative, qualitative, or mixed methods. It also identifies the specific domain of assistive technology being studied, such as robotics, smart home technologies, or eHealth services, and lists the specific acceptance factors measured, including usability, accessibility, affordability, and perceived utility. These factors are then organised into broader categories like psychological, social, economic, and technical for thematic analysis.

This meticulously refined coding strategy not only enhances the specificity and detail of our data extraction process but also aligns with our thematic analysis objectives. By systematically categorising the extracted data, we aim to construct a comprehensive framework that vividly captures the multifaceted barriers and facilitators affecting older adults' adoption of assistive technologies. This groundwork is pivotal for our systematic review and meta-analysis, providing a richer understanding of the current research landscape and spotlighting gaps for future investigation.

2.3. Distribution of Papers Across Codes

Our comprehensive analysis of the distribution of papers across different themes reveals significant trends that are summarised below. We reviewed a total of 64 primary sources, among which 46 were empirical studies that involved the collection and analysis of data. Additionally, 48 of these sources explicitly identified and listed their acceptance factors, providing clear insights into the criteria considered important in their respective studies. This breakdown highlights the emphasis we placed on empirical evidence and the clear articulation of acceptance factors within the literature. From the pool of primary sources examined:

2.3.1. Sample Size Disclosure

An impressive 93% (43 out of 46) of the empirical studies explicitly disclosed their sample size or provided sufficient data to deduce it. This high level of transparency facilitates a deeper understanding of the study's scope and applicability.

2.3.2. Gender Ratio

Approximately 83% (38 out of 46) of the empirical studies offered insights into the gender distribution of their samples, either by directly presenting the gender ratio or by providing enough information to calculate it. This detail is crucial for assessing the diversity and inclusiveness of the research.

2.3.3. Mean Age Reporting

More than half (59%, 27 out of 46) of the empirical studies reported the mean age of their samples or presented enough data to estimate it, enriching the demographic profiling of their research subjects.

2.3.4. Technology Domains

The studies predominantly focused on five key technology domains: Ambient Assisted Living (AAL), Internet of Things (IoT), Smart Cities, Smart Homes, and Assistive Technology, representing 42% (27 out of 64) of the total studies analysed. This concentration underscores the growing interest and relevance of these domains in current technological research.

2.3.5. Acceptance Factors Assessment

A notable 75% (48 out of 64) of the studies explicitly addressed or considered various technology acceptance factors. It is important to note that this is not necessarily an indicator of the study's quality, as some research may prioritise implementation details over technology acceptance analysis.

2.3.6. Prevalent Acceptance Factors

The analysis identified the five most common acceptance factors cited in the studies: Perceived Ease of Use (56%, 27 out of 48), Perceived Usefulness (48%, 23 out of 48), Attitude Towards Technology (31%, 15 out of 48), Facilitating Conditions (31%, 15 out of 48), and Affordability (25%, 12 out of 48). These factors highlight key considerations influencing the adoption and acceptance of new technologies.

2.4. Extracted and Consolidated Acceptance Factors

Building on our initial preliminary analysis, we streamlined the identified acceptance factors from the primary studies, reducing the original 223 factors down to 50 consolidated and refined factors. This was achieved by thoroughly examining the factors for semantic similarities beyond their titles, allowing us to merge those with overlapping meanings. This step streamlined our analysis, focusing on the core themes influencing technology acceptance among older adults and enhancing the clarity of our findings.

2.5. Acceptance Factor Typings

In the structuring of acceptance factor typings, each identified factor was evaluated for similarities and categorised into dual groupings for analytical clarity. The first grouping delineated the context of the acceptance factor—whether it pertains to individual, technology, social, or environmental considerations.

The second grouping captured the nature of the factor's impact, classifying it into knowledge-material, belief-feeling, relevance-specificity, or limitation-assistance categories. This bifurcated classification system was instrumental in coding the data, leading to the inclusion of a categorical feature for each study. This feature documents the unique combinations explored by the studies, such as "Individual: Knowledge-material" or "Technology: Relevance-specificity," streamlining the analysis of acceptance factors within our systematic review. studies, such as "Individual: Knowledge-material" or "Technology: Relevance-specificity," streamlining the analysis of acceptance factors within our systematic review.

3. Systematic Review Results

This literature review serves to identify and synthesise the key factors influencing technology adoption among older adults, with the specific aim of informing the co-design activities and guiding the development of the proposed framework. While traditional technology acceptance models offer a foundational understanding, they often fall short in addressing the distinct needs and challenges experienced by older adults, such as frailty, cognitive decline, and socio-emotional barriers [19–21]. To effectively support this demographic, a deeper exploration of user-centred design principles, inclusive learning environments, and adaptive technologies is essential.

The review is organised around four critical themes that shaped both our participatory co-design process and the structure of our framework. First, we explore how conventional technology adoption models must be adapted to reflect the lived experiences of older adults, particularly the importance of perceived ease of use, emotional reassurance, and social value in determining engagement. Second, we emphasise the diversity in needs within this population, noting that effective technological solutions must address a wide range of needs, from chronic disease management to assistive tools for physical limitations, which is an insight that directly influenced the breadth of user personas used in our co-design sessions.

Third, recognising the growing prevalence of frailty, we discuss the need for technologies that are not only accessible and reliable but also tailored to cognitive and physical changes. Finally, we highlight the critical role of user-centred and inclusive design approaches, focusing on how social context, clarity of design, and perceived usefulness can enhance technology adoption. These principles underpinned the structure of our co-design workshops and informed the iterative development of our framework.

This review ensures that our co-design and framework development are both evidence-based and attuned to the real-world needs of older adults. It sets the stage for a practical and inclusive approach to designing technologies that foster digital participation, social inclusion, and independent living.

3.1. Acceptance Models

Acceptance models are pivotal frameworks that are widely debated, expanded, and applied in research. These models offer structured insights into the intricate dynamics influencing individuals' acceptance and adoption of technology across various demographics, including older adults. By leveraging these models, researchers gained valuable tools to explore nuanced factors shaping technology adoption behaviours, thereby enhancing our understanding of how to design and implement technologies tailored to the unique needs and preferences of older populations. The most prominent models are the Technology Acceptance Model (TAM) [28], the Unified Theory of Acceptance and Use of Technology (UTAUT) [29] and the Senior Technology Acceptance Model (STAM) [30].

TAM posits that two main factors drive the acceptance and use of technology: Perceived Usefulness (PU), the belief that a system will improve job performance, and Perceived Ease of Use (PEOU), the belief that a system will be effortless to use. These components are crucial in understanding how individuals adopt and integrate new technologies into their routines [28].

For example, TAM was used both directly as a framework [31] for data collection and as a base for extensions [32]. Extensions introduce new variables with the goal of specialising the basic model for a defined context. However, the generality of the TAM and its own lack of capacity to derive actionable design insights have been criticised [33].

Addressing the limitations of TAM, the authors in [34] proposed recommendations for Ambient Assisted Living (AAL) adoption by older adults through an extension of the model. Similarly, the authors in [35] proposed an extension of TAM focused on smart home technology adoption by older adults. While their technology domains are close, the former includes new constructs primarily based on perceived traits of the technology (e.g., perceived availability, perceived ubiquity) while the latter also uses constructs that describe an individual's emotional response (e.g., social connectedness, anxiety, life quality expectancy).

Venkatesh et al. [29] highlighted the significance of understanding user acceptance of IT in organisations and the need for a unified model that integrates the determinants of acceptance from different existing models. The authors reviewed and discussed eight prominent models, including the theory of reasoned action, the technology acceptance model, the motivational model, the theory of planned behaviour, and others. The analysis revealed that the models explain between 17% and 53% of the variance in user intentions to use information technology. The authors formulated a unified model called the Unified Theory of Acceptance and Use of Technology (UTAUT). The authors also highlighted the need for future research to deepen the understanding of dynamic influences, refine measurement constructs, and explore organisational outcomes associated with new technology use.

Chen and Chan [30] explored gerontechnology acceptance among elderly Hong Kong Chinese by developing the Senior Technology Acceptance Model (STAM). This novel model builds on established factors like perceived ease of use and usefulness while incorporating social influence specific to this cultural context. Their mixed-method study with surveys and interviews used a 38-item instrument to assess the 11 constructs within STAM, providing a deeper understanding of technology adoption among older adults in Hong Kong.

Chen and Lou [36] later addressed the length of the initial STAM questionnaire, arguing it burdened participants. They used data from the 2014 study to condense the questionnaire to a more manageable 14 items.

The research presented in [37] explored the acceptance of technology among older people and identified four phases in the process: pre-acceptance/rejection. The first phase is objectification, where individuals assess the usefulness and ease of use of the technology.

The second phase is incorporation, involving further exploration and experimentation with the technology. The third phase is conversion, where individuals decide to accept or reject the technology based on real-life experience. Finally, the fourth phase is the intention to learn, which includes factors like self-efficacy and motivation to acquire new technological skills. These phases play a crucial role in determining the acceptance or rejection of technology by older individuals.

The authors in [38] presented an integrated acceptance framework (IAF) for older users' acceptance of eHealth based on a systematic review of 43 studies. The framework consists of five dimensions: personal, user-technology relational, technological, service-related, and environmental, comprising a total of 23 factors. The study analysed the differences in these factors based on participants' health conditions, verification time, and year. The proposed framework aims to guide research on eHealth acceptance and emphasises the need for specific measures to facilitate acceptance among older adults.

Acceptance models provide a foundational framework for researchers to explore the complex factors influencing technology adoption among older adults. These models, like TAM and UTAUT, offer a structured approach to understanding the motivations and challenges faced by this demographic. Examining extensions of these models, like STAM, reveals the importance of tailoring the models to specific contexts and incorporating culturally relevant factors like social influence. However, limitations exist, with criticisms highlighting the need for models to move beyond basic acceptance to inform actionable design principles. However, while models like TAM and UTAUT provide theoretical insights, their generality often limits the derivation of actionable design insights specific to the nuanced needs and preferences of specific demographics, such as pre-frail older adults in home settings. This gap directly informed the necessity of our co-design activities to gather more context-specific data.

The concept of user experience goes beyond just perceived ease of use and usefulness. Studies exploring the four phases of technology acceptance (objectification, incorporation, conversion, and intention to learn) emphasise the importance of understanding how older adults interact with technology over time. Frameworks like the IAF delve even deeper, identifying 23 factors across five dimensions that influence technology adoption in older populations. These insights are crucial for designing technologies that cater to the unique needs and preferences of older adults, ultimately empowering them to embrace the benefits technology offers.

In summary, acceptance models such as TAM, UTAUT, and STAM provide essential theoretical foundations for understanding technology adoption among older adults. However, their limitations, particularly the lack of actionable design insights, underscore the need for participatory approaches like co-design workshops and activities. The reviewed extensions of these models introduce critical contextual, emotional, and social factors, demonstrating the importance of tailoring acceptance frameworks to specific populations.

3.2. Digital Divide

The digital divide, the unequal access to information and communication technology (ICT) among different age groups, presents a growing challenge for social inclusion. Fortunately, solutions lie at the intersection of psychology and technology design, as technology skills become increasingly crucial for full social participation [39].

The digital divide manifests in various forms beyond just access to ICT. Studies reveal discrepancies in technology usage behaviours [40]. For example, some individuals may rely on non-electrical assistive devices while neglecting potentially beneficial electronic alternatives. Additionally, generational preferences can come into play, with some favouring familiar, established technologies over newer computerised options [41]. Even within smart home advancements, recent research suggests a preference for simpler innovations over highly automated systems [42]. These nuances highlight the importance of understanding not just access, but also individual needs, comfort levels, and potential apprehension towards newer technologies.

Digital inclusion for older adults faces challenges beyond just physical limitations. In [43], the authors identified internalised ageism, negative self-perceptions about technology use due to age, as a significant barrier. This psychological factor lowers motivation and hinders technology adoption.

Beyond internalised ageism, external factors also play a role. The authors of [44] highlighted the emotional impact of assistive technologies (ATs). While ATs, such as mobile phones, can offer benefits like safety and independence, it can also evoke negative emotions like anxiety or feelings of stigma. Current AT design often prioritises usability over emotional and psychological needs. Chen advocated for a holistic design approach that considers aesthetics, usability, and user well-being to improve acceptance and user experience.

The authors in [45] proposed the Smart Wearables Acceptance Model (SWAM) to understand factors influencing wearable health technology adoption among older adults. Their model incorporates established technology acceptance factors alongside age-related health characteristics. Their findings confirm that perceived ease of use, usefulness, social influence, and positive attitudes significantly impact technology acceptance. Additionally, age, education, computer experience, and health literacy were found to moderate these relationships. The study suggested that interventions promoting ease of use, highlighting usefulness, leveraging social influence, and fostering positive attitudes can increase wearable technology acceptance in older populations.

Further research by [46] delved into the multifaceted nature of the digital divide among older adults. Their work identified challenges that extend beyond mere access to technology, including a lack of familiarity, fear of mistakes, and anxieties surrounding social implications. The authors emphasised the need for collaborative efforts, including digital literacy programmes, to bridge this gap. Their research aligns with the concept of a multi-layered digital divide, encompassing access, usage proficiency, and the skills required for effective technology use. By acknowledging these complexities, solutions like targeted education and training initiatives can be implemented to empower older adults and ensure their inclusion in our increasingly digital world.

Chen [44] added another layer of complexity to the digital divide, exploring the psychological factors that influence adoption. The study highlighted how anticipation of external prejudice and internalised stereotypes can lead older adults to downplay their need for assistive technologies. This resistance may stem from a desire to maintain dignity or a sense of aesthetics, even when acknowledging the potential benefits of the technology. Iancu and Iancu [47] further explored this tension, documenting cases where individuals grapple with balancing the usefulness of familiar devices with concerns about their complexity or security. These insights emphasise the need for technologies that are not only accessible and user-friendly but also address the social and emotional considerations that can influence adoption among older adults.

Köttl et al. [43] delved deeper into the psychological barriers associated with the digital divide. Their research identified internalised ageism as a significant factor contributing to technology non-use. They further categorised this phenomenon into four distinct subcategories, highlighting the complex ways social cues and technology design can discourage older adults. Internalised ageism erodes confidence in one's ability to learn and benefit from technology, ultimately leading to low engagement. This emphasises the critical need for design that not only addresses physical limitations but also combats negative societal messages about ageing and technology use.

Unfortunately, even when design guidelines exist, their implementation remains inconsistent. Alamo and Golpayegani's [48] study analysed 43 design recommendations across 22 mobile applications, revealing a concerning reality. Only 23% of the apps were deemed truly accessible to older adults. Even worse, some apps offered accessibility features that were themselves difficult to access. These findings underscore the importance of moving beyond the creation of design principles to ensure their consistent and effective application.

