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Survey paper

# Assistance from the Ambient Intelligence: Cyber–physical system applications in smart buildings for cognitively declined occupants

Xinghua Gao [a,*], Saeid Alimoradi [a], Jianli Chen [b], Yuqing Hu [c], Shu Tang [d]

[a] Myers-Lawson School of Construction, Virginia Polytechnic Institute and State University, 1345 Perry Street, Blacksburg, VA 24061, USA
[b] Department of Civil and Environmental Engineering, University of Utah, Salt Lake City, UT 84112, USA
[c] Department of Architectural Engineering, The Pennsylvania State University, University Park, PA 16802, USA
[d] Design School, Xi'an Jiaotong-Liverpool University, 111 Ren'ai Rd., Suzhou, 215123, PR China

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## ABSTRACT

Caregivers have traditionally provided assistance and care to patients with cognitive decline, but this has resulted in financial and emotional burdens for both caregivers and patients, impacting their quality of life. To address this issue, Ambient Assistive Living (AAL) technologies that incorporate Internet of Things (IoT) and Artificial Intelligence (AI) can replace or complement caregivers by enabling intelligent learning in smart buildings. This review evaluates the intelligence complements provided by smart buildings enabled with such capabilities to increase the quality of life and autonomy of cognitively declined occupants. Existing contributions primarily focus on learning occupants' behavior to identify assistive services and solutions, which are delivered through technological interventions or caregivers. However, there are several key research gaps that need to be addressed. The most important is the lack of adequate implementation of technological interventions to fully support the occupants' autonomy and independence. Other gaps include challenges in usability and acceptability, ethical concerns, systems' comprehensiveness, and the need for human-in-the-loop. To address these gaps, a conceptual framework is proposed as future research directions for the applications of smart buildings supporting cognitively declined occupants. The framework aims to facilitate the implementation of technological interventions that can enhance occupants' autonomy and independence, address usability and acceptability challenges, and ensure ethical considerations and system comprehensiveness. This review provides insights into the current state-of-the-art of AAL technologies and highlights research directions for improving the quality of life and autonomy of cognitively declined occupants.

## 1. Introduction

Individuals with cognitive decline commonly experience difficulties with problem-solving, memory, comprehension, and attention (Maresova et al., 2018). These challenges often result in incoherent behavior and errors when performing tasks, as compared to healthy individuals (Bouchard et al., 2007; Chaurasia et al., 2014). The capacity of individuals with cognitive decline to perform simple tasks and instrumental activities of daily living (IADLs) is decreased, limiting their ability to live independently at home (Bouchard et al., 2007; Chaurasia et al., 2014). Activities such as cooking, dressing, grooming, bathing, and housework, are particularly challenging for these individuals to initiate or complete (Seelye et al., 2012; Ganesan et al., 2019). Institutionalized or hospitalized care, or support from family members or caregivers at home, are often required for these individuals to successfully perform activities of daily living (ADLs) (Lam et al., 2017). Due to forgetfulness associated with cognitive decline, caregivers often need to provide frequent reminders to patients. In advanced stages of cognitive decline, caregivers, whether formal or informal, may need to intervene and compensate for the lack of intelligence in performing ADLs by carrying out a portion of the activities.

The societal and economic burden of providing sufficient resources to train professional caregivers, and long-term hospitalizations or institutionalizations, affects public finances and the provision of healthcare services (Ienca et al., 2017). Additionally, many patients prefer to receive care in their homes (Al-Shaqi et al., 2016; Stucki et al., 2014). However, informal caregivers often face psychological burdens such as emotional stress, anxiety, and depression, as they perform heavy caregiving tasks without proper compensation. Similarly, the dependency on others to perform simple everyday activities also places emotional pressure on patients (Ienca et al., 2017; Guisado-Fernández et al., 2019b,a). As a result, the quality of life for patients and the quality of

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* Corresponding author.

*E-mail addresses:* xinghua@vt.edu (X. Gao), sa1imora@vt.edu (S. Alimoradi), jianli.chen@utah.edu (J. Chen), yfh5204@psu.edu (Y. Hu), Shu.Tang@xjtlu.edu.cn (S. Tang).

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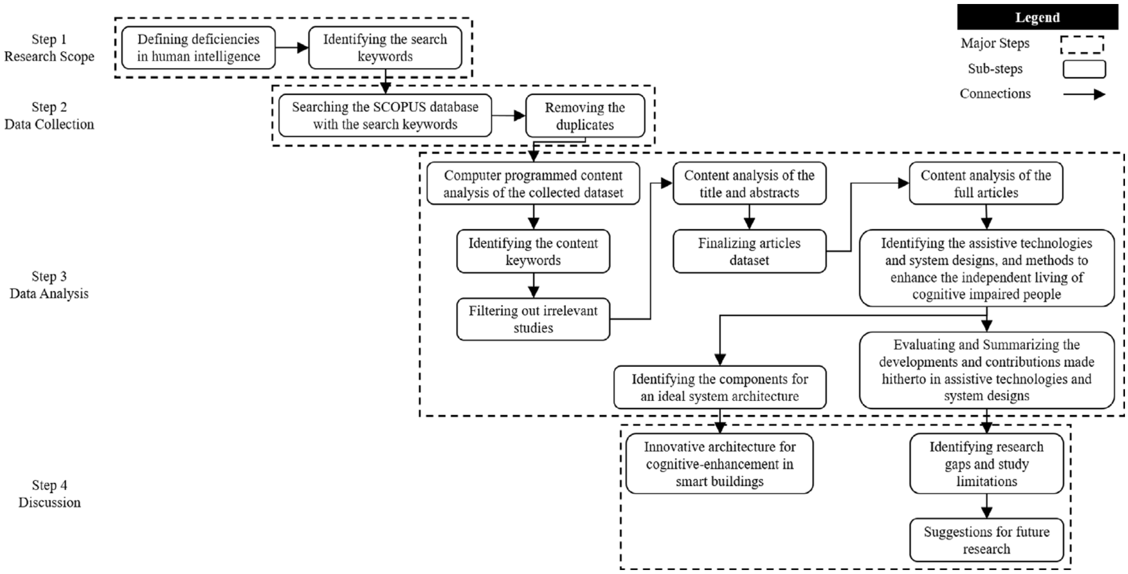


**Fig. 1.** Article Search Method.

care provided decrease significantly with care home admissions (Brims and Oliver, 2019; Das et al., 2012).

Technology has proven to be beneficial in improving the quality of life for patients by automating caregiving responsibilities (Daly Lynn et al., 2019; Preum et al., 2021). The provision of support as an intelligence compensation promotes independence for cognitively declined occupants, reduces the burden on public finances, alleviates the struggles caregivers experience, and enhances and optimizes the quality of care provided (Brims and Oliver, 2019; Preum et al., 2021; Olsson et al., 2018).

Recent developments in the fields of Artificial Intelligence (AI), Internet of Things (IoT), robotics, and human–computer interaction have created new possibilities for in-home care for people with cognitive decline, without the need for caregivers (Preum et al., 2021; Abioye et al., 2021). These developments can be analyzed within the broader domain of Cyber–Physical Systems (CPS), which involves the integration of physical processes with computational (AI) and communicational (IoT) components through robotics and human–computer interactions (Criado et al., 2018; Calderita et al., 2020; Pishdad-bozorgi and Gao, 2020; Böke et al., 2020). The application of CPS in the smart building domain involves delivering therapeutic or assistive interventions into built environments through the control of planted actuators and effectors to provide intelligent compensations to the cognitively declined occupants.

CPS and IoT-enabled smart buildings have been a topic of interest in recent years (Sadri, 2011; Ensafi et al., 2021). However, there is a need to understand what smart buildings can offer to people with cognitive decline and how the ubiquitous intelligence of the built environment can compensate for the decrease in occupants' intelligence. This study provides insights for researchers and industry professionals into the potential benefits of smart buildings for cognitively declined occupants. The authors evaluate the previous adoption of CPS, IoT-enabled sensing, and learning capabilities that support the independence of occupants with cognitive decline. This review explores and explains current research developments, identifies research gaps, and provides future research directions. The remainder of the study is organized as follows: Section 2 explains the methodology of the review, Section 3 provides an overview of the current contributions, Section 4 discusses the research gaps and limitations, and Section 5 proposes a conceptual framework for future research on CPS-enabled smart buildings for cognitively declined occupants.

## 2. Methodology

This review aimed to identify, evaluate, and summarize the contributions made to answer the overall research question: How can CPS embedded in smart buildings improve the quality of life (QoL) for occupants with cognitive impairment and enhance their independence? More specific research questions are: (1) what have been done in the domain of smart building providing assistance to cognitively declined occupants; (2) what are the research gaps in this area; and (3) what can be done in the future to advance this domain.

The review process, inspired by (Gao and Pishdad-Bozorgi, 2019), involved four major steps (see Fig. 1): (1) defining the research scope and identifying search terms to be used in search databases, (2) collecting relevant documents within the defined scope, (3) analyzing the content and identifying advancements and developments made in various components of assistive technologies used to help people with cognitive impairment live independently, which is presented in Section 3, (4) evaluating the identified research gaps, challenges, and limitations, and proposing suggestions and strategies for future research, which is discussed in Section 4, and proposing a conceptual framework for future research on CPS-enabled smart buildings for cognitively declined occupants (in Section 5).

To collect articles related to the compensations and complements that smart buildings offer to people with decreased intelligence, a general search was first performed to identify relevant search keywords. These keywords were then used to perform the main search on academic databases. Only journal published articles and review papers were considered to ensure a threshold for the quality of the study's materials for content analysis. Fig. 1 outlines the research methods and processes that the authors went through for this study.

### 2.1. Research scope

Diminished intelligence refers to any medical condition that affects cognitive abilities, which is also known as "Cognitive Disability" (A.P. American Psychiatric Association, A.P. Association, 2013). Various terminologies have been used to label and describe different causes of diminished intelligence, including cognitive impairment, cognitive disorder, and cognitive dysfunction. In this study, the general term "cognitive decline" is used to encompass all causes of cognitive disabilities, disorders, impairments, etc.

Smart homes and buildings enabled with IoT or CPS can offer an alternative care option for individuals with cognitive disabilities,

**Table 1**
The most repeated words to use in the search script.

| Primary Words | Descriptive Words |
|---|---|
| Cognitive | Impairment, Decline, Disability, Dysfunction, Disorder, Defect, Deficit, Assistance |
| Disease | Alzheimer, Parkinson, Mental, Brain |
| Disorder | Neurocognitive, Mental, Memory |
| Dementia | Assessment, Mild, Syndrome |
| Disability | Intellectual, Neurological |
| Intelligent/ Intelligence | Building, Environment, Artificial, Ambient Sensor, Home, Assistance |
| Smart | Home, Environment, Hospital, Living, Monitoring, Habitat, Health, House |
| Living | Assisted, Independent, Assistive, Elderly, Sensorised, Sensorized |
| Activity | Recognition, Living, Human, Monitoring, Detection, Prediction |
| Behavior | Detection, Pattern |

allowing them to remain at home and live independently with the assistance of embedded assistive solutions (Chaurasia et al., 2014). This review examines the assistive solutions integrated within smart buildings that aim to enhance the independence and, consequently, the quality of life of occupants with cognitive disabilities. The authors have included studies published in English from around the world in their analysis.

### *2.2. Literature search*

To conduct the initial search, we utilized two groups of search terms with the Boolean operator “OR” to search through the entire body of text in publications available on the Scopus database (www.scopus.com). This database was selected for its comprehensiveness and access to academic publishers and online libraries such as Science Direct, Taylor & Francis, Wiley, PubMed, IEEE, ACM, and others. The first group was defined to represent cognitive disabilities and included “cognitive disability”, ”cognitive impairment”, “cognitive disorder”, and ”cognitive dysfunction”. The second group represented the scope of the environment and included “smart built environment”, ”intelligent built environment”, “smart home”, ”intelligent building”, “smart building”, and ”intelligent building”. We identified 925 scientific articles that were written exclusively in English, published between 2005 and 2020, and limited to technical and review papers published only in scientific journals to establish a quality threshold for the search results.

