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Enabling Independence: Assessing Activities of Daily Living to Inform Safety Standards for Built Environments

Final Research Report

2026-03-31

Carleton University

Contents

Table of acronyms

ADL	Activities of Daily Living
IADL	Instrumental Activities of Daily Living
AAL	Active/Ambient Assisted Living
ASC	Accessibility Standards Canada
IoT	Internet of Things
WHO	World Health Organization
ICF	International Classification of Functioning, Disability and Health
ISO	International Organization for Standardization
IEC	International Electrotechnical Commission
ETSI	European Telecommunications Standards Institute
IEEE	Institute of Electrical and Electronics Engineers
CSA	Canadian Standards Association
CSA	Connectivity Standards Alliance
ITU	International Telecommunication Union
AI	Artificial Intelligence
PHD	Personal Health Device

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1. Executive summary

What this project was about

Enabling Independence: Assessing Activities of Daily Living to Inform Safety Standards for Built Environments was a three-year research project (2023–2026) led by researchers at Carleton University's Accessibility Institute and Faculty of Engineering and Design. Accessibility Standards Canada funded the work.

We studied how smart technologies in the places people live, work, and spend time can help support activities of daily living (everyday tasks that people need or want to do to live independently). We did this to help the design of future accessibility and safety standards.

The project focused mainly on:

- people with disabilities, and
- older adults who want to age in place (live safely in their own home as they get older).

What we learned can also apply to many settings, including private homes, workplaces, rental and shared housing, and long-term care.

What we did

This project brought together two kinds of expertise:

- community-based research (learning from lived experience), and
- engineering research (understanding how technology works, and where it falls short).

We organized the work into three connected parts.

1) We reviewed research, reports, and standards

We looked at academic studies, public reports, and international standards. We focused on:

- common barriers to independent living, and

- the types of technologies people currently use to support their everyday living.

2) We learned directly from people

We worked with community members through:

- workshops where young adults with disabilities helped shape ideas and priorities, and
- focus groups with older adults and care partners.

3) We explored current and emerging technologies

We examined existing and new tools that could help monitor and support everyday life. We focused on the needs and ideas raised by participants. We shared findings through conferences, invited talks, and peer-reviewed publications to build understanding of accessible design in engineering.

What we found

Smart home technologies and wearable devices can support independence in practical ways, such as:

- reminders,
- basic automation (for example, simple actions triggered automatically),
- health tracking, and
- support for everyday routines.

But people also raised important concerns, including:

- privacy and who controls personal information,
- unfair outcomes when technology works better for some people than others,
- loss of control if technology "takes over" instead of supporting the person, and
- unequal access because of cost, complexity, or poor design.

Our review of standards suggested that some risks could be reduced by following existing guidance about protecting devices and information, handling health information responsibly, and helping different devices work together. However, this guidance is not widely used in real-world products—especially when people use consumer smart home products as supports for independent living.

Across both age groups, many people said they were interested in using technology that helps them live more independently. They often cared most about help with small, everyday needs, not only rare emergencies like falls.

Participants also emphasized that accessibility matters across the whole life of a product, including:

- setup and installation,
- updates,
- repairs and maintenance, and
- long-term support.

People also valued:

- being able to tailor settings to their own needs,
- having more than one way to use a tool (for example, voice, touch, or other options), and
- keeping control over what the technology does.

Recommendations

Based on what we learned, we recommend the following to keep the focus on user control and independence:

- Plan for the full life of the product. Design and standards should include setup, installation, updates, maintenance, and long-term support.
- Make products dependable and safe. Technology should keep working in a safe way, even if one part fails, especially when it supports essential daily activities.
- Ask for permission and respect choices. Companies should clearly ask users what they agree to when it comes to privacy, data ownership, and how personal information is used (including when it is used to build or improve AI tools).
- Help devices work together. People should be able to connect different tools and choose what works best for them, rather than being locked into one system.
- Recognize how people actually use technology. Standards and designers should plan for and help with the growing practice of using everyday consumer devices for personal monitoring and support.

2. Project background

2.1. Mandate and motivation

The purpose of the research project *Enabling Independence: Assessing Activities of Daily Living to Inform Safety Standards for Built Environments* was to investigate best practices for the integration of technology into built environments to assess and support activities of daily living. The project aimed to inform accessibility standards by exploring how standards for the use of technology in built environments could improve safety for persons with disabilities. While the principal aim was to inform accessibility standards for higher degrees of independent living, the research is applicable to a range of living spaces including work environments, private dwellings, rentals, shared accommodations, and suites/units in both public and third-party long-term care facilities.

The project was funded by Accessibility Standards Canada (ASC) for three years (2023 – 2026). Key outputs of this project include:

- Literature review of the current state of research and standards related to the use of technology to assess and enable the daily living activities of persons with disabilities or aging in place.
- Research to improve understanding of the technical possibilities of the field, and to produce new data about how technology can be used to monitor activities of daily living to enable increased independent living, disseminated through peer-reviewed articles to the scientific, engineering, and accessibility communities.
- Development of a set of actionable best practices to inform the next generation of model accessibility standards for assessing daily living activities in built environments to improve safety and facilitate independent living.
- Final research report to be made publicly available in an accessible format in both official languages.

2.2. Team

The project was conducted through the Accessibility Institute at Carleton University and was driven by a cross-functional research group. With backgrounds in engineering, sensor and signal processing, supportive aging-in-place, and accessibility studies, the project team goal was to address accessibility through both social science and engineering lenses. The social science lens was used to uncover the real barriers encountered by individuals living with disabilities through our focus groups and co-design projects. The engineering side focused on actionable measures to reduce barriers, improve standards, and employ technology to support independent living and daily activities.

Principal Investigators

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Research Team

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2.3. Context

a) Language

This work references disability-related literature from medical, social science, and engineering. These fields often use differing language to describe people with disabilities and their associated sensory impairments or functional limitations; these differences may be reflected in the wording of different sections.

We use the terms disability and barrier as they are defined in the Accessible Canada Act (Naef and Perez-Leclerc 2019):

> "Disability means any impairment, including a physical, mental, intellectual, cognitive, learning, communication or sensory impairment—or a functional limitation—whether permanent, temporary or episodic in

nature, or evident or not, that, in interaction with a barrier, hinders a person's full and equal participation in society".

"Barrier means anything—including anything physical, architectural, technological or attitudinal, anything that is based on information or communications or anything that is the result of a policy or a practice—that hinders the full and equal participation in society of persons with an impairment, including a physical, mental, intellectual, cognitive, learning, communication or sensory impairment or a functional limitation."

b) Functioning and disability

This project considers the accessibility of the built environment through a biopsychosocial model, as used by the World Health Organization International Classification of Functioning, Disability and Health (WHO ICF) (World Health Organization 2001a). This model recognizes the roles of health conditions, personal experience, activities, and environmental factors, and how their interactions inform an individual's functioning and disability. The model also stresses aetiological neutrality and the significance of shifting from a binary classification of individuals based on health condition, to a view of disability existing on a continuum with functioning. Anyone can experience disability, including intermittently or temporarily, and we cannot infer participation from diagnosis alone.

2.4. Report structure

The remainder of the report summarizes the research and findings of the project as follows:

- **Section 3** presents a literature review of research related to challenges and barriers to independent living, and standards for accessible technology and independent living.
- **Section 4** presents our community engagement to identify barriers in activities of daily living, and to understand the roles and perception of technology to support independent living.
- **Section 5** summarizes our engineering research efforts where we used human-focused approaches to develop and assess technologies to monitor and support activities of daily living.

3. Literature reviews

3.1. Research

We reviewed academic and grey literature to provide scoping and alignment for our standards review. In this section we outline the research areas we explored and summarize the challenges and barriers to independent living that we identified from the literature.

Key areas for literature in the Activities of Daily Living space include the following categories:

- *Caregiving* – Where the solutions are focused on the needs of a caregiver supporting another person. Typically, this will be a family member such as a spouse parent or child of the person being supported. These solutions could address a wide range of ages for the person being supported.
- *Education* – Where the solutions are focused on supporting the educational needs of the person needing assistance and hence the solutions will focus typically on a younger age group.
- *Independence* – Where the solution is focus on supporting the independence of an adult and this ranges from younger adults that are now on their own or older adults.
- *AAL "Active/Ambient Assisted Living"* – These are solutions/systems that are being developed typically to support Independence or Caregiving. The work in that space is more focused on the technology challenges and solutions.

a) Caregiving

Most literature that looks at caregiving within the social and health sciences spaces is focused on the impacts of caregiving burden on the caregiver such as stress or depression within the caregiver. These numerous works have been omitted as they do not dig into the cause of these issues to any level and hence do not identify solutions and instead focus on the stress/depression itself.

The papers reviewed, including (Bialon and Coke 2012; Etters et al. 2008; Baronet 1999; Savundranayagam et al. 2005; Clyburn et al. 2000), do provide some insight into the challenges of caregiving and the reasons why caregiving burden may be higher in some cases. However, no papers have been found so far that looks at solutions to address caregiving burden directly beyond those discussed in the AAL section below as these works focus on human (social service, health services) solutions to reduce caregiving burden.

b) Education

Much of the education literature is on access to education for students with special needs and some crosses into access for all students. Revant works include, (Guha and Druin 2008; Sadikovna and Azimjon oʻgʻli 2023; Meynert 2014; Hornby 2011; Janus et al. 2007; Eckes and Ochoa 2005; Hasselbring and Glaser 2023). Education models are based on a teacher-student model with supportive technology and as a result the key issues are raised based on student needs and not technical solutions in most cases. Computer use does come into play.

