Examining the Feasibility of Internet of Things Technologies to Support Aging-in-Place

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Abstract

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The older adult population is one of the fastest growing demographic groups in the United States. Older adults face challenges such as chronic health conditions, reduced mobility, and cognitive decline. Technological solutions may be valuable resources to assist older adults in maintaining their quality of life. One such solution involves the Internet of Things (IoT) connected smart home devices. IoT smart home technologies have a unique opportunity to support healthy aging of the older adult population by identifying potential patterns in health and detecting anomalous

activities. Such technologies could support detection of trends over time (for example, decrease in overall activity level, increase in sedentary behavior or reduced number of visitors) that call for intervention. This could assist older adults to maintain independence by connecting them with family members, support systems or other caregivers, and ultimately support quality of life. Despite the promise of these technologies to improve health outcomes and quality of life in older adults, there still remains a challenge in understanding older adults' specific perceptions and concerns. This dissertation explored the feasibility of using of IoT smart home devices with older adults and understand their acceptability of these tools within their home. The specific aims of this project are to: 1) Assess the feasibility of an IoT smart home devices in their residential setting; 2) Examine older adults' acceptability of an IoT smart sensor system and how this perception may change over time and after exposure to such a system; 3) Develop design recommendations for a future IoT smart home system to better assist older adults' aging-in-place and maximize their user experience.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Chapter 1. INTRODUCTION

1.1 SIGNIFICANCE OF THE PROBLEM

Older adults, typically defined as people aged 65 and older, are a rapidly growing demographic group projected to triple in size worldwide rising from 524 million people in 2010 to 1.6 billion people in 2050 (Suzman & Beard, 2011). Furthermore, the number of older adults aged 80 and above is predicted to more than double from about 57 million in 2013 to 124 million in 2050. The uprising trend of the aging population is attributed to improvements in public health and hygiene, technological developments, and advances in health care (Ahn, Beamish, & Goss, 2008). Following the worldwide trends, it has been predicted that the population of older adults aged 65 and older in the United States is estimated to increase from 43 million to 92 million by 2060 (Jacobsen, Kent, Lee, & Mather, 2011). This would bring the proportion of older adults from its’ current 15.2% to 21.4% by the year 2050, meaning that one in five Americans is expected to be 65 years of age or older by 2050 (Jacobsen et al., 2011). At the same time, the life expectancy at birth in the U.S. is predicted to increase from 78.9 of 2010~2015 to 83.5 years by 2045~2050 (Department of Economic and Social Affairs. Population Division., 2017).

As people age, sensory functions such as vision, hearing and motor perception normally decline (Carmeli, Patish, & Coleman, 2003; Mynatt & Rogers, 2001). With these and other aging-related changes, older adults are more prone to chronic health conditions, fall-related injuries, and limitations in memory and physical function (Gerteis et al., 2014; Shumway-Cook et al., 2009). Chronic diseases such as heart disease, stroke, cancer, and diabetes are among the most common and costly health conditions in the United States and three in four American older adults report having multiple chronic conditions (Gerteis et al., 2014). The progression of multiple chronic diseases could be a significant threat to the health and independence of older adults.

The unprecedented demographic shift brings out new demands and challenges in many areas of society. One domain that necessitates immediate attention is healthcare and caregiving. Even before this population shift, older Americans are primary consumers of health care and receive more medical attention than any other U.S. demographic group (De Nardi, French, Jones, & McCauley, 2016). In fact, older adults 65 and older which made up 13 percent of the U.S. population accounted for 34 percent of total healthcare-related spending in 2010 ("Centers for Medicare & Medicaid Services" 2018). In addition, Center for Disease Control and Prevention estimates that total health care spending will increase by 25% by 2030 largely due to aging population(Prevention, 2013). Medicare spending is projected to increase from $555 billion in 2011 to $903 billion in 2020 ("Centers for Disease Control and Prevention", 2013). Experts also warn about the shortage of healthcare professionals and care workers to provide care for older adults in near future (Stone & Harahan, 2010). Governments worldwide are finding it more challenging to support the aging population and innovative solutions are needed to improve safety and positive outcomes while decreasing cost and demand on healthcare workers (Agoulmine, Jamal Deen, Lee, & Meyyappan, 2011).

Another important aspect to note is the older adults' desire for and expectation of successful aging. In the last decade, general health of older adults have improved and functional limitations and disabilities affecting activities of daily living have declined (Freedman, Martin, & Schoeni, 2002). With the increased lifespan and improved general health of older adults, the notion of aging is shifting towards from the focus on disease management to promotion of wellness and successful aging (McMahon & Fleury, 2012). Therefore, older adults no longer wish to ‘live longer’ but put greater value on the quality of life, independence and continued productivity along with maintaining physical and mental health (Boult et al., 2009).