To narrow down the initial search results to articles relevant to the study’s scope, the authors utilized a Python script for text mining. They downloaded an .xlsx file from Scopus that included information on author names, titles, published year, abstracts, author keywords, and index keywords. Duplicates were removed, leaving 671 articles for analysis. The abstracts were preprocessed by removing stop words and changing all letters to lowercase to create a consistent dataset. The most frequently occurring words were then calculated and used to extract search terms related to the research scope. The search terms were used as input for the Python code, which searched the article information for combinations of keywords representing occupants’ condition and the type of built environment. The code identified 249 articles containing at least one combination of these keywords in their titles, abstracts, author keywords, or index keywords. Any technical paper containing a combination of words from the primary words column of Table 1 and the corresponding words in the descriptive words column were included in this step.

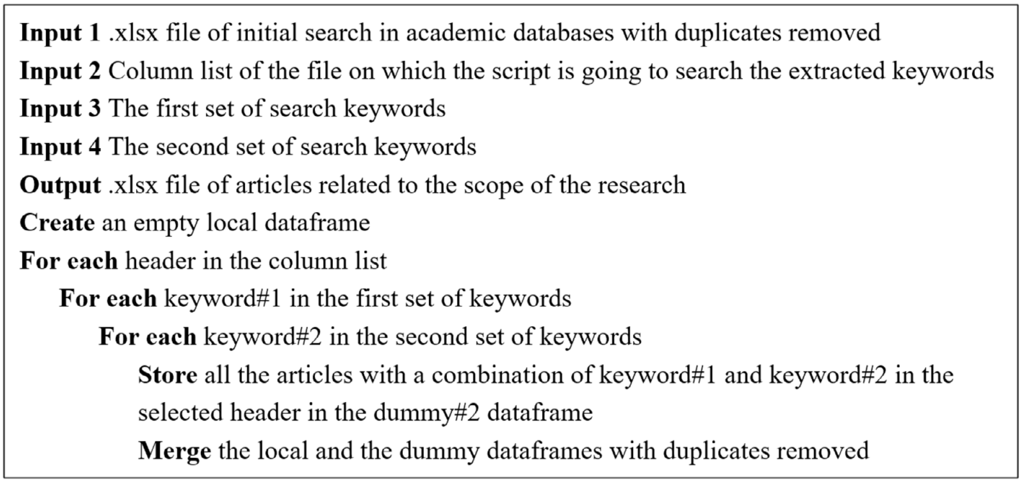
### *2.3. Content analysis*

First, the authors reviewed the abstracts of the 249 articles to determine whether the studies were about cyber–physical system applications in smart buildings for cognitively declined occupants. A total of 151 articles were deemed relevant to the research topic. Subsequently, a thorough analysis of the content of these articles was conducted, leading to the identification of 46 technical papers, 23 review papers, and 18 reports or survey studies that fully addressed the research scope. Articles that solely assessed the cognitive profile of occupants without offering any assistive solutions or services, provided assistive solutions or services outside of a living environment, did not address the cognitive profile of occupants, or focused on other types of occupants (such as caregivers) instead of cognitively declined patients, were considered out of scope and therefore removed.

The authors conducted a thorough review of each paper with regard to the following aspects: (1) outcome of the research, (2) the research method, (3) data collection method, (4) the algorithms that were utilized to process the data, (5) the demographic group that were studied, (6) requirements to live independently, (7) types of the assistive solutions and service that were offered, (8) how the solutions and services were delivered, (9) the research gaps that were covered by the studies, 1(0) the environment wherein the studies were conducted, 1(1) whether any challenges, obstacles, or limitations were discussed, and 1(2) whether any direction for future research were suggested.

In the process of conducting this review, our team employed a meticulous and rigorous approach to categorizing and evaluating the various studies we encountered. Specifically, we carefully assessed each study from the 12 aspects, summarizing its content, providing insightful commentary, comparing it to relevant works in the field, and offering constructive criticism as needed. Throughout this process, we identified a number of key research patterns, both in terms of the topics being explored and the methodologies being employed by different researchers. We made a concerted effort to highlight the most innovative and impactful studies we encountered, emphasizing the key contributions they made to advancing our understanding of this field. We were able to extract several common themes from the studies we reviewed, providing important insights into the current state of research in this area and identifying the most promising directions for future inquiry. Through this process, we sought to provide a comprehensive and nuanced analysis of the existing literature, while also laying the groundwork for continued innovation and progress in the field.

Fig. 2 presents the distribution of the reviewed technical papers on these aspects. Chart A illustrates the number of reviewed technical papers by their research and validation method. Chart B depicts where the studies were conducted; real environment is the representative of taking the whole system to patients’ house, controlled environment is when researchers brought patients into a previously set up environment, and simulation is when the data is generated virtually or downloaded from existing data bases. Chart C represents the number of papers that proposed a system/framework/platform (as opposed to continue a previously conducted study), the discussed challenges and limitations the researchers faced during their work, and the suggestions for future research.



```
Input 1 .xlsx file of initial search in academic databases with duplicates removed
Input 2 Column list of the file on which the script is going to search the extracted keywords
Input 3 The first set of search keywords
Input 4 The second set of search keywords
Output .xlsx file of articles related to the scope of the research
Create an empty local dataframe
For each header in the column list
    For each keyword#1 in the first set of keywords
        For each keyword#2 in the second set of keywords
            Store all the articles with a combination of keyword#1 and keyword#2 in the
            selected header in the dummy#2 dataframe
            Merge the local and the dummy dataframes with duplicates removed
```

**Algorithm 1 – Pseudocode of the selection process**

### 2.4. Originality

Utilization of technologies to assist the cognitively declined people has been evaluated and summarized before. Except one review paper (Al-Shaqi et al., 2016) published in 2016, others had different scope including partial discussions on smart homes (Ienca et al., 2017; Daly Lynn et al., 2019; Neubauer et al., 2018; Khosravi and Ghapanchi, 2015; Archer et al., 2014; Tomaskova and Cimler, 2018; Piau et al., 2014), evaluation of the usability, requirements, or issues related to the technology implementations (Guisado-Fernández et al., 2019a; Archer et al., 2014; Holthe et al., 2018; Niemeijer et al., 2010; Dawson et al., 2015; Wong et al., 2017), assessing the treatment responses to technologies (Husebo et al., 2020), evaluation of technologies for a broader range of disabilities (Ganesan et al., 2019; Maskeliunas et al., 2019), evaluation of technologies for wandering (Neubauer et al., 2018; MacAndrew et al., 2019; Hassan and Khan, 2019; Lin et al., 2014), evaluation of other users such as caregivers (Guisado-Fernández et al., 2019a; D'Onofrio et al., 2017), evaluation of specific function of smart buildings (Brims and Oliver, 2019; Carswell et al., 2009), partially discussed the services and solutions provided by the built environment (Maresova et al., 2018). The other literature review (Al-Shaqi et al., 2016) focuses on systems for independent living by the elderly and evaluates the developments in sensor systems in buildings. However, it does not discuss much about the methods and techniques for prompting and intervention using CPS. While cognitive impairments, disabilities, disorders, or dysfunctions can occur due to different causes, all existing review papers focus on older adults suffering from chronic diseases such as Alzheimer's or dementia.

The remaining porting of the articles includes survey studies of the usability, implementation, or functionality of assistive technologies (Olsson et al., 2018; Meiland et al., 2014; Martin et al., 2013; Lancioni et al., 2009; Biswas et al., 2010), reports or survey studies on the developments of the assistive technologies (Seelye et al., 2012; Cheek et al., 2005; Mokhtari et al., 2012; Swann, 2008; Frisardi and Imbimbo, 2011; Boger and Mihailidis, 2011; Haymes et al., 2015; Gerka et al., 2017), reports on the ethical considerations of the technology implementations (Stip and Rialle, 2005; Bennett et al., 2017), and survey studies for need assessment of the end-users of assistive technologies (Forsyth et al., 2019; Brunete González et al., 2017).

Preum et al. (2021) conducted a survey on existing technologies related to healthcare cognitive assistants (HCAs) and proposed a comprehensive definition for HCAs. They presented a new practical categorization of existing HCAs according to their target user role and the underlying application goals. This study summarizes and organizes existing HCAs based on their characteristic features such as interactive, context-aware, and adaptive, as well as their enabling technological aspects such as sensing, actuation, control, and computation. It identifies critical research questions and design recommendations to accelerate the development of the next generation of HCAs.

To our knowledge there is no comprehensive review that particularly aim to evaluate recent developments and contributions in the technological interventions that smart built environment can provide by adopting CPS, IoT-enabled sensing, and learning capabilities to compensate for the lack of intelligence in occupants. This review is more focused towards the assessing the utilization of CPS in the built environment (mainly residential buildings) to offer a full independency of caregivers to occupants suffering from cognitive decline. The aim of this study is to assess the ways in which IoT and AI-enabled smart buildings can complement the intelligence of cognitively impaired individuals, thereby enhancing their quality of life and autonomy, while also identifying the existing research gaps in this field. An overview of the technologies used to aid individuals with cognitive decline is provided in Appendix A (Alimoradi and Gao, 2021).

## 3. Overview of existing smart building technologies for cognitively declined occupants

Smart buildings equipped with CPS and IoT have the capability to detect areas where cognitively impaired occupants lack intelligence (Lam et al., 2017; Piau et al., 2014; Frisardi and Imbimbo, 2011). This information is processed by the system to determine corresponding assistive services and solutions (Hoey et al., 2012). The next step involves the system controlling the deployed actuators to implement the determined assistive services and solutions to the physical environment in the form of reminders and technological interventions (Criado et al., 2018; Pishdad-bozorgi and Gao, 2020). These assistive services and solutions act as intelligence compensations, either preventing or mitigating unwanted situations and helping those with cognitive decline to improve their quality of life while simultaneously preserving their independence (Seelye et al., 2012; Niemeijer et al., 2010; Lazarou et al., 2019; Belley et al., 2015). The intelligent systems in smart buildings typically comprise three main components: ***the Data Collection Layer***, ***the Processing Layer***, and ***the Control Layer***. Fig. 3 provides an overview of recent developments in the field of smart buildings. *The Data Collection Layer* is the first component, consisting of various interconnected sensing technologies that transmit real-time information to be stored on servers.

With the stored real-time data, *the Processing Layer* performs assessments and interpretations to derive meaningful solutions and decisions on how to provide assistive services and intelligence compensations.