The work on technology for education access is focused on point solutions for specific student needs with limited focus across needs or across the educational system. i.e. A software application to use on a PC or Tablet that focuses on the needs for student with need "x".

c) Independence

The works on independence start to introduce technical solutions and identify that technology solutions that were expected to have barriers themselves did not have these barriers. The works such as (Agree 2014a; Waldschmidt and Sépulchre 2019; Thompson 2018; Fisher et al. 2009; El-Basioni et al. 2014; Carmien and Fischer 2008; Zheng et al. 2022) also identify forces driving the need for independence such as Human Rights (UN Human Rights Agreements) and a Citizenship lens on enabling independence. These drive new and different needs-based approaches starting from the person. The works provide some specific technology examples.

d) AAL "Active/Ambient Assisted Living"

Several reviews of technology, including (Bin Noon et al. 2023; Byrne et al. 2018; Fadrique et al. 2020; Lam et al. 2022; Mujirishvili et al. 2023; Quesada-García et al. 2023; Scott et al. 2022), examine the AAL space from a usability/acceptability and hence focus on areas where tech/solutions work and where they fall down; some areas where standards are required are identified. Some specific work on areas where standards/policy are required include:

1. Monetization of data emerging from AAL systems

2. Accountability and liability associated with the AAL system data.
3. AAL system cost to purchase and maintain vs benefit and the encroachment on privacy.
4. Institutional decision-making process where people are dependent on others for what they can and can't do.
5. Equity of access (affordability, internet access).
6. Privacy of the data and the person – who gets access to what data such as themselves, caregivers, family etc.

Solutions dictating specific behaviours or restrict their autonomy rather than empowering.

e) Summary: Challenges and barriers to independent living

Challenges to independent living and aging in place arise from the interactions of barriers with the functional limitations and personal factors of the individual who is living independently. Technological solutions for independent daily living aim to increase participation by reducing barriers and facilitating functioning.

Goals of technologies for enabling independence

Supportive Smart Homes (Wallace et al. 2023; Knoefel et al. 2024) incorporate multiple interacting hardware and software technical innovations such as sensors, actuators, and hubs for data integration and analysis. These smart spaces can sense and interact with their occupants, and can support independent living by, for example:

- providing automated, computerized, or voice-activated control over electrical and mechanical devices
- identifying usage patterns that can be optimized to improve functioning
- identifying and managing changes in physical and cognitive health by monitoring activity levels and behavior patterns
- detecting and monitoring activity to identify and provide notification of emergency situations
- detecting and monitoring vital signs to identify immediate emergencies as well as gradual health changes.

Barriers related to technologies for enabling independence

Design shortcomings, side-effects, or misuse of technologies designed to facilitate independent living can create new barriers or reinforce existing ones. Concerns associated with the use of these technologies include (Agree 2014b; Bin Noon et al. 2023; Boger 2022; Chu et al. 2022; Scott et al. 2022; Sixsmith 2022; Wallace and Knoefel 2022a; Wang et al. 2023; World Health Organization 2022; Zheng et al. 2022):

- **Data ownership and privacy**: Smart home sensors can collect sensitive information, including audio and video, which raises privacy concerns about who owns and stores the data and who can access it. Even anonymized data can be a privacy concern when multiple streams of data are aggregated. Emerging data ownership concerns include the sale of aggregated data, and the use of personal data for training AI models.
- **Ageist and ableist design**: Many smart home technologies are designed for people with disabilities or older adults, without consulting these individuals on their needs and desires. The resulting products may not meet the needs of end-users, and instead reflect stereotypical views about their goals, desires, and behaviors. Products may have narrow usage models or poor accessible design that does not account for the diversity of users.
- **Algorithmic bias**: The datasets used to train AI models often under-sample or completely exclude older adults or people with disabilities (Kunz et al. 2025). The resulting models and algorithms may perform poorly for end-users, and may fail to properly generalize to the physical, functional, and behavioral diversity of the population.
- **Loss of autonomy**: Individuals living independently may vary their behavior, activity, or sleep patterns for reasons of personal preference or spontaneous desire. Monitoring systems may alert family members or care givers to these “unexpected” changes, creating a feeling among end-users that the system is acting against their interests, coercing them into behavior patterns that are more suitable for monitoring, and depriving of them of autonomy. Similarly, assistive and supportive technologies may limit individuals to functioning within the defined "accessible" path or set of activities. In addition to reducing autonomy, this can lead to reduced capacity as individuals lose the ability to perform tasks outside the accessible path.

- **Loss of human contact**: Automated sensing, monitoring, and support technologies that replace in-person well-being and care visits can lead to reduced social interaction and increased loneliness and isolation.
- **Functional safety**: Technology that is relied on to support activities of daily living can cause harm when it breaks down or behaves unexpectedly. Consumer smart home technologies may not be designed with proper functional safety concerns like redundancy and fail-safe operation.
- **Technology reliability:** Technology-based solutions often require, or are perceived to require, more effort to maintain than low-tech solutions. The utility of high-tech devices comes from their active technology components; however, software may crash or need to be updated, and batteries may need to be charged. These devices may become useless if they are not maintained, creating barriers to individuals who rely on them. In contrast, the usability of many low-tech devices and solutions, such as reach aids or magnifying lenses, comes from their physical design. Their reliability is determined by their physical robustness.
- **Technology change and obsolescence**: Technologies to support activities of daily living may be tightly integrated into the routines of the end-user, and also physically integrated into their living space. This makes it difficult to change systems and raises concerns about ongoing support and maintenance of the hardware, and security and functional updates of the software components.
- **Equity of access**: There are several dimensions of equity concerns associated with technology to support activities of daily living. Devices and systems may have high upfront and ongoing costs, which creates financial barriers to access. Insurance plans may only cover the cost of well-established and approved devices. Use of the systems may assume some level comfort and familiarity with technology, or may require reliable high-speed internet access, creating barriers for individuals from rural and remote areas and those who lack digital connectivity. A more subtle issue of equity is in the types of technologies that are built; individuals and populations may be excluded from technological assistance because there is no profit potential.

Some of these concerns are intrinsic to the use of technology, while others arise when repurposing consumer smart home technology for supportive smart homes. They highlight the importance of person-centred design, and of the need to incorporate accessible and inclusive design considerations throughout the product lifecycle.

Table 1 uses the concept of Life Domains from our technology review (Masson et al. 2025) to summarize and categorize some of the independent living challenges targeted by technology.

Table 1: Barriers and challenges to independent daily living classified by life domain.

Category	Concerns, challenges, and barriers	Associated functional limitations
Health and Self-Esteem - increasing or maintaining personal health and self-esteem		
Management and monitoring of health conditions	Medication reminders and administration Physical therapy and guided rehabilitation care Vital sign monitoring and tracking	physical functioning, cognitive capacity, memory, attention, and executive functioning
Personal health and wellness	Sleep quality and quantity Exercise and fitness	physical functional, mental health
Emergency response and egress	Alarm perception and response Access to emergency assistance Options for safe exit	physical functioning, sensory capacity, cognitive capacity
Housing (Physical Space) - modifications and maintenance of the physical space of a home		
Comfort control	Management of lighting, temperature, ventilation	physical functioning, sensory capacity, cognitive capacity
Domestic maintenance	Cleaning, household upkeep, landscaping and outdoor maintenance	Physical functioning, sensory capacity, cognitive capacity, mental health state
Activities of Daily Living (ADL) - regular activities of daily life which have to do with one's own body		

Category	Concerns, challenges, and barriers	Associated functional limitations
Personal hygiene	Toileting and bathing	physical functioning, cognitive capacity, mental health state
Food and nutrition	Meal planning and preparation Food safety Healthy eating	Physical functioning, cognitive capacity, mental health state, executive functioning
Instrumental Activities of Daily Living (IADL) - regular activities of daily life which involve the use of tools and technology		
Appliance usage	Appliance accessibility and safe usage	physical functioning, cognitive capacity, attention and executive functioning
Computer and technology usage	Access and use of technology for shopping, banking, entertainment	physical functioning, sensory capacity, cognitive capacity
Mobility and Transportation - the ability to displace oneself to desired locations through various means		
Navigation	Safe navigation and wayfinding Prevention and detection of wandering	physical functioning, sensory capacity, cognitive capacity
Falls and immobilization	Detection and emergency assistance	physical functioning
Personal mobility	Mobility aids Assisted transportation Personal vehicle usage	physical functioning, executive functioning
Communication and Governance - ability to attain information and communicate with other people, communities, organizations, and government		
Socialization	Community contact	cognitive capacity, mental health state, sensory capacity
Computer and devices usage for voice and messaging	Access and use of technology for communication Social media usage	physical functioning, sensory capacity, cognitive capacity, mental health state
Information access	Internet usage	cognitive capacity

Category	Concerns, challenges, and barriers	Associated functional limitations
Education, Work, and Leisure - continuing or extending personal education, work, career, and leisure activities		
Time management and planning	Task and activity reminders Short and long-term planning	executive functioning, cognitive capacity
Gaining, improving, or maintaining skills	Access and accessibility of learning materials and training programs	sensory capacity, cognitive capacity, executive functioning, physical functioning

3.2. Standards

Technologies designed to support ADL are integrated into the lives of the users who rely on them to assist and monitor their essential daily tasks. Standards can help ensure that technologies are safe to use, work as the user expects, and that the behavior of technologies is aligned to the needs of the user. The aims of standardization and the types of standards are detailed in (UNIDO 2006). In the context of technology for ADL the key aims of standardization include:

- **Ensuring fitness for purpose**: Standards for design and performance, combined with standards for testing and quality control, can provide confidence that a product or process does what it is supposed to do. For ADL tech this includes requirements on physical parameters such as impact resistance or battery life, also electrical or software parameters such as sensor sensitivity or algorithm performance. It also includes requirements for accessibility and usability, to ensure that the target of the standard is fit for the purposes of a diverse range of individuals.

- **Facilitating interchangeability and compatibility**: Manufacturing and design standards allow products, components, and processes to work together and be substituted for one another. This improves efficiency, promotes fair competition, and improves consumer choice. For ADL tech this compatibility extends beyond physical connectors to include software interfaces, communication protocols, and data storage formats.

- **Protecting health and safety**: Safety standards ensure that the manufacture and use of products does not harm human health, property, or the environment. This role is especially important in the in the ADL tech context where devices may serve a medical function or interact physically with an individual. Safety in this case includes the physical safety of the device and materials, functional safety of critical devices, as well as responsible manufacturing and lifecycle. A broader view of health and safety covers standards that regulate data security, data ownership, and privacy.