Several studies propose solutions to bridge the digital divide among older adults. Köttl at al. [43] advocated for inclusive learning environments that cater to diverse learning styles and comfort levels. Saibene et al. [49] envisioned adaptive AI-powered solutions that can personalise the user experience based on individual digital literacy levels. Pena Barros et al. [41] highlighted the importance of transparent and easily maintainable technologies to address concerns about complexity and security.

Research consistently challenges the stereotype of a homogenous older adult population with uniform needs. Tam et al. [50] and Ma et al. [51] emphasised the need for targeted interventions and product segmentation to accommodate diverse demographics and health conditions. Moody et al. [52] illustrated this point by demonstrating how reasons for non-adoption of eHealth solutions differ even among older adults with chronic conditions. Paul and Spiru [53] introduced the influence of physical and mental health on technology adoption. Their research suggested that individuals with psychological challenges may not only adopt technologies later in life but also have different perceptions of their usefulness.

Ma et al.'s [51] meta-analysis shed light on the complex interplay between demographics and technology acceptance factors. Their findings revealed that factors like social influence and perceived usefulness may have varying impacts depending on age, gender, and even regional cultural contexts. For example, social influence appears to be more significant for older adults in Asian cultures compared to their European counterparts, where perceived ease of use takes greater precedence. Yu-Huei et al. [54] supported this notion by suggesting that collectivist cultures, where social pressure plays a stronger role, can influence adoption decisions more than individualist cultures.

As presented in this subsection, the digital divide goes beyond just access to technology for older adults. It encompasses comfort levels, apprehension towards new technology, and internalised ageism. Usability is crucial, but design must also address psychological factors and combat negative stereotypes. While design principles exist, inconsistent implementation remains a challenge. Solutions like inclusive learning environments and adaptable AI offer promise. However, a one-size-fits-all approach will not work. Research highlights the diverse needs of older adults, influenced by demographics, health, and cultural contexts. The pervasive nature of the digital divide underscores the importance of engaging directly with older adults, such as through co-design activities, to understand these challenges in their lived experiences and convert them to design decisions. By acknowledging these complexities and embracing human-centred design, we can bridge the digital divide and empower older adults in our increasingly digital world.

3.3. Frailty

Frailty in older adults presents a complex challenge for technology developers and caregivers alike. Studies by Chen [44] and Orellano-Colón et al. [40] highlight the physical limitations associated with frailty and the potential of assistive technologies to address them. However, the concept of frailty extends beyond the purely physical. Research by Arthanat et al. [42] and Biermann et al. [55] suggests a strong correlation between perceived health and technology adoption, with individuals more likely to embrace technology when they perceive a direct benefit to their well-being. Interestingly, Bolaños et al. [56] found that even those in good health are receptive to technologies like digital home assistants, indicating that adoption is driven by factors beyond just physical limitations.

Technology can play a vital role in monitoring health and detecting changes in functional abilities. Studies by Hedman et al. [23] and Pires et al. [57] showcase the potential of monitoring systems to not only support caregivers but also to identify early signs of cognitive decline. These advancements hold promise for proactive interventions and improved patient outcomes.

While improving patient outcomes remains a primary focus, research also highlights the importance of influencing adoption behaviours. The concept of "pre-frailty" is particularly relevant, as studies by [47] suggest that targeting this group offers distinct advantages. By focusing on pragmatic functions, user-friendliness, and addressing concerns about privacy and accuracy, developers can create technologies that are not only appealing but also encourage adoption before the onset of frailty.

Furthermore, research by [58] underscores the need for tailored interventions based on frailty status. Frail individuals may be influenced by fewer factors when considering technology adoption, suggesting a proactive approach is crucial. Understanding these distinctions is essential for developers and researchers alike, paving the way for more inclusive and effective technology solutions for older adults across the frailty spectrum.

The multifaceted nature of frailty, encompassing physical, cognitive, and perceptual dimensions, demands a nuanced approach to technology design and implementation. These insights demonstrate that adoption is not solely driven by physical need but also by perceived benefits, health status, and the usability of technological solutions. This highlights the value of engaging older adults, particularly those in pre-frailty stages, in the co-design of technologies that are intuitive, respectful of privacy, and responsive to individual contexts. Tailoring interventions based on frailty status enables more precise alignment with users' capabilities and expectations, ultimately enhancing adoption.

3.4. Barriers and Facilitators to Adoption

Technology adoption among older adults is a balancing act. It hinges on three key factors—the individual's characteristics, the features of the technology itself, and the social context surrounding its use. This subsection will explore these factors and how they can influence whether older adults embrace or resist new technologies.

Crucially, technological experience shapes how older adults view and approach new technologies. Research by [59] reveals a clear distinction between novices and tech-savvy older adults. Those with lower experience exhibit less enthusiasm and encounter more learning difficulties. Interestingly, the challenges differ. New users struggle with the initial learning stages and prefer task-oriented approaches. Experienced users, on the other hand, grapple with finding the right learning methods and applying their knowledge to new technologies. These findings highlight the need for diverse learning strategies tailored to individual experience levels.

Several studies, including [60,61], identify key motivators for technology adoption. They point to perceived value, the belief that technology will improve quality of life, and confidence in using it. These factors align with established models like UTAUT, which emphasises the importance of both perceived usefulness and ease of use. Optimism about technology's potential further strengthens adoption intentions. Positive user experiences are crucial for building this confidence and fostering long-term adoption.

Social networks play a crucial role in shaping attitudes and behaviours towards technology use. Studies by [61,62] highlight the influence of social networks, both through direct use and by observing the experiences of others. Social networks can provide encouragement and even gentle restrictions on technology use. However, they can also be a source of barriers. Privacy concerns, financial limitations, and technological complexities are common hurdles identified in these studies. To bridge this gap, user-friendly designs that consider social dynamics and address these concerns are essential, especially for those with cognitive impairments.

For individuals with cognitive challenges, the social network emerges as a crucial factor influencing their ability to embrace technology. Research by [62] reveals that ICTs can address social and emotional needs when supported by a social network. This network can provide assistance, encouragement, and even restrictions on technology use. This study emphasises the importance of individualised approaches and the positive influence of a supportive social environment on technology experiences for older adults with cognitive challenges.

One of the key roadblocks to wider technology use by older adults is a lack of awareness about what these tools can do and how they can benefit their lives. Research by [61,63] underscores the importance of clear communication strategies. By effectively communicating the benefits and functionalities of technology, we can empower older adults to overcome these barriers and utilise technology to its full potential. This is particularly important for functionalities related to cognitive functions and memory improvement.

From data security to control over personal information, a range of privacy considerations warrant careful attention for successful technology adoption in older adults. The study in [64] advocates for user studies that move beyond generic solutions and delve into the real-world contexts of older adults. Inclusive research involving all stakeholders, including older users, caregivers, and family members, is crucial for gaining holistic insights into privacy and security dynamics within households. Human-centred design approaches that actively involve older adults in the design process are recommended to enhance technology acceptance.

The playful approach adopted in [65] sheds light on the evolving decision criteria for Ambient Assisted Living (AAL) technologies. Privacy concerns remain a significant factor, but participants also weigh them against the need for support in scenarios like fall detection. This study underscores the importance of considering individual support requirements and the persistent desire for independent living among older adults.

The study by [65] highlights the impact of cultural and generational factors on wearable device adoption in Taiwan. The gifting of wearables by younger generations and the influence of their internet expertise are noteworthy findings. This research emphasises the importance of human interaction, user-friendly design, and a focus on healthcare functionalities to promote wearable device adoption among older adults.

Technology adoption among older adults is a dynamic interplay of personal experience, design features, and social influences. Understanding this complexity is vital for designing technologies that are both inclusive and empowering. Differences in technological proficiency call for differentiated learning strategies, while motivators like perceived usefulness, ease of use, and optimism about technology's potential must be embedded in design choices. Equally important is the social context, support networks, cultural norms, and privacy concerns all shape technology perceptions and behaviours.

The surveyed literature reveals several critical shortcomings in current understanding of technology acceptance amongst older adults. Whilst foundational models such as the Technology Acceptance Model (TAM) provide essential theoretical frameworks, they suffer from excessive generality and a fundamental inability to generate actionable design insights, explaining a small percentage of variance in user intentions to adopt information technology. A concerning disconnect exists between theoretical design guidelines and practical implementation, evidenced a fraction of the analysed mobile applications were genuinely accessible to older adults despite existing recommendations. Furthermore, traditional acceptance models inadequately address psychological and social factors, particularly internalised ageism, stigma, and emotional responses to assistive technologies, which constitute significant barriers to adoption.

The literature consistently challenges assumptions of a homogeneous older adult population, showing that factors like social influence and perceived usefulness differ widely depending on personal and contextual characteristics—a diversity that existing frameworks struggle to capture effectively. Additionally, current research provides an insufficient understanding of the dynamic nature of technology acceptance over time, particularly in relation to how attitudes and behaviours evolve throughout the adoption process for older adults experiencing cognitive or physical changes. Finally, many studies superficially address the multifaceted nature of barriers beyond basic access issues, overlooking the complex interplay of usage proficiency, emotional comfort, social support, and cultural considerations that comprise the digital divide, thereby necessitating more nuanced, culturally sensitive, and psychologically informed approaches that effectively translate theoretical insights into practical design solutions.

For those experiencing frailty or cognitive decline, early-stage interventions and pragmatic, easy-to-use technologies tailored to specific functional needs are particularly impactful. In designing our co-design workshop, we were influenced by this understanding and deliberately incorporated commercial off-the-shelf products (COTS) as assistive devices, recognising their familiarity, accessibility, and potential for rapid adoption. Furthermore, addressing privacy concerns, combating ageist design assumptions, and raising awareness about technology's real-life benefits are essential to foster trust and long-term engagement.

4. Research and Workshop Methodology

Our systematic survey results guided us in the design and implementation of our co-creation workshop aimed at engaging 20–30 participants through a series of structured activities, including brainstorming, affinity mapping, dot voting, quantitative questionnaires, and semi-structured interviews. The selection and adaptation of these instruments were informed by our systematic review, ensuring that each activity was not only contextually relevant but also scientifically grounded, as illustrated in Figure 3. All 30 identified core constructs informed the design of the brainstorming sessions, affinity mapping, and semi-structured interviews. The 10 most frequently cited constructs in the literature served as the basis for the questionnaire, while the top five categories of assistive and robotic technologies identified were used to structure the dot voting activity.

The co-creation workshop was designed to foster engagement, creativity, and data collection through a thoughtfully curated set of activities. These activities were strategically scheduled throughout the event, interspersed with breaks to maintain participant engagement and cognitive freshness. All workshop documents and materials are publicly shared as a part of this contribution, please see Supplementary Materials section for a direct link to our shared GitHub repo (https://github.com/). This initial phase of the workshop relied on an engaging brainstorming activity aimed at generating a wealth of ideas from participants, which were then organised through affinity mapping. This technique helped in clustering similar ideas and themes that emerged during the brainstorming session, facilitating a structured synthesis of participant input and highlighting prevalent trends and perspectives within the groups.

Following the idea generation and organisation stages, dot voting was employed as a democratic tool to gauge the focus of our group members on the most relevant assistive and robotic technologies in their daily lives. Each participant was given a limited number of votes or 'dots' to vote on the assistive and robotic technologies they found most compelling or vital for their activities of daily living (ADL).

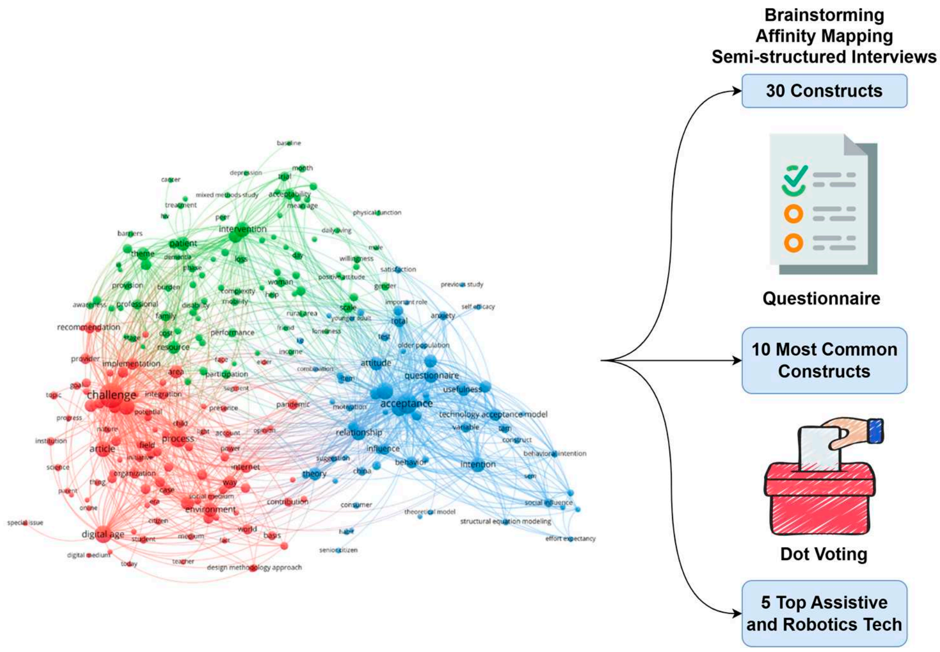


Figure 3. Overview of co-creation workshop and patient and public involvement (PPI) activities.

To supplement the qualitative insights garnered from the brainstorming and voting activities, a quantitative questionnaire was distributed. This instrument was carefully developed from existing validated tools identified during the systematic review and adapted to ensure relevance and context-specific applicability. The questionnaire aimed to quantitatively measure participants' attitudes, perceptions, and other relevant metrics that could be statistically analysed.

In the latter part of the workshop, semi-structured interviews were conducted to delve deeper into specific themes or issues that had emerged. These interviews were guided by a set of predefined questions inspired by the systematic review's findings, but they also allowed for open-ended responses, providing flexibility to explore new or unexpected topics raised by the participants. Each of these activities utilised content and instruments that were closely adapted from a diverse collection of research instruments gathered during the systematic review. In the next subsection, we explore in detail the methodology we followed in adapting the instruments to ensure their relevance and effectiveness in achieving our research objectives.

4.1. Instrument Adaptation

During the systematic review, we categorised the types of instruments used and assessed whether they were adapted from other sources. These instruments were then linked to the specific variables they were designed to measure and target. Given that most sources detailed their models, dimensions, and constructs, many instruments could be consolidated by their semantics and desired insights rather than superficial differences in the terms used by their sources. For example, an instrument intended to examine "social influence" has an almost identical purpose in context as an instrument from another source targeting "subjective norm".

After consolidation, 37 variables were identified and the collected instruments were labelled using them, most not changing from their original labels. This collection was reviewed, and variables were excluded and further consolidated to produce a new set of 30 variables relevant to this study.