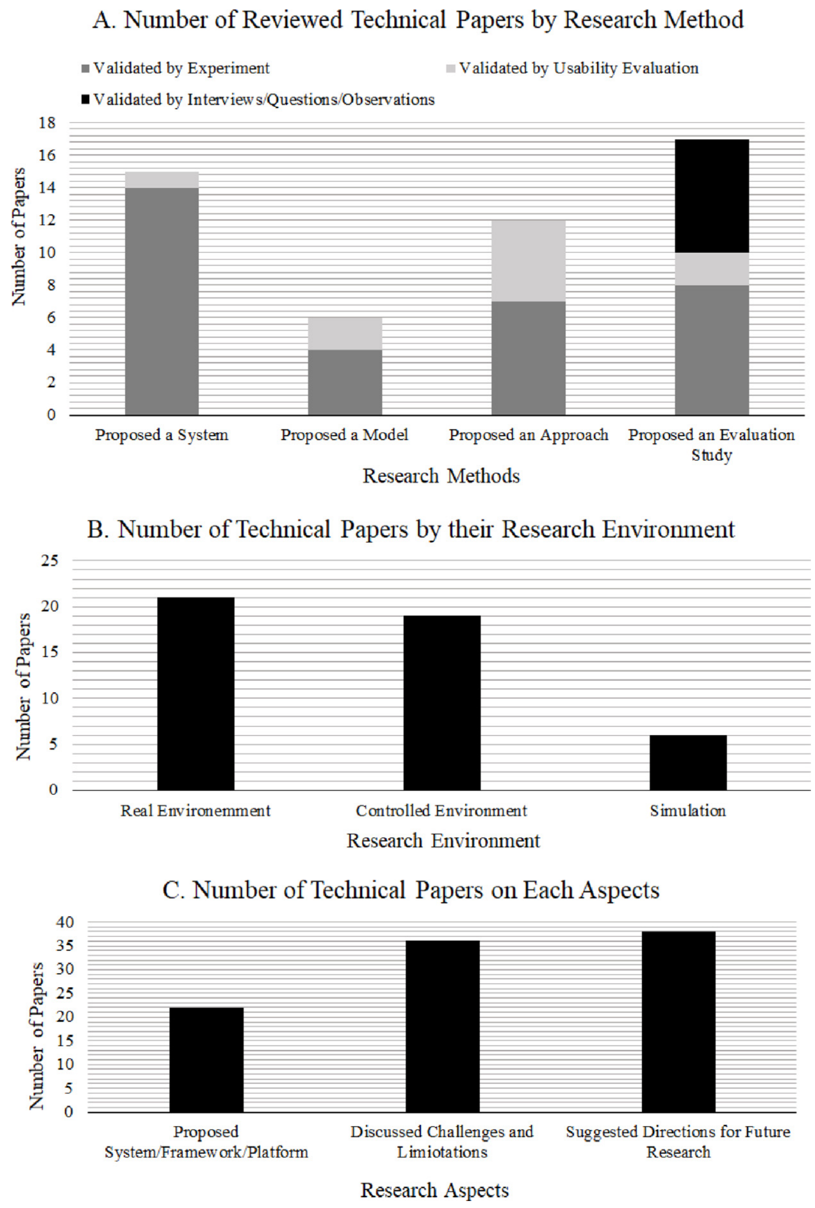


**Fig. 2.** Distribution of the reviewed technical papers on each aspect.

The solutions and services are typically identified through three types of analysis carried out by *the Processing Layer*, namely anomaly detection, activity recognition, and behavioral analysis. Anomaly detection involves identifying conditions or situations that may put the occupants at risk of harm or injury, such as wandering or falling (Kikhia et al., 2018). Activity recognition, also referred to as plan recognition, aims to understand the actions and intentions of the occupants through the performance of activities of daily living (ADLs) (Roy et al., 2011). In behavioral monitoring, the Processing Layer evaluates the occupants' performance of various activities and identifies patterns of behavior (Keum et al., 2020), or performs both activity recognition and anomaly detection (Lam et al., 2017).

The identified solutions and services are then delivered to the occupants through either prompts or interventions. While the majority of the reviewed articles targeted a general demographic group with cognitive impairment (Meiland et al., 2014; Lazarou et al., 2019; Belley et al., 2015; Aloulou et al., 2014; Abbate et al., 2012; Lazarou et al., 2016; Hao et al., 2018; Moutacalli et al., 2015), others carried out their studies on specific sub-categories of cognitive impairment such as traumatic brain injury (TBI) (O'Neill et al., 2018; Pinard et al., 2019), dementia (Hoey et al., 2012; Kikhia et al., 2018; Keum et al., 2020; Mihailidis et al., 2008; Enshaeifar et al., 2018a; Stavropoulos et al., 2017), stroke rehabilitation (Hoey et al., 2012), Alzheimer's disease (Lam et al., 2017; Stucki et al., 2014), Parkinson's disease (Alvarez et al., 2018), Apraxia, and action disorganization syndrome (Pastorino et al., 2014).

The collected database of technical and review papers is diverse in terms of study domain, methodology, and application. The papers come from various domains, including psychology, computer science, gerontology, electrical engineering, and medicine. The most frequently occurring journal in the database is the "Journal of Ambient Intelligence and Humanized Computing", with four articles. The methodologies range from simple explanatory analysis of the collected sensing data to advanced algorithms and machine learning techniques. The results of the evaluated methods vary and, in some cases, are contradictory. For example, one technology such as wearable or visual sensors is considered both intrusive and non-intrusive in different studies. While most of the collected articles aimed to develop a comprehensive assistive system for cognitively declined occupants, their focus varied from introducing novel data collection methods, data processing techniques, or

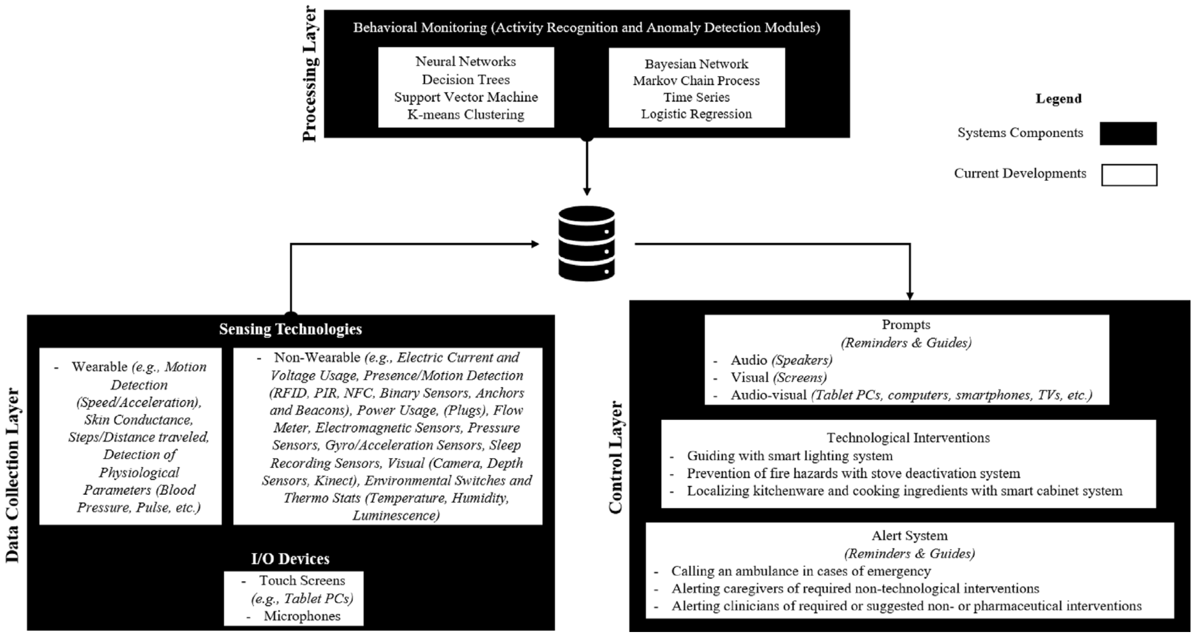


**Fig. 3.** Summary of current developments in the field of smart building.

intervention approaches to evaluating the usability of proposed frameworks developed with existing methods, techniques, and approaches. Nevertheless, the research findings regarding the identification and delivery methods of intelligent compensations are discussed in the following. Appendix B presents a summary of the reviewed technical papers (Alimoradi and Gao, 2021).

### 3.1. Anomaly detection

A fall is defined as the act of an individual coming to rest on the ground or another lower level without any intentional movement or major intrinsic event or extrinsic force (Tchalla et al., 2013). The Processing Layer of a smart building is responsible for recognizing falls by analyzing real-time data and determining if a threshold has been exceeded (Abbate et al., 2012; Charlon et al., 2013b,a). These thresholds are determined either empirically in a lab or during the learning phase using machine learning methods. Through the utilization of a network of anchor points, the location of subjects is tracked and their position and movement data are collected. The determined thresholds are then compared with the real-time feed to detect falls (Abbate et al., 2012).

Further studies should evaluate the use of probabilistic models and learning algorithms to predict falls, even though it is complicated, more time-consuming, and requires extended resources. Abbate et al. (2012) used Support Vector Machines (SVM) to automatically monitor and predict events with a certain probability. Their system records brainwave data as well. The adopted learning technique identifies signal patterns under normal conditions and tries to predict whether any future data point would differ from the pattern, indicating a fall. In contrast, Charlon et al. (2013b,a) analyzed their collected data with machine learning in two studies to detect falls without offering the prediction advantage. Fall detection is beneficial for elderly adults living alone, and caregivers or clinicians arrive after the system detects a fall and take care of the situation. However, the learning and prediction capabilities of the smart environment will even reduce the caregiving responsibilities further by preventing unwanted situations from happening. Tchalla et al. (2013) detected falls with an electronic bracelet. One challenge is that such systems tend to produce many false positives because of the current limitations in learning techniques.

Wandering is defined as repetitive locomotion behavior with temporally disoriented nature, accompanied by lapping, random, or pacing patterns (Abioye et al., 2021). It occurs either during sleep or as a result of stress (Gerka et al., 2017; Kikhia et al., 2018). At night, when the pressure sensors under the mattress cannot detect the occupant and motion sensors on the bedroom ceiling or doorway are triggered, the system interprets that the occupant is wandering (Martin et al., 2013; Aloulou et al., 2014, 2013; Rowe et al., 2007). Smart buildings can learn the circadian rhythm of the occupants to detect nighttime wandering (Martin et al., 2013). Based on occupants' cognitive profile or clinicians' expert opinion, smart buildings can detect high stress levels and sleep-related abnormalities such as sleep interruptions, latencies, and duration using pre-defined thresholds (Kikhia et al., 2018). Falls and wandering can also be recognized with wearable sensors such as electronic bracelets (Tchalla et al., 2013), or a combination of wearable tags and anchor nodes in a radio localization system (Kolakowski et al., 2020).

Wandering has typically been detected using a network of sensors (Aloulou et al., 2014; Tchalla et al., 2013; Aloulou et al., 2013; Rowe et al., 2007). However, by applying learning techniques, the system can monitor multiple occupants and estimate their movement trajectories. Kolakowski et al. (2020) accurately estimated the trajectory of occupants' indoor wandering using an extended Kalman filter-based algorithm. This estimation helps prevent wandering-related incidents. More advanced learning techniques, when provided with adequate training data, can also help prevent false positives.

### 3.2. Activity recognition

Following the classification by Bouchard et al. (2007), activity recognition methods can be grouped into three categories: (1) deterministic, (2) non-learning probabilistic, and (3) learning-based approaches.

The deterministic approach involves observing occupants' actions based on a pre-defined activity pattern consisting of several tasks required to be performed in specific orders to complete the activity successfully. *The Processing Layer* compares the real-time feed of ongoing activity with the pre-defined pattern to detect deviations (Belley et al., 2015; Pinard et al., 2019). Belley et al. (2015) proposed an algorithmic approach that measures the electric current and voltage of home appliances to detect incorrect usage of appliances during breakfast preparation. Pinard et al. (2019) analyzed the real-time data of occupants via a context-aware approach to ensure they are performing activities as instructed and recognize abnormalities.

The non-learning probabilistic approach aims to predict subsequent tasks by observing a few initial ones with a pre-defined pattern. An activity can be recognized by the activation of a specific order of sensors that monitor relevant movements. When sensors detect the initial steps of an activity or partially collect data, the Processing Layer calculates the probability of potential activity patterns to predict the following steps (Bouchard et al., 2007; Chaurasia et al., 2014; Moutacalli et al., 2015; Aloulou et al., 2013; Fortin-Simard et al., 2015). A commonly used approach for calculating the probability of upcoming steps is the classic probabilistic method known as Markov Decision-making Process (MDP)-based methods (Hoey et al., 2012; Mihailidis et al., 2008; Pastorino et al., 2014).

Mihailidis et al. (2008) employed a tracking system that utilizes a Bayesian sequential estimation technique to process the images captured by video cameras for detecting activity-specific gestures when washing hands. Then, they applied a Partially Observable Markov Decision Process (POMDP) to obtain user-specific intelligent inferences. Hoey et al. (2012) developed a unifying model based on POMDP that models the tasks as the elements of a user's activities and considers them as reactions to a caregiver's actions. Pastorino et al. (2014) identified the occupants' activities by using an Action Recognition (AR) algorithm during the natural execution of activities. After an activity is identified, the Task Model (TM) algorithm is employed to detect possible mistakes committed by a subject. Additionally, TM predicts the next task to be performed for the subject to follow the action goal. To decode the continuous signals of the sensors, Pastorino et al. (2014) adopted a Markov Decision Process (MDP), which the TM uses to verify the tasks recognized by the AR and to follow the subject's progress in an activity.