‘Aging-in-place’ is a concept that has been proposed to address older adults’ needs and expectations of successful aging. It is a notion that describes older adults’ desire to remain and live in their own homes without having to relocate to support facilities such as nursing homes (Wiles, Leibing, Guberman, Reeve, & Allen, 2011). The importance of aging-in-place has been shown consistently across different surveys of older adults (Wiles et al., 2011). However, while older adults show a strong desire to stay independent without having to give up their own lifestyle as they age, aging-in-place can introduce some challenges including managing their own health, performing various activities of daily living, and maintaining a social connection on their own. Previous research has shown that older adults who live alone could face issues related to isolation, mobility, hygiene, finances, health management, home management, safety, and nutrition (Heinz et al., 2013; Mynatt & Rogers, 2001; Singh & Misra, 2009). Consequently, there is a need for interventions to support successful aging-in-place of older adults. To this end, there has been a growing interest in the use of technologies for older adults, including those that can support health monitoring of older adults in their residence to support aging in their own homes. One example of ongoing work in Human-Computer Interaction in this area is the Aware Home Research Initiative Project (Mynatt, Essa, & Rogers, 2000), where they have built an experimental living laboratory for ubiquitous computing in support of aging in place of older adults as opposed to moving to an institutional care setting. The laboratory creates an intelligent environment that is aware of the activities of its occupants and serves as a testbed for numerous research projects designed to examine the usefulness and usability of smart home technology to support independence and quality of life.

The need for this type of technological interventions is amplified by the growing older adult population associated increases in healthcare utilization, and the desire of older adults to age in their own homes.

1.2 Internet of Things Smart Home Technology to Support Aging

Advances in information and communication technology (ICT) brought forth an emergence of the concept of smart homes. In 1992, Lutolf first formalized the concept defining it as the integration of different services within a home environment by using a common communication protocol (Lutolf, 1992). More recently in the aging literature, Demiris et al. defined smart homes as residences that integrate technology within the home to enhance residents' comfortable living by monitoring their health and wellness (G Demiris & Hensel, 2008). The concept of smart home for older adults is centered on the idea of helping them live independently and comfortably with the help of technology. More recently, the emerging paradigm of the Internet of Things (IoT) has significantly contributed to the advancement of smart home technology. The term "Internet of Things" (IoT) is defined as the network of everyday objects equipped with internet connectivity, enabling them to send and receive data (Höller et al., 2014). In general, the term refers to network-enabled objects interacting with each other and cooperating to achieve specific goals. As a concept, the objects or "Things" in IoT could include everything and anything around us. This new paradigm has broadened the possibility of smart homes. An IoT-based smart home could consist of all smart appliances (washers, dryers, refrigerators, etc.), smart home safety and security systems (sensors, monitors, cameras, and alarm systems), and smart home energy equipment, like smart thermostats and smart lighting. Following the IoT approach, these various devices designed by different companies using different protocols can be integrated together to form a home network to exchange and integrate data to achieve a more comprehensive knowledge or goals and provide more intelligent services to a user.

With the IoT smart home industry expected to grow to $39 billion industry by 2019 in the United States (Ablondi, 2013), an increasing number of IoT smart home devices are being developed and introduced in the market. By 2019, about 50 million or 40% of American households are expected to have at least one type of smart home device installed (Ablondi, 2013). Current commercially available examples include home automation such as the control of lighting and heating and recording movement through motion tracking. Users can control such systems by using a smartphone app or accessing a web interface or even with voice interaction due to recent development of artificial intelligence (AI)-based voice-operated smart speakers that may enhance the ease of use of IoT systems. Such IoT “smart” residences equipped with connected devices could potentially make the lives of older adults easier, more convenient, and safer. For example, persons with limited mobility will be able to control their doors, window blinds, or light switches by simply giving voice commands. For such individuals, being empowered to do these daily activities on their own may be the difference between being able to live independently or needing assistance at home or moving to an assisted living facility. In addition, the advancement in IoT sensor technologies along with advanced data analytics present an opportunity to support independent aging of the older adults by identifying potential patterns in health, detecting anomalous activities, and prompting early intervention to prevent adverse health events. For instance, sensors can be placed throughout the home to detect motion, sound, vital signs, or other environmental situations. The data generated by these sensors could be integrated through IoT networks to be processed and analyzed by a data monitoring service to support aging in place. For example, the data monitoring service could be programmed to send a notification to a caregiver if there is no movement detected for a predetermined period of time. In addition, the monitoring service could also analyze the activity patterns of older adults using machine learning techniques to detect unexpected events such as falls and slips. Additionally, such data collected by various sensors can be analyzed to infer users' activities throughout everyday life and encourage physical activity of users with sedentary lifestyles (S Consolvo et al., 2008).