An excerpt of these adaptations is outlined in Table 3, containing:

- Adapted variable names

- User-facing topics representing the truncated form of the variable names, presented as a broad topic to participants
- Adapted instruments from literature sources
- Truncated form of the instruments, presented as prompts or questions to participants
- References cited by the instruments that were adapted

Table 3. Excerpt from the systematic analysis process and adaptation of literature-based instruments for participation perspectives.

Variable	User-Facing Topic	Adapted Instrument	Truncated Instrument	References
Nonspecific Acceptance	Acceptance	How interested are you in incorporating smart home technology into your daily life?	How interested are you in using smart home tech in your daily life?	[30,66]
Access to support	Access to Support	How much help could you get with technology difficulties, if you needed it?	How much help could you get with tech problems if you needed it?	[29,30,67,68]
Aesthetic sensibilities	Aesthetics	To what extent do you feel that smart home technology looks fashionable or aesthetically pleasing?	How fashionable is smart home tech to you?	[67,68]
Affordability	Affordability	How affordable do you feel smart home technology is to buy and maintain?	How affordable to buy and maintain smart home tech?	[38,69–71]
Ageism/prejudice	Ageism and Prejudice	To what extent do you feel excluded from things because of your age?	To what extent do you feel excluded from things because of your age?	[72]

4.2. Icebreaker Activity

The workshop began with an engaging icebreaker activity designed to put participants at ease and to start them thinking about how assistive technology can be relevant to their daily lives. Participants, a mix of PwF and professional experts and caregivers working with PwF, were all novices with the specific assistive technology and robotic devices being introduced. The activity involved exploring different combinations of SmartBot sensors and bots, Alexa devices, Philips Hue bulbs, and Xiaomi sensors. This hands-on experience not only helped break the ice but also served a valuable purpose. It demonstrated to participants that there is a variety of affordable, commercially available COTS assistive technologies that can potentially assist them in their daily activities.

This realisation was key, as it addressed a concern about cost that some participants might have had. Furthermore, learning about these COTS devices as opposed to research prototypes made participants feel more invested in the workshop's outcome. They saw the potential for real-world application in their homes and felt their input could directly influence solutions closer to deployment. Overall, the icebreaker activity successfully fostered a sense of excitement about the research project and created a comfortable atmosphere for participants to share their preferences and concerns.

4.3. Brainstorming Activity

The next activity, and the first used to formally collect data, was a structured brainstorming session, with twofold objectives. First, elucidate the diverse perceptions and interactions that participants have with technology. Second, identify their needs, challenges, and current approaches to resolving these challenges through the utilisation of existing technologies. The open nature of this brainstorming activity offered participants the opportunity to spontaneously generate responses that addressed these objectives and laid the foundation for addressing the research question **R1a**.

To achieve the above, workshop session goals were established in icebreaking and brainstorming activities. These goals aimed to encourage participants to express themselves freely, effectively use prompts to inspire and cultivate thoughts and perspectives about assistive technology, represent their viewpoints and priorities as clearly and comprehensively as possible, and maintain a focused discussion on understanding their needs and challenges. Specific details, nuances, and in-depth discussions were reserved for the subsequent activity, affinity mapping.

To facilitate discussions around each of the 30 consolidated instruments identified from the systematic literature review, a set of 30 prompt cards was meticulously designed (see Figure 4 for an example). These print-ready prompt cards featured abbreviated forms of the terms and topics and were generated using nanDECK v.1.7.3 [73,74]. The prompt cards were divided into six pools, each containing five prompts. The six brainstorming groups, each facilitated by a designated facilitator, were assigned two pools of prompts for discussion. Specifically, groups 1 through 6 were allocated pools AB, BC, CD, DE, EF, and FA, respectively. Consequently, each group examined ten of the prompt cards, and each prompt was discussed by two groups. This division was a necessary measure to conserve time and mitigate potential participant fatigue.

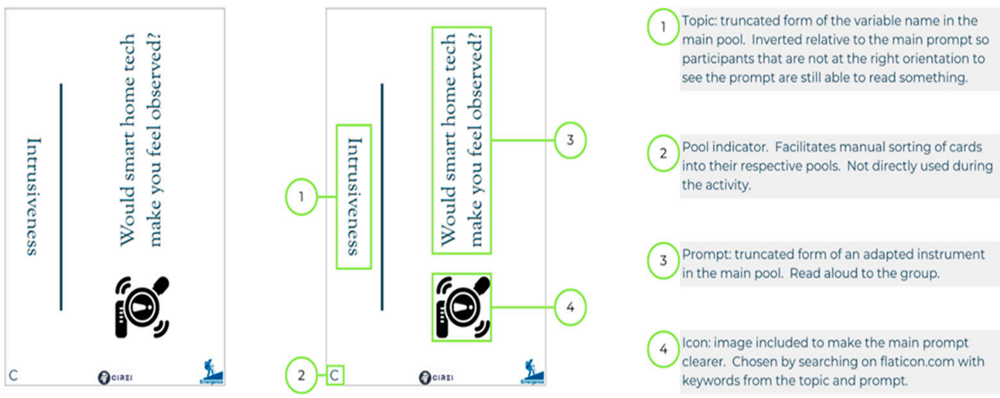


Figure 4. Design and anatomy of prompt cards used in co-creation workshop. Example unannotated prompt card (**left**) and prompt card anatomy guide (**right**).

The facilitators drew one prompt card at a time, and the group engaged in a discussion based on that prompt. For each card, the facilitators provided follow-up prompts and encouraged participants to express their thoughts and perspectives on the topic. If a prompt did not generate substantial conversation or appeared to be misunderstood, the facilitators referred to alternative questions provided in their corresponding notes for each prompt card, as shown in Figure 5. The facilitators actively encouraged participants to share anecdotes and personal stories to foster a deeper understanding of perspectives across group members.

Additionally, they promoted the recognition of shared experiences and the building upon one another's ideas within the groups. Participants' responses were transcribed onto sticky notes, with a focus on capturing a diverse range of expressions and ideas, rather than critiquing, assessing feasibility, or refining them.

The brainstorming session had an approximate duration of 35 min, during which the facilitators aimed to cover all the topics represented by the assigned prompt cards. General guidelines were established, suggesting a time allocation of approximately one minute per topic. However, it was acknowledged that more complex discussions would likely span across multiple topics, potentially requiring a longer duration to address comprehensively.

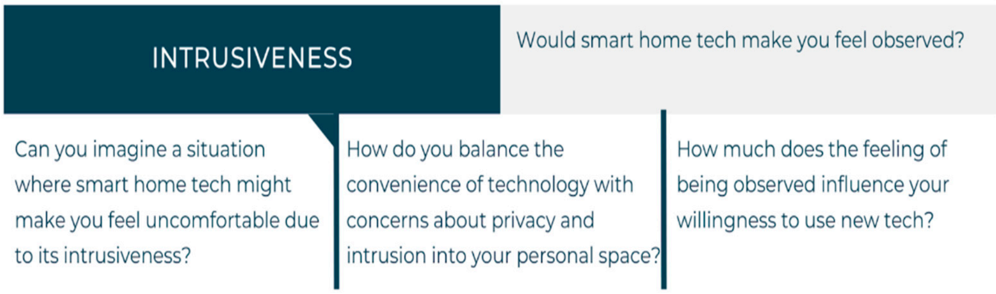


Figure 5. Excerpt from the Facilitator Brainstorming Guide with Prompt Card Instructions (Appendix A). The lower-left prompt (marked with a filled corner) offers an alternative to the main prompt, while the centre and right prompts are suggested follow-up questions.

4.4. Affinity Mapping Activity

The affinity mapping activity used the unstructured responses from the prior brainstorming session, with threefold objectives: (1) identify the existing problems more precisely, (2) explore potential solutions, and (3) determine the barriers hindering their resolution. This focused activity provided participants the opportunity to clarify and refine ideas and articulate their views on key challenges in integrating assistive technology within the home environment. Consequently, this activity directly addressed research question **R1a**.

To accomplish the above, the workshop session goals for the affinity mapping activity were carefully designed. These goals included enabling participants to reflect on the comprehensive output from the brainstorming activity, facilitating the development and refinement of participants' understandings of potential solutions to overcome barriers to technology use, and defining and visually representing a holistic mental model for the key issues raised. In contrast to the previous session, which involved collaborative elements but was ultimately driven by individual viewpoints, this session was explicitly developed with the goal of fostering consensus among participants.

Following a brief comfort break after the brainstorming session, participants reconvened with their respective groups and the same facilitators. To familiarise participants with the task at hand and refocus their attention on the items generated, particularly those from the beginning of the brainstorming session, the facilitators instructed the groups to review the items and identify any areas requiring clarification. As preparatory work for the task, the facilitators requested participants to individually consider the distinctions between the ideas represented by the items and contemplate how these items could be better organised into groupings.

The facilitators initiated the task for the groups by selecting two items and asking participants to distinguish between them, explain the differences, and identify separate clusters to which they might belong. The facilitators repeated this process until the participants began to take the lead. This process of bringing together similar terms or topics, known as *clustering*, marked the first of the three key phases of the affinity mapping activity.

As clusters began to form, the facilitators initiated the second key phase (*Labelling*) and asked participants to identify names for each cluster. In the process of naming the clusters, participants established criteria for inclusion and had the opportunity to provide further elaborations on their decision-making process. During this phase, items could be moved from one cluster to another, although they typically remained in their original cluster.

Once the clusters were named and established, the facilitators prompted the third key phase (*Explaining*) by asking participants to explain the relationships between the clusters, for example, by identifying causal connections or dependencies. Participants were further requested to reflect on the groupings and draw out any observable patterns across these connections, identifying larger structures and properties of the system as a whole. The resulting structure aimed to represent the participants' internal conceptual models, illustrating how ideas interrelate and how systems currently operate or should ideally function.

Throughout this activity, particularly during the final phase, the facilitators encouraged the participant groups to prioritise ideas for features and concepts using the MoSCoW method [75]. Similarly, the groups were asked to identify functional and non-functional requirements. Contextualising the structures and insights with these analytical tools helped produce actionable artefacts and informed the subsequent development of the Software Requirements Specification (SRS) [76]. The affinity mapping activity had an approximate duration of 30 min.

4.5. Dot Voting Activity

In the dot voting activity, participants cast their votes by writing the number of the corresponding assistive technology, following the instructions in the reference shown in Figure 6, on a green card to indicate interest or approval, or on a yellow card to indicate disinterest or disapproval. Participants had the option to use multiple green cards for a single item/technology to indicate the strength of their positive impression. To promote candid feedback, participants were instructed not to include any personal identifiers on their voting cards. Once completed, participants sealed their cards in an envelope, ensuring confidentiality. Envelopes were collected and handed over to the facilitator for further qualitative data analysis.

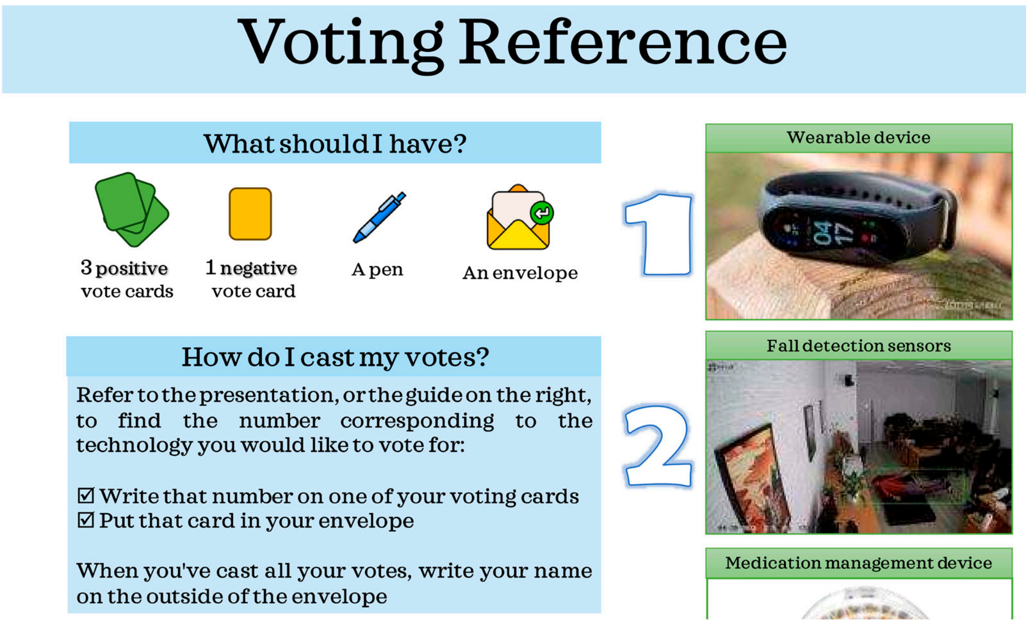


Figure 6. Excerpt from dot voting activity instructions. Full details presented in Appendix B.

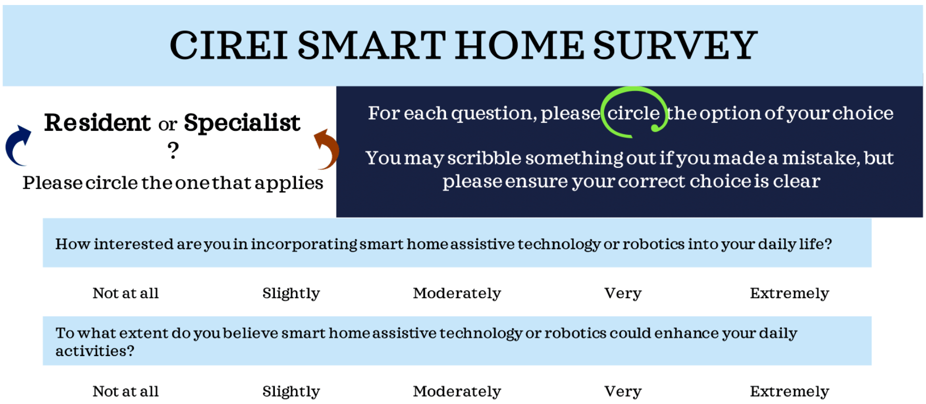
This voting activity played a crucial role in determining the preferences of people living with frailty (PwF) regarding assistive technologies. By allowing participants to express their positive or negative sentiments towards each item or technology, the researchers aimed to gain insights into the specific preferences and concerns of this vulnerable population. The use of green and red cards provided a simple yet effective method for participants to convey their opinions, while the option to use multiple green cards allowed them to indicate the strength of their positive impressions, offering valuable nuance to the data. Moreover, the confidential nature of the voting process, achieved through the use of sealed envelopes and the absence of personal identifiers, encouraged participants to provide honest feedback without fear of judgement or repercussions. This approach was particularly important when working with PwF, as it helped to create a safe and comfortable environment for them to express their genuine thoughts and concerns regarding assistive technologies.