Bouchard et al. (2007) employed lattice theory and an action model based on description logics to recognize plausible abnormalities in performing ADLs, which turned activity recognition into classification. Roy et al. (2011) used possibility theory for activity recognition and assisting occupants in their ADLs. Their proposed model recognizes the sequence of tasks performed to complete an activity. Tasks are formed based on a context-transition model that quantifies the transitions between contexts, obtained by task realization, with a possibility value. Aloulou et al. (2013) developed a next-hour-activity-prediction service that predicts patient activity using Decision Tree algorithms. Chaurasia et al. (2014) incorporated a duration-based probabilistic model into their proposed system that assists the occupants in making drinks. The occupant's activity pattern is described with the joint probability distributions of the tasks within the pattern. The sequence of completed tasks and the time spent on the activity were used to calculate the distributions using maximum likelihood estimation. Fortin-Simard et al. (2015) identified tasks of an activity through the combination of RFID and the electrical load signature of appliances and the spatial interaction of the occupant with objects or appliances. Then, plausible activities associated with likelihoods were drawn with the use of Bayesian recognition process.

With the aid of sensing technologies and machine learning algorithms, smart buildings can employ a learning approach to identify patterns that occupants follow when performing a specific task. The system can then detect when occupants perform an activity incorrectly due to deviations from the learned pattern (Hao et al., 2018; Moutacalli et al., 2015). To create activity models, Moutacalli et al. (2015) collected the activated sensors in order with the duration time between adjacent sensors. Activated adjacent sensors represent occupants' actions. Fuzzy C-Means was used to cluster frequent sensor orders into activities. If an out-of-order sensor was activated, the system would detect that the occupant made a mistake. Hao et al. (2018) proposed an inference engine that learns the sequential tasks of an activity to form patterns. The engine transformed the activity prediction into a graph searching problem solving with a new half-duplex graph searching algorithm (HDGS) based on Breadth-first search (BFS). However, predictions are inaccurate during the initial stages of executing an activity, and some activities have semantically similar tasks and sequences. Therefore, Hao et al. (2018) applied approximate predictions by clustering the tasks of interest according to their semantic similarities using Formal Concept Analysis (FCA).

To enhance the quality of life for cognitively impaired occupants, smart buildings must have learning and predictive capabilities. Occupants' activities are stochastic, and even simple routines can be performed in different ways, causing deterministic approaches to fail in detecting ADLs accurately. A combination of learning and predictive capabilities can account for this stochastic nature and enable the systems to adapt to changes in the execution of ADLs. Moreover, predictive capabilities can prepare *the Processing Layer* to make more robust decisions and stay ahead of occupants' behavior. This can lead to the provision of more accurate services and solutions.

### 3.3. Behavioral monitoring

A behavior is composed of a series of activities, and an activity is comprised of a sequence of tasks. *The Processing Layer* can recognize behavioral patterns and monitor occupants through three approaches: deterministic (comparing real-time data with pre-defined patterns or rules), non-learning probabilistic (predicting following activities in a behavioral pattern), or learning (learning the pattern of occupants' behaviors).

The classic MDP-based algorithms are a probabilistic approach that has been employed by Najjar et al. (2009, 2010) and Chu et al. (2012) to identify and recognize multiple activities of occupants. Najjar et al. (2009, 2010) equipped their recognition module with reinforced learning. To resolve the issue of ambiguous sensor data, Chu et al. (2012) used POMDP and proposed a non-learning heuristic approach based on a dual control algorithm that uses selective-inquiry to solve the POMDP. However, the use of MDP as a probabilistic method is computationally exhaustive and demanding. To improve the accuracy of activity detection, Lam et al. (2017) proposed a learning activity monitoring system that used classification algorithms such as SVM, Random Forests (RF), and Naive Bayes (NB) along with a context-based approach. Among the algorithms, SVM showed the highest accuracy. Further evaluation of machine learning algorithms is needed to find an alternative to MDP that possesses both predictive and learning capabilities.

Stucki et al. (2014) developed a web-based system to identify and classify activities of daily living (ADL) using a rule-based forward chaining inference engine. Collected data were compared to a set of predefined rules to determine if they fit a corresponding ADL. Lazarou et al. (2019, 2016) and Stavropoulos et al. (2017) used semantic interpretation and fusion to extract meaningful behavioral patterns and complex activities from raw data. They employed processing methods ranging from simple data retrieval to complex activity recognition and computer vision algorithms from previous studies. The system utilizes a set of predefined rules (expressed in SPARQL) that clinicians adjusted based on each occupant's profile. To detect daily routines, Enshaeifar et al. (2018a) applied pattern recognition algorithms, including rule-based reasoning algorithms and adaptive learning. These studies introduce a deterministic approach to monitoring ADLs that can monitor multiple activities with high accuracy. However, over time, the execution of ADLs undergoes slight to moderate changes, and if not implemented and planned correctly in the system, errors can occur. These errors can be prevented with the help of learning techniques instead of rule- or logic-based approaches.

Anomalies are another type of behavior that can be detected by smart buildings. Lotfi et al. (2012) transformed anomaly detection into a classification problem and evaluated a solution based on various clustering algorithms such as self-organizing maps (SOM), K-means clustering, and fuzzy C-means (FCM). Charlon et al. (2013b) extracted a behavioral model from movement and activity data using supervised classification-based learning techniques. They then determined danger detection thresholds based on the average of detected events over 30 days and recognized anomalies based on real-time events and the determined thresholds. Alvarez et al. (2018) utilized movement trajectories with a Sparse Autoencoder (SAE) algorithm to differentiate between anomalies like wandering and normal behaviors. To consider the reliability of data collected from low-level subsystems, they used a weighted probabilistic model. If sufficient training data is available, they applied a Bayesian Network (BN) to retrieve high-level information such as executed tasks of an activity and their temporal data. Additionally, they employed Recurrent Neural Networks (RNN) to detect the Freeze of Gait (FoG). Keum et al. (2020) proposed a system that constructed behavior patterns based on analyzing the sequential timing of single activities to recognize abnormalities in ADLs using edge computing. Enshaeifar et al. (2019) developed two algorithms, using Non-negative Matrix Factorization (NMF) and Isolation Forest (iForest) techniques, to detect Urinary Tract Infections (UTI) and changes in activity patterns of the occupants to provide personalized assistive services.

Smart buildings must be capable of monitoring various aspects of occupants' lives to offer complete independence from caregivers. This involves monitoring their behavior, which is a combination of simple activities like washing hands, complex activities of daily living (ADLs) such as cooking, and anomaly detection to prevent fall and wandering-related incidents. Advanced *Data Collection* and *Processing Layers* equipped with behavioral modeling, learning, and predictive techniques enable smart buildings to take over the majority of caregiving responsibilities.

### 3.4. *Prompting*

In the context of smart buildings, a prompt is a form of assistance that can be delivered to occupants to help them complete an ongoing activity. These prompts can be based on various factors such as time, context, or acquired intelligence (Seelye et al., 2012; Belley et al., 2015; Das et al., 2011). Smart buildings typically offer four types of prompts: audio, visual, audiovisual, and lighting (Belley et al., 2015). Audio prompts involve verbal cues, reminders, or step-by-step instructions delivered through speakers that are installed in the building (O'Neill et al., 2018; Kolanowski et al., 2018). Visual prompts offer non-verbal or pictorial assistance to occupants via screens of various devices such as smartphones, TVs, and tablets (Lam et al., 2017; Enshaeifar et al., 2018a; Alvarez et al., 2018; Najjar et al., 2010). Audiovisual prompting is a combination of both (Fortin-Simard et al., 2015; Seelye et al., 2013; Ficocelli and Nejat, 2012; Hattink et al., 2016). Lighting-based prompts involve using a laser or a bulb that changes colors to indicate the status of a situation, flashes or points to help the occupant locate an object (Bouchard et al., 2007; Belley et al., 2015; Kolakowski et al., 2020). Prompting can also be used as an alert system. In cases where *the Processing Layer* detects anomalies, *the Control Layer* can send emergency alerts and messages to caregivers, nurses, or hospitals (Abbate et al., 2012; Kolakowski et al., 2020; Gerka et al., 2019).

Prompts must be selected based on the occupants' cognitive profile and the specific mistakes they make while performing ADLs (Belley et al., 2015). Belley et al. (2015) and Fortin-Simard et al. (2015) categorized these errors into omission, sequence, perseveration, temporal, and cognitive overload. Omission occurs when the user forgets to perform a task or step in an activity. Sequence refers to the disruption of the execution order of tasks required to complete an activity. Perseveration occurs when the occupant persists on a task or step. Temporal issues arise when there are inconsistencies with the predefined time constraints for performing tasks and completing activities. Lastly, cognitive overload happens when the user tries to multitask, causing distractions and errors due to cognitive decline. *The Processing Layer* first identifies the type of mistake made and then signals the appropriate instructions to *the Control Layer*, which delivers them through prompting.

Cognitively declined occupants often struggle with short-term memory loss, scheduling activities, and learning from past mistakes (Seelye et al., 2012; Lam et al., 2017; Hao et al., 2018). This forgetfulness can lead to misplacing personal belongings, disrupting necessary medication, and poor nutrition (Lam et al., 2017; Lazarou et al., 2016; Kolakowski et al., 2020). To assist with these issues, *the Processing Layer* signals reminders to *the Control Layer*, which notifies the occupant of their past mistakes, scheduled activities, medication plans, and assists in locating misplaced objects.

### 3.5. *Intervention*

Devices such as actuators and effectors have been deployed in smart buildings to intervene in the built environment and keep occupants safe (Martin et al., 2013; Gerka et al., 2017; Tchalla et al., 2013; Gerka et al., 2019), or to guide them through completion of an activity (Ficocelli and Nejat, 2012). Gerka et al. (2017, 2019) developed a stove deactivation system to prevent fire hazards. The system monitors the stove with motion detectors and temperature sensors. If the temperature exceeds a threshold and the motion sensors do not detect any activities, it automatically turns the stove off. Tchalla et al. (2013) and Martin et al. (2013) implemented actuators to provide lighting guidance in cases of nighttime wandering to prevent falls. Motion detectors planted in the bedroom or pressure sensors placed under the mattress detect movement, and then actuators are triggered to light the path to bathrooms or other rooms of the house. The system deployed by Martin et al. (2013) provides automatic therapeutic interventions by playing music when occupants have sleeping troubles to prevent wandering caused by stress. Ficocelli and Nejat (2012) designed and developed an initial prototype of an interactive assistive system that helps occupants perform kitchen-based ADLs. The system features an automated cabinet system that assists with storing and retrieving kitchenware and ingredients during cooking. The cabinets can move towards the occupants to provide access to the items they need or to help them store the items in the correct places. The system initiates and receives requests/orders with direct verbal prompts from the user. The speech recognition module incorporates Hidden Markov Models to recognize the user's prompts.

## 4. Identified research gaps and recommendations for future research

### 4.1. *Usability and acceptability*

The introduction and utilization of new technologies often come with challenges such as acceptability, durability, ease of use, and power requirements (Maresova et al., 2018). Smart homes, as an example of such technologies, are complex and require specific skills to install and operate (Stucki et al., 2014). Many complex and advanced systems have only been tested and implemented in controlled environments where trained experts were available during experiments to operate and maintain the systems. However, these conditions are far from the living environment of patients and are insufficient for evaluating acceptability and usability. End-users have reported technical issues such as false alarms, wrong prompts, poor connectivity, low batteries, and high costs, all of which affect the usability of the systems (Daly Lynn et al., 2019; Neubauer et al., 2018; Mehrabian et al., 2014). To successfully implement smart homes, structured and individually tailored procedures are necessary. Regular follow-ups are also required to provide the necessary support (Olsson et al., 2018).

When designing assistive systems for cognitively declined people, ensuring their acceptability becomes crucial. A significant obstacle to the adoption of such systems in smart built environments is the end-users' lack of familiarity with technology in general (Guisado-Fernández et al., 2019a; Lazarou et al., 2019; Pastorino et al., 2014).

The systematic design of smart homes significantly affects the difficulties the end-users face in learning how to use the systems (Olsson et al., 2018). To increase acceptability, designs must be simple and easy-to-use, requiring minimal involvement of end-users in system installation, operation, and maintenance (Stucki et al., 2014; Neubauer et al., 2018; Martin et al., 2013). According to Holthe et al. (2018), the usability of any technology is determined by its user-friendliness, usefulness, and effectiveness in helping users achieve specific goals. Incorporating the principles of "universal design", a broad concept in the design spectrum of any product or environment, is one approach to enhancing the acceptability of these technologies. By employing universal design, cognitively declined individuals can be reassured that the implemented system has been used by many other users, which can lead to an increased inclination towards accepting the technology.