Furthermore, older adults with depression could sometimes isolate themselves and not leave the house for a long time or have sleep disorder. Being capable of detecting these patterns can help in either preventing these conditions or assist in diagnosing these illnesses earlier. Over a longer period of time, the sensor-based monitoring can generate an objective record of activity patterns, making it possible to reduce reliance on older adults' self-report and memory recall of past events and changes in their health status. Services like this could empower older adults to stay in their home safely, while still giving them independence and autonomy and promoting self-care. Despite the potential benefits of IoT-based continuous monitoring solutions for older adults, these devices pose significant privacy risks for older adults and numerous previous research have identified privacy concerns to be a major barrier in the adoption of remote home monitoring technology by older adults (J. Chung, 2014; G Demiris & Hensel, 2008; Reeder et al., 2016). The 'DigiSwitch' project by Caine et al. (Caine et al., 2010) was an attempt to overcome such privacy barriers by designing a system that raise older adults' awareness of the data being collected about them and give them control to temporarily cease data transmission for privacy reasons. The evaluation results suggest that allowing older adults to regulate the data flow is helpful for maintaining user privacy. There have been some previous research investigating the use of in-home sensor technologies to passively monitor activity levels of older adults (Chen, Harniss, Patel, & Johnson, 2014; Kaye et al., 2011; Rantz et al., 2013; Reeder, Chung, et al., 2013; Sixsmith et al., 2007; F. Wang et al., 2013; Wild, Boise, Lundell, & Foucek, 2008b). However, these projects used systems with hardware components that capture and transmit data but do not have ways to interact with other devices and aggregate the data in a central repository as would be the case in an IoT-based smart home system. In addition, many of previous research did not perform a real-world evaluation with older adults, did not assess older adults' preferences of different types of devices, or used non-commercially available sensors.

To our knowledge, there has been little research on real-word testing of the IoT smart home devices with older adults. In addition, understanding older adults' perceptions and concerns with the use of these new IoT smart home devices remains a challenge. The feasibility testing of an IoT smart home sensor system may identify barriers and limitations of the technology features critical to rapid adoption among older adults. This work may inform the follow-up assessment of IoT technologies and their impact on health related outcomes, and advance our understanding of the role of IoT home-based monitoring technologies to promote successfully aging-in-place for older adults.

1.3 Statement of the Study Purpose

There are three main objectives to this study:

Aim 1: To assess the feasibility of an IoT smart sensor system used to monitor older adults in their residential setting.

Aim 2: To explore older adults' acceptability of an IoT smart system. Specifically, we will:

- Assess older adults' attitudes, needs, and preferences of an IoT smart sensor system and how these factors may change over time and after exposure to such a system.

- Assess older adults' perceived level of obtrusiveness of an IoT smart sensor system after exposure to such a system.

Aim 3: To propose design recommendations for a future IoT smart home system to better assist older adults' aging-in-place and maximize their user experience

1.4 Content of the Dissertation

This dissertation discusses how IoT smart home devices may support healthy aging-in-place of older adults. The dissertation consists of 4 main chapters. Below is an outline of the content of each chapter.

In chapter 2, I present findings from a 2-month feasibility study in which various Internet-of-Things (IoT) smart home devices were deployed within the participants' home. I focus on the feasibility performing the study by examining following key aspects of study design, including 1) recruitment and retention, 2) participants' preference on device choices, 3) device deployment and maintenance, 4) feasibility data collection and acceptability of the selected health outcome measures.

In chapter 3, I present qualitative findings from the interviews conducted during the 2-month feasibility study to describe older adults' perceptions of IoT smart home devices. I specifically focus on the following themes: 1) perceived benefits, 2) preferred features, 3) perceived concerns, 4) perceived needs.

In chapter 4, I examine older adults' perceptions of obtrusiveness to a different commercially available IoT smart home devices by examining if the dimensions and sub-categories of the obtrusiveness framework were represented in older adult's responses collected at the final study visits.

In chapter 5, I summarize my dissertation findings from all studies. I discuss design recommendations for a future IoT smart home system to better support older adults' aging-in-place. Furthermore, I outline how my findings can be used to inform future work in technology and aging.

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Chapter 2. USE OF AN INTERNET-OF-THINGS SMART HOME SYSTEM TO MONITOR OLDER ADULTS IN THEIR RESIDENTIAL SETTING: A FEASIBILITY STUDY

2.1 ABSTRACT

Background: The Internet of Things (IoT) technologies can create “smart” residences that integrate technology within the home to enhance residents’ safety as well as monitor their health and wellness. However, there has been little research on real-word testing of IoT smart home devices with older adults, and the feasibility and acceptance of such tools have not been systematically examined.