The research objectives of this activity included understanding user preferences and the strengths of those preferences for each assistive device, identifying any concerns or reservations users may have regarding specific technologies, and conducting a comparative analysis of the popularity and endorsement strength for each assistive device. By analysing the distribution of positive and negative votes, as well as the number of green cards used for each item, researchers could gain valuable insights into the overall acceptance, concerns, and relative popularity of different assistive technologies among PwF. The combination of quantitative and qualitative data from this activity could potentially reveal underlying patterns, motivations, and specific needs of PwF, informing the development and adoption of assistive technologies tailored to their unique requirements.

This activity informs **R2b** by capturing the preferences and concerns of participants regarding assistive technologies. The voting activity provides insights into what features or aspects of assistive and robotic technologies are most valued by older adults and their caregivers. This feedback can inform the design and implementation of assistive technologies, including educational mechanisms like chatbots, to ensure they align with user preferences and enhance adoption, thereby impacting quality of life improvements.

4.6. Questionnaire Activity

The activity involved administering a structured questionnaire, an excerpt shown in Figure 7, consisting of 10 diverse instruments adapted from the larger pool of 30 instruments used in the brainstorming activity. The selection of these instruments was guided by two primary criteria: First, some instruments were chosen due to their widespread use and acceptance in the relevant literature, such as *effort expectancy* [66,77–84]. Second, other instruments were selected based on their specific relevance to the project, such as *compatibility and privacy concerns*.


CIREI SMART HOME SURVEY

Resident or Specialist ?
Please circle the one that applies

For each question, please circle the option of your choice

You may scribble something out if you made a mistake, but please ensure your correct choice is clear

How interested are you in incorporating smart home assistive technology or robotics into your daily life?

Not at all | Slightly | Moderately | Very | Extremely

To what extent do you believe smart home assistive technology or robotics could enhance your daily activities?

Not at all | Slightly | Moderately | Very | Extremely

Figure 7. Excerpt from CIREI questionnaire form. Full details are presented in Appendix C.

Participants, identified as either PwF residents or specialists (i.e., healthcare professionals or caregivers), were asked to provide their responses on a 5-item unipolar Likert scale, indicating their level of agreement or disagreement with statements related to each construct. This workshop activity aimed to collect quantitative data on the preferences, concerns, and factors influencing technology adoption among PwF and relevant specialists. This would reveal specific preferences, expectations, and concerns regarding aspects like ease of use, perceived usefulness, compatibility with routines, and privacy considerations.

It would also shed light on potential barriers, such as perceived difficulty, lack of compatibility, or privacy concerns, as well as facilitators such as perceived benefits or social influence. By analysing the data, we could highlight areas requiring interventions or support strategies, such as training for improved ease of use or transparent data management practices to address privacy concerns. Additionally, comparative analysis between the perspectives of PwF and specialists could reveal areas of alignment or divergence, informing more inclusive and holistic technology design.

This activity, as discussed, seeks to quantify preferences, concerns, and factors influencing technology adoption, providing valuable data on learning preferences and barriers to comfort with new technologies, thus addressing both **R2a** and **R2b**. Its results can inform the design of educational content and interfaces to enhance ease of use and perceived usefulness, aligning with the learning preferences of older adults in independent living communities and facilitating better technology adoption.

4.7. Group Semi-Structured Interviews

The final activity of the workshop featured open-ended semi-structured interviews. This took place immediately after participants had completed the questionnaire, and interviews were conducted with the group together. The aims of these interview sessions were twofold: consolidating thoughts from the overall workshop and addressing specified overarching issues in the potential acceptance and use of smart-home technologies. In covering both aims, the semi-structured interviews address both research question **R1a** by further establishing perspectives on the challenges of integrating smart-home technologies and research question **R2a** by drawing out how PwF may approach these.

Facilitators were provided with a set of 8 topics relating to usability, self-confidence, learning curves, trust, intrusiveness, peer influence, affordability, and use intention to cover during the interviews. Topics were characterised by a specific but open prompt question offered to the group—for example, *to what extent do you feel that you could learn how to use smart home assistive technology and robotics by yourself?* If the prompt question generated little response or uncertainty in how to address it, facilitators could offer clarification or elaboration as needed. Facilitators also provided the opening question to start the activity: *How do you feel about using smart home assistive technology and robotics?* Participants were allowed to approach the initial question from any direction; the facilitators then found an appropriate point to raise a specific topic or prompt a question based on the responses. Topics could be broached by facilitators in any order, ideally based on maintaining a natural flow of conversation and discussion.

The overall structure of tackling the questions posed follows a specified common loop. This was set with the intention to raise each topic and to make the data more standardised and interpretable across group responses. The standardised interview loop progressed as shown in Figure 8. The developed standardised interview loop is a systematic process designed to capture participant responses and facilitate group discussions effectively. It begins with presenting an interview question (prompt) to participants and accurately recording their responses. This step ensures that initial reactions and thoughts are documented comprehensively.

Following the individual responses, a group discussion is facilitated to engage participants on the topic, encouraging a deeper exploration of the subject matter. During this discussion, key phrases and ideas are identified and recorded as verbatim quotes, capturing the essence of the participants' contributions. To ensure accuracy and collective agreement, the recorded quotes are read back to the group. Participants provide their opinions on these quotes, and the level of consensus is assessed. This step is crucial for validating the recorded information and ensuring it reflects the group's views accurately. During the consensus check, individual stances on the quotes are collected using shorthand notation, as shown in Figure 9, along with any further elaboration from participants. This ensures that individual perspectives are captured and considered in the analysis.

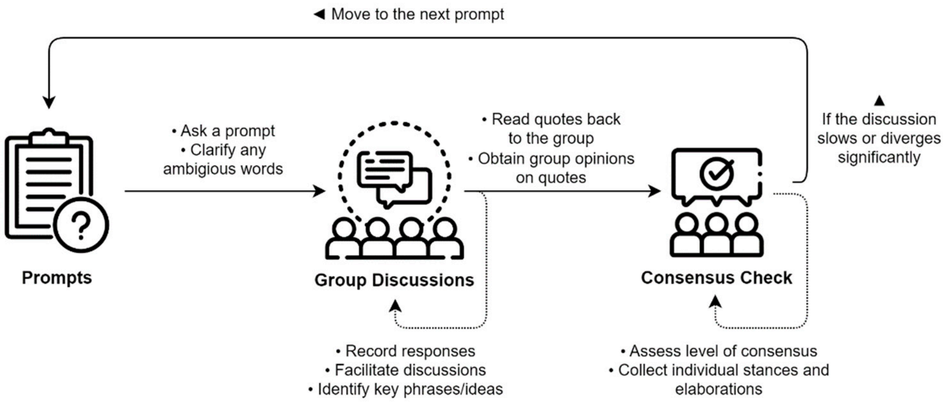


Figure 8. Implemented semi-structured interview process for each prompt. Prompts or questions are read; opinions are obtained from discussion; key quotes or points are summarised to the group for understanding; and the level of consensus before moving to the next prompt.

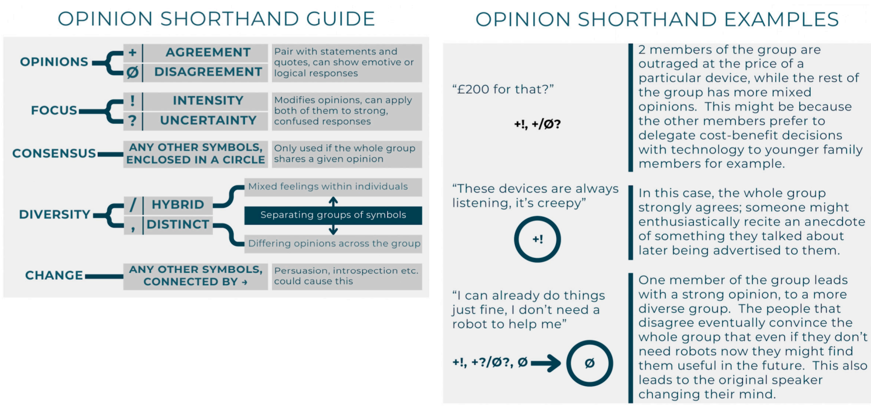


Figure 9. Excerpt from opinion shorthand guide for facilitators (**Left**) and examples of annotation (**Right**). Full details are presented in Appendix D.

The loop continues until the discussion slows or diverges significantly, marking the end of the iteration. This structured approach ensures thorough and organised data collection during interviews, providing a clear and accurate representation of participant responses. A basic shorthand method for transcribing opinions and the extent of opinion diversity in the group was developed for the activity. Facilitators could note (dis)agreement of views between group members, intensity and certainty of viewpoints, group consensus, diversity of feeling on topics and whether people changed views through discussion.

In the upcoming section, we present and analyse the results derived from these activities. By examining the participants' responses, verbatim quotes, and the consensus achieved during the workshop, we validate the effectiveness of the adapted instruments in capturing nuanced data and gaining insights into participant perspectives and experiences.

5. Workshop Results and Analysis

Participants in the co-design workshop came from two key groups: residents (i.e., those with lived experience of frailty and receiving care) and specialists (healthcare professionals or caregivers). Twenty residents took part in the workshop; of these, 6 (30%) were male and 14 (70%) were female. Residents from the JJ Housing scheme in the South Yorkshire region were invited for participation in the workshop on the basis of their experience in requiring some assistive technology support due to age related concerns; participants were predominantly white, aged between 55 and 75 years old, and were identified by their caregivers as "managing well" on the Rockwood Frailty Scale. Ten specialists, of which 3 were male and 7 were female, participated in the co-design workshop, these participants were recruited based on their experiences with care from Darnell Well Being, JJ Housing, and Sheffield Hallam University.

5.1. Qualitative Data Digitisation Process

Qualitative data from brainstorming/affinity mapping activities and interviews were captured using photographs and facilitator notes. Each brainstorming note was assigned to its corresponding affinity cluster. Interview data points were derived from transcribed quotations or facilitator annotations, excluding opinion annotations due to their low volume. An inductive thematic analysis approach was conducted separately on the brainstorming and interview data to account for differences in participant expression and transcription methods. The results were then consolidated using constructs from both analyses, aggregating semantically similar content where necessary.

The intermediary constructs of the inductive thematic analysis approach for qualitative data processing are illustrated by the following example. Consider the concept of "learning difficulties" that emerged from interviews. Transcripts mentioning struggles with learning new technology (e.g., "…needs explaining 2 or 3 times…") were initially coded as "Able to learn (-)" within the sub-theme "Learning curves." This was then consolidated with semantically similar items into the primary theme of "Learning," incorporating elements from other sub-themes like "Individual limitations."

Other interview data points revealed positive connections to learning, such as preferences for "…tutoring, not instructions," which were coded as "Able to learn (+)" and "Personalised support" within the larger "Learning" theme. These were also labelled with the recurring concept of "Personalisation." The final coding for qualitative data, once consolidated, included their primary theme and, if applicable, the recurring concept they expressed. The final set of broad "themes" and specific "concepts" is presented during the discussion of the CIREI framework in Section 6.

5.2. Dot Voting Activity Results

The results of the dot voting activity, where participants allocated weighted votes (single, double, triple, or negative) to express their preferences for various assistive technologies, are summarised in Figure 10.

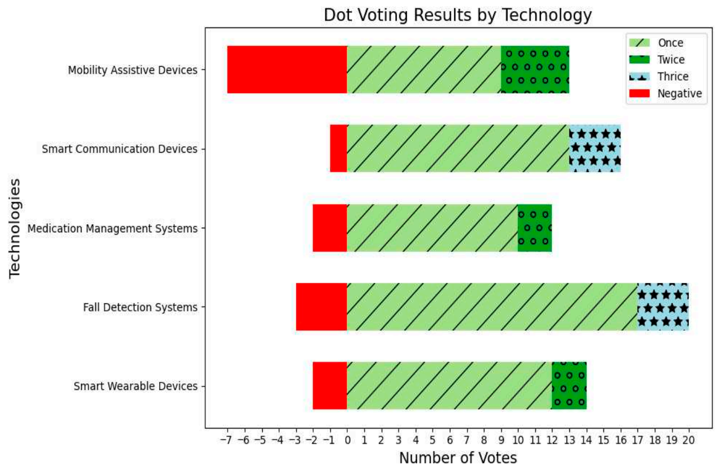


Figure 10. Summarised distribution of all positive votes, including single (green stripes), double (green circles), and triple voting (blue Stars), as well as negative votes (red) for assistive technologies.

The strong preference for Fall Detection Systems among pre-frail adults underscores their prioritisation of safety and security. This choice reflects a deep awareness of the risks associated with falls, which can lead to severe injuries and a loss of independence. The appeal of these systems lies in their ability to provide immediate alerts to caregivers or emergency services, offering a sense of reassurance and aligning with the increasing focus on proactive measures to prevent fall-related incidents.

The significant adoption of Wearable Devices and Smart Communication technologies highlights a growing comfort with and trust in technology among pre-frail adults. Their preference for these tools suggests a desire for continuous health monitoring and enhanced communication, driven by the potential to maintain a higher quality of life. Wearable Devices are favoured for their capacity to monitor vital signs, activity levels, and sleep patterns, which offer pre-frail adults valuable health insights and a greater sense of control over their well-being. Similarly, Smart Communication technologies are chosen for their ability to facilitate social interaction, provide easy access to information, and allow for remote monitoring, all of which contribute to a stronger sense of security and connectedness.

The moderate interest in Medication Management Systems indicates that while medication adherence is a concern, it may be a lower priority compared to other health technologies. This choice suggests that while pre-frail adults recognise the potential benefits of these systems, such as reminders and tracking for medication adherence, they may not yet see them as essential, or they may be exploring simpler solutions. Their moderate interest might also point to a need for more intuitive or customisable features that align more closely with their daily routines and specific health needs.

The low preference for Mobility Assistants may suggest that pre-frail adults prioritise maintaining independence over the potential benefits of mobility aids. This choice reflects a complex relationship with assistive technologies, where the desire to avoid being perceived as dependent or frail may outweigh the practical benefits of using such devices. Concerns about stigma, cost, and the practicality of mobility aids may influence this decision, indicating a preference for solutions that support autonomy without compromising self-perception.

Overall, these preferences reveal that pre-frail adults are carefully selecting technologies that align with their values and concerns, emphasising safety, autonomy, and proactive health management. Their choices reflect a nuanced approach to technology adoption, where the perceived benefits of maintaining independence and well-being are balanced against potential drawbacks, such as stigma or complexity.

Table 4 presents the questionnaire data statistics, calculated to three decimal places. The table compares the responses of pre-frail older residents (n = 18) with those of specialists (n = 9). Notably, the standard deviation among residents is generally higher than that of specialists, indicating greater variability in their responses. This suggests that the residents' experiences and perceptions of technology are more heterogeneous, likely due to varying levels of familiarity and comfort with technology among this demographic.