- **Providing a common language**: The acronyms, terms, and definitions used in standards provide a common language to describe products and processes in a precise and unambiguous way. This makes it easier for customers to compare offerings and for researchers and companies to interoperate and share technologies.

There are different types of standards, a standards document may serve one or more roles. The main types of standards include:

- **Vocabulary and basic standards**: Provide glossaries and definitions for common terms, and specifications for basic units of measure.
- **Product standards**: Provide specifications for products including physical quantities, performance specifications, packaging requirements, and safety specifications.
- **Inspection and test standards**: Describe processes and methods for product quality and performance, inspection, testing, and analysis.
- **Process management standards**: Describe best practices for management processes, including logistics, inventory management, maintenance, project management, and data and information management.

The following sub-sections discuss standards relevant to the use of technology to assess and enable the daily living activities of persons with disabilities or aging in place.

a) Accessible design processes

ISO/IEC Guide 71:2014 Guide for addressing accessibility in standards and ISO/TR 22411 Ergonomics data for the use in the application of ISO/IEC Guide 71:2014

ISO/IEC Guide 71:2014 provides guidance for standards developers on how to approach accessibility. It is both a vocabulary standard with a set of terminology related to accessibility, and a process management standard that details a process for identifying and defining accessibility requirements and recommendations for the product or service targeted for standardization. The guide provides two complementary approaches to addressing accessibility:

1. *Accessibility goals approach* – this approach begins by identifying a set of 11 accessibility goals for the system under consideration. These goals are sourced from existing accessibility guides, including *The 7 Principles of Universal Design* (CEUD, n.d.), example goals include:

    - Suitability for the widest range of users
    - Conformity with user expectations
    - Support for individualization

    The next stage is to identify what is needed to achieve these accessibility goals. Designers must recognize that these needs vary between individuals, and for the same individual in different contexts and circumstances.

2. *Human abilities and characteristics approach* – this approach begins by identifying the actions or activities required to interact with the system, and the human abilities and characteristics associated with those actions. This stage uses the concepts from the *WHO International Classification of Functioning, Disability and Health* (World Health Organization 2001b), also known as the ICF, to recognize the diversity of human abilities that results from health conditions and impairments in body functions, and how these can interact with personal and environmental barriers to create activity limitations and participation restrictions. The guide identifies design considerations for a wide range of physical abilities and characteristics, including:

    - **sensory abilities** such as seeing, hearing, touch, taste and smell;
    - **immunological conditions** such as allergies;

- **physical abilities** such as size, strength, and endurance; and
- **cognitive abilities**.

The next stage in both approaches is to develop strategies to address the design considerations and accessibility needs in the target system. There may be conflicts in accessibility needs between users, and a diversity of approaches may be needed to meet these diverse needs. These accessibility strategies then become requirements and recommendations in the developed standard. The parallel approaches are summarized in the following figure, adapted from the guide.

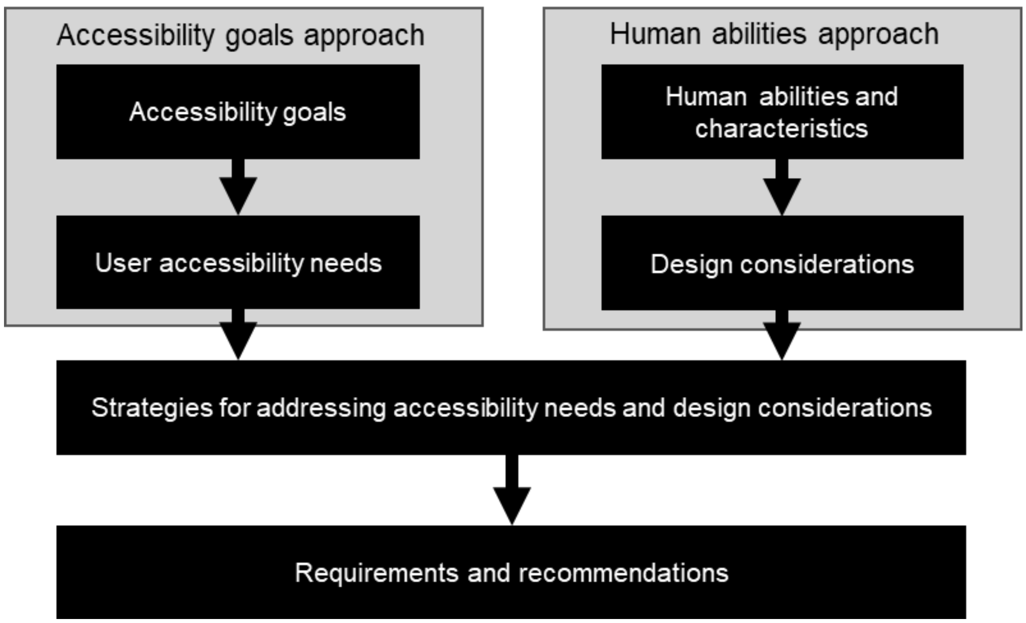

Figure 1: Parallel approaches to addressing accessibility in standards, adapted from ISO/IEC Guide 71:2014.

The companion document *ISO/TR 22411 Ergonomics data for the use in the application of ISO/IEC Guide 71:2014* provides examples of research studies that quantify and describe the variation of sensory, physical, and cognitive capabilities. This document does not provide specific requirements or recommendations, but it does provide some accessibility considerations and application examples of how the data can be used.

While the target of the guide is standards development, the approaches are general and can be applied to the development of other accessible products and services. The type of analysis outlined in the guide is necessary when designing effective technological solutions to support activities of daily living for persons with disabilities or aging in place, owing to the vast diversity of user abilities and accessibility needs. As noted in the guide, "[a]ddressing user accessibility needs earlier rather than later in the design process enables producers, possibly at little or no extra cost, to design and produce systems that are accessible" (ISO 2014).

ISO/TC 314 Ageing societies

The Ageing societies technical committee aims to address the challenges and opportunities associated with increased life expectancy and the resulting shift to aged societies. The developed standards work towards the creation of an age-inclusive society where older adults and caregivers can fully participate in work and leisure activities while also living safely and with dignity.

ISO/TR 25555:2024 Accessibility and usability considerations for home healthcare products, related services and environments

ISO 25555:2024 is a product and process management standard developed by ISO/TC 314 that assembles previously distributed information and recommendations relating to the design and delivery of home healthcare products and services. The standard provides examples of home healthcare applications along with design considerations and specific usability and accessibility concerns.

ISO 25550:2022 – General requirements and guidelines for an age-inclusive workforce

ISO 25550:2022 is a process management standard developed by ISO/TC 314 that provides guidelines and best practices for organizations to create and promote an age-inclusive workplace. There are overlapping concerns between aging-in-place and age-inclusive workplaces, and between age-inclusive and disability-inclusive spaces – activities of daily living take place in the workplace as well as at home, and policies and technologies are needed to support individuals in both locations.

The recommendations and requirements in ISO 25550:2022 are grouped into the following categories:

- **Strategies and public statements**: leadership, workforce planning and recruitment

- **Policies and procedures**: organizational culture, career development, ergonomics and digitalization
- **Health**: health management and promotion, occupational health and safety
- **Supports**: flexible work, training and development

The recommendations and requirements are for policies the workplace should implement; there are no requirements for standards for technologies in the workplace. However, technological solutions can be used to support the implementation of the policy recommendation. For example, technologies for activities of daily living may:

- Support continued workplace participation for people with dementia by helping them monitor their personal safety, schedule and monitor the status of their work, and facilitate adapted workloads.
- Support a universal design approach to occupational health and safety by helping workers monitor their cognitive and physical exertion levels to modify task intensity based on their individual capabilities.
- Promote workplace physical and mental health by helping employees track their health and sleep patterns. This can also be used to evaluate the effects of workload and shift changes to identify accommodation needs.

b) Accessible buildings and products

Accessibility of the built environment

Multiple standards organizations have published standards for accessibility and usability of the built environment, such as:

- ISO 21542:2021 Building Construction — Accessibility and Usability of the Built Environment
- ICC/ANSI A117.1-2017: Standard for Accessible and Usable Buildings and Facilities
- 2010 ADA Standards for Accessible Design
- CSA B651-12: Accessible design for the built environment

These are product standards for built spaces, especially public spaces. They provide guidelines for physical accessibility, such as floorplans and layouts that are wheelchair accessible, and requirements for accessibility-focused design features, such as grab rails and access ramps. These standards are essential for building accessible spaces that support independence and aging in place, but they are less relevant to this work as their focus is on the physical design rather than technological supports.

IEC 63008 Household and similar electrical appliances - Accessibility of control elements, doors, lids, drawers and handles

IEC 63008 is a product standard with general considerations for accessible design of components that are manipulated by a user, and specific requirements for the following features:

- control elements such as knobs, dials, sliders, and switches;
- doors, lids, and drawers; and
- handles

Of these features, the requirements for control elements are most relevant for the design of ADL technology. The methodology used to develop the standard is also applicable, as it provides a practical example of the use of the processes described in ISO/IEC Guide 71:2014. The methodology breaks the interaction with the product down into stages and develops requirements for each stage with consideration for the physical and cognitive capabilities of the product users. A summary of guidelines for control elements broken, down by stage, is:

1. **Perceive**: requirements stress the ability to locate elements by multiple modes such as visual and tactile or visual and audible, including at least one control element when the device is in standby or sleep mode.
2. **Recognize**: as with perceive, requirements for recognize emphasize that it shall be possible recognize and distinguish control elements, including touch-controls, by multiple means.
3. **Reach**: requirements aim to make control elements easy to access, advising against countersunk controls and providing guidance for spacing between adjacent elements to prevent inadvertent activation.
4. **Operate**: there are detailed general and specific requirements for types of movements, and force required to operate controls to reduce physical and cognitive demands. For example, simultaneous actions such as pushing

and turning are to be avoided, and it shall be possible to under the last single setting without impacting other settings.