Introduction: The purpose of this study was to address this gap by conducting a pilot study to investigate the feasibility of IoT-based passive monitoring smart home systems in actual residences of older adults.

Materials and Methods: We conducted a 2-month feasibility study that enrolled community-dwelling older adults to choose among different IoT devices to be installed and deployed within their homes.

Results: We recruited total 37 older adults for this study. Results suggest that perceived privacy concerns, perceived usefulness, and curiosity to technology were strong factors when considering which device to have it installed in their home.

Discussion: Future trials should consider older adults’ preferences to the different types of smart home devices to be installed in real world residential setting.

Conclusions: These findings may inform the follow-up assessment of IoT technologies and their impact on health related outcomes, and advance our understanding of the role of IoT home-based monitoring technologies to promote successfully aging in place for older adults.

Keywords: Internet-of Things, IoT, smart home, aging-in-place

2.2 INTRODUCTION

'Aging-in-place' is a concept that has been proposed to address older adults' needs and expectations of successful aging. It calls for supporting older adults' desire to remain and live in their own homes without having to relocate to support facilities such as nursing homes (Wiles et al., 2011). The importance of aging-in-place has been shown consistently across different surveys of older adults (Wiles et al., 2011). However, while older adults show a strong desire to stay independent without having to give up their own lifestyle as they age, aging-in-place can introduce some challenges. These include managing one's own health, performing various activities of daily living, and maintaining social connections while experiencing health related changes. Previous research has shown that older adults who live alone can face issues related to isolation, mobility, hygiene, finances, health management, home management, safety, and nutrition (Heinz et al., 2013; Mynatt & Rogers, 2001; Singh & Misra, 2009). Consequently, there is an increased need for interventions to support successful aging-in-place of older adults. To this end, there has been a growing interest in the use of technologies for older adults, including those that can facilitate health monitoring of older adults in their residence to promote aging in their own homes. The need for this type of technological intervention is amplified by the growing older adult population, increasing healthcare needs, and the desire of older adults to age in their own homes.

The Internet of Things (IoT) technologies can create "smart" residences that integrate technology within the home to enhance residents' safety as well as monitor their health and wellness. The residences equipped with the IoT smart home devices could potentially make the lives of older adults easier, more convenient, and safer. For example, older adults with limited mobility will be able to control their doors, window blinds, or light switches by simply giving voice commands. For these older adults, being empowered to do these daily activities on their own is the difference between being able to live independently or needing assistance at home or moving to an assisted living facility. In addition, the advancement in IoT sensor technologies along with advanced data analytics present an opportunity to support independent aging by identifying potential patterns in health, detecting anomalous activities, and prompting early intervention to prevent adverse health events.

The use of home-based sensor technologies to passively monitor activity levels of older adults is a concept that has been tested previously (Chen et al., 2014; Kaye et al., 2011; Rantz et al., 2013; Reeder, Chung, et al., 2013; Sixsmith et al., 2007; F. Wang et al., 2013; Wild et al., 2008b). Previous research has shown that such technologies could accurately detect abnormal movement or behaviors (Ni, Hernando, & de la Cruz, 2015) and older adults are interested in receiving data from sensor technologies that provide better insight into their health status (Lee & Dey, 2010). In addition, older adults have demonstrated their belief that sensor-based passive monitoring systems in their homes have the potential to enhance their quality of life (George Demiris et al., 2004).

While these projects provide initial insights into the potential of passive monitoring using smart home sensors, most of these efforts were not real-world evaluation studies with older adults and did not assess older adults' preferences for different smart home devices. In addition, previous research focused on monitoring of residents' activities without including environmental parameters. Further, research to date has used systems with hardware components that capture and transmit data, but do not have ways to interact with other devices and aggregate the data in a central repository as would be the case in an IoT-based smart home system. To our knowledge, there has been little research on real-word testing of IoT smart home devices with older adults, and the feasibility and acceptance of such tools have not been systematically examined. Therefore, the purpose of this study was to address this gap by conducting a pilot study to investigate the feasibility of IoT-based passive monitoring smart home systems in actual residences of older adults.

2.3 RESEARCH DESIGN AND METHODS

The primary aim of the study was to investigate the feasibility of using an IoT smart home devices in real-world residential settings of older adults. To demonstrate feasibility, we assess the following key aspects of future trial design, including 1) recruitment and retention, 2) participants' preference on device choices, 3) device deployment and maintenance, 4) feasibility data collection and acceptability of the selected health outcome measures. As this was a feasibility study, no controls or randomization were used and no specific interventions were administered during the study.