In particular, the residents reported lower scores on the subjective norm question and moderate scores on the loss of independence question. These findings align with the agency construct identified earlier in the qualitative analysis, where residents expressed concerns about how technology might influence their independence and how they perceive societal expectations around its use.

A noteworthy observation is that residents did not perceive compatibility as a significant issue. When this is considered alongside their responses regarding performance expectancy and loss of independence, it suggests a portrait of individuals who value their independence and possess a strong sense of agency. Despite their pre-frail status, these residents appear to maintain a confident and self-directed approach to adopting new technologies.

Table 4. Descriptive statistics for CIREI questionnaire responses.

Construct	All Samples [*n* = 27]		Residents [*n* = 18]		Specialists [*n* = 9]	
	Mean	Std	Mean	Std	Mean	Std
Nonspecific Acceptance	3.370	0.742	3.222	0.808	3.667	0.500
Performance Expectancy	3.222	0.847	3.056	0.938	3.556	0.527
Effort Expectancy	3.519	1.087	3.278	1.127	4.000	0.866
Ageism/Prejudice	1.963	1.224	2.278	1.364	1.333	0.500
Loss of Independence	2.704	1.382	3.056	1.305	2.000	1.323
Technology Anxiety	2.481	1.252	2.778	1.353	1.889	0.782
Privacy Concerns	3.259	1.095	3.111	1.183	3.556	0.882
Compatibility	2.333	1.240	2.611	1.335	1.778	0.833
Access to Support	2.963	1.126	2.667	0.970	3.556	1.236
Subjective Norm	3.185	1.001	2.833	0.924	3.889	0.782

Additionally, residents reported higher levels of ageism/prejudice and technology anxiety compared to specialists, indicating that they might face more psychological barriers when engaging with new technologies. This could be due to societal stereotypes about ageing, which may impact their comfort and willingness to embrace technological solutions.

Interestingly, while residents scored relatively high on privacy concerns, the current questionnaire data, supported by qualitative feedback, suggested that privacy was not their primary concern compared to other factors such as usability and support needs. This suggests that while privacy is an important consideration, it may not be as critical a barrier to technology acceptance for this group as it might be for other demographics.

Finally, the lower mean value for access to support among residents highlights a potential area for intervention. Ensuring that adequate support systems are in place could significantly enhance their overall acceptance and effective use of technology, helping to mitigate some of the anxieties and challenges they face.

Figure 11 represents the distributions of the responses to our technology acceptance questionnaire. The analysis of the questionnaire responses from both medical and care specialists and residents reveals varying levels of interest and confidence in adopting smart home assistive technology. Both groups generally show a moderate interest in incorporating these technologies into daily life, with specialists being slightly more optimistic about the potential benefits. Residents, while also recognising the potential for enhanced daily activities, may have more reservations, reflecting a cautious approach to new technologies.

Confidence in operating smart home technology for simple tasks is relatively high among both groups, indicating that usability is not a major barrier. However, residents may require more support and training to feel fully comfortable with these technologies. Specialists appear more confident, likely due to their professional experience with similar technologies, which could make them important advocates and trainers for residents.

Ageism and feelings of exclusion are not prominent concerns for either group, suggesting that age-related prejudice does not significantly affect their attitudes toward technology adoption. However, concerns about losing independence as they age are more pronounced among residents. This fear could either motivate the adoption of assistive technologies as a means of maintaining independence or create resistance if the technology is perceived as diminishing personal autonomy.

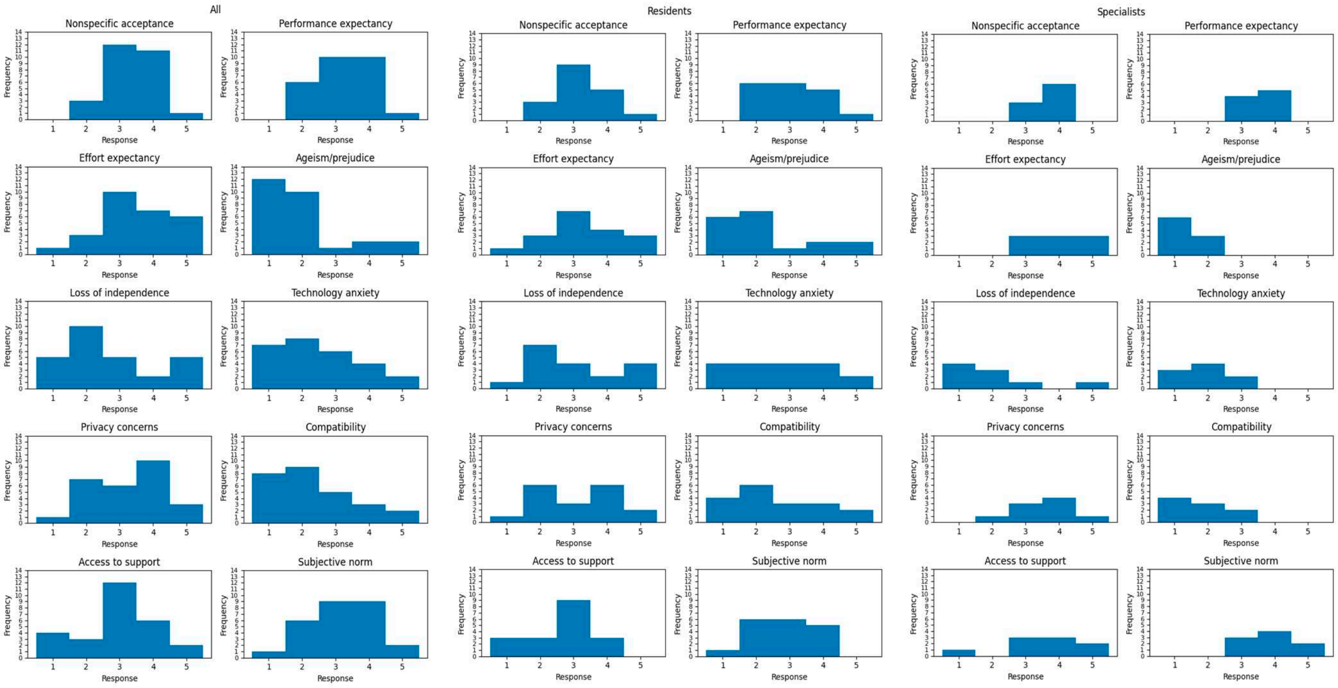


Figure 11. Summarised distribution of questionnaire responses for all participants (**left**), residents (**centre**), and experts (**right**) for each question.

Privacy concerns are a significant barrier, particularly among residents, who are wary of disclosing personal information to technology providers. Both groups also recognise the importance of social influence, with the likelihood of adopting technology increasing if it becomes more mainstream. Compatibility with existing devices and access to support are viewed positively, suggesting that with the right assurances and assistance, the adoption of smart home technologies among pre-frail older adults could be successful.

6. Discussions of Workshop Results

In this section, we introduce our *Conceptual framework for Integrating Robots with Embodied Intelligence* in the homes of older people living with frailty, or CIREI, which was developed to organise and interpret the data and insights generated from our workshop. The framework is the result of our inductive thematic analysis of the qualitative data, capturing the key components and relationships that emerged during our discussions with participants. The CIREI framework is designed to categorise these findings into *Themes* and *Concepts*. Following the development of this model, we also conducted a comparative analysis with existing technology acceptance models to highlight overlaps, gaps, and unique aspects of our findings.

6.1. CIREI Framework

The development of the CIREI framework was shaped by a dynamic integration of systematic literature review and co-design workshops, each playing a distinct yet complementary role. The literature review established a theoretical foundation by identifying prevailing models, existing gaps, and critical factors within the field, which guided the initial direction and focus of our framework. Building on this foundation, the co-design workshops engaged key stakeholders, providing valuable practical insights and contextual feedback. This iterative interplay ensured that the resulting CIREI framework is both grounded in robust academic evidence and responsive to real-world needs, effectively bridging theory and practice to deliver a solution that is comprehensive, relevant, and user-informed.

To organise the data and insights produced by the workshop, our framework was developed following a thematic analysis of the qualitative data. This framework features two main key components, or building blocks, as follows:

(1) "Themes", which are broad, non-situational and fewer in number (*Economic*, *Learning*, *Privacy*, *Trust*, *Usability*).
(2) "Concepts", which are often based on recurring anecdotes or situations described by participants (*Aesthetic concerns*, *Agency*, *Current use of technology*, *Delegating tech actions*, *Individual limitations*, *Intergenerational interaction*, *Logistics of use*, *Low-tech use contexts*, *Online study/video tutorials*, *Personalisation*, *Rate of technological advancement*, *Social connectedness*, *Technology anxiety*).

Some concepts are largely bound to a single theme, while others are cross-cutting or not clearly within the purview of a single identified theme.

The *Learning and Usability* themes are most closely connected to our research questions, but the presence of other themes in the data justifies their inclusion in the framework. Social factors were not prominent or distinct enough to form a separate *Social* theme. However, many items coded under *Agency* reflected participants' agency regarding social pressure, such as their assertion that they would not be influenced by subjective norms.

Most connections between themes and concepts are one-to-one, as illustrated in Figure 12. However, there is a notable three-way intersection *between Intergenerational Interaction*, *Agency*, and *Usability*. Participants reported that usability issues led them to rely on younger relatives for using technology, hindering their proficiency and confidence. This intersection was significant in the data, with multiple data points across groups and activities, warranting its inclusion. The other three-way intersections were not prominent enough to be shown here.

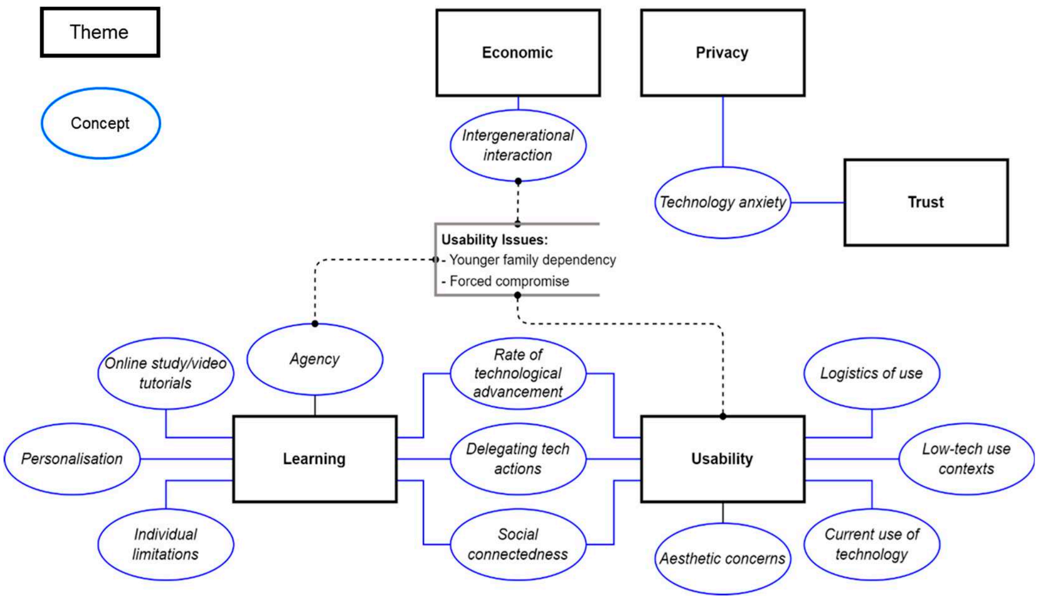


Figure 12. Conceptual framework for integrating robots with embodied intelligence (the CIREI framework). This brings together broad, situational themes (black boxes), linked through concepts drawn from recurring contributions in the participant workshop (blue ovals). Solid lines indicate direct links, and dashed lines indicate indirect links.

6.2. Comparisons Between Identified Constructs in CIREI and Classic TAMs

After developing our model with constructs and relationships based on the collected data, we compared it to the most prominent previously established technology acceptance models, shown in Figure 13, that were identified during the literature review: TAM2 [28] and UTAUT2 [29]. Additionally, we included STAM [30] in this comparison due to its specialisation toward older adults, making it particularly relevant for certain aspects of our analysis.

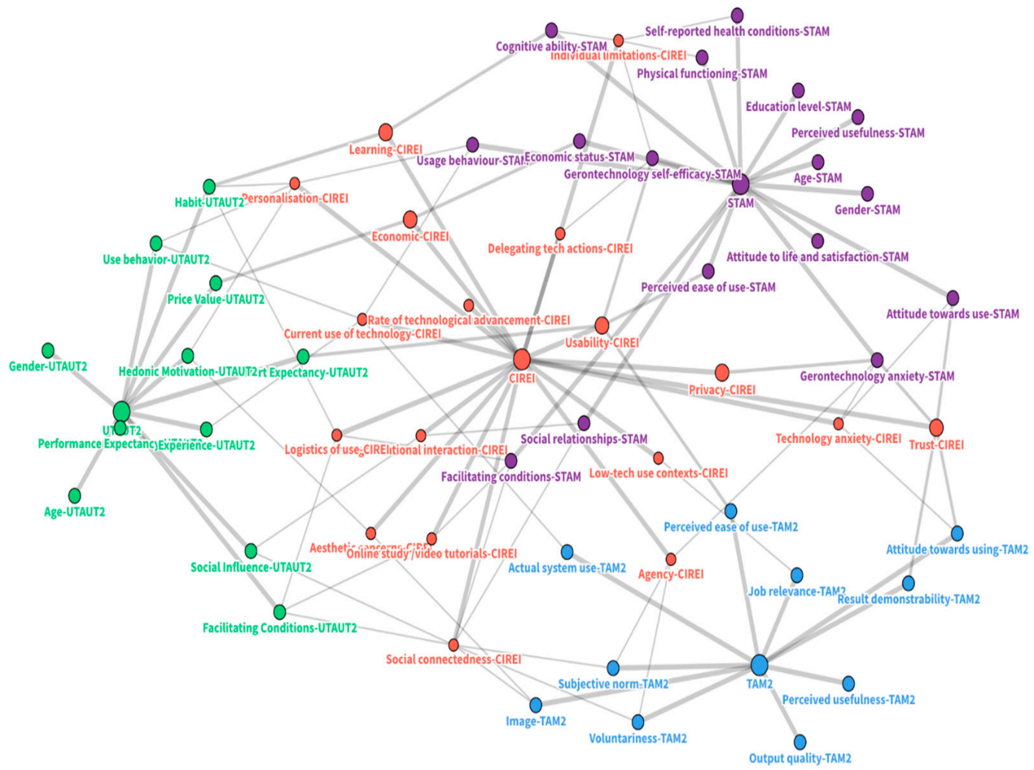


Figure 13. A network graph of connections between constructs in our CIREI model (orange) and constructs in pre-existing models: TAM2 (blue), UTAUT2 (green), and STAM (purple).