### 4.2. Ethical concerns

Occupants have reported avoiding the use of smart home systems due to ethical concerns, such as privacy and intrusiveness (Piau et al., 2014; Belley et al., 2015; Alvarez et al., 2018). The use of video and audio-based sensors for monitoring makes these systems intrusive (Piau et al., 2014; Belley et al., 2015; Alvarez et al., 2018), invasive (Das et al., 2012; Hoey et al., 2012), or obtrusive (Seelye et al., 2012; Maskeliunas et al., 2019) in the literature. The collection of behavioral data through cameras or microphones requires the consent of end-users, which may not be possible for cognitively declined patients. In some cases, researchers have ignored obtaining consent and assumed that end-users will accept the original design of the system with vision and audio-based sensing technologies. Survey studies show that users are aware of the benefits of new technologies and are more likely to accept them if they are proved to be unintrusive or if their consent is sought.

The use of surveillance technologies to control cognitively declined individuals can imply a need for control and restraint. With the use of IoT, wireless devices, and information storage facilities, privacy, data ownership, and cybersecurity issues can arise. Therefore, data ownership and security must be clarified and structured before implementing smart home technologies. Despite the lack of a comprehensive approach to address these gaps, the following criteria must be considered when designing such technologies: (1) the ability of cognitively declined individuals to provide informed consent, (2) the protection of their privacy, (3) the confidentiality level of the collected data, (4) who can access the data, and who owns it.

### 4.3. Comprehensiveness of the system

Assistive systems developed for smart homes are often limited to predefined services and scenarios to address specific user needs. However, these systems are unable to evolve and adapt to new requirements or accommodate new users. Furthermore, some assistive technologies only address single needs of occupants rather than providing solutions for multiple requirements that arise during different stages of their cognitive decline, such as wandering, falls, sleep quality, and daily tasks. Considering that individuals have varying cognitive profiles, incorporating comprehensive cognitive assessments into the implementation of these systems is necessary. This would enable the classification of cognitive profiles and facilitate the delivery of personalized and tailored assistive services that meet the preferences and needs of individual users.

Most of the implemented smart home systems lack the capability to distinguish between the user and other occupants, resulting in multiple occupancy recognition issues. To address this issue, more research is needed to develop systems that can recognize activation of multiple sensors while maintaining the users' sense of control.

In many reviewed studies, it was assumed that smart home systems are based on the incorrect assumption that the activity and behavioral patterns of the occupants will remain consistent over time. As a result, only a limited number of specific patterns have been developed for each monitored activity or behavior. To enable smart homes with learning capabilities, probabilistic and learning analytical methods, such as combining deep learning models with probabilistic machine learning techniques, should be evaluated and incorporated into the systems. Despite a few applications of machine learning and probabilistic methods, the uncertainties, imprecision, and fuzziness associated with the collected information have not been properly addressed. Developing predictive and incremental learning models can also provide additional insights and information from monitoring physiological data (Enshaeifar et al., 2018b).

### 4.4. System evaluation and human-in-the-loop

Assistive technologies and smart homes serve as a substitute for caregivers, providing services to cognitively declined people. To prove their adequacy, maturity, and efficacy, clinical trials are necessary. One major drawback of the developed smart home systems is the lack of feedback from clinical experts and proof during the experimental phase of the systems. In some cases, developers launched their prototypes without proper testing trials (Al-Shaqi et al., 2016; Roy et al., 2011; Seelye et al., 2013). Linguistic and neuropsychological research is a must, especially for the design and effective delivery of prompts and interventions. Proper testing trials must include laboratory testing with the presence of clinicians. However, conducting experiments in a controlled environment such as a laboratory can eliminate the variability of the real environment and produce only polished data, making experiments in the patients' daily living environment necessary. Several reviewed studies involving experiments only tested their developed systems in a controlled testbed, resulting in a questionable efficiency of the systems in a real environment, such as the patients' houses.

Conducting experiments in a controlled environment has limitations, particularly in terms of sample size. Many studies have reported that the number of participants was not sufficient to draw conclusive evidence (Daly Lynn et al., 2019; Fortin-Simard et al., 2015; Gerka et al., 2019). Obtaining an adequate sample size can be complicated and challenging, resulting in a small population size that leads to general and, in some cases, derivative findings. Moreover, small samples may not effectively represent the entire population, as variability may be sacrificed due to a homogeneous sample. Therefore, there is a need for further studies with larger sample sizes, including individuals with different cognitive profiles in various environments.

The concept and approach of user-centered design should be adopted more when developing assistive technologies. In many of the reviewed studies, the users' perspectives were not often considered, which is crucial for introducing and developing new technologies. To increase the role of end-users in the whole process, system designers and developers should involve them in all the stages of design, evaluation, and deployment of the assistive technologies. According to Czarnuch and Mihailidis (2011), this includes needs assessment, idea generation, device prototyping, and efficacy testing. Evaluation studies of users' needs are not sufficient if individuals are not directly included in the design and development process. In experiments, subjects who attempted to communicate with the testing systems but did not receive interactive responses tend to have negative opinions on the proposed systems. On the other hand, subjects presented positive body language and facial expressions when the experimenters intervened to communicate with the subjects. Therefore, smart homes with prompting as their delivery method should be equipped with interactive user interfaces so that appropriate responses would be generated in any bidirectional communication attempted.

Tailoring the content of prompts to users' cognitive profiles is crucial to increase positive emotions and encourage task completion. To achieve this, a comprehensive study of prompts is necessary to determine the best phrasing, whether questions, orders, or suggestions are most effective, the optimal number of words, and the best ways to elicit users' responses.

### 4.5. Implementation of cyber–physical systems

Buildings that are equipped with IoT-enabled sensors, actuators, and effectors are known as smart buildings and share many features with Cyber–Physical Systems (CPS) (Pishdad-bozorgi and Gao, 2020). These buildings can measure physical aspects of the environment, collect data related to occupants, and transmit this data to processors to control the functionality of the built environment. Machine learning tools are typically used to enhance computational performance. This integration of physical devices with cyber components (computation and communication capabilities) creates an intelligent analytical system that can respond to changes in the real world and occupants' behavior (Pishdad-bozorgi and Gao, 2020; Li et al., 2021). With the help of actuators and effectors, the physical built environment can respond to the needs of occupants and add more intelligence to their daily lives (Haque et al., 2014).

In the context of smart buildings, CPS has a wide range of applications, such as smart medical technology, indoor environmental control, energy management, and ambient assisted living (AAL) (Pishdad-bozorgi and Gao, 2020; Haque et al., 2014). An AAL environment is a combination of assistive technologies, solutions, and services that positively impact the occupants' quality of life (Sadri, 2011; Maskeliunas et al., 2019). Cognitively declined occupants depend on others, such as caregivers, to carry out their ADLs. CPS-enabled smart buildings can complement their lack of intelligence and increase their independence, thus enhancing their autonomy in performing everyday activities. These buildings can monitor the occupants and provide assistive services and solutions through prompting or intervention.

The effectiveness of prompting is influenced by the severity of cognitive decline, as higher levels of prompting are needed with increasing severity of the disease. However, there is a limit to the effectiveness of prompting, and patients with a high severity of illness may become agitated with too many prompts, leading to task failure. This is where interventions become necessary. Caregivers traditionally assist cognitively declined individuals with their ADLs, but technology can also play a role in improving their quality of life.

To increase the autonomy of occupants, limited technologies have been developed to replace caregivers' responsibilities in specific activities. Robotic systems have also been introduced to act as companions for the occupants (Daly Lynn et al., 2019; Preum et al., 2021). The studies reviewed have introduced various forms of CPS integration in the smart building concept. Technological interventions range from simple verbal cues delivered through installed speakers (Aloulou et al., 2013) to the use of embedded robotics in moving cabinets to the occupants (Ficocelli and Nejat, 2012). However, the application of CPS in the smart home domain has not been thoroughly studied and researched.

## 5. A conceptual framework for future research on CPS-enabled smart buildings for cognitively declined occupants

In this section, we propose a conceptual framework to outline the suggested future research on CPS-enabled smart building applications within the context of AALs in residential buildings. As presented in Fig. 4, the framework consists of three main components: *the Knowledge Base*, *the Processing Layer*, and *the Control Layer*.

*The Knowledge Base* is composed of IoT-enabled sensors that collect, transmit, and store real-time data. Sensing technologies used so far can be classified into two major groups: Wearable and Non-Wearable. Wearable sensors include smart bracelets, smart watches, or tags that can be worn by end-users. Researchers have used these sensors to localize, detect movements, and collect physiological signs and parameters of subjects. By deploying a combination of both wearable and non-wearable sensors with the consent of end-users, sufficient behavioral data can be collected for *the Processing Layer* to learn behavioral patterns and produce tailored assistive solutions and services. The Plug & Play mechanism enables attachment of new sensors without reconfiguring the whole system, and it can discover and connect newly deployed sensors to the existing network at runtime. *The Knowledge Base* also includes input/output (I/O) devices that provide human-in-the-loop capabilities for the systems to interact with end-users via voice commands, buttons, or other forms of input. The I/O devices can receive feedback from end-users and experts to further improve or ameliorate the solutions and services generated by the system. Specific interfaces have been developed separately for occupants, caregivers, and clinicians to receive feedback.

*The Processing Layer* utilizes probabilistic machine learning and AI algorithms and tools for learning and predictive capabilities. These capabilities remove the use of rule/agent/logic-based algorithms, which are beneficial but may fail to consider changes in behavior patterns. Learning capabilities are crucial to recognizing different activities, addressing various needs, and detecting anomalies based on the user's behavioral pattern. They can also distinguish between users and other occupants or offer assistive services for multiple occupants. Additionally, *the Processing Layer* can assess the cognitive profiles of occupants in different stages of their condition from real-time data. Predictive capabilities enable the system to be one step ahead by predicting the following tasks of a recognized activity and guiding the user through completion or preventing unwanted events such as falling. Probabilistic models such as Markov Chain Process (MCP) or Markov Decision Process (MDP) and its derivatives, such as Hidden Markov Model (HMM), are examples of models used in Reinforcement Learning.

Although cognitively declined occupants may have limitations in their cognitive abilities, there are instances where they have complete control over modifying the way they perform ADLs, which can affect the accuracy of activity prediction (Belley et al., 2015; O'Neill et al., 2018). To overcome this challenge, input/output (I/O) devices provide occupants with triggering options so they can self-initiate specific assistive services, such as prompting. Reminders for these options should be set to reduce the possibility of forgetfulness. This enables the identification of more personalized and tailored assistive solutions and services for the users. The content of the prompts is tailored to users' cognitive profiles, and the services can be adapted and updated when changes are recorded in their behavioral patterns.

CPS involves problem-solving and control of a physical environment (Criado et al., 2018). By connecting the sensing technology with processors and actuators, CPS improves the performance of an IoT system, allowing actions to be carried out, interactions with the physical world to occur, and even the physical world to be changed (Pishdad-bozorgi and Gao, 2020). This improvement is necessary to increase the independence and quality of life for cognitively declined occupants without relying on caregivers (Calderita et al., 2020; Lazarou et al., 2016; Pastorino et al., 2014). The Control Layer is where the Physical Twin of a CPS is implemented. When prompting alone is not effective, the smart built environment should be capable of offering different forms of technological interventions with the help of embedded robotics and automation. Examples of previously developed technological interventions include positioning misplaced items and preventing wandering through interactive verbal communication with the system (Kolakowski et al., 2020; Ficocelli and Nejat, 2012), an automatic cabinet system, appliance activation/deactivation, cooking guide, and planner systems in the kitchen (Gerka et al., 2017; Pinard et al., 2019; Fortin-Simard et al., 2015; Ficocelli and Nejat, 2012), an automated handwashing guide (Mihailidis et al., 2008), and an automated lighting system for pathfinding when nighttime wandering occurs (Charlon et al., 2013b). In cases of emergency when interventions by caregivers or clinicians are required, they should be alerted immediately by the system (Charlon et al., 2013b). Future studies can focus their efforts on evaluating the incorporation of more embedded robotics and automation, such as altering the physical built environment and floor layout to prevent fatal accidents from falls.