2.3.1 *Study Setting/Recruitment*

This study was a 2-month feasibility study that enrolled community-dwelling older adults in the Puget Sound area to choose among different IoT devices to be installed and deployed within their homes. The devices varied depending on preference of the participant, and options included door/window sensor, multi-purpose sensor, a voice-operated smart speaker, and an IP-video camera (See the **2.3.2 IoT Device description and deployment** for more detail). Over the study period, participants were interviewed at three different time points: baseline, 1-month, and 2-month (study exit) to understand their thoughts about the devices.

We recruited participants through collaboration with local retirement communities in the Puget Sound area. In order to be eligible for the study, participants needed to be (a) community-dwelling older adults (including those residing in assisted living facilities), (b) able to read and write English, (c) have Internet connection at their residence, and (d) choose at least one or more devices for installation in the home.

Recruitment occurred at six different senior housing communities to include individuals across a range of lower to middle-upper socio-economic status. The communities house older adults who have capacity to live independently with minimal help in maintaining their home or activities of daily living. Working with facility administrators, we posted recruitment flyers and held information sessions that included a short presentation about the research project, followed by a question and answer session. After the presentation, interested individuals either went through informed consent process with study team members or filled out contact information to be later contacted for enrollment to the study. In the latter case, informed consent was obtained during the baseline visit prior to any study procedures. We also conducted snowball sampling to identify potential participants who may be interested in participation. During the informed consent process, the subject chose the devices to be installed and indicated their choice on the form. To compensate participants for their time, we provided $25 gift cards following the first and second month interview visits.

In this study, recruitment occurred in two different phases. For Phase 1, a voice-operated smart speaker was not one of the available IoT devices and eligible participants had to be living alone on top of aforementioned inclusion criteria. For Phase 2, we added the option of a voice-operated smart speaker and made it eligible for interested couples who live together to join the study together. The recruitment process and the study procedures remained the same between two phases. In total, we had 37 participants in the study. Fifteen participants were recruited during Phase 1 (12 female, 3 male) and 22 participants were recruited during Phase 2 (17 female, 5 male).

2.3.2 *Internet-of-Things device description and deployment*

Error! Reference source not found. provides the overview of the IoT devices available for the participants to choose and evaluate for this study. All devices were commercially available. The primary investigator conducted installations of the devices and provided technical support via phone or making in-home visits during the duration of the study when necessary. The frequency and the reasons for additional visits outside the scheduled study visits were recorded. Participants were also encouraged to contact the primary investigator if they had any questions or issues related to the devices. The pictures of devices used are shown in **Figure 1**.

Table 1. IoT smart home devices used in this study

Device	**Data Collected**	**Data Transfer Protocol**	**Location of deployment within the home**
Door/Window Sensor	Binary on/off signal when the switch is activated	Z-wave	Front door, Refrigerator
Multi-Purpose Sensor	Luminosity, temperature, humidity, motion	Z-wave	Living room, Bedroom
A voice-operated smart speaker	The transcripts of the questions and requests made during the study period.	Wifi	Living room
IP Web Camera	Live video streaming. No video recording was collected.	Wifi	Living room, Bedroom

2.3.2.1 Door/Window sensor and Multi-purpose sensor deployment

The door/window sensor records a binary on/off signal when the magnetic switch is activated. The multi-purpose sensor collects data on motion, temperature, luminosity, and humidity. The door/window sensor was installed either at the front entrance of the residence or the fridge. The multi-purpose sensor was installed in the living room area or the bedroom depending on the preference of the participant. To deploy these two sensors, we used the open source so called "Lab of Things" software platform developed by Microsoft Research (A. J. B. Brush et al., 2013; A. Brush, Jung, Mahajan, & Scott, 2012). This platform was installed in a small study laptop and deployed together with a Door/Window sensor and a multi-sensor. For the communication between the Lab of Things platform and the sensors a Z-wave USB dongle was attached to the laptop. During the study, the laptop was plugged into the outlet and left on all the time for processing and sending the sensor data to our research cloud server. The laptop was closed-lid and placed to be as unobtrusive as possible to the participant's home.

2.3.2.2 A voice-controlled smart speaker deployment

The smart speakers are equipped with a far field microphone that supports voice recognition. This allows for various hands-free operations including playing music, retrieving information, and setting reminders and alarms. For this study, we used Echo Dot, a smart speaker manufactured by Amazon. Amazon smart-speakers provide capabilities, or skills that enable users to try out features created by the third-party designers and developers for more personalized experience. For example, 'WebMD' skill allows users to ask basic health-related questions. The initial training of how to use the smart speaker was provided by a member of the research team. The participants were encouraged to explore various features during the study period and think about potential uses of a smart speaker in the management of health context. In addition to the initial training, a list of basic commands was provided to the participants to facilitate the usage of the smart speaker.