It is worth emphasising that our model is not intended to be a universal acceptance predictor; instead, it specifically focuses on ambient assistive smart home technology used by a vulnerable or frail older adult population living independently. TAM2 and UTAUT2 aim for broad applicability across demographics and technology domains. STAM targets older adults using gerontechnology but maintains a wider scope of technology domains. Our model's inclusion of varying granularities—broad themes and specific recurring concepts—is also not mirrored in established models.

Despite these differences, we found some significant overlaps and absences thereof between our model and the established models. Our Agency construct had semantic overlap with TAM2's *Voluntariness* and *Subjective norm*, as well as STAM's *Gerontechnology anxiety*. TAM2 suggests social phenomena, the need to fulfil social obligations, as infringing on one's agency; STAM presents technology use itself as the cause for this concern.

There is a particularly strong connection between our *Individual limitations* concept and the constructs within STAM: *Physical functioning*, *Cognitive ability*, *Self-reported health conditions*, and *Gerontechnology self-efficacy*. This reflects the shared target demographic and the difference in granularity, i.e., we have only a single construct, while STAM has 4 in this case, which could be a product of noise artefacts and our limited data volume.

Other points of convergence are our *Usability* theme and the Current use of technology concept, aligning with constructs across all three existing models: *Gerontechnology self-efficacy*, *Perceived ease of use*, *Effort expectancy*, *Use behaviour* and [past] Experience. Our *Economic* theme overlapped with UTAUT2's *Price value* and STAM's *Economic status*, while *Learning* overlapped with UTAUT2's *Habit* and STAM's *Cognitive ability*. *Logistics of use* found common ground with *Facilitating conditions* in both UTAUT2 and STAM, as well as

Habit in UTAUT2. *Technology anxiety* and *Trust* in our model echoed *Attitudes towards using* in TAM2 and STAM, along with *Gerontechnology anxiety* in STAM.

The only construct unique to our model was the *Rate of technological advancement*. This could be due to its high specificity and the user focus of the compared models, i.e., compared to a focus on the technology. It is also possible that the earlier development of TAM2 and UTAUT2 coincided with a time of rapid advancement, where public awareness of such change was lower. The proliferation of the internet, constant news cycles, and ubiquitous technology may have contributed to a heightened awareness of how current and prospective users relate to changing technologies.

Therefore, the absence of a construct related to the *Rate of technological advancement* in these older models could be seen as a limitation due to their period of origin rather than a difference in user-technology focus. While further research is needed, it seems plausible that explicitly considering the relationship between older adult users and the pace of technological change could improve the explanatory power of acceptance models.

One approach to incorporating this concept could involve framing and presentation of technology as an acceptance factor, which is more controllable and measurable than an abstract *Rate of technological advancement*. There is a precedent for framing's importance, as Dermody et al. [85] identified *Framing* as a major theme when interviewing older adults' caregivers on the possibility of adopting smart home technology to assist with care. Another notable difference is the absence of a *Performance expectancy* or *Perceived usefulness* construct in our model. While workshop participants did not explicitly discuss output quality or performance expectancy as a theme, they seemed to generally assume the effectiveness of the devices.

This omission may be attributed to the context of our study, where participants were introduced to COTS devices during the initial ice-breaking activity. During this session, participants were shown examples of the practical benefits and usefulness of these devices. This implicit understanding likely reduced the need for participants to focus on performance-related factors, as the demonstrated usefulness during the ice-breaking activity may have set a baseline expectation of effectiveness for these COTS devices. This also emphasises the need to provide proper training for PwF to better explain the usefulness of the devices and how they could fit into their environments and daily activities, rather than relying solely on their basic understanding of the devices' functionalities.

Usability was a limiting factor for some technologies, but the data suggests limited participant doubt about the overall performance of the technology itself. It is possible that this is a product of talking points presented by the researchers during the workshop, and not indicative of a change in the general population's beliefs about technology. The CIREI framework provides a structured approach to understanding the factors influencing technology acceptance among older adults, particularly those living with frailty. By categorising data into broad *Themes* and specific *Concepts*, the framework captures the complex interactions between usability, learning, social factors, and individual limitations.

Our comparison with established models, such as TAM2, UTAUT2, and STAM revealed significant overlaps, especially in areas related to usability and individual limitations. However, our model introduces unique constructs, such as the *Rate of Technological Advancement*, that are not present in older models. This highlights the importance of considering contemporary factors, such as rapid technological change, when studying technology acceptance in older populations. Additionally, the absence of *Performance Expectancy* in our model underscores the need for effective training and education, particularly in how these technologies can be integrated into the daily lives of frail older adults. The findings suggest that while older adults may assume the effectiveness of technology, there is still a crucial need for tailored support to enhance their understanding and confidence in using these devices.

Our presented model contributes to the field by introducing the *Rate of Technological Advancement* construct, which fills a critical gap in existing models by capturing older adults' relationship with rapid technological change in today's ubiquitous technology landscape. Our model's dual-granularity approach, incorporating both broad themes and specific concepts, provides more nuanced insights than the uniform construct level of TAM2, UTAUT2, and STAM. The absence of *Performance Expectancy* reveals that proper technology demonstration can establish baseline effectiveness assumptions, shifting focus from performance concerns to usability and integration challenges.

6.3. WISE-WARE: Intelligent Middleware

The proliferation of advanced robotic systems and Internet of Things (IoT) devices presents unprecedented opportunities to enhance the quality of life for individuals living with frailty. However, the full potential of these technologies in creating a truly 'smart and assistive' home environment remains largely unrealised. Based on our research findings, we introduce WISE-WARE, an innovative intelligent middleware framework designed to address the current fragmentation of COTS assistive devices. By creating such a middleware, we aim to (1) synthesise data from connected devices to automate and augment residents' daily activities, and (2) facilitate the secure sharing of anonymised data to foster the development of evidence-based solutions.

By seamlessly integrating diverse assistive technologies and leveraging previously untapped data streams, WISE-WARE serves as a crucial catalyst for cutting-edge research and applied robotics. This integrative approach enables precise identification of support needs, facilitates targeted interventions, and provides profound insights to inform the development of personalised, next-generation home support systems.

We applied the MoSCoW prioritisation method as a part of our semi-structured interviews to ensure that our development efforts were tightly aligned with user needs and project constraints, allowing us to create a minimum viable product that delivers immediate value to People living with Frailty while maintaining a clear roadmap for future enhancements. The application of the MoSCoW method in the development of WISE-WARE proved invaluable for our co-design approach. By categorising features into *Must have*, *Should have*, *Could have*, and *Won't have*, we established a clear hierarchy of priorities that guided our development process.

As shown in Table 5, there is a strong emphasis on user-centred design, accessibility, and adaptability. The *Must-haves* (M1 and M2) prioritise usability and independence, ensuring that users can learn at their own pace and troubleshoot problems easily. The *Should-haves* (S1, S2, and S3) focus on flexibility, user control, and adaptability, highlighting the importance of accommodating individual needs and preferences.

The *Could-haves* (C1 and C2) introduce advanced features that could enhance the user experience, such as personalised tutoring and integrated assistance from multiple devices. Notably, the *Won't-have* (W1) requirement indicates that WISE-WARE design and implementation should not focus on developing various control modalities as user faculties deteriorate at this current stage, emphasising the need for a simple and intuitive interface.

Building on these recommendations, we designed our intelligent middleware based on the open-source FIWARE v.8.6 architecture to enable standardised and interoperable intelligent solutions, shown in Figure 14. This approach allowed us to integrate proprietary 3rd-party robotic and assistive technology services and expose their functionalities using technologies similar to FIWARE next-generation service interfaces (NGSI) API. This approach not only enhances the flexibility and scalability of WISE-WARE but also fosters a collaborative ecosystem, where diverse stakeholders can contribute to the development of innovative, user-centred solutions for individuals living with frailty.

Table 5. MoSCoW analysis results for WISE-WARE system requirements.

Category	Features
Must	**(M1)** Give users the ability to *learn* how to use it based on their own pace and learning style **(M2)** It is easy to *troubleshoot* problems to maintain independence
Should	**(S1)** Allow the use of *varied, affordable* devices **(S2)** Allow users to control *data privacy* and avoid feeling observed **(S3)** Adapt to individual *needs* and *preferences*
Could	**(C1)** Integrate chatbots to provide *personalised tutoring* **(C2)** Provide *integrated assistance* (from multiple devices) to help maintain independence
Won't	**(W1)** Use various *control modalities* as the user's faculties deteriorate

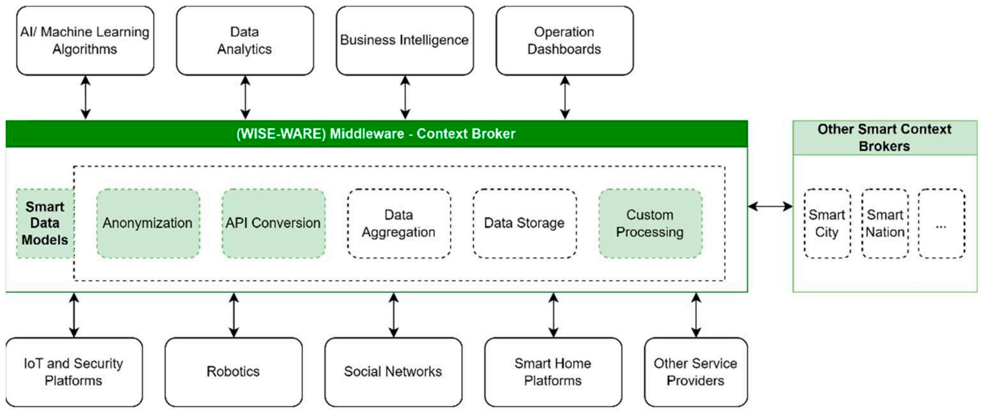


Figure 14. WISE-WARE middleware architecture. WISE-WARE enables the integration of smart data models for anonymisation, API conversion, and data aggregation and storage. This middleware multi-layer architecture facilitates communication with home and external smart systems, including home IoT devices, smart home platforms, and other smart context brokers.

The FIWARE-based design of WISE-WARE enables seamless integration of a diverse array of robotics and assistive technology devices, as well as other services, allowing for streamlined processing and consumption by various AI, operational, business, and data analytics applications. Furthermore, this architecture facilitates the integration of the home environment with other smart solutions and systems at different geographical levels, fostering a holistic and interconnected ecosystem.

A critical aspect of this design is the emphasis on data privacy and security, where all data is stored locally on the user's home device, thereby limiting exposure of personal data without proper anonymisation, encryption, and explicit user consent. By aggregating data from multiple sources and sensors, this approach enables the development of multi-modal intelligent solutions capable of delivering unprecedented preventive care and interventions, ultimately enhancing the quality of life for individuals living with frailty.

It is essential to acknowledge the importance of obtaining explicit and informed consent from the users of the system and its connected devices, particularly if they are used in sensitive environments such as bathrooms and bedrooms, where privacy concerns are heightened. To address this, researchers and service providers need to ensure that users provide clear and informed consent before participating in any aspect of these activities. In accordance with GDPR regulations, participants should be fully informed about how their data will be collected, used, and stored, and that they have the right to withdraw consent at any time. Furthermore, participants should be made aware of their "right to be forgotten," which allows them to request the deletion or the anonymisation of their data at any point during or after the conclusion of these activities.

We successfully implemented our intelligent middleware by leveraging a suite of open-source technologies, including Apache Kafka for distributed event streaming, Home Assistant for home automation, and Python v.3.11.2 as the primary programming language. The middleware was deployed on a Raspberry Pi 4 (RPi4) (Cambridge, UK) using Docker v.23.0, an open-source software platform for virtualised applications, to ensure seamless execution and portability. Our implementation was rigorously tested with a diverse array of assistive devices from prominent providers, such as SwitchBot (Beijing, China), Aldebaran Robotics (NAO Robot) (Paris, France), TP-Link (Shenzhen, China), Amazon (Alexa) (Synnyvale, CA, USA), FIBARO (Poznan, Poland), and Philips (Eindhoven, Netherlands), at two state-of-the-art facilities—the Sheffield Hallam University Robotics Lab and the University of Nottingham's Cobot Maker Space. Testing was conducted by the researchers and did not involve other human participants. While the intricacies of the middleware implementation and testing scenarios are beyond the scope of this paper, we have made all developed software, documentation, and installation videos publicly available on our dedicated GitHub (San Francisco, CA, USA) repository, facilitating reproducibility and future collaboration.

Several Proof of Concept (PoC) applications were developed to facilitate experiments assessing the feasibility and usability of the WISE-WARE middleware for integrating and processing data streams from diverse robotics and assistive technology devices. The experimental work was structured around three usage scenarios, shown in Table 6. The selection of these applications was guided by the most-requested features emerging from the workshop (see Table 5), prioritising deployments that were feasible for lab testing and directly applicable to enhancing Activities of Daily Living (ADLs).

These usage scenarios highlight the potentials of integrated smart home systems to enhance the ADLs through context-aware automation and behaviour monitoring. By integrating environmental and activity sensors, the system provides insights into user habits, such as meal patterns and movement, enabling early detection of behavioural changes or health risks like falls, all while maintaining privacy. Furthermore, automation based on natural events, like sunrise and sunset, promotes a seamless and personalised user experience, fostering comfort and well-being. These examples demonstrate the broader potential of such systems to support independent living, proactive health management, and improved quality of life.

The proof-of-concept applications developed to demonstrate the benefits of WISE-WARE were designed with accessibility in mind, ensuring they can be used effectively by individuals with minimal technical expertise. The educational level required to operate these applications is comparable to that of using everyday smartphone applications, making them intuitive and user-friendly. While initial setup may require some assistance, significant efforts were made to streamline the user experience, enabling users to access core functions effortlessly without the need for specialised training or advanced technical knowledge.

Systems and applications can be configured to reduce cognitive complexity by simplifying language, incorporating coloured or animated graphics and symbols, or utilising voice-based virtual assistants. To enhance accessibility and usability, it is essential to ensure that all communicated information is available in multiple formats (text, visual, and auditory) and to personalise these communication channels according to user preferences. Such measures would significantly improve the solution's accessibility, perceived usability, and overall effectiveness.

Table 6. WISE-WARE testing and usage scenarios for proof-of-concept applications.