5. **Monitor**: requirements focus on the ability to identify the status of the device and its settings, without requiring interactions that may inadvertently change those settings.

This approach to decomposing the function of the object allows designers to identify the core behavior of the product and determine how to expose that behavior in a usable and universal way.

c) Accessible human computer interaction

ISO TC 159 SC 4 Ergonomics of human-system interaction

The ISO ergonomics subcommittee 4 (ISO/TC 159/SC 4 Ergonomics of human-system interaction) has developed an extensive set of standards for interactions between computer-based systems and people who use, interact with, and are affected by them. Those most relevant to ADL-supporting technology include those that give recommendations for how to design user-centric and accessible products, such as:

- ISO 9241-20:2021 Ergonomics of human-system interaction — Part 20: An ergonomic approach to accessibility within the ISO 9241 series. This document identifies and combines the accessibility guidance from standards in the ISO 9241 series (Ergonomics of human-system interaction) and other related standards to provide a unified discussion of accessibility in human-computer interaction. It is discussed in more detail in the following section.
- ISO 9241-11:2018 Ergonomics of human-system interaction — Part 11: Usability: Definitions and concepts
- ISO 9241-210:2019 Ergonomics of human-system interaction — Part 210: Human-centred design for interactive systems

Also, those that provide guidance and specifications for accessible ways of presenting information to users, including:

- ISO 24552:2020 Ergonomics — Accessible design — Accessibility of information presented on visual displays of small consumer products
- ISO 24503:2011 Ergonomics — Accessible design — Tactile dots and bars on consumer products

- ISO/TS 9241-126:2019 Ergonomics of human-system interaction — Part 126: Guidance on the presentation of auditory information
- ISO 9241-125:2017 Ergonomics of human-system interaction — Part 125: Guidance on visual presentation of information

Use of these standards and design processes can help system designers build technology with the ADL user in mind.

ISO 9241-20:2021 Ergonomics of human-system interaction — Part 20: An ergonomic approach to accessibility within the ISO 9241 series

ISO 9341-20:2021 collects and assembles the accessibility-specific guidance from standards within the ISO 9241 series, especially:

- ISO 9241-171:2008 Ergonomics of human-system interaction — Part 171: Guidance on software accessibility; and
- ISO 9241-971:2020 Ergonomics of human-system interaction — Part 971: Accessibility of tactile/haptic interactive systems.

The focus is on design principles and design processes that recognize the importance of accessibility, rather than specific product requirements.

Many of the design principles for accessible human-system interaction are based on the universal design principles, such as: equitable use, self-descriptiveness, learnability, and tolerance for user error. Other principles are technology-specific, such as presenting information in a distraction-free way, and ensuring that content with similar intent is presented in a consistent way.

The design processes are based on ISO/IEC Guide 71:2014, and are broken down into three stages:

1. Understand and identify the users and the context of use;
2. Produce solutions to meet the user requirements; and
3. Evaluate from the earliest stages and throughout the product development.

ISO 9241-20 also provides a list of references to read for more in-depth understanding, making it a good entry point for accessible design of software and interactive technology.

d) Active Assisted Living (AAL)

IEC SyC AAL

The objective of the IEC Active Assisted Living Systems Committee (SyC AAL) is to foster the creation of standards that (IEC 2023):

- enable usability and accessibility of AAL systems and services;
- support interoperability of AAL systems, services, products and components; and
- address cross-functional concerns such as safety, security and privacy.

The work of the committee is actively underway; the first documents were released in 2020 and others are expected through 2026. The published standards have focused on establishing and describing frameworks for the technical and organizational foundations of AAL. These documents include:

- IEC SRD 63234-1/2:2020 *Economic evaluation of AAL service Part 1: Framework* and *Part 2: Example of use – Monitoring patients with chronic diseases*, which provide a template and example of how to estimate the economic benefit of an AAL system, to facilitate comparisons with alternate services or interventions.
- IEC SRD 63240-1/2:2020 *AAL reference architecture and architecture model - Part 1: Reference architecture* and *Part 2: Architecture model*, which define concepts and terminology for to AAL systems and components, to provide common language and descriptions, and foster interoperability;
- IEC TS 63134:2020/AMD1:2022 *AAL use case standards inventory and mapping* which provides a framework with examples that can be used to analyze the needs of AAL systems and services. This document brings together concepts from the other framework documents and is discussed in more detail in the following section.

Upcoming documents in development that are relevant for technology to assist activities of daily living include:

- AAL functional safety for cooperative systems in connected home environments (63168-1/2/3/4 ED1, 63240 ED1)
- Design considerations for AAL users in connected home environment + specifications for each element (63271-1/2)

- Functional performance for robots in AAL (63310 ED1)
- Ethical considerations of AI in AAL (63416 ED1)

IEC TS 63134:2020/AMD1:2022 AAL use case standards inventory and mapping

IEC TS 63134 is a vocabulary and process management standard; it was first released in 2020 and updated in 2022. It was one of the first documents from IEC SyC AAL and is a foundation document for other standardization efforts. The goal of the standards is to provide a template with examples of a consistent and systematic analysis of AAL use cases from a care recipient viewpoint. The analysis framework and the example use cases are intended to assist developers and service providers develop systems, devices, and solutions that address the needs of AAL users.

The use case template includes the following concepts:

- **Description of use case**: a narrative of the use case including individuals involved in the use case, and their relationship with the care recipient.
- **Level of criticality**: an estimate of the severity of injury that could result from the system, whether through failure or intended use. The levels are Minor, Moderate, and Major, where Major indicates a failure or unknown design flaw could result in death or injury.
- **Level of assistance**: indication of the level of assistance provided by the AAL system, which corresponds to the level of user needs (referred to as user domains). The scale has the following levels:
    - Independent (Level 0): AAL services assist an independent user who is not dependent on assistive technology.
    - Some assistance (Level 1): AAL users need assistance at some points in time, or with some activities.
    - IADL assistance (Level 2): users need assistance with task that are not essential to functioning, but allow them to live independently (instrumental activities of daily living); the AAL system is not fully automated and requires input or supervision.
    - ADL assistance (Level 3): users need assistance with basic self-care tasks (activities of daily living); the system can run automatically without supervision or intervention by the user.

- **Use case category**: describes the functional role of the AAL system for the care recipient. The categories are:
    - Prevention and management of chronic long-term conditions
    - Social interaction
    - Mobility
    - Health and wellness
    - (Self-)management of daily life activities at home
- **Context of use**: describes where the AAL system is used. The categories are:
    - Global, or outdoor environment
    - Public buildings
    - Personal mobile and personal vehicle
    - Home
    - Body and personal
    - Workspace
- **System component composition**: describes the parts of the AAL system, including AAL devices, AAL platform backend system, and information systems.
- **Actors**: entities that play a role in the use case, actors can be:
    - Persons, including:
        - Care recipient
        - Informal care assistant
        - Formal care assistant
        - Healthcare professional
        - AAL operator
        - AAL technical assistant
    - Technical Component, such as an AAL device

  - Organization, such as a healthcare provider or research organization.

Once documented, the use case is analyzed to identify user requirements based on the following categories:

- **Safety**: functional safety, and safety of use
- **Security**: cyber security and physical security
- **Privacy and data protection**: protection of personal data / informed consent
- **Functional requirements**: resilience and reliability, usability and accessibility, training and instructions for use

The use of a consistent template and terminology exposes overlaps and similarities between systems in the use-cases, which helps determine higher level system requirements and identify challenges or considerations for interoperability, security, or other areas of standardization.

e) Data interchange, security, and privacy

ISO TC 215 Health informatics

The ISO 215 health informatics technical committee goals are to "facilitate capture, interchange and use of health-related data, information and knowledge to support and enable all aspects of the health system". Many standards are vocabulary and basic standards that describe medical procedures and processes in common language, however some are directly relevant to supporting and monitoring ADL:

- IEC 82304-1:2016 *Health Software Part 1: General requirements for product safety* and IEC 82304-2:2021 *Health Software Part 2: Health and wellness apps Quality and Reliability*. These standards provide guidelines for software that have a health function that is not tied to specific hardware such as a blood glucose monitor. Examples of health and wellness software include apps for tracking stress, diet and nutrition, and fitness. The standards define quality requirements that cover the entire lifecycle of health software: design, documentation, configuration management, software implementation, release and change control. Considerations include health benefits and potential harms (including societal harms), accessibility and usability, data privacy and security, and robustness and interoperability.

- ISO/CD TS 6201.2 *Personalized Digital Health – Framework*. This standard, which is in development, will specify a framework for interoperability of health records, with the primary goal of supporting individuals and their caregivers. Considerations include interoperability and knowledge sharing across different levels of healthcare, brokered by patient consent. This differs from other standards which focus on the mechanisms of electronic health records, without specific considerations for the role of the individual care recipient.

- ISO/IEEE 11073 *Personal health device communication*. The ISO/IEEE 11073 family of standards originally defined interoperability and interconnection standards for point-of-care medical devices in healthcare settings. The rise in consumer electronics with health monitoring capabilities motivated this effort being extended to include personal health devices (PHDs). The standards are built around the use-cases and background described in ISO/IEEE 11073-00103:2015 and the base framework described in ISO/IEEE 11073-20601:2022. There are application-specific specializations covering a diverse set of PHDs, such as ISO/IEEE 11073-10471:2010, and ISO/IEEE 11073-10441:2015. These specializations describe the concepts and terminology from the application domain, along with the associated measurements and reporting formats.

ISO/IEC 27001:2022 Information security management systems

ISO/IEC 27001:2022 is a broad and high-level standard that provides requirements and best practices for organizations to develop a coherent and systematic approach to information security. It is not targeted at a specific product, service, or field, and the concept of data protection extends to non-IT information assets such as physical access, printed information, and employee use of proprietary knowledge. An annex in the standard provides an extensive list of information security controls that organizations may choose to implement, including:

- Organizational controls specifying processes, policies, and procedures;

- People controls for hiring, training, and employment conditions;

- Physical controls for the site and equipment; and
- Technological controls to secure and monitor data and infrastructure.