This study has several limitations. Firstly, while the authors reviewed the computational applications of the existing research, a more

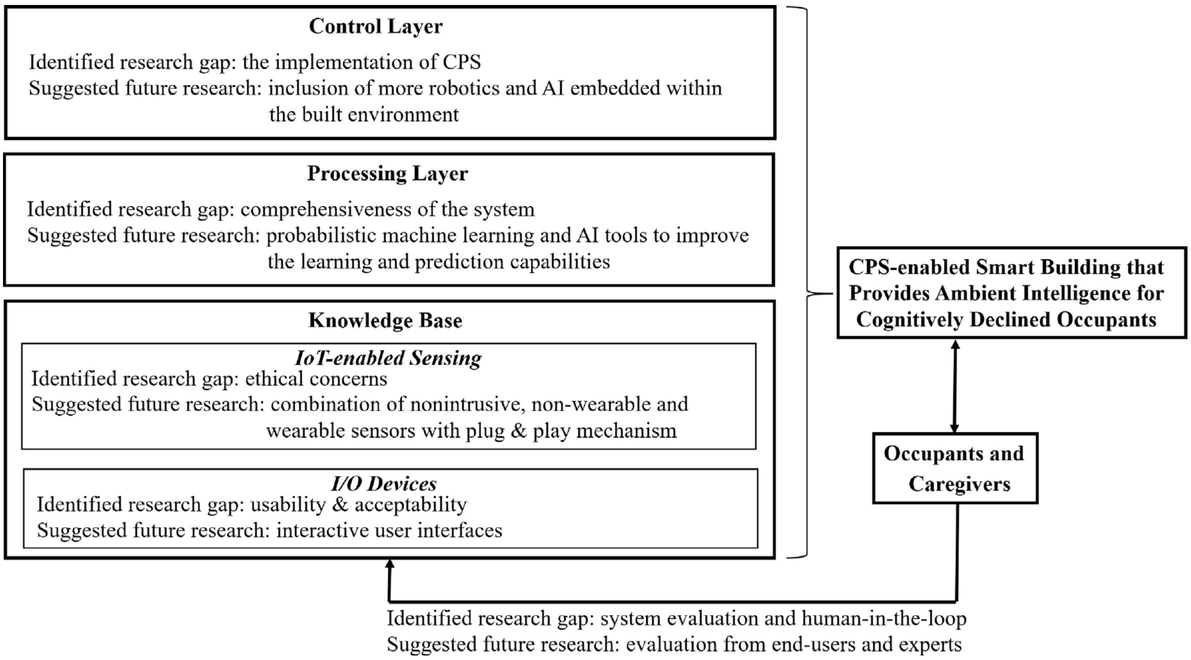


**Fig. 4.** Conceptual framework for future research on CPS-enabled smart buildings for cognitively declined occupants.

in-depth analysis of the technological aspects of the proposed framework, such as the computational power and accuracy, as well as the hardware including sensors and networks, could have improved the proposed framework. Secondly, the literature search excluded articles published in conference proceedings due to the multitude of papers and to ensure a quality threshold for the research material, but this decision may have limited the scope of the study. Additionally, some conference proceedings may only be available to a specific cohort or for a limited time. Finally, seeking expert opinions from formal caregivers or clinicians could have provided valuable insights on how to better address the existing issues, including the viewpoints of users and a better understanding of patients' needs and conditions.

## 6. Conclusions

This study contributes to the body of knowledge by (1) systematically summarizing and evaluating the existing literature on CPS-enabled smart buildings for assisting cognitively declined occupants, (2) identifying key research gaps, including the lack of adequate implementation of technological interventions to fully support the autonomy and independence of occupants, challenges in usability and acceptability, ethical concerns, systems' comprehensiveness, and the need for human-in-the-loop, and (3) proposing a research framework that outlines the current state of research and highlights promising future research directions for the applications of smart buildings supporting cognitively declined occupants.

Studies evaluated in this review indicate that the developed ambient intelligent systems have the capability to assist occupants with cognitive disabilities in various ways, increasing their independence and quality of life. These systems consist of three main components: *the Data Collection Layer*, *the Processing Layer*, and *the Control Layer*. These systems collect and transmit data through IoT-enabled sensing, analyze and process the data, provide information to caregivers and patients, and automate some caregiving responsibilities.

The authors identified several key research gaps. First, there is a need for user-centered and user-friendly designs and interfaces to improve the system's acceptability and usability for both cognitively impaired occupants and their caregivers. A universal system design and interface are required to convey the impression that the implemented system has a generic cohort of users. Second, ethical concerns regarding sensing technologies should be addressed to improve the privacy of the occupants. Obtaining consent from cognitively impaired end-users can be challenging. Third, to derive more complex and comprehensive assistive services, smart building applications need to be capable of evolving with the emergence of new requirements and addressing multiple needs of cognitively impaired occupants. Finally, multiple occupancy is another shortcoming of the existing body of research that needs to be addressed.

Previous studies have utilized machine learning and AI for anomaly detection, activity recognition, or behavioral monitoring to identify appropriate assistive services and solutions. However, there is a need to increase the incorporation of predictive methods and algorithms to provide the Processing Layer with both learning and predictive capabilities. Various testing phases are required in both controlled environments, such as laboratories, and real environments, such as patients' homes, to integrate user and expert perceptions of the designed systems. Despite a universal system design, the final product, which is the assistive services and solutions, must be tailored and personalized based on occupants' cognitive profiles and assessments. Most of the reviewed studies focused on delivering the assistive services and solutions through prompting only. While prompts are valuable, they are only effective for a certain cognitive profile. With more advanced cognitive decline, prompts can be unhelpful and make the user agitated. There has been a gap in developing a sufficient *Control Layer* that can offer technological interventions. To fully support cognitively declined occupants in performing ADLs and automate caregiving responsibilities, more focus should be put into in-depth analysis and development of a comprehensive Control Layer for CPS-enabled smart buildings.

The authors propose a conceptual framework as a system design for CPS-enabled smart homes, which outlines how to address the identified research gaps and incorporate the recommendations for future research in the development of an assistive system enabled with CPS for cognitively impaired individuals.

## CRediT authorship contribution statement

**Xinghua Gao:** Conceptualization, Methodology, Writing – review & editing, Supervision. **Saeid Alimoradi:** Data curation, Formal analysis, Writing – original draft. **Jianli Chen:** Supervision, Writing – review & editing. **Yuqing Hu:** Writing – review & editing. **Shu Tang:** Writing – review & editing.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

## Appendix A

See Table A.1.

## Appendix B

See Table B.1.

**Table A.1**
Literature Reviews on the use of technologies to assist cognitively declined people.

| Article | Research Scope | Findings | Suggested Future Research |
|---|---|---|---|
| Maresova et al. (2018) | Technological solutions for people with Alzheimer's disease (AD). | (1) Technological solutions are divided into four groups: wearable, non-wearable invasive, non-wearable non-invasive, and others. The most discussed solutions are wearable devices and ambient non-invasive sensors.<br>(3) Activity detection is conducted with different methodologies, such as machine learning, ontology-based classification, and rule-based classification.<br>(4) The most discussed devices are for activity detection and monitoring.<br>(5) Technological solutions can promote safety and rehabilitation of the patients to prevent social isolation and increase their autonomy. | (1) Understanding the sociocultural aspects and acceptability of the technological devices among different groups.<br>(2) Improving of the systems' security, privacy, and operability.<br>(3) Developing a national guidance on how assistive technology should be provided. |
| Ganesan et al. (2019) | Ambient Assisted Living (AAL) for older adults with physical, cognitive impairments, and their social participation | (1) AAL is useful for elderly with problems in memory.<br>(2) Numerous commercial devices are found available to prevent wandering behavior.<br>(3) Older women perceived wearable sensors more useful that smart homes since most of their activities are outside of their living area.<br>(4) AAL systems can deliver specific social functionalities, which consist of social gaming technologies, simplified electronic mailing, video telephoning, and digital picture frames. | (1) Removing the barriers for the elderly with cognitive and physical impairments to use innovative assistive technologies.<br>(2) Performing methodological and clinical investigation to prove the effectiveness of the AAL technologies.<br>(3) Considering cognitive impairments more than physical impairments in developing the AAL technologies. |
| Ienca et al. (2017) | Intelligent Assistive Technologies (IAT) in dementia care | (1) Technological types applied in dementia care are distributed systems, robotics, mobility & rehabilitation aids, handheld/multimedia, software/apps, wearables, human-machine interfaces. The most discussed field is distributed systems which include smart service platforms and AAL technologies.<br>(2) Arranged in descending order, IAT applications are ADL completion, monitoring occupants, physical and cognitive assistance, promoting interaction and engagement, facilitating care and rehabilitation, and emotional assistance.<br>(4) Functions assisted via IATs are in descending order general purpose, cognition, motor function, emotional/mood, and social interaction.<br>(5) Increased utilization of pervasive and ubiquitous for automation of delivering services. | (1) Improvement of the user-center design.<br>(2) Increase in the clinical validation of the IATs<br>(3) Development of artificial emotional intelligence and assistance.<br>(4) Improvement of the IATs' adaptability to various cognitive profiles.<br>(5) Provision of holistic and multi-level support to encompass different disabilities.<br>(6) Development of a multinational plan to for technology development, facilitating technology transfer, and establishing a framework for public–private partnership.<br>(7) Consideration of privacy issues, and information security during product development. |
| Al-Shaqi et al. (2016) | The frameworks and sensor systems used in various ambient assisted living systems | (1) Innovations in Assisted Cognition Environment (ACE) are in two domains: (a) creation of activity models, and (b) developing structured prompters.<br>(2) Health-related AAL systems are divided into six main categories: physiological and functional assessment, safety and security monitoring, social interaction, and cognitive monitoring.<br>(3) Most frameworks focused on activity monitoring, while the opportunities for integrating environmental factors for analytics and decision-making, for the long-term care were often overlooked. | (1) Consideration of commercial concerns.<br>(2) Development of standards specifying the elements of an assisted living technology.<br>(3) Consideration of users' consents in systems' design. |

(*continued on next page*)