2.3.2.3 IP web-camera deployment

The use of an Internet Protocol (IP) Camera allows for synchronous monitoring of a room or other area in the home by the participants. The camera was installed in the living room area or the bedroom location according to the preference of the participants. The participants had the option to have the accompanying monitoring app installed on their smartphone or just use a regular desktop browser to view the live feed from the camera. The research team did not monitor the live feed from the camera because providing a monitoring service was not the goal of this study. However, the participants could choose to share the access to the camera with someone in their life by sharing the web address of the secured camera dashboard and accompanying id and password.

Door/Window sensor

Multi-purpose sensor

IP web-camera

Smart speaker

Figure 1. Device Pictures

2.3.3 *Study procedures*

Baseline session: Once participants agreed to participate in the study and provided written informed consent, we scheduled an in-person appointment with the participant for the baseline visit. During the baseline visit, we installed the participant-selected IoT devices in the subject's residence. Installation took approximately 30-45 minutes if a participant were to select all offered devices. After the installation was complete, we collected demographics data including age, gender, marital status, education, insurance status, history of chronic conditions and current medications, and the use of assistive devices. In addition, we administered the e-health Literacy Scale (eHEALS) (Norman & Skinner, 2006) to measure one's comfort level with the technology. Health-related data that incorporate physical, psychosocial, functional, and mobility related parameters were collected using validated self-report instruments. For a complete description of instruments and the collection schedule, see *2.3.5 Data Collection* section. After all the questionnaire data were collected, a semi-structured interview was conducted to assess initial participant perspectives on IoT smart home devices. The questionnaires and interview questions took 30-45 minutes and in conjunction with installation, the first visit lasted between 60-90 minutes total. The interviews were digitally recorded.

Midpoint (one-month) session: During the midpoint visit, we conducted an in-person interview to assess perceived usefulness of the installed IoT smart home technology, any challenges, privacy or other concerns as well as any recommendations or feedback subjects had at this point. During this visit, we presented participants with graphs of their own sensor data collected during the first month, asking for thoughts and feedback **(**see data visualization section below**).** The visit lasted 30-45 minutes. The interviews were digitally recorded.

Exit (two-month) session: After two months, we conducted the last visit in subjects' homes. The installed devices were removed at the beginning of the visit. We administered exit questionnaires and conducted a semi-structured interview to assess perceived obtrusiveness of the IoT smart home technology, any challenges, privacy or other concerns as well as any recommendations or feedback (pertaining to their overall experience) subjects may have as they conclude their participation. The third visit took approximately 60 minutes. The interviews were digitally recorded.

2.3.4 *Smart home activity data visualization*

For those participants who selected motion tracking sensors (e.g. a door/window sensor, a multi-purpose sensor) were presented with graphs of their own sensor data obtained from the motion sensors. The line graphs and bar graphs were created by PI by aggregating the sensor data using

R Software to show the activity trends and pattern changes over time (See Figure 2 below). The number of graphs shown to the participants varied based on the selection of devices. Participants who selected a smart speaker or an IP camera did not see the graphs and no questions were asked related to the visualization.