While it is not targeted specifically at technology developers, the data security controls in the standard are especially important for organizations that collect, store, or process sensitive information such as health data. Implementation of ISO 27001 may also help demonstrate compliance with privacy regulations (Lopes et al. 2019).

ETSI EN 303 645 v2.1.1 Cyber Security for Consumer Internet of Things: Baseline Requirements

ETSI EN 303 645 is a product standard that aims to protect consumers of Internet of Things (IoT) devices that may include: wearable health trackers, connected appliances, connected smart sensors, smart home assistants, and connected home automation systems. While many security standards are cross-functional and describe generic policies or frameworks for risk mitigation, ETSI EN 303 645 focuses on specific guidance to address the most significant and widespread security vulnerabilities seen in IoT devices. Implementing the provisions in the standard is intended to provide a baseline level of security to harden IoT devices against unsophisticated attacks that exploit basic design weaknesses.

The standard provides 68 specific and verifiable provisions divided into two sections: cyber security and data protection. The cyber security provisions are grouped under the following themes:

1. No universal default passwords
2. Implement a means to manage reports of vulnerabilities
3. Keep software updated
4. Securely store sensitive security parameters
5. Communicate securely
6. Minimize exposed attack surfaces
7. Ensure software integrity
8. Ensure that personal data is secure
9. Make systems resilient to outages

10. Examine system telemetry data

11. Make it easy for users to delete user data

12. Make installation and maintenance of devices easy

13. Validate input data

The provisions under each theme provide requirements as well as examples and guidelines for implementation and conformance. For example, theme 5 "communicate securely" has provisions requiring devices to use best practice cryptography to communicate securely. The standard does not provide prescriptive advice on specific cryptographic algorithms to be used, noting that this depends on the usage context, and that the field is ever evolving. Another provision recommends that cryptographic algorithms and primitives to be upgradeable, while noting this is not possible in some devices.

There are no numbered themes under data protection, the five provisions focus on providing clear information about how and where personal data is processed and used, obtaining and withdrawing consent for data processing and telemetry, and minimizing the amount of telemetry information that is collected.

Conformance to the provisions can be verified, either through self-assessment or by a third party, using the methodology provided in the companion document *ETSI TS 103 701 V1.1.1 Cyber Security for Consumer Internet of Things: Conformance Assessment of Baseline Requirements*.

Annexes in the standard provide examples of reference architectures for IoT devices that includes the network protocols used for each type of connection, and a lifecycle model of a consumer IoT device with examples of what kind of data would be stored on the device during each stage (e.g. configuration data, user information).

f) Smart home connectivity

Smart home technologies are a sub-category of IoT, which refers to physical and virtual "objects" that are network connected to process information about events and environments. The functions and capabilities of IoT devices are described in *ITU-T Y.2060 Overview of the Internet of Things* using a layered reference model. A simplified representation of the reference model is shown in

Error! Reference source not found., it includes the following layers (Kafle et al. 2016):

- **Application layer**: contains the IoT applications that aggregate data to perform functions related to, e.g., smart home and e-health.
- **Service and application support layer**: provides support to the application layer, such as data aggregation, processing, and storage (cloud or local).
- **Network layer**: includes networking and transport capabilities that allow the device to communicate with other devices, gateways, and the internet.
- **Device layer**: includes the device capabilities such as sensors, as well as gateway capabilities to manage and translate between different types of network connections.
- **Management and security capabilities**: these capabilities span the layers, and include device management functions such as status monitoring and software updating, and security capabilities such as access control and authentication.

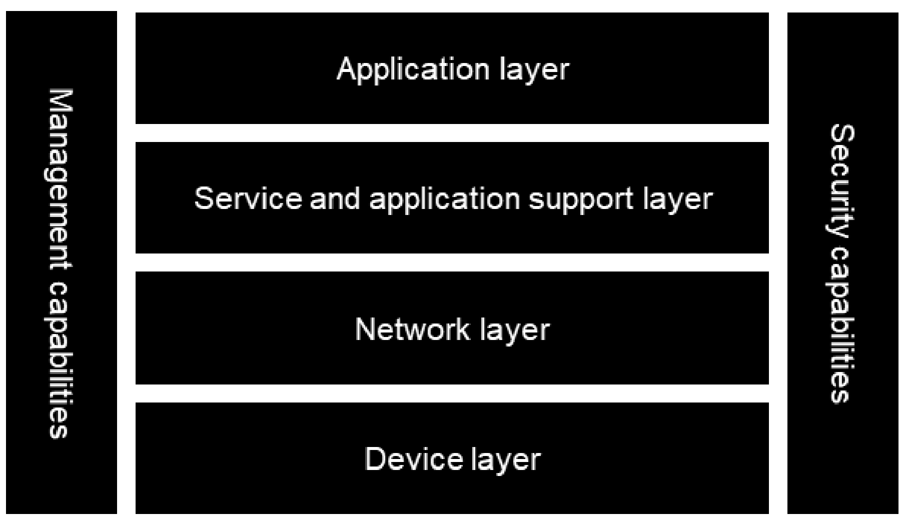

Figure 2: IoT reference model, adapted from ITU-T Y.2060.

There are benefits to standards and interoperability at all layers: interoperability at the application layer would allow devices from different vendors to work together in a unified smart home; data storage and presentation standards in the application support layer would enable smart home data to be shared and accessed more easily; standards at the network layer allow network interfaces from different hardware vendors to interconnect and interact without interference; and interoperability at the device layer allows diverse sensing technologies to be integrated into smart devices.

While ITU-T Y.2060 describes a reference model, it does not standardize the protocols or technologies at each layer. Smart home and IoT vendors have built solutions based on combinations of standardized and proprietary protocols, leading to incompatibility and fragmentation (Aly et al. 2019).

Standards or protocols that are used for connectivity in smart homes include:

- *IEEE 802.15.4*: a technical standard that defines the physical and media access layers of a low-rate wireless personal area network. These layers provide the base hardware functionality of the network layer of the IoT reference model. The standard is maintained by the IEEE 802 standards committee that also maintains the 802.11 family of WiFi standards.
- *Zigbee*: a wireless communication protocol that builds on IEEE 802.15.4. Uses the radio access of IEEE 802.15.4 and adds higher level concepts such as network topologies and device roles to manage the flow of data between devices and through the sensor network (CSA-IOT, n.d.). It is developed by the Connectivity Standards Alliance, an industry alliance.
- *Z-Wave*: a wireless communication protocol working. Originally developed as a fully proprietary solution, the lower-level network layers have been standardized as ITU 9959 radio, and the higher network layers are developed by the Z-Wave Alliance, an industry alliance.
- *Thread*: a wireless communication protocol that builds on IEEE 802.15.4. Uses the radio access of IEEE 802.15.4 and incorporates the Internet Engineering Task Force (IETF) standard 6LoWPAN (IPv6 over Low-Power Wireless Personal Area Networks) that allows devices to directly carry Internet Protocol (IP) data so they can connect to other devices and the internet through IP routers ("Thread," n.d.). Originally developed by Nest labs (now a Google subsidiary), now managed by the Thread Group, an industry alliance.
- *Matter*: a connectivity standard for smart home and IoT devices, operating at the application and the service and application support layers of the IoT reference model. It provides a common application layer and data and interaction models that can be used by devices to communicate and

control one another (Connectivity Standards Alliance [2020] 2023). Managed by the Connectivity Standards Alliance, an industry alliance.

From this group, Z-Wave, Zigbee, and Thread are competing low-power wireless mesh technologies. Bluetooth and WiFi are ubiquitous general purpose wireless communication standards that are also used in some smart home applications, but their high data rate comes with high power consumption and component costs, so they are often avoided in smart sensors and embedded edge devices. Matter is intended to connect devices from multiple manufacturers, but it is IP-based so it only works directly with Thread, WiFi, or ethernet; other devices can be supported using a bridge to translate between protocols.

g) Summary

Developers of technology solutions to support ADL have access to standards to support the entire development cycle, including:

- Understanding situations where technology can serve individuals, and analysing the use case the technology is aiming to meet: IEC TS 63134 and ISO 25550.
- Identifying the accessibility needs of users of the product or service, especially for individuals with disability including older adults who are aging in place: ISO Guide 71.
- Designing the user interactions, user interface, and physical control elements of the product or service in a way that is universal and inclusive: IEC 63008 and the ISO TC 159 SC 4 publications.
- Ensuring user data is collected and stored in an ethical and secure way: ETSI EN 303 645.
- Defining the data interchange architecture: ISO/IEEE 11073 family.

However, there remain opportunities to increase the coverage or usage of standards, including:

- Extending the understanding of accessibility and ergonomics beyond the physical, sensory, and cognitive impairments. For example, individuals who are neurodiverse, or who have mental health, attention, or learning disabilities will have different goals and use cases for their use of technology. They may also have different considerations for their interactions with technology, such as how alarms and notifications are presented.

- Expanding and unifying considerations for the collection and use of data. Implementing ETSI EN 303 645 creates a system with a solid baseline of security and privacy – a system that requests user consent for collection of telemetry and personal data, secures the data on the device and in transit, and provides a means for users to delete their data. The critical and sensitive role of technologies that support the daily activities of people with disabilities and older adults aging in place calls for privacy and security that extends beyond this baseline. Additional ethical considerations are outlined in (Wallace and Knoefel 2022b), and include:
    - Ongoing informed consent based on the user understanding of the potential benefits and negative effects of the collection and use of their data, as well as assent for persons who are not legally capable of consenting to collection of their data;
    - Ownership of personal identifiable data including the ability for a user to access and manage their own data, and to control who else has access to it; and
    - Aggregation and use of non-identifiable data including the ability to de-anonymize data, the brokering or resale of aggregated data, and the use of data to train big data or artificial intelligence (AI) models.
- Establishing guidelines and best practices for repurposing consumer tech for ADL applications. Several reviewed standards discuss the importance of addressing requirements for accessibility, functional safety, interoperability, security, and privacy early in the design phase. However, products used for ADL are often not designed as assistive or medical devices but are repurposed by users or acquire additional capabilities through software extensions. Designers updating systems to meet accessibility, ethical, or regulatory requirements, face additional challenges and constraints compared to designing a system from the ground up. The ISO/IEEE 11073 family of standards provides a framework for interoperability, but these have not been widely adopted by industry.