**Table A.1** (*continued*).

| Article | Research Scope | Findings | Suggested Future Research |
|---|---|---|---|
| Guisado-Fernández et al. (2019a) | Smart Health (s-Health) Technologies for People with Dementia (PwD) and Their Informal Caregivers | (1) The use of s-Health technologies for dementia includes assisted living technology, ambient assisted living technologies, and smart homes.<br>(2) S-Health technologies fall into four categories: safety promotion, provision of multisensory simulation, memory enhancers, fostering communication.<br>(3) Although elderlies are reluctant users, gradually introducing technologies to PwD increases usability.<br>(4) Use of devices that mimics the technology frequently used by PwD increases the usability. | (1) Adoption of more user-friendly, simplified, and easy-to-use designs.<br>(2) Personalization of assistive services to each users' cognitive profile.<br>(3) Development of the capability for technologies to adapt to different stages of dementia.<br>(4) Establishment of a uniform nomenclature or taxonomy. |
| Brims and Oliver (2019) | Assistive Technologies (AT) in improving the safety of people with dementia living in the domestic setting | (1) No major concerns were reported on the acceptability and feasibility.<br>(2) No adverse effects were reported on implementation of AT. | (1) Consideration of users' perception and preferences in the systems design and implementation.<br>(2) Isolation of AT as the independent variable to infer causality.<br>(3) Development of tests with adequate length to evaluate long-term outcomes of implementation of the systems.<br>(4) Incorporation of cost effectiveness studies. |
| Daly Lynn et al. (2019) | Electronic assistive technology within long-term residential care settings | (1) The assistive technologies were categorized based on the technological intervention into telecare, light therapy, well-being and leisure, simulated presence, and orientation and ADLs.<br>(2) Technology solutions were considered both an invasion of privacy and a way to prevent unnecessary intrusion on privacy.<br>(3) Often it is forgotten to collect the opinion of the users. | (1) Improvement of users' privacy.<br>(2) Personalization of the assistive systems.<br>(3) Increase in the sample size of the participants.<br>(4) More inclusion of the end-users to validate the assistive technologies.<br>(5) Provision of more robust proof to support the effectiveness of non-pharmaceutical interventions |
| Neubauer et al. (2018) | Technologies used to manage dementia-related wandering behavior | (1) 26 types of devices were identified.<br>(2) Low scientific evidence of clinically oriented studies.<br>(3) Overall acceptability and usability of mobile locator, sensor and alarms devices, and wayfinding devices are high among users. | (1) Improvement of usability testing and user-centered design.<br>(2) Comparison study among different technology types. |
| Khosravi and Ghapanchi (2015) | Assistive Technologies designed to help seniors | (1) Senior problems are categorized into chronic disease, dementia, depression, fall risks, dependent living, poor medication management, social isolation, poor wellbeing.<br>(2) The identified technologies used to assist the seniors are ICT, robotics, telemedicine, sensor technology, video games, Medicine dispensing devices.<br>(3) Positive impacts are reported by the application of ICT and sensor technologies for senior wit dementia. | (1) Randomized controlled trials are required to provide more robust proof of effectiveness.<br>(2) Medical researchers should be more involved in studying assistive technologies. |
| Archer et al. (2014) | Online and mobile support for self-management of chronic illnesses | (1) Numerous chronic diseases are associated with the presence of cognitive impairment. This negatively impacts the technology usage.<br>(2) Use of smart home technologies to help people with mild dementia and cope with chronic disease,<br>(3) The interaction of users with dementia should be minimized with the technologies. | (1) Further research into ethical, legal, clinical, and economic issues is required. |
| Tomaskova and Cimler (2018) | Smart technologies designed for people with dementia | (1) Smart technologies and smart wearables are identified to help with memory and routine tasks. | None |
| Piau et al. (2014) | Technology appropriate for older adults' home use | (1) Technologies discussed were using for mobility aids, prompting for ADLs, ADL monitoring.<br>(2) The proponents of surveillance devices have met considerable resistance from those who perceive it as contrary to freedom.<br>(3) Technologies can assist the elders compensate for their impairments in performing ADLs, monitor their progress, and provide feedback to clinicians.<br>(4) High rates of satisfaction with telecare and telemedicine were reported. | (1) Conducting real-world trials.<br>(2) Participation of end-users in the design process.<br>(3) Obtaining a consensus on the terminologies and definitions. |

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**Table A.1** (*continued*).

| Article | Research Scope | Findings | Suggested Future Research |
|---|---|---|---|
| Holthe et al. (2018) | Technologies explored with older adults with mild cognitive impairment and dementia (MCI/D) | (1) Four domains of technologies have been used including safe walking indoors and outdoors, safe living, independent living, entertainment and social Communication.<br>(2) It is important to include people with MCI/D in the design to increase usability and acceptability.<br>(3) The acceptability of the technologies is always low at the first stages of implementation.<br>(4) User involvement requires a bottom-up approach. | (1) Clinical trials allowing patients to test the technologies at their houses.<br>(2) More research towards the length of the trials so that the change in the users' attitude towards accepting the technologies can be seen. |
| Niemeijer et al. (2010) | Surveillance technologies in residential care for people with dementia | (1) Practical problems regarding functional efficacy of the systems include removal of the devices by the users, false alarms or system misses, or power failures.<br>(2) There has been a great deal of legal debate surrounding the safety advantages and privacy disadvantages of surveillance technologies.<br>(3) Three central themes were identified for residential concerns: freedom and consent, privacy, and dignity/stigma.<br>(4) Lack of in-depth analysis of the ethical issues. | (1) More research to identify ethical and practical viabilities.<br>(2) More research to delineate ethical values such as dignity, privacy, and autonomy.<br>(3) Inclusion of users' perspectives. |
| Dawson et al. (2015) | Services that support people with dementia to live at home | (1) Use of ICT has been identified as an assistive service with positive affect and feelings of safety. | (1) More focus towards perspective of people with dementia in provision of services. |
| Wong et al. (2017) | Age-friendly technologies in high-rise residential buildings | 1) Four intelligence scope for smart home technologies includes autonomy, controllability of complicated dynamics, man-machine, interaction, and bio-inspired behavior are identified.<br>(2) Four indicators of systems' autonomy are self-governing in special conditions, automatic switches, automatic functions for assisting with physical and memory limitations, automatic reminder.<br>(3) Four themes of controllability of complicated dynamics are remote controlling, system flexibility, timer setting, integrated system.<br>(4) Three identified themes for bio-inspired behavior are suitable for built environment, biological adaptation and learning, human-like behavior. | (1) Increasing the sample size of the participants with wide range of disabilities and profiles<br>(2) Analyzing performance of the smart home technologies<br>(3) Identifying the functionalities and capacities of smart home technologies that are optimal for increasing the quality of seniors' lives |
| Husebo et al. (2020) | Sensing technology to assess behavioral and psychological symptoms and to monitor treatment response in people with dementia | (1) Based on the technology type, four broad categories are identified including wearable, non-wearable, assistive/smart home, and other technologies.<br>(2) Most studies have small sample sizes.<br>(3) More immediate and accurate diagnosis and management of behavioral disturbances are the benefits of continuous motion monitoring of patients that also delay long-term care admissions.<br>(4) People with advanced dementia are unable to provide informed consent.<br>(5) Few numbers of studies developed intervention approaches. | (1) Investigating the validity of the technologies for prognostics, acceptability, feasibility, and responsiveness in clinical trials. |
| Maskeliunas et al. (2019) | IoT technology to the domain of AAL systems and assistive technologies | (1) Domains related to the application of IoT technologies include smart homes and environments, ambient assisted living (AAL), agent-based pervasive computing and decision-making methods, and IoT sensing technologies.<br>(2) Challenges in application of IoT are identified in areas such as intelligence, security, integration, and unobtrusive sensing.<br>(3) The most developed smart home systems are based on rules, logics, and actions that system designers and developers pre-defined and pre-programmed.<br>(4) A major problem with implementation of IoT for smart homes is the lack of common interoperability standards for IoT technologies.<br>(5) Collection of position or movement data can be performed device-based or device-free.<br>(6) Novel and innovative services, technologies, and methods for improving the occupants' quality of life are identified. | (1) More implementation of machine learning and intelligent decision making to automate the control in smart homes.<br>(2) Incorporation of adaptive, interactive, and contextual IoT for smart homes. |

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**Table A.1** (*continued*).

| Article | Research Scope | Findings | Suggested Future Research |
|---|---|---|---|
| MacAndrew et al. (2019) | Nonpharmacological interventions for wandering | (1) Identified interventions are grouped into activity-based, external stimulation, mart home technology, and environmental modification. | (1) More participants in experiments.<br>(2) Accurate assessment of wandering characteristics.<br>(3) Comparison study among different interventions to find the best suitable one for people with dementia. |
| Hassan and Khan (2019) | Technology and algorithms for detection and management of wandering behavior | (1) Technologies for wandering detection are identified and categorized into indoor and outdoor systems.<br>(2) Nine different algorithms are identified for wandering detection.<br>(3) Factors in usability of the technologies are discussed.<br>(4) Design suggestions and special features for the technologies are presented from user studies.<br>(5) Challenges in experiment design and practical use of the technologies are discussed. | None |
| Lin et al. (2014) | Technological solutions on wandering in the context of assisted living | (1) Identified solutions are grouped into event monitoring-based discovery, trajectory tracking-based detection, and location-based prevention.<br>(2) Features of existing research efforts are discussed. | (1) Large-scale data collection.<br>(2) Personalization of detection models and algorithms.<br>(3) In-depth analysis of wandering behavior and its related factors |
| Carswell et al. (2009) | ICTs to support people with dementia | (1) Identified technologies are categorized into technologies used by patients or carers, monitoring systems, ambient assisted living, tracking and wayfinding. | (1) Increase in clinical trials for technology implementations.<br>(2) Development of technology for emotional detection.<br>(3) Long-term evaluation of the technologies to assess the real efficiency of them. |
| Meiland et al. (2014) | Healthcare technologies for nighttime care | (1) Three broad classifications of technologies are identified: night specific, night and day, and day applicable to the nighttime scenario.<br>(2) Narrower classification of the technologies includes monitoring, lighting and guidance, education and treatment, wandering, therapy and simulated presence, and reminiscence. | (1) Consideration of ethical issues in both design and implementation.<br>(2) More research into the aspects and hazards of the nighttime environment for people with dementia. |

**Table B.1**
Summary of the technical papers on assistive technologies provided by smart built environment to the people with cognitive decline.

| Article | Research method | Outcome | Technologies used for data collection | Processing techniques | Human-building interaction interface | Validation methods |
|---|---|---|---|---|---|---|
| Bouchard et al. (2007) | Model development | Recognition of the incoherent behaviors in Alzheimer's Disease (AD) patients | Movement detectors, electromagnetic contacts on doors and cabinets, fridge, lighting system, pressure mats, and RFID tags | Keyhole Recognition Plan using Lattice Theory | Use of Smart Boards, Tablet PC, PDAs, Icebox, lights, and speakers as effectors | Usability evaluation in a controlled environment |
| Chaurasia et al. (2014) | System development | online sensor-based support system for cognitive impaired people | Binary sensors (contact switches and movement detectors), webcam (activity verification) | A learning algorithm that learns a joint probability distribution over different sensor sequences, incomplete durations, and other attributes. | – | Experiments in a controlled environment |
| Lam et al. (2017) | System development | activity tracking and monitoring system for AD patients | Kinect (Motion Sensor), Wearable movement sensor to record speed or acceleration of movement (fall detection), NFC readers + tags for performing specific localization functions, presence detection | - Support vector machines (SVM)<br>- Random forests (RF)<br>- Naive Bayes (NB) | Smartphones for activity reminders | Experiments in real environment |
| Stucki et al. (2014) | System development | Web-based non-intrusive ambient system to recognize and classify ADLs for AD patients | Wireless sensor box and wireless protocol device worn by participant | A rule-based forward chaining inference engine | – | Experiments in real environment |

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**Table B.1** (*continued*).

| Article | Research method | Outcome | Technologies used for data collection | Processing techniques | Human-building interaction interface | Validation methods |
|---|---|---|---|---|---|---|
| Das et al. (2012) | System development | An automated prompting-based interventions without any predefined rule sets or user feedback for people suffering from mild cognitive disorders (MCI) | A grid of motion sensors on the ceiling, door sensors on the apartment entrance and on doors for cabinets, refrigerator, and microwave oven, item sensors on containers in the cabinet, temperature sensors in each room, a power meter, analog sensors for burner and water usage, and a sensor that keeps track of telephone use. | - J48 decision tree<br>- LogitBoost<br>- sequential minimal optimization (SMO) | Touch screen monitors with embedded speakers | Experiments in a controlled environment |
| Hoey et al. (2012) | Approach proposal | Description of formulating a general-purpose activity recognition model that can capture Customizability, Generalizability, and Adaptivity | – | A Partially Observable Markov Decision Process (POMDP) | – | Usability evaluation (Applied the model in five assistive systems) |
| Lazarou et al. (2019) | Evaluation study | Efficiency investigation of an assistive technology combined with tailored non-pharmacological interventions for people with mild cognitive impairment and AD | Ambient depth cameras, plug sensors, tags, presence sensors, and a Sleep sensor | Logic-based algorithms | – | Usability evaluations in a real environment |
| Belley et al. (2015) | - System development<br>- Approach proposal | - An assistive system based on electrical device identification to detect problems with ADLs among people with cognitive disorders<br>- An algorithmic approach to recognize erratic behaviors | Radio Frequency Identification or RFID-based and power usage sensors | Developed a nonintrusive and economic model for assistance | Prompting through embedded iPads, speakers, lighting systems | Experiments in a controlled environment |
| Kikhia et al. (2018) | Framework proposal | The monitoring framework of DemaWare system that detects behavioral problems among persons with behavioral and psychological symptoms of dementia (BPSD) | Ambient sensor is Gear4 Sleep clock,2, and wearable sensor is the Philips sensor bracelet DTI-2 | Rule-based techniques for the detection of behavior problems | – | Experiments in real environment |
| Roy et al. (2011) | Model development | An activity recognition model to detect problems associated with dementia in performing an activity | – | Possibility Theory | – | Simulation |
| Keum et al. (2020) | Framework proposal | A self-organized device network structure to perform user perception, location perception, and behavioral perception simultaneously among persons with chronic brain disease | Passive infrared (PIR), ambient light, acceleration, gyro, flame detection, temperature, power usage, and wearable sensors | Ege Computing | – | Experiments in a controlled environment |
| Aloulou et al. (2014) | Evaluation study | Discussion on the different mechanisms to ensure the dynamic aspect of their previously proposed ontological-based approach which integrates new services at runtime and enables binding to specific patients with cognitive decline | Vibrator sensors, proximity sensors, and presence sensors | - Reasoning Engine<br>- Semantic Plug & Play mechanism | – | Experiments in a real environment |
| Abbate et al. (2012) | System development | A minimally invasive sensor platform to detect and predict anomalous events through monitoring occupants' movements and physiological signals among elderlies with dementia and AD | Wearable sensors (Shimmer and Enobio sensors) | Support Vector Machine (SVM) | Emergency alarms sent to caregivers | Experiments in a real environment |