Example Usage Scenario	Devices (Brand)	Location
A kitchen cupboard contact sensor logs "door open/close" events in HomeAssistant to track eating habits and forgetfulness, while triggering Alexa to announce the weather on the first morning opening.	Contact sensor (Switchbot) Smart speaker (Amazon)	Robotics Lab, Sheffield Hallam University
Corresponding MoSCoW Features	**(S1)** Allow the use of *varied, affordable* devices **(S3)** Adapt to individual *needs* and *preferences*	
Motion sensors track inactivity and movement patterns, cross-referencing wearables to detect falls without cameras, while analysing activity trends for fitness insights.	Motion sensors (Switchbot, Fibaro) Wearable device (Fitbit, San Francisco, CA, USA)	Cobot Maker Space, University of Nottingham
Corresponding MoSCoW Features	**(S2)** Allow users to control *data privacy* and avoid feeling observed **(C2)** Provide *integrated assistance* (from multiple devices) to help maintain independence	
A light sensor detects sunrise/sunset to automate curtains, while a mattress pressure sensor confirms wake-up and triggers Alexa to play music for a gentle morning routine.	Light sensor (Switchbot) Motorised curtain rod (Switchbot) Smart speaker (Amazon)	Robotics Lab, Sheffield Hallam University
Corresponding MoSCoW Features	**(S1)** Allow the use of *varied, affordable* devices **(S3)** Adapt to individual *needs* and *preferences* **(C2)** Provide *integrated assistance* (from multiple devices) to help maintain independence	

The success of WISE-WARE depends on several external factors, including reliable internet connectivity for seamless data transmission and monitoring activities, with user consent, continuous power supply for connected devices, effective collaboration and support from caregivers and healthcare providers for timely responses in emergencies, and the integration with local community services to provide holistic care management.

For a smart home middleware serving individuals with frailty, such as WISE-WARE, regular software updates on a quarterly basis are essential to ensure security and functionality, addressing vulnerabilities that could impact user safety, as recommended by NIST cybersecurity guidelines and industry best practices [86]. In addition, hardware checks and calibration for the used hardware, in this case, it was deployed on a RPi4, should be conducted every 6–12 months to maintain and test device responsiveness, which is critical for potential cases where the middleware is connected to systems performing emergency detection and monitoring frail individuals [87].

System monitoring and diagnostics should be an ongoing activity, with automated reports generated monthly to detect connectivity issues or device malfunctions, minimising downtime. Finally, user interface adjustments might be necessary every 6–12 months or as needed to accommodate the evolving needs of frail individuals, ensuring the system remains intuitive and accessible. Ultimately, this research positions WISE-WARE as a transformative platform, poised to significantly advance the field of smart assistive technologies and improve the lives of individuals with frailty.

7. Limitations

The practical aspects of our workshop methodology encountered several limitations that warrant attention for future improvements. First, a significant challenge was the varying degree of facilitator engagement with the provided materials, which likely influenced the consistency and effectiveness of the facilitation across different sessions. Furthermore, the data collected from interviews exhibited some variability due to deviations from the set protocols and the application of diverse interview techniques by the facilitators. While this introduced a degree of inconsistency, it also provided a broader range of perspectives, which, although challenging, enriched the overall analysis.

Another notable limitation was the scope of our sample size and its representation. The study was limited to a single workshop, which constrained the volume and variety of insights we were able to gather. Moreover, our participants were exclusively residents of (JJ) Housing schemes in the South Yorkshire region, representing a narrow segment of the potential user base for assistive technologies. Despite including residents from various schemes within JJ Housing, the lack of external representation limited the broader applicability of our findings. JJ Housing was considered in this study due to its existing digital infrastructure, established partnerships with care providers, and willingness to support pilot deployment, making it a feasible and representative testbed for evaluating the WISE-WARE system under real-world conditions.

Additionally, the demographic makeup of our sample was predominantly white, further narrowing the diversity of perspectives and experiences captured in our study. This limited representation of racial and ethnic minorities constrains the generalisability of our findings across different demographic groups, which may have distinct interactions with and opinions about assistive technologies. These limitations highlight the necessity for adopting a more inclusive and standardised approach in future research efforts. Expanding participant recruitment, ensuring thorough facilitator preparation, and enforcing rigorous standardisation of interview processes will be crucial steps toward enhancing the validity and applicability of future studies.

8. Conclusions

In this study, we investigated the barriers and facilitators to the adoption of smart home technology by older adults living independently and explored how their use of these technologies could contribute to their care and management of chronic conditions. Our approach consisted of a systematic literature review and the design and delivery of a co-creation workshop with 30 participants sourced with the support of our partners: Astraline, JJ Housing and Darnel Wellbeing. The data analysis resulted in the development of a proof-of-concept middleware, viz. WISE-WARE, and the creation of documentation for its development process, usage, and guides for aiding integration and extension of the proposed system.

The systematic review identified four major themes: acceptance models, digital divide, frailty, and barriers and facilitators to adoption. The review revealed the importance of understanding user acceptance for technology adoption among older adults and highlighted the role of established models like TAM, UTAUT, and STAM in exploring motivations and challenges. However, there is a need to move beyond basic acceptance towards actionable design principles. The review also emphasised the digital divide, which goes beyond access to technology and encompasses usage skills and comfort levels. Psychological factors, such as internalised ageism, can hinder adoption, and design should address not just usability, but also social and emotional considerations. Frailty presents a challenge for technology adoption due to physical and cognitive limitations, and tailored solutions are crucial based on the individual's frailty status. The review also highlighted the importance of factors such as technology experience, perceived value, and confidence in influencing adoption, and the need for user-centred design, clear communication strategies, and inclusive research.

The co-creation workshop results led to the creation of a model, viz. The CIREI framework, which represents the workshop findings, featuring broad themes and recurring concepts. These constructs reveal factors influencing technology acceptance, some of which are specific to older adult users, such as economic considerations, learning preferences, privacy concerns, and usability. The new model, with its focus on user-specific themes and the rate of technological advancement concept, offers a potential starting point for further research on technology acceptance in this population.

The CIREI framework advances technology acceptance models by introducing the *Rate of Technological Advancement* construct and employing a dual-granularity approach that provides more nuanced insights than existing uniform-level models. The framework's specificity to vulnerable older adult populations and emphasis on contemporary technological contexts represents a meaningful evolution in understanding technology acceptance among frail older adults living independently.

The proof-of-concept middleware development demonstrated that commercially available, off-the-shelf smart home technologies can be integrated with smart home management systems like Home Assistant, collating data into a single data stream. This data can be stored, transported, and processed using industry-standard tools, allowing for modular and effective business intelligence, resident monitoring, and rich insight-generating solutions.

Our other research questions focused on the design and implementation of assistive technology that can be easily retrofitted into existing homes (R1b), the learning preferences of older adults for new technology (R2a), and the impact of these preferences on the design and implementation of assistive technologies (R2b).

To answer R1b, we conducted a co-creation workshop to explore the perceptions of older adults regarding the challenges of integrating COTS assistive technology into their homes. The workshop identified themes such as economic considerations, usability issues, privacy concerns, and the importance of maintaining agency. The workshop findings inform the design of assistive technologies that can be easily retrofitted into existing homes, with usability being a key factor for user adoption. Designers should consider the potential limitations (cognitive, physical) of older adults to ensure that the technology is accessible and easy to use.

To address R2a, we explored the learning preferences of older adults for new technology. Although the co-creation workshop did not directly address preferred learning methods, it highlighted the importance of user-centred design and education. Future research can explore how older adults prefer to learn about new technologies, such as through hands-on training, written materials, or video tutorials. This information can be used to develop educational mechanisms that enhance technology adoption and improve the quality of life for older adults.

R2b focused on the impact of learning preferences on the design and implementation of assistive technologies, including educational mechanisms like chatbots. The workshop highlighted a need for educational mechanisms to improve technology adoption, and participants discussed options like chatbots. Future research can explore user preferences for educational tools alongside user needs identified in the workshop. By understanding the learning preferences of older adults, we can create educational mechanisms that are tailored to their needs, ultimately enhancing technology adoption and improving their quality of life.

In conclusion, this study provides valuable insights into the barriers and facilitators to smart home technology adoption among older adults living independently. The systematic review and co-creation workshop results highlight the importance of user-centric design, consideration of socio-emotional impactors on technology acceptance, and the need to focus on actionable design insights. The proof-of-concept development presents a compelling case that the available technology is sufficiently usable and fit for purpose to create such systems, while being cost-effective and easy to deploy. Future research should focus on longitudinal studies, exploration of learning preferences, performance expectancy, social aspects of technology adoption, and quantifying user needs to refine the newly developed model.

9. Responsible Research and Innovation (RRI) Practices

This research demonstrates the effective application of Responsible Research and Innovation (RRI) principles in a research project, specifically adhering to the Anticipate-Reflect-Engage-Act (AREA) framework recommended by the Engineering and Physical Sciences Research Council (EPSRC) [88]. The integration of these principles ensured that our research not only met scientific objectives but also aligned with broader societal values, contributing positively to both the scientific community and the public.

Prior to the design phase, we conducted a virtual stakeholder workshop using RRI Prompt & Practice Cards [89]. This facilitated discussions on potential regulatory, societal, legal, and ethical impacts on project success. The workshop aimed to anticipate both positive and negative outcomes, enabling proactive addressing of challenges in the study design. Figure 15 illustrates an example of an "Anticipate" card used during the workshop, designed to stimulate discussion on potential impacts and future considerations.

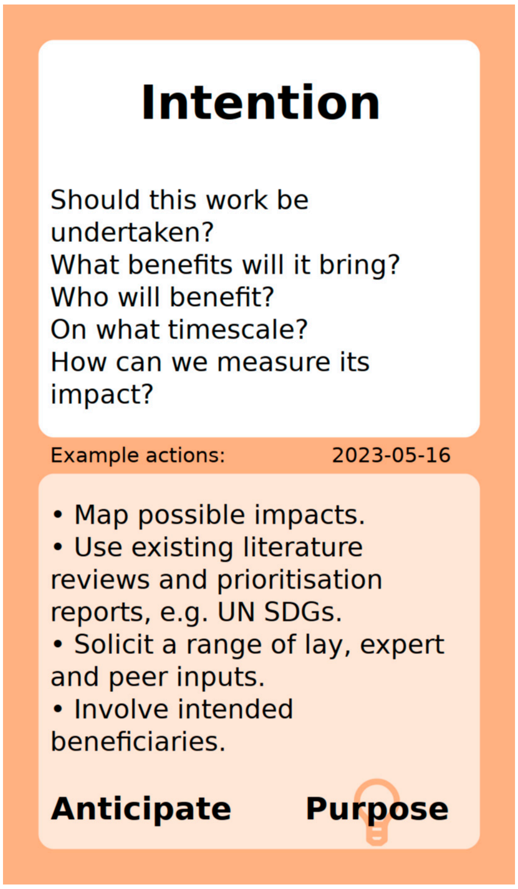


Figure 15. Example of an AREA brainstorming card used during the workshop. This card represents one of the "Anticipate" cards, designed to facilitate discussions on our project's potential impact and future considerations.

Informed consent was a critical element of our methodology. Prior to participation in the experiments and co-design activities, all participants signed a consent form. They were provided with detailed information about the study's objectives, procedures, potential risks, and benefits through a *Participant Information Sheet*. Participants were assured that any data collected would be used exclusively for research purposes and treated with strict confidentiality. The project also underwent a thorough ethical review and received approval, ensuring compliance with relevant ethical standards.

Throughout the project lifecycle, we maintained an ongoing assessment of potential research impacts, including both intended and unintended outcomes. This continuous anticipation process informed decision-making at every stage, ensuring that our research remained responsive to emerging challenges and opportunities. Reflection was a cornerstone of our RRI approach, involving continuous examination of the broader societal, ethical, and legal implications of our research. This process aligned with the framework's emphasis on thoughtful consideration of assumptions and uncertainties inherent in scientific inquiry. A second workshop was held to critically evaluate the design choices of our codesign activities, recruitment challenges, and lessons learned from interacting with people living with frailty and experts in the field.

We applied a systematic approach to evaluate our activities, assessing whether they achieved desired outcomes, particularly in terms of inclusivity and accessibility. Special attention was given to the cognitive demands of the activities and their potential for replication with different participant groups. This reflection helped identify limitations in our research, particularly regarding demographic diversity among participants. These limitations are discussed in length in the next section.

Inclusive dialogue with a wide range of stakeholders played a key role in our process. We engaged diverse groups throughout the project, including individuals living with frailty, field experts, and members of the public. This approach ensured that multiple perspectives were incorporated into our decision-making process. Co-design activities were employed to involve stakeholders in the development of research outputs, ensuring relevance and meaningfulness to target users. These activities were carefully designed to accommodate participants with varying cognitive abilities, with ongoing efforts to enhance research accessibility.

Our engagement process revealed that the designed activities were appropriate for the chosen demographic, and we did not encounter significant issues related to participants' understanding of technology and its impact. This insight was crucial for validating our approach and ensuring meaningful participation across our activities.

Our action phase involved implementing comprehensive strategies to address identified limitations and challenges, with a particular focus on enhancing demographic diversity and inclusivity. Recognising the need for a more representative participant pool, we took immediate steps to broaden our recruitment efforts. We successfully engaged participants from multiple JJ Housing schemes, which significantly expanded the range of perspectives and experiences represented in our study. This approach not only increased the diversity of our participant base but also provided valuable insights into how different housing environments might influence the experiences and needs of our target population. Additionally, we discussed concrete plans to actively recruit participants from a wider range of backgrounds in future research initiatives.

As part of our commitment to RRI, we have planned a comprehensive dissemination strategy. Research results will be shared with participants, providing opportunities for further discussion and feedback. Follow-up on-demand sessions will be organised to facilitate in-depth discussions about research implications, offering a platform for questions and insights from participants. This ongoing dialogue is crucial for ensuring that our research remains relevant and responsive to community needs. We are committed to actively incorporating feedback from these sessions into our future work, creating a cycle of continuous improvement and stakeholder engagement.

Our experience highlighted both the benefits and challenges of implementing RRI principles. While we successfully engaged diverse stakeholders and anticipated various impacts, we also identified areas for improvement, particularly in relation to achieving greater demographic diversity among participants. Moving forward, we are committed to building upon these experiences to further enhance our RRI practices. This includes developing more robust strategies for inclusive participant recruitment, refining our reflection processes, and expanding our engagement methods to reach even broader segments of society.

Supplementary Materials: The following supporting information can be downloaded at: https://github.com/A-Al-Tamimi/CIREI (last accessed 26 July 2025), All project software, research instruments, and supporting information.

Author Contributions: Conceptualisation, A.-K.A.-T.; methodology, A.-K.A.-T. and L.H.; software, L.H. and A.-K.A.-T.; validation, L.H. and A.-K.A.-T.; formal analysis, L.H., A.-K.A.-T., D.C. and M.S.; investigation, L.H., A.-K.A.-T. and A.M.; resources, A.-K.A.-T.; data curation, L.H. and A.-K.A.-T.; writing—original draft preparation, A.-K.A.-T., L.H., D.C. and M.S.; writing—review and editing, A.M.; visualisation, L.H. and A.-K.A.-T.; supervision, A.-K.A.-T.; project administration, A.-K.A.-T. and L.H.; funding acquisition, A.-K.A.-T. and A.M. All authors have read and agreed to the published version of the manuscript.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author (a.al-tamimi@shu.ac.uk).