  Examples of this repurposing include:

- smart watches or fitness trackers tracking sleep, estimating stress levels, and diagnosing health conditions such as heart arrhythmias; or
- home automation, home security, and smart speaker systems being used to support or monitor the daily activities of an older adult aging in place, or a person with disabilities living independently.

A recent scoping review (Abhari et al. 2024) explored literature covering guidelines or standards for AgeTech, but not the standards themselves. Our project team served on the advisory panel that expanded this scoping review into a broader report (Abhari et al. 2025) that is intended to serve as a foundation for a standards-driven approach to technology for aging in place. The report highlights that literature focused primarily on technical aspects of AgeTech, such as design and development techniques and user experience, while little focus was placed on accessibility, interoperability, or data privacy concerns. Also, while a large portion of documents focus on usability guidelines for older adults, most treat older adults as a single group, rather than focusing on specific categories such as "older adults living with chronic conditions" or "older adults living with cognitive impairment". As with individuals with other forms of disability, the needs of older adults with care needs will vary widely depending on their combination of health conditions and personal factors. The recent standard CSA Z2202:25, *Technology in home and community care settings* (CSA Group 2025) aims to fill some of the gaps identified in the report, by providing recommendations for a technology management system to support the continuum of care for individuals being supported across home and community settings.

4. Community Input

4.1. Industry outreach

We engaged with industry partners in the smart home and supportive living sectors to discuss existing and upcoming products intended to support or assess activities of daily living in the built environment. We discussed the intended uses of the products as well as the underlying technologies, and in some cases obtained products for data collection, testing, and evaluation by our participant groups.

4.2. Focus group sessions

We conducted two focus group sessions with older adults, including those with lived experience of disability and caregivers, to understand their views on barriers faced in activities of daily living, and on the use of technology to aid or assess those activities. The sessions were open-ended discussions mostly led by the participants, with occasional prompting or follow-up questions from the research team.

a) Method

A total of 7 participants responded to our recruitment email; 4 females and 3 males. Since the sessions focused on individual experience rather than inter-population comparisons, detailed demographic information was not collected, though some participants volunteered information about their health and disability status when it related to the discussion. Minimizing sensitive data collection also reduced participant burden and encouraged openness in the exploratory discussions. Participants were not compensated for their time; however, transportation and parking expenses were reimbursed. All participants provided written informed consent. The project was cleared by the Carleton University Research Ethics Board (CUREB-B #120495).

The sessions began with a presentation by the research team that outlined the research aims of the project, provided some examples of activities of daily living and supportive technology, and offered some starter prompts such as:

- "My biggest challenges to activities of daily living are ..."
- "I use technology to help ..."
  - "I like that it ..."

    - “It would be better if …”
- “I wish there were a technology to …”

After the priming presentation, each participant was given an opportunity to share their individual perspectives, then the floor was opened-up to the fully interactive discussion.

b) Findings

Challenges, barriers, and enablers of activities of daily living

The participants' individual perspective sharing primarily focused on aspects of their personal health state that impacted their participation in activities of daily living, including:

- **Pain and mobility limitations** – both chronic and temporary, arising from surgery, arthritis or hip and knee degeneration and replacement. Participants reported impacts on everyday movement through the home, especially navigating stairs, and on the frequency and duration of time spent outside the home. For example, one participant reported planning grocery trips and other outings based on their medication schedule, to ensure they could complete the trip pain-free.

- **Strength and dexterity limitations** – from degenerative health conditions such as arthritis, as well as age-related changes. The impacts of these limitations are felt in many small frustrating ways every day, in activities ranging from pulling on socks, fastening buttons, to opening food jars. Participants noted special difficulty with tamper resistant packaging and blister packs. One participant reported changing pharmacies to obtain more accessible medication packaging. Participants shared examples of low-tech solutions they use to manage these barriers include a sock aid or dressing stick for pulling on socks, and silicone mats or levered handles for opening jars. Some participants noted that they that they thought these challenges were unique to them, so they were unaware that solutions existed.

Another primary focus of conversation was the activities of daily living where barriers are faced, including:

- **Household maintenance** – such as cleaning, small repairs, and landscape maintenance. These tasks can require reaching high or low places, balancing on ladders or stools, and using tools and equipment that are heavy or difficult to grasp. Rather than viewing these tasks as "chores" several participants reported enjoying them and the sense of pride and purpose they bring, so they continue with them despite the difficulties.

- **Personal safety and emergency situations** – such as fire or falls. Participants were concerned with their ability to escape through an alternate route, such as through a window, if their primary exit was blocked, and consequently with emergency responders' ability to locate them.

- **Socialization and entertainment** – such as social visits and leisure activities outside the home. Participants noted barriers related to transportation as increasing the difficulty of participating in activities outside the home. Besides transportation, one participant noted the difficulty of hearing in crowded environments, even with hearing aids, limits their participation in social activities.

Smart Home technology – uses and benefits

All the participants reported using and being generally comfortable with smartphones and computers. Several rely on family members or service desks such as Geek Squad or the Genius Bar to help them learn about new device features and to handle initial device setup and data transfer. Participants remarked on the need for trust in these situations, as smartphones are the key to our digital lives. Most participants were aware of "smart home" technologies, and many had incorporated some devices into their homes, including:

- Smart doorbell and cameras
- App controlled or automated lighting
- Robot vacuum
- Remote thermostat

Reported benefits of the technologies included convenience, accessibility, security and peace of mind, and even simple interest in or enjoyment of the technology. Some participants were not aware of capabilities, and the discussion prompted a round of brainstorming other potential applications. One participant noted that a smartphone-controlled light could be turned on from bed to avoid walking in the dark, another suggested using occupancy sensing to share location information with first responders.

Smart Home technology – concerns and opportunities

Despite their use and embrace of smart home technologies, participants were very vocal with their concerns and reservations, including:

- **Privacy and security** – Participants expressed strong concerns about the use and abuse of personal home data by companies for targeted advertising or selling and profiting from user data, as well as by criminal hackers stealing information or using personal information for scams and fraud. Several participants expressed that they had little or no trust in big technology companies keeping their interests in mind, and this caused them to view all technology with suspicion.

- **Usability and accessibility** – Participants felt smart home technology was not designed for them or with them in mind. While several have learned to use devices, the usage paradigms are different than prior consumer devices and appliances, and several expressed anger or frustration with being made to feel inferior or lacking intelligence for not wanting to spend time keeping up with the latest changes. Setup and configuration were a prime usability concern. Many new devices no longer have printed manuals or physical documentation, relying instead on QR code links to instructional videos, or configuration via a companion app on a smartphone. Setup is often a multi-step process, with no indication if the process can be paused or if steps can be repeated or corrected. One participant shared that they had purchased two separate smart switches to control a light but was not able to configure either one. Another participant commented that they would be interested in smart home technology, but they didn't know where to begin and were worried they would break things during setup.

- **Forced technology usage** – Participants expressed that they felt they are being forced to adopt new technologies, and that new technologies are unnecessarily linked together. Televisions and cars were given as examples of devices that have become more "smart" and consequently less usable without configuration and a companion phone application. Participants noted that technology is changing rapidly, and the need to have the latest device creates financial barriers. Also, frequent forced updates and upgrades put individuals in a position where they must constantly re-learn how to use their devices, as updates can bring unexpected changes in functionality, user interface, or privacy and configuration settings.

- **Overreliance on technology** – Participants expressed concern with a creeping reliance on technology, and what it means for individuals and society. At the individual level, concern was expressed that too much smart home automation can lead to a loss of control and a loss of capacity, as individuals no longer need to get up and move around to turn on lights or appliances. Multiple participants noted that while they use robot vacuums, they find that emptying the machine after it is done connects them to the cleaning task and makes them feel more engaged with it. One participant noted they would rather move than automate or give up maintaining their yard. At the social level, participants expressed concern that automation and technology would replace human interactions such as health and wellness checks, further reducing the already limited social contact of many older adults. One participant noted that they will on occasion order groceries online, but they prefer going to the store to be among people, even if it is challenging due to pain or mobility issues. Participants were also wary of depending on technology that may be unreliable or prone to misuse. Some examples given were a smart oven that cannot be controlled if the internet is down and a smart doorbell with malfunctioning software. In these cases, when the "smart" component is removed, the product does not function as a regular device.

c) Recommendations

Based on the findings of the focus group, we summarize the following recommendations for the development and use of smart home applications to support aging in place:

- Focus on applications that assist rather than replace human roles.
- Employ user-focused design principles, including usability and accessibility and consideration for different groups of users with different modes of interaction.

- Recognize that the user is the owner of their data. Be transparent with data usage and storage and use best practices for privacy and data security.
- Provide a path for long term device support and consistency. Allow devices to receive security updates without requiring users to also accept changes in behavior or functionality.
- Prioritize reliability and functional safety. Ensure the device works in its default safe and has fail safe operation. A smart light or switch should function as a regular light or switch if the smart component is removed or malfunctioning.

4.3. Co-design explorations

We conducted a co-design project where young adults with disabilities collaborated with our engineering researchers to evaluate the suitability of smart home technologies for independent living and to propose modifications or enhancements that address specific activities and use cases identified by the participants. The project explored how "digital natives", individuals who have grown up in the information age, leverage pervasive technology to support and build independence during their transition from family-provided care to more independent assisted living.

a) Method

Participants were recruited through an email distributed to clients of Carleton University's Attendant Services Program. Students in this program live in accessible suites in campus residence buildings and have access to attendant and personal care services to support their activities of daily living and their regular household tasks. The program is open to Ontario students with physical disabilities, and receives funding form the Ontario Ministry of Health and Long-Term Care.