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**Table B.1** (*continued*).

| Article | Research method | Outcome | Technologies used for data collection | Processing techniques | Human-building interaction interface | Validation methods |
|---|---|---|---|---|---|---|
| Lazarou et al. (2016) | System development | A system for remote monitoring to detect problems in ADLs and design personalized clinical interventions | wearable, sleep, object motion, presence, and utility usage sensors | Range from simple retrieval of sensor measurements to complex human activity recognition methods based on image data | – | Experiments in a real environment |
| Hao et al. (2018) | Model development | An inference engine to perform activity recognition and prediction for ambient assisted living of cognitively impaired people | – | - Graph searching algorithm<br>- Ontological clustering algorithm by formal concept analysis (FCA) | – | Simulation |
| Moutacalli et al. (2015) | Model development | An algorithm to detect and predict steps of an activity to support persons with cognitive dysfunctions | Infrared, pressure mats, electromagnetic contacts, temperature, light sensors, and RFID antennas | - Unsupervised algorithm for regular behaviors creation<br>- Time series forecasting technique for predicting activities started times<br>- Bayesian network for started activity search | – | Experiments in a controlled environment |
| O'Neill et al. (2018, 2013, 2010) | Evaluation study | Reports on the trial of a n automated interactive prompting technology, Guide, in supporting of persons with acquired brain injury | An Acoustic Magic Voice Tracker II directional microphone | Dragon Naturally Speaking speech recognition software | Verbal responses through an activity protocol player | Experiments in a controlled environment |
| Pinard et al. (2019) | System development | A technology to support meal preparation for persons with Traumatic Brain Injury (TBI) | Power, infra-red, electromagnetic, and pressure sensors, and RFID, and flowmeters | Context-aware technology | Audio and visual prompts through planted speakers and tablet screen | Usability evaluation in a controlled environment |
| Mihailidis et al. (2008) | Evaluation study | Discussion around the research question on the usability of the previously developed system that autonomously guide elderlies with dementia through ADL | Video Camera | Partially observable Markov decision process (POMDP) | Audio and visual prompts | Experiments in a controlled environment |
| Enshaeifar et al. (2018a) | Evaluation study | Reports on the trial of the THIM system which allows obtaining real-time insights into the health status of occupants with dementia | - Passive sensors such as humidity and temperature conditions, appliance usage, etc.<br>- medical devices and wearable technologies such as blood pressure, pulse, etc. | - Rule-based reasoning methods for vital measurements<br>- Machine-learning techniques to learn the individuals' activities | Reminders generated through the users' interactive application | Experiments in a controlled environment |
| Stavropoulos et al. (2017) | Framework proposal | A holistic framework to integrate several heterogeneous modalities to provide appropriate feedback of patients with dementia to enhance clinical workflow | Images and Depth, Sleep Recording, Audiovisual, Wearable (DTI-2, UP24), power usage, and Motion Sensors. | a context-based fusion using OWL 2 as the underlying knowledge representation and reasoning language | – | Usability evaluation in both controlled and real environment |
| Alvarez et al. (2018) | System development | A system for health monitoring of people suffering from Parkinson's or Alzheimer's Disease | Multisensory band (bracelet), Binary sensor, RGB-D (Microsoft Kinect v2) camera, Zenith camera, Wireless sensor network (WSN) anchors or beacons. | - Sparse AutoEncoder (SAE) algorithm for producing more meaningful and compact features<br>- SVMs or the Logistic Regression to assign labels to data samples<br>- Bayesian network (BN) model to infer the high-level information regarding the patient's health status<br>- Recurrent neural network (RNN) for detection of the freezing of gait (FoG) action | Alerts and reminders via user interfaces in smartphone, TV, or web interface | Experiments in a real environment |

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**Table B.1** (*continued*).

| Article | Research method | Outcome | Technologies used for data collection | Processing techniques | Human-building interaction interface | Validation methods |
|---|---|---|---|---|---|---|
| Pastorino et al. (2014) | Evaluation study | Reports on the usability of CogWatch system to support patients with apraxia and action disorganization syndrome | - Objects consisted of everyday tools, equipped with instrumented sensorized coasters.<br>- The sensors contained in the CogWatch Coaster include a 3-axis accelerometer and 3 force-sensitive resistors | - The actions of the users are determined by an action recognition (AR) algorithm.<br>- The task model algorithm (TM) detects possible mistakes.<br>- Markov decision process (MDP) for processing time-varying sequences of data | - Multimodal feedback through speakers and visual displays<br>- Visual, auditory or vibro-tactile cues through a smartwatch | Usability evaluation in a real environment |
| Tchalla et al. (2013) | Evaluation study | Discussed the effectiveness of teleassistance service (HBTec-TS) among elders with AD that prevents indoor falls | Electronic bracelet | – | Light Path | Interviews/ Questionnaires/ Observations |
| Charlon et al. (2013b) | System development | A monitoring system for elders suffering from AD | A motion sensor network, and a wearable electronic patch | Supervised Learning | Alert messages to medical staff | Experiments in a controlled environment |
| Charlon et al. (2013a) | System development | A monitoring system for detection of abnormal situations | A network of IR motion sensors, and a wearable electronic patch | Neural Network | Alert messages to medical staff | Experiments in a real environment |
| Aloulou et al. (2013) | Approach proposal | An approach to develop and deploy an ambient assistive system for activity detection and prediction among patients with dementia | Pressure, proximity, vibration, motion sensors, and RFID tags | - Reasoning Engine for activity detection<br>- Decision tree ensemble and active learning for activity prediction | Reminders and notifications through speakers and tablet screens for patients and through smartphones to caregivers | Usability evaluation in a real environment |
| Rowe et al. (2007) | Evaluation study | Report on the clinical trials of effectiveness testing of CareWatch system that supports people with cognitive impairments | Motion sensors, door opening, and bed occupancy sensors | – | Alerts the caregivers | Experiments in a real environment |
| Kolakowski et al. (2020) | System development | A positioning System to detect dementia related wandering | - UWB (Ultra-Wideband) technology for persons mobility and behavior<br>- BLE (Bluetooth Low Energy) technology for item search support and determining the areas, where the patients are located<br>- Inertial sensors for fall detection | - An extended Kalman filter-based algorithm for user localization<br>- Received Signal Strength Difference (RSSD) based method for item localization | - Tags equipped with additional light and sound signaling devices (for Item search)<br>- Alerting the caregivers (for fall detection) | Experiments in a real environment |
| Fortin-Simard et al. (2015) | System development | A nonintrusive system based on the load signature of appliances to assist cognitively impaired people with ADLs and detect errors | RFID-based and power usage sensors | Bayesian Network | Audio and visual prompts | Experiments in a controlled environment |
| Najjar et al. (2009) | Approach proposal | A recognition approach of undertaken ADLs performed by patients with cognitive impairments | – | - A Hidden Markov Model (HMM) | – | Simulation |
| Najjar et al. (2010) | Framework proposal | A modular architecture for an intelligent assistive system to realize of cognitively impaired people's ADLs | – | HMM | Color Prompts | Simulation |
| Chu et al. (2012) | Approach proposal | A heuristic approach to solve an interactive activity recognition model or use in an assistive system for persons with cognitive disabilities | IR motion, RFID object touch, and appliance operation, contact sensors, and wearable RFID readers | The model is built upon an option-based hierarchical POMDP | Audio and graphic prompts and queries through smartphones | - Simulation (for solving the model)<br>- Experiments in a real environment (to test the model in a system) |

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**Table B.1** (*continued*).

| Article | Research method | Outcome | Technologies used for data collection | Processing techniques | Human-building interaction interface | Validation methods |
|---|---|---|---|---|---|---|
| Lotfi et al. (2012) | Approach proposal | A solution to support the independent living of the old adults with dementia that can detect and predict activities | PIR or motion detectors, Door/window entry point sensors, Electricity power usage sensors, Bed/sofa pressure sensors, Flood sensors | - Echo State Network (ESN), Back Propagation Through Time (BPTT) and Real Time Recurrent Learning (RTRL) | Alerting the caregivers | Experiments in a real environment |
| Enshaeifar et al. (2019) | System and model development | - Use of IoT, and in-home sensors with machine learning to monitor health of occupants with dementia<br>- An algorithm to detect Urinary Tract Infection (UTI) | - PIR, motion, pressure, and door sensors<br>- Central energy consumption monitoring and Bluetooth enabled medical devices | - Isolation Forest (iForest) technique for activity monitoring<br>- Non-negative Matrix Factorization (NMF) technique for UTI detection | - Alerting the caregivers<br>- Notifications to patients | Experiments in a real environment |
| Seelye et al. (2013) | Approach proposal | A graded hierarchy of technology-based prompts | Web cameras (Live Feed) | - Graded cue hierarchies<br>- Human selection of prompts | Video and verbal prompting through laptops | Usability evaluation in a controlled environment |
| Ficocelli and Nejat (2012) | Framework proposal | Design of an assistive kitchen system consisting of a user interface with two-way speech communication for people with mild to moderate cognitive decline | Voice Commands (Mic) | - Hidden Markov Models for speech recognition engine<br>- A finite-state machine (FSM) approach to design the high-level controller | - Verbal and Visual Prompts Through speakers and a screen<br>- An automated cabinet system | Experiments in both controlled and real environments |
| Hattink et al. (2016) | Evaluation study | Evaluating the integration of three previously developed assistive technologies into one to support people with dementia | – | – | – | Experiments in a real environment |
| Gerka et al. (2019) | Framework proposal | A care concept for dementia patients that can detect wandering and ADLs | Smoke and flood detectors, motion, power, and wireless contact sensors | - Knowledge-driven approaches<br>- Supervised Machine Learning | - Alerting the caregiver<br>- Automatic Stove deactivation | Experiments in a real environment |
| Mehrabian et al. (2014) | Evaluation study | Acceptability analysis of a user-friendly approach that provides cognitive prosthesis to patient through medications, tasks, and scheduling | – | – | – | Interviews/ Questionnaires/ Observations |
| Enshaeifar et al. (2018b) | Model development | A machine learning algorithm to discover the underlying pattern of activities among the people with dementia | – | - K-means algorithm for data clustering<br>- MCP for anomaly detection in daily routines<br>- HMM for the prediction of movement pattern based on hourly sequences | – | Simulation |
| Czarnuch and Mihailidis (2011) | Evaluation study | Determination of the dementia patients' needs and the role of the assistive technologies to overcome and support the needs | – | – | – | Interviews/ Questionnaires/ Observations |
| Braley et al. (2019) | Evaluation study | Evaluation of effectiveness of the prompting technologies through review of archived video of the users with dementia | Video Camera | – | – | Interviews/ Questionnaires/ Observations |
| Das et al. (2016) | Approach proposal | A machine learning approach for activity recognition and error detection among individuals with dementia | Passive infrared motion detectors, pressure-based item, magnetic door, and accelerometer-based vibration sensors. | one-class classification-based SVM | – | Experiments in a controlled environment |

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