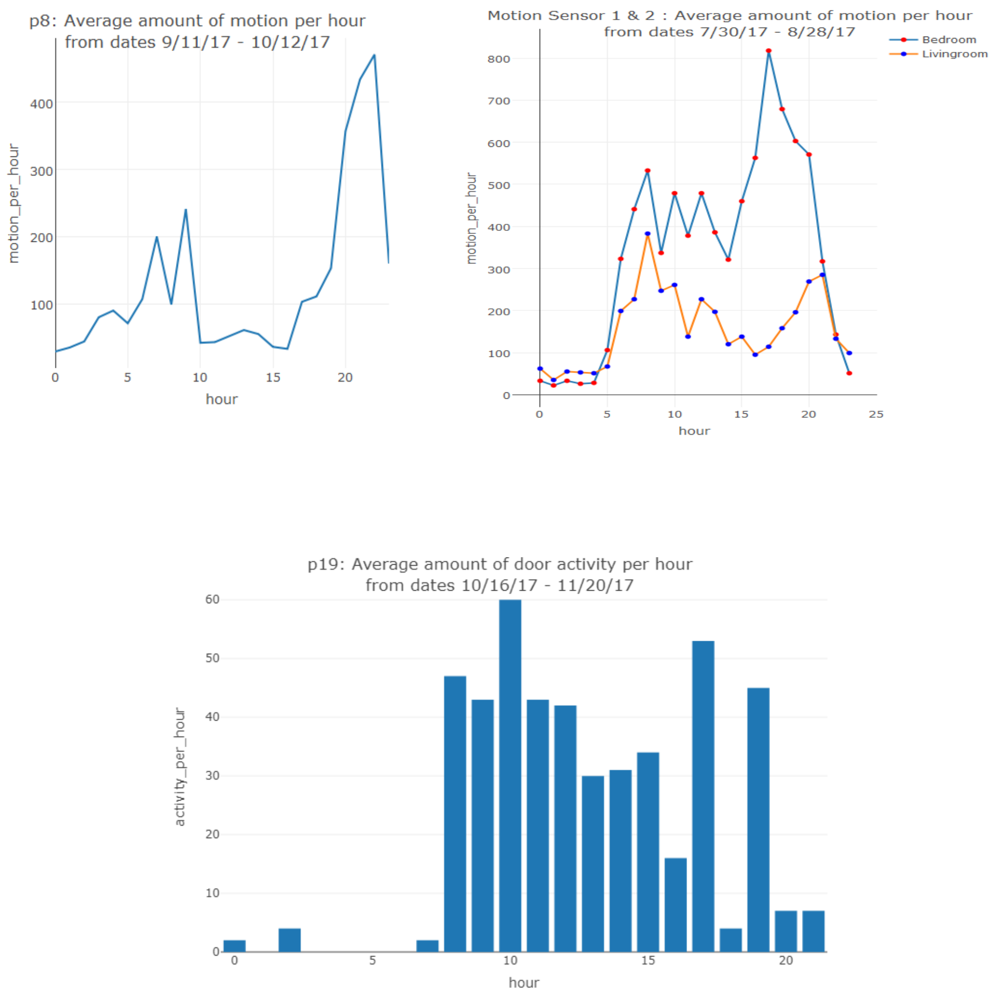

Figure 2. Example visualizations of participant's sensor data

2.3.5 *Data Collection*

Error! Reference source not found. outlines the instruments used for this study and the data collection schedule. Instruments were selected to test for feasibility of data collection and acceptability for measuring health status outcomes for future smart home studies.

Table 2. Overview of Instruments and Data Collection Schedule

Types of Data Collected		Instrument	Description	Schedule
Participant characteristics	Demographics	Demographics questionnaire	at baseline age, gender, education level, marital status, insurance status, history of chronic conditions, current medications, and use of assistive devices	Baseline
	Electronic health literacy	eHEALS[1]	8 item designed to measure consumers' combined knowledge	Baseline
Health status indicators	Physical	SF-12v2[2]	6 item SF-12v2 PCS subscale	Baseline, Exit
	Psychosocial	SF-12v2[2]	6 item SF-12v2 MCS subscale	Baseline, Exit
	Activities of Daily Living	Lawton IADL[3]	8 domains of independent activities of daily living skills	Baseline, Exit
	Mobility	Life Space Assessment[4]	Extent of mobility and space occupied during the previous 4 weeks	Baseline, Exit

1. The eHealth Literacy Scale (Norman & Skinner, 2006); 2. SF-12v2 (Ware, Kosinski, & Keller, 1996); 3. Instrumental activities of daily living (Lawton & Brody, 1969); 4. Life Space Assessment (Baker, Bodner, & Allman, 2003)

In addition to the above data, we conducted semi-structured interviews at baseline, midpoint and exit to examine older adults' attitudes, needs, and preferences, and perceived level of obtrusiveness of an IoT smart home system. The in-depth findings from this qualitative data are described in <u>Chapter 3 and 4.</u>

2.4 RESULTS

2.4.1 *Recruitment and retention*

Fifty-one people enquired about the study with initial interests to join after attending the recruitment information session or contacting the research team member using the recruitment flyer. Among the 51 inquiries about the study, 47 contacts were from the information session, 2 from the study flyer information and 2 were contacts from snowball sampling from the enrolled participants. Following **Table 3** summarizes the recorded reasons that were identified to exclude participation.

Table 3. Reasons for exclusion

Reasons for exclusion not recruited to the study	**No. of people**
Does not live alone*	2
Younger than 65	4
No Internet connection at home	5
Lost to follow-up contact/ no reasons recorded	3

* Phase 1 required people to live alone to be eligible. This criterion was relaxed in phase 2 recruitment.

We recruited total 37 older adults for this study (15 in Phase 1 and 22 in Phase 2). For those who were recruited, one participant (ph1_p1) during Phase 1 did not complete the full 2 month study, dropping out after completing the midpoint visit. This individual mentioned very low perceived utility of the devices and complained about unidentified technical issues experienced at home. Another participant (ph1_p7) was lost to follow up for the midpoint visit but the contact was re-established for the exit interview. All other participants (n=35) successfully completed all the procedures in the 2-month study.