Participants were compensated as experts with lived experience of disability. Their honorarium reflected their specialized knowledge based on their lived experience and the time they spent contributing to our study. All participants provided written informed consent. The project was cleared by the Carleton University Research Ethics Board (CUREB-B #121238).

The project was divided into three tasks:

1. **A day in the life**: Participants were asked to draw on their lived experience by journalling a day in the life of a person with a disability, either themselves or an imagined persona. The goal of this task was to get participants thinking about the role of the built environment and its impact on their everyday activities, as well as any technology or non-technology solutions used to navigate challenges and barriers.
2. **Tech demo**: Participants and researchers met in-person in the smart home technology lab. The research team shared technology demos of commercially available and research prototype smart home technologies, including some from our industry partners. Participants then had the opportunity to take part in a group co-design discussion around the technology: questions about how the technology works, potential uses, concerns with their use, and how these technologies could be modified (or improved) to support disability.
3. **Evaluation and use-case report**: Participants created a use-case report for the demonstrated technology, providing scenarios of use and suggestions for improvements to the technology to make it more accessible or better suited to their purposes.

Demographics

A total of 7 participants responded to our recruitment email – 1 female, 3 male, 2 non-binary, and 1 gender-fluid – with ages ranging in age from 20 – 24. All participants had physical disabilities and used power wheelchairs; however, their self-descriptions illustrated the diversity of their disability profile in terms of:

- **Onset**: congenital, progressive, or acquired;
- **Dynamics**: continuous, progressive, episodic, or fluctuating;
- **Functional limitations**: mobility limitations, strength and dexterity limitations, sensory limitations, sensory sensitivities, focus and executive functioning limitations, speech functioning, and mental health conditions.

b) Findings

Barriers related to wheelchair use in the built environment

Many of the challenges identified in the journaling activity, and much of the conversation in the tech demo brainstorming, centred on wheelchair use. Although wheelchairs are not generally considered smart technologies, their use and related accessibility considerations inform and provide context for many of the participants' daily activities.

Physical access

Barriers to physical access in the built environment remain for users of wheelchairs, despite this being the primary focus of many accessibility efforts. Design standards for accessible approaches and doors exist, however they are not universally adopted. In some cases, the main door to a building is accessible, but individual rooms are not. In other cases, broken or unmaintained assistive technologies make spaces less accessible than their low-tech alternatives. For example, participants noted they often use their footplate to push open non-powered doors; however, this mitigation does not work with heavy power doors with broken or inactivated motors. Similarly, several participants noted that ramps are preferred over lifts because they can be used independently and are less likely to be broken, however uncleared snow and other physical obstructions are a common problem with ramps.

Reachability

Items such as elevator buttons, soap and towel dispensers, electrical outlets, and the dispensing areas of vending machines are often too high or too low to be used from a seated position. These design failures exist even in washrooms marked accessible. Participants noted that elevator access was improved by the app-controlled buttons that were added to high traffic buildings on campus to allow contact-free access during the COVID-19 pandemic, and they hoped this technology would be expanded to more elevators.

Powered and manual wheelchairs

All participants use power chairs at least some of the time and some use manual chairs on days when their symptoms are less severe. Participants noted that there are differences in accessibility even between the two classes of chairs. Power chairs are larger and taller which makes them more difficult to maneuver into smaller spaces or fit under tables or sinks. Participants also expressed concern about control of power chairs, and the risk of hitting other people, especially when backing up. Power chairs can also lose traction on loose surfaces such as sand, snow, or wood chips, causing the chair to become stuck and stranding the user. Participants noted that they take care to plan their routes on campus to avoid areas where they may become stuck.

Health concerns arising from wheelchair use

Multiple participants reported head and neck pain caused by their head bouncing off the headrest during bumpy travel; this problem is especially acute for participants with reduced neck control and strength. Participants also noted that repositioning in their chair is necessary to restore proper posture, relieve discomfort, and avoid pressure sores; however, this can be difficult for individuals with reduced strength and dexterity, or those who have intellectual or sensory impairments.

Power wheelchairs have failsafe electromagnetic brakes that automatically engage and disengage with a loud clicking noise each time the driving joystick is moved. Participants noted this is a source of noise disturbance, especially for those with sound sensitivities, and a source of annoyance and frustration when they are trying to maneuver their chair in quiet environments without being disruptive. Participants also noted disturbance with the constant tonal motor and wheel noise while driving and charger noise when charging at night.

Independence in daily living

Participants emphasized that independence in their activities of daily living is highly valued; they recognize and accept that they need help accomplishing certain tasks, but they still desire ownership and agency over these activities.

Accessible transit

Participants discussed how they rely on the accessible public transit service to get around the city but are frustrated by the additional time and effort they must invest compared to their peers using the standard transit. The accessible service requires advance booking, and the pickup time is only provided as a 1-hour window. Trip duration is also variable since the service is shared and the driver may make multiple stops and detours to combine passenger trips. Participants noted that these limitations require them to leave large time buffers to ensure they arrive at scheduled appointments on time, and largely prevent them from planning or participating in spontaneous activities.

Role of attendants

Attendant services can either be scheduled for a specific time or on demand. Participants will typically use scheduled calls for their morning or evening routines, but this prevents them from adjusting their sleep schedules based on their mood or the quality of sleep. Participants with fluctuating disability symptoms may rely on demand calls, as they only require assistance for their daily routines on days when their symptoms are more severe. Demand calls are more flexible but are only served when an attendant becomes available; this can mean long waits during busy periods.

Attendants in the program are fellow students, and some participants shared that they felt more comfortable working with these peers rather than older professional attendants. Participants are conscious of how they are perceived by the attendants, and several remarked that they limit or simplify their requests to avoid feeling like they are "being lazy" or "ordering around" the attendants. For example, when attendants are assisting them with meal preparation, they keep their food choices simple or accept food that is not prepared to their preference, to avoid feeling like they are being difficult or a burden. Participants noted that food and cooking in general are areas where they would like more independence to be free to experiment with their own recipes and cater food to their tastes.

Financial barriers to independence

Specialized technology to support specific disability needs does not benefit from the economics of scale of mass-market consumer technology, so devices are more expensive, and selection is more limited. Essential but costly devices such as power wheelchairs are subsidised by government programs, but funding is restricted to specified devices and features. Participants gave the example of power height adjustment ("eye-level") as a feature that is highly beneficial for independence in daily living – it allows users to overcome design barriers to reach high shelves and countertops, and even to independently use stacking laundry machines – however, the feature is not considered medically necessary, so only users who are able to afford the substantial cost are able to benefit.

Technology – uses, benefits, and opportunities

Participants reported being enthusiastic adopters of any technology that meets their needs and increases their independence, even in small ways. Monitoring and automation tech can increase individuals' agency over daily activities, allowing them to control how and when those activities are done and without assistance. As one participant remarked, they don't feel bad ordering a robot around.

In most cases the devices being used by participants to support their independence are consumer technology that has been repurposed for use as assistive or medical devices. Compared to medical devices, consumer devices are lower cost, more readily available, and faster evolving. Even if they are not designed for accessible use, they can be adapted to create a solution that works "well enough". For example, several participants reported using noise cancelling headphones to either reduce sensory input to improve focus, or to reduce the noise disturbance of their wheelchairs. Participants reported that new technologies, and ideas for adapting technology, spread virally through the community over group chats and in person. Most participants reported learning of new technologies directly from another person with disabilities, or online from social media groups or from disabled influencers.

Smartphone as a universal assistive device

Participants reported using smartphones as routinely as their peers without disabilities for communication, entertainment, education, food delivery, and task management; they also use them for disability-specific needs.

Smartphones are essential for personal safety, allowing individuals to call for help if they are stranded with a non-functioning wheelchair, or to contact attendants if they have fallen, are immobilized, or otherwise need assistance. Participants shared that there is a group chat (ad-hoc social network) where students with disabilities alert each other about accessibility concerns around campus such as construction, potholes, broken door switches, or obstructed ramps.

Participants reported using smartphones as assistive devices in novel ways, for example:

- AI transcription for note taking and as a typing replacement
- Text to speech (TTS) to support reading for individuals who are blind or low vision, and as a communication aid for individuals who are non-verbal or temporarily unable to speak clearly because of their symptoms
- Google map live street view, to support navigation for individuals with functional limitations in spatial awareness.
- Vocal shortcuts built into the Apple Accessibility framework as a hands-free way to call an attendant for support or assistance when the phone cannot be reached.

A primary complaint of using smartphones for accessibility is the "app tax", where each peripheral or service requires its own standalone app, and there is no interoperability or data sharing between apps. Participants reported that the requirement to repeatedly switch between apps while multi-tasking creates a physical barrier, while cognitive barriers are created by the loss of situational context when switching apps, and the need to remember which app is required in each circumstance. Some participants noted that their ideal would be single assistive tech "hub" where they could manage their personal health trackers, assistive devices, and smart home technology.

Smart watches and fitness trackers for health management

Personal health management was reported as an important and continual part of their daily activities, and many participants used consumer smart watches or activity trackers to monitor and support this. Smart watches can be used for medication reminder notifications, and to track and monitor activity levels and vital signs such as heart rate and blood oxygen levels. Several participants noted that their energy levels regulate the severity of their symptoms, so health tracking can help predict and manage their future state. For example, participants reported using sleep duration and quality measured by a sleep tracker are used to help predict their fatigue levels for the day and decide whether to use manual or power wheelchair. Similarly, integrated heart rate monitors are used to keep their activity levels in the right zone during exercise and physical therapy. While participants joked about the 'step count' feature of their trackers being improperly labelled for wheelchair users, they noted that it is a useful indicator of overall energy output: a notification that they have achieved their step goal is treated as a warning that they have over-exerted themselves and can expect fatigue.

Consumer technology for automation

Most participants reported using smart home devices for automation, including:

- adjustable lightbulbs
- switches
- plugs
- curtain controllers.

Participants also reported using programmable devices without connectivity, such as rice cookers and light timers, to partially automate their activities. They controlled smart devices through apps on their phones, or through voice assistants such as Alexa. Voice assistants were also used for setting reminders and alarms, and for calling attendants.