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Abbreviations

The following abbreviations are used in this manuscript:

AAL	Ambient Assisted Living
ADL	Activities of Daily Living
AI	Artificial Intelligence
AREA	Anticipate-Reflect-Engage-Act
AT	Assistive Technology
CIREI	Conceptual framework for Integrating Robots with Embodied Intelligence
COTS	Commercial Off-The-Shelf
EPSRC	Engineering and Physical Science Research Council
FIWARE	Future Internet-ware
GDPR	General Data Protection Regulation
IAF	Integrated Acceptance Framework
ICT	Information and Communication Technology
IoT	Internet of Things
JJ	Johnnie Johnson
MoSCoW	Must have, Should have, Could have, and Won't have
NGSI	Next Generation Service Interfaces
NIST	National Institute of Standards and Technology
PEOU	Perceived Ease of Use
PPI	Patient and Public Involvement
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
PU	Perceived Usefulness
PwF	People living with Frailty
RPi4	Raspberry Pi 4
RRI	Responsible Research and Innovation
SRS	Software Requirements Specifications
STAM	Senior Technology Acceptance Model
SWAM	Smart Wearable Acceptance Model
TAM	Technology Acceptance Model
UNWPP	United Nations World Population Prospects
UTAUT	Unified Theory of Acceptance and Use of Technology

Appendix A

Figure A1. Brainstorming Facilitator Guide. This is a part of the presented structured protocol for the co-creation workshop's brainstorming activity, consisting of: the dual-purpose prompt card system (cf. Figure 4), facilitator techniques or guide for eliciting participant experiences (presented here), and the timed group discussion format with six parallel teams addressing rotated prompt sets.

Appendix B

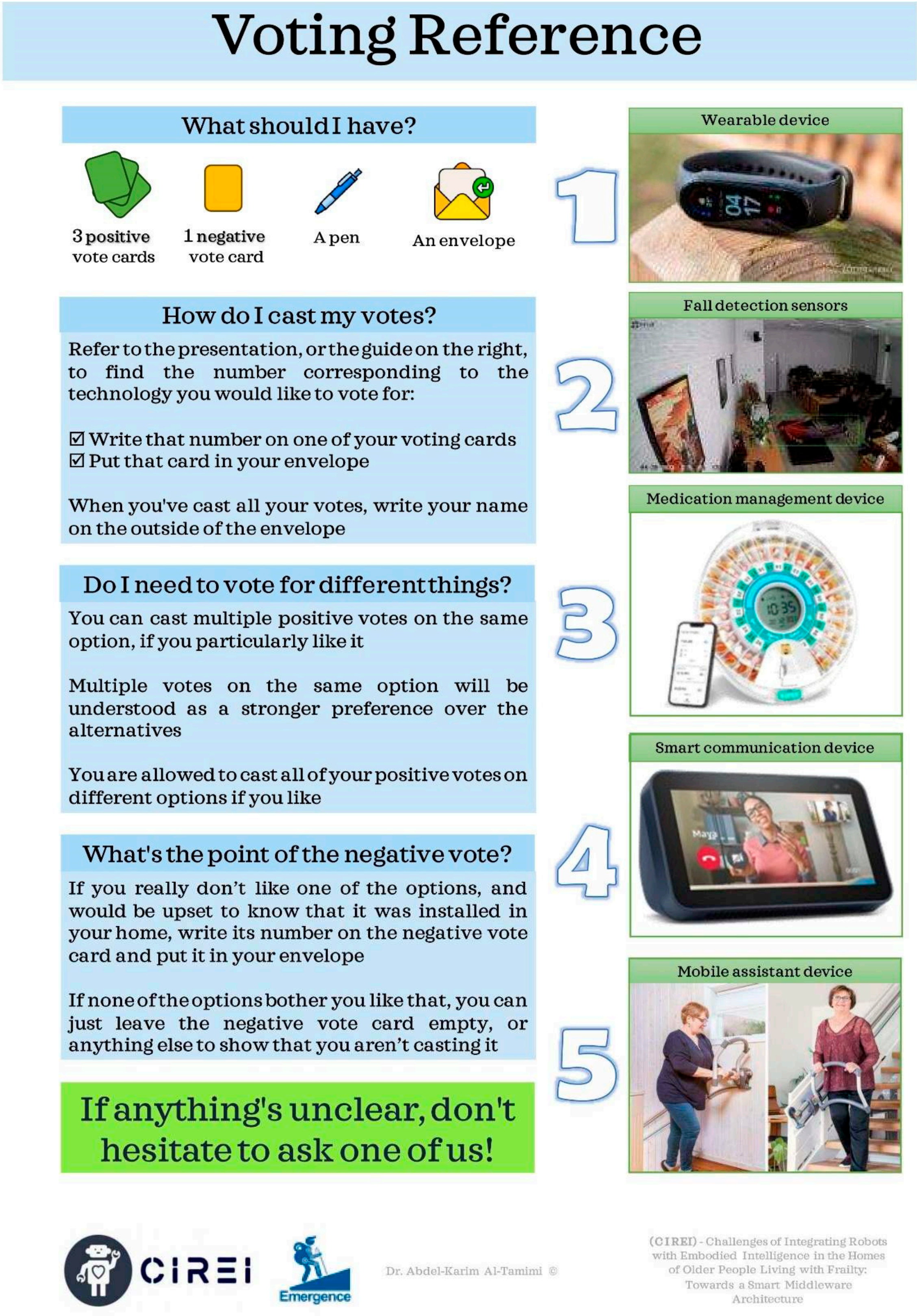

Figure A2. Dot Voting Reference Document. Participants voted by writing a technology number on green cards (approval) or yellow cards (disapproval), with multiple green cards indicating stronger support. Votes were submitted anonymously in sealed envelopes for confidential analysis. The reference document guided this structured feedback process.

Appendix C

CIREI SMART HOME SURVEY

Resident or **Specialist**
?
Please circle the one that applies

For each question, please circle the option of your choice

You may scribble something out if you made a mistake, but please ensure your correct choice is clear

Construct	Question				
Nonspecific Acceptance	How interested are you in incorporating smart home assistive technology or robotics into your daily life?				
	Not at all	Slightly	Moderately	Very	Extremely
Performance Expectancy	To what extent do you believe smart home assistive technology or robotics could enhance your daily activities?				
	Not at all	Slightly	Moderately	Very	Extremely
Effort Expectancy	How confident are you in your ability to operate smart home assistive technology or robotics for simple tasks?				
	Not at all	Slightly	Moderately	Very	Extremely
Ageism/ prejudice	To what extent do you feel excluded from things because of your age?				
	Not at all	Slightly	Moderately	Very	Extremely
Loss of Independence	To what extent do you feel that you are becoming less independent as you get older?				
	Not at all	Slightly	Moderately	Very	Extremely
Technology anxiety	How apprehensive do you feel about using modern, computerised technology?				
	Not at all	Slightly	Moderately	Very	Extremely
Privacy Concerns	How risky do you feel it is to disclose personal information to smart home assistive technology or robotics providers?				
	Not at all	Slightly	Moderately	Very	Extremely
Compatibility	How difficult do you feel it would be to use smart home assistive technology or robotics with your current technology (eg. smartphone, tablet)?				
	Not at all	Slightly	Moderately	Very	Extremely
Access to support	How much help could you get with technology difficulties, if you needed it?				
	Not at all	Slightly	Moderately	Very	Extremely
Subjective norm	How likely would you be to start using smart home assistive technology and robotics if it became more popular and mainstream?				
	Not at all	Slightly	Moderately	Very	Extremely

CIREI   Emergence

If any of the questions don't make sense, or you need help with something, feel free to ask one of us!

Figure A3. CIREI Survey Form. This structured questionnaire featuring 10 key instruments selected for their empirical validity and project relevance. Administered to residents and specialists, the form captured quantitative responses on a 5-point Likert scale to assess technology adoption drivers (e.g., ease of use, compatibility) and barriers.

Appendix D

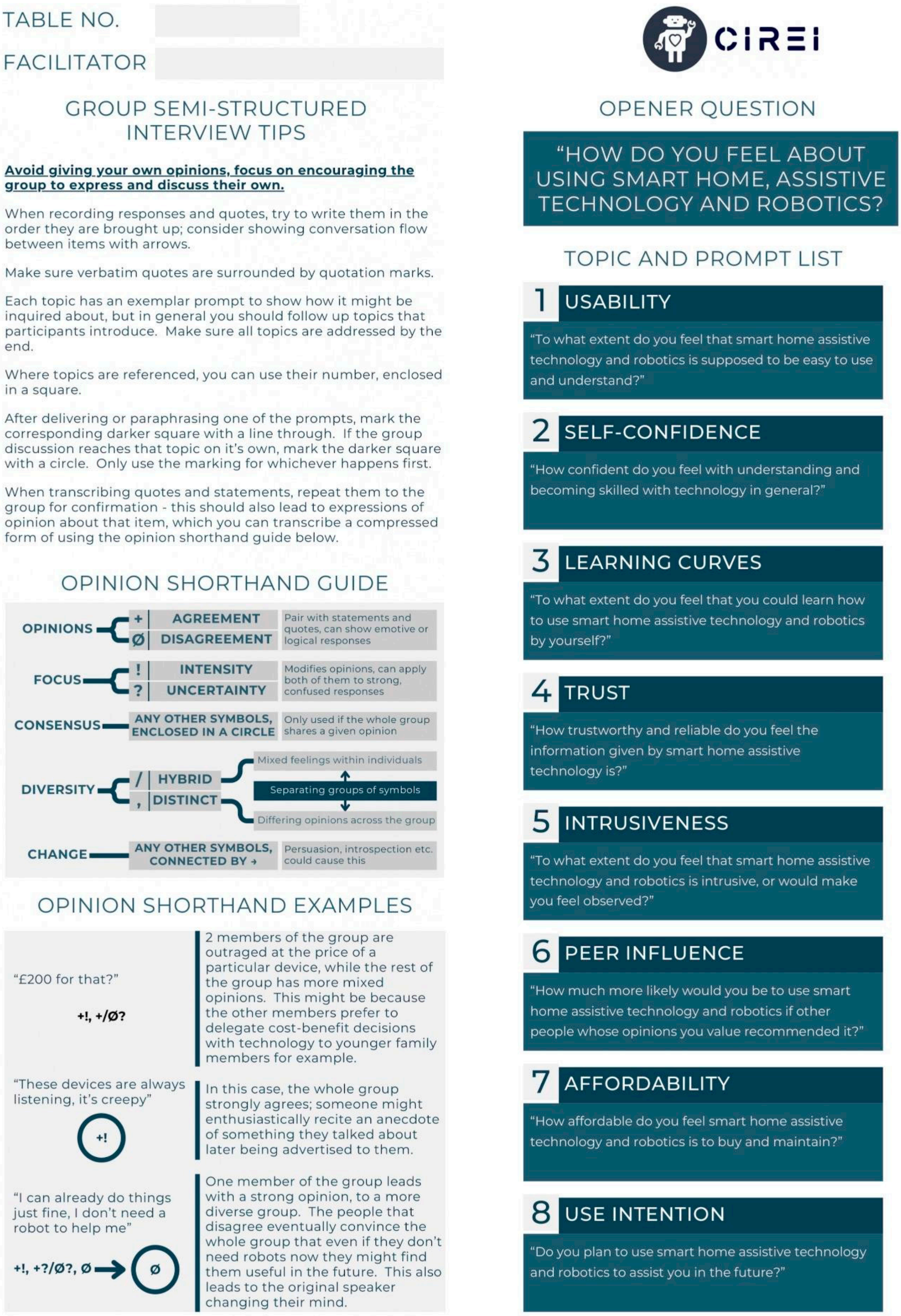

Figure A4. Facilitator Guide for Semi-Structured Interviews. This guide is used in the presented structured protocol for conducting group interviews, featuring 8 core topics (e.g., usability, trust) with open-ended prompts and a standardised discussion loop. Facilitators guided conversations organically while documenting responses through verbatim quotes and consensus checks, using shorthand notation to capture opinion diversity and shifts.

Appendix E

Table A1. Boolean Search Strings for Systematic Literature Review. These Boolean search terms were used to query Scopus, PubMed, and Web of Science databases for related studies. Each database's unique syntax requirements were accommodated while maintaining consistent search logic across platforms.

Database	Search String
Scopus	TITLE ((“Challenge*” OR “Limit*” OR “Barrier*” OR “Accept*” OR “Access*” OR “Concern*” OR “Obstacle*” OR “Issue*” OR “Inhibt*” OR “Constraint*” OR “Restrict*” OR “Adopt*” OR “Embrace*” OR “Imped*”) AND (“Assistive” OR “Technolog*” OR “Digital” OR “Integrat*” OR “Automat*” OR “home management” OR “smart*” OR “aid*” OR “inclusive*” OR “support*”) AND (“Old*” OR “Aging” OR “Senior*” OR “Elder*” OR “Age” OR “Geriatric*”)) AND PUBYEAR > 2017 AND PUBYEAR < 2024 AND (LIMIT-TO (DOCTYPE, “ar”) OR LIMIT-TO (DOCTYPE, “cp”) OR LIMIT-TO (DOCTYPE, “ed”)) AND (LIMIT-TO (LANGUAGE, “English”))
PubMed	((Challenge [Title]) OR (limit [Title]) OR (Barrier [Title]) OR (Accept [Title]) OR (Access [Title]) OR (concern [Title]) OR (obstacle [Title]) OR (issue [Title]) OR (inhibit [Title]) OR (constraint [Title]) OR (restrict [Title]) OR (adopt [Title]) OR (embrace [Title]) OR (imped [Title])) AND ((assistive [Title]) OR (technology [Title]) OR (technologies [Title]) OR (digital [Title]) OR (integrate [Title]) OR (integration [Title]) OR (automate [Title]) OR (automation [Title]) OR (home management [Title]) OR (smart [Title]) OR (aid [Title]) OR (inclusive [Title]) OR (support [Title]))) AND ((old [Title]) OR (aging [Title]) OR (age [Title]) OR (senior [Title]) OR (elder [Title]) OR (geriatric [Title]))
Web of Science	(TI = (Challenge) OR TI = (limit) OR TI = (barrier) OR TI = (accept) OR TI = (access) OR TI = (concern) OR TI = (obstacle) OR TI = (issue) OR TI = (inhibit) OR TI = (constraint) OR TI = (restrict) OR TI = (adopt) OR TI = (embrace) OR TI = (imped)) AND (TI = (assistive) OR TI = (technology) OR TI = (technologies) OR TI = (digital) OR TI = (integrate) OR TI = (integration) OR TI = (automate) OR TI = (automation) OR TI = (home management) OR TI = (smart) OR TI = (aid) OR TI = (inclusive) OR TI = (support)) AND (TI = (old) OR TI = (aging) OR TI = (age) OR TI = (senior) OR TI = (elder) OR TI = (geriatric))

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