Despite using and appreciating the benefits of these consumer devices, participants noted several instances of non-inclusive design, including:

- voice assistants timing out during delayed speech or having difficulty understanding their speaking patterns
- smart plugs with featureless shapes that are difficult to grasp and manipulate
- battery compartments that are hard to open

Cost was also identified as a barrier, not only the upfront cost of the devices, but also installation and maintenance. Since a battery change may require hiring someone to come into the house, solutions that can be installed once and left were reported to be preferable.

Low-tech enablers

While the focus of the co-design was technology and smart devices, several participants mentioned low-tech enablers that they use to increase their functioning and support independence in their daily activities, including:

- reaching and grabbing tools, for picking objects off the floor
- T-bars grabber, for closing doors
- rolling laundry basket, for transporting clothes and other items
- wheelchair seatbelt, to hold books, bags, and computers during transit

It's notable that uses of these low-tech devices spread in the community through tech-based social media. Participants were keen to adopt technology when in it provided a benefit but cautioned against an over-reliance on technology that can break or fail: low-tech devices are predictable and dependable.

c) Recommendations

The co-design project looked at the supportive smart home landscape through three complimentary perspectives: the lived experiences captured in the 'Day in the Life' journals, the interactive critiques from our technology demonstrations, and the specific scenarios and improvements outlined in the participant-led use-case reports. We synthesized these perspectives into the following recommendations for the development and use of smart home applications to support healthy independent living of young adults with physical disabilities:

- Recognize that smart home devices are used as assistive tech even if they aren't designed for it. Plan for this in the design phase by employing diversity-focused design methods that consider how different groups of users can use the device.
    - Employ user-focused design principles for the physical design – grasping and manipulating the device – as well as interactions with any software.
    - Consider design requirements for the whole product lifecycle: installation, upgrades, maintenance.
- Recognize that assistive technologies are more than a convenience – they become extensions of the user and impact how they interact with their surroundings and their communities. Technology should keep the user in control: the device should augment, rather than replace, the role of the user in an activity.
    - Provide options for personalization and customization of the device look and feel. Avoid overt branding that takes ownership away from the user, or sterile "medical" designs that make devices feel like treatments rather than assistance.
    - Support interoperability and provide different modes of control to allow users to customize how they interact with Interoperability. Users may use voice, apps, or home automation tools depending on their application.
    - Do not ignore low-technology solutions. Learn from and integrate with them.

4.4. Follow-up survey

We conducted a follow-up survey to cross-reference the findings from our focus group and co-design projects. The survey questions focused on the types of smart devices the participants use, why they chose to use them, and what they see as the advantages and disadvantages of their use. The anonymous survey was distributed to both sets of research participants, as well as other mailing lists of older adults and individuals with disabilities. We received 11 responses. The survey project was cleared by the Carleton University Research Ethics Board (CUREB-B # 124869).

Only one respondent reported using no devices, indicating a preference for doing things manually. Among those who used smart devices, wearable health monitors were the most common (60%), followed by smart thermostats (50%), smart speakers (40%), and smart plugs (40%).

The primary reason for considering smart devices were convenience (90% of respondents), health monitoring and support (60%), energy efficiency (50%), and safety and security (40%). However, devices were not used only for practical reasons. One participant reported that they used the devices to learn about new products, and 30% reported using them for fun or general interest in technology.

The average satisfaction rating was 3.5/5 with 60% of respondents giving a score of 4, indicating that overall, participants were uniformly "somewhat satisfied" with their devices. In contrast, the areas of concern revealed differences in opinions. For example, while the average concern for security and privacy was 3.5 (moderate), 7 respondents indicated that they were very or extremely concerned and 2 reported that they were not concerned at all. Similarly, on the question of reliability, 5 participants indicated they were very or extremely concerned, while 5 reported being not concerned or only slightly concerned. More agreement was found on questions of cost, ease of use, and setup and installation, with most respondents reporting moderate levels of concern.

Overall, the responses aligned with the findings of our community engagement sessions. Taken together, they describe a landscape where people are willing and even eager to use smart devices to assist their daily living, despite concerns about usability and privacy.

5. Engineering research

The goal of our engineering research was to improve understanding of the technical possibilities of sensing and home automation technologies, and to produce new data about how these developments can be used to assess and monitor activities of daily living. Ultimately, this knowledge will inform relevant standards and contribute to an improved quality of life for Canadians with disabilities.

The focus areas of our engineering research efforts were informed by our community input sessions. We evaluated existing products against their stated design goals and assessed them using criteria developed through these interactions. We also explored human-centered designs for assistive smart home technology that build on and enhance the ways participants reported using smart devices. As these studies have been published externally, this section provides high-level summaries of each project, supported by references to the original publications for further details.

5.1. Review of technology products for ADL

We reviewed technology-based products and services designed to support independent, healthy living, with the goal of identifying best practices in product development and features, uncovering gaps in current offerings, and providing guidance on the use and development of relevant standards. The primary focus was on solutions that enable Aging-in-Place (AiP) for Persons Living with Dementia (PLWD), as this represents the most developed area within supportive living technologies. The products reviewed were a representative sample of those commercially available as of August 2023.

Areas we highlighted for improved standards and compliance include:

- **Security/Privacy:** Public documentation rarely addresses how systems protect data privacy and security, despite existing health data standards.
- **Data Ownership:** Most product descriptions lack clarity on data storage practices and who has access to user data.
- **Interoperability:** Products provided little mention of integration or interoperability with other systems.
- **Geographic Domains:** U.S.-centric design and documentation limit clarity for users outside the United States.

- **Ethical Considerations:** Many products overlook ethical concerns, such as excluding aging adults from meaningful participation in their own care solutions.

The full report is available as:

- Philipe Masson, Kelly Milne, Bruce Wallace, et al. 2025. *Supportive Systems for Cognitive Health and Dementia : Survey of Technology and the Role of Standards*. Accessibility Institute, Carleton University. https://doi.org/10.22215/rcgl/25dr1.

5.2. Expanding smart home capabilities to support daily living

a) Automated cough evaluation for health management

All our participant groups listed personal health management as a priority area where technology is currently used to support independent living and where they would like to see expanded capabilities. To support this, we researched a smart cough sensor that can identify coughs from a specific person and look for changes in the cough sound or coughing behavior. The goal for this system is to help detect diseases early on, to limit spread and allow for early intervention, and to help people monitor chronic conditions like asthma, allergies, or COPD.

As part of the research, we applied speech processing methods to model the airway during cough sounds and found that we could distinguish between wet and dry coughs based on physiological differences in how the cough sounds are produced. This work was reported as:

- B. Laska *et al.*, "Cough Sound Analysis using Vocal Tract Models," *2024 IEEE International Instrumentation and Measurement Technology Conference (I2MTC)*, Glasgow, United Kingdom, 2024, pp. 01-06, doi: 10.1109/I2MTC60896.2024.10560576.

We also used large neural networks trained on speech data to model the cough sound; we found that these models could be used to identify the cougher and to monitor changes in their cough behavior. This work was reported in the following publications:

- B. Laska, P. Xi, J. J. Valdés, B. Wallace and R. Goubran, "Zero-Shot Multi-Task Cough Sound Analysis with Speech Foundation Model Embeddings," *2024 IEEE International Symposium on Medical Measurements and Applications (MeMeA)*, Eindhoven, Netherlands, 2024, pp. 1-6, doi: 10.1109/MeMeA60663.2024.10596816.

- B. Laska *et al.*, "Coughprint: Distilled Cough Representations from Speech Foundation Model Embeddings," in *IEEE Transactions on Instrumentation and Measurement*, vol. 74, pp. 1-10, 2025, Art no. 2532210, doi: 10.1109/TIM.2025.3568985

b) A sense of smell for supportive smart homes

Our older adult participants reported being concerned with the privacy of smart home devices with cameras and microphones. To address this, we investigated novel sensors that were more privacy compliant. Specifically, we looked at using a gas sensor to make a smart smell sensor that can detect when food has gone bad. The original goal was to help people with sensory or cognitive limitations who may not be able to identify the signs of spoilage, but we also found that the system may be able to detect early signs of spoilage before the food starts to smell. This work was reported as:

- B. Laska, B. Wallace, R. Goubran and F. Knoefel, "Environment-Compensated Gas Sensor Time-Series Analysis for Tracking Food Spoilage," *2025 IEEE Medical Measurements & Applications (MeMeA)*, Chania, Greece, 2025, pp. 1-6, doi: 10.1109/MeMeA65319.2025.11068061.

5.3. Measuring sound accessibility in the built environment

Participants with a wide range of disabilities noted that noise affects their focus and concentration and can make spaces uncomfortable to be in. The effort to filter out noise to hear a person of interest can lead to physical and mental fatigue. This was a common concern, even among people who are not hard of hearing. Motivated by this finding, we investigated how to improve the experience of sound in loud and noisy spaces. We developed a method that uses the LiDAR scanner built into a smartphone to create a 3D model of how sound moves through the space. Prompted by our student participants concerns with their acoustics, we used the Carleton tunnels as an example to show how the model can be used to experiment with different designs to reduce noise and echoes. This work was reported as:

- A. Laghai, B. Wallace, B. Laska and R. Goubran, "Ray Tracing Modelling Using LiDAR 3D Scans for Rapid Acoustical Measurement and

Simulation," *2025 IEEE International Instrumentation and Measurement Technology Conference (I2MTC)*, Chemnitz, Germany, 2025, pp. 1-6, doi: 10.1109/I2MTC62753.2025.11079164.

Since many people rely on noise cancelling headphones in these loud spaces, we also developed ways of measuring the performance of these headphones to see how they change the sounds we want to hear. This work was reported as:

- B. Laska, R. Goubran and B. Wallace, "Binaural Characterization of Active Noise Cancelling Headphones," *2024 IEEE International Instrumentation and Measurement Technology Conference (I2MTC)*, Glasgow, United Kingdom, 2024, pp. 01-06, doi: 10.1109/I2MTC60896.2024.10560585.

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