2.4.2 *Device selection by the participants*

Table 4 shows the choice of IoT device selection by the participants. Among Phase 1 group, the most widely chosen device was the multi-purpose sensor (93.3%) closely followed by the door/window sensor (80%) in Phase 1. Among Phase 2 group participants, a smart speaker (86.4%) was the most widely chosen device followed by the multi-sensor (81.2%) and the door/window sensor (68.2%). An IP camera was significantly unpopular choice among participants in both phases (Phase 1: 13.3%, Phase 2: 13.6%). Most participants commented that the potential privacy risks deterred them from choosing the camera. For both phases, the participants had options to choose more than one device. The most frequently selected combinations of devices for Phase 1 was Door/window + Multi-sensor (60%). For phase 2, with addition of a smart speaker in the available devices to choose from, the majority of the participants chose the combination of Door/Window + Multi-sensor + Smart speaker (50%).

Table 4. IoT device selection by the participants

Devices	**Phase 1 (n=15)**	**Phase 2 (n=22)**
Door/Window Sensor	12 (80.0%)	15 (68.2%)
Multi-purpose sensor	14 (93.3%)	18 (81.2%)
IP-camera	2 (13.3%)	3 (13.6%)
Smart-speaker	Not Applicable*	19 (86.4%)
Combinations of devices selected		
Door/Window only	1 (6.7%)	1 (4.5%)
Multi-purpose sensor only	3 (20%)	0 (0%)
Smart-speaker only	Not Applicable*	1 (4.5%)
Door/Window + Multi-purpose sensor	9 (60%)	2 (9.1%)
Door/Window + Multi-purpose sensor + IP-camera	2 (13.3%)	0 (0%)
Door/Window + Multi-purpose sensor + Smart-speaker	Not Applicable*	11 (50%)
Multi-purpose sensor + Smart-speaker	Not Applicable*	4 (18.2%)
IP-camera + Smart-speaker	Not Applicable*	2 (9.1%)
Door/Window + Multi-purpose sensor + IP-camera + Smart-speaker	Not Applicable*	1 (4.5%)

*Smart-speaker was not offered during Phase 1.

2.4.3 *Device deployment and maintenance*

Over the course of the study, the primary investigator reviewed the status of the deployed sensor system remotely. The status of the sensor devices (door/window sensor, multi-purpose sensor) was managed through the cloud remote management system of the Lab of Things platform. If the deployed system was offline, the primary investigator contacted the participants to schedule a maintenance visit. We recorded 22 maintenance visits outside the scheduled study visits throughout the study.

Eleven maintenance visits were made to reboot the netbook used in the study. The netbook was used to receive and upload the sensor data for the deployment of door/window sensor and multi-sensor and had to be left on all the time 24/7 throughout the study. In some occasions, the netbook system froze up due to memory overflow and the manual reboot of the system was necessary. This issue was less of a problem for Phase 2 where newer netbooks with bigger internal memory was used for the study. Eight maintenance visits were made to re-establish the Internet connection. One facility went through switching the Internet service provider during the study and therefore, all the participants enrolled at that time from that specific building required additional visits for setting up the devices.

2.4.4 *Feasibility of data collection*

Overall, the study participants were able to easily complete the demographics and eHEALS questionnaires on their own when the primary investigator was installing the devices during the baseline visit. Some participants mentioned that they were confused as several eHEALS items seemed repetitive. All health-related questionnaires (IADL, LSA, and SF12) were administered by the research team during the baseline and exit visits. There were no missing items in the questionnaires data collected. In one instance, a participant (ph2_p19) noted discomfort with the mental health related questions in SF-12 but still provided responses. One participant (ph1_p7) declined to complete the exit questionnaires due to time restraint.

2.4.5 *Participant characteristics*

Table 5 shows the demographic information of all study participants. There were no statistically significant differences in demographic parameters between the Phase 1 and Phase 2 participants. Overall, the participants in the study had a mean age (SD) of 77.6 (8.9), were likely to be female (78.5%) and have Bachelor's degree or higher (86.1%). Four couples living together (n=8 married individuals) enrolled in the study together in Phase 2 and rest of the participants (n=29) in the study lived alone. The mean eHEALS score for participants was 31.8 out of maximum 40 (SD: 6.3) indicating that the participants were in general comfortable using information technology for health situations. The majority of participants in the study had one or more self-reported chronic conditions (89.2%) and took more than 3 current medications (54%). About half of participants used some form of assistive devices (54.1%) such as a cane, a walker, or a wheelchair.

Table 5. Participant characteristics

	Phase 1 (n=15)	**Phase 2 (n=22)**	**Combined (n=37)**
Age	77.2 (SD: 11.1)	77.8 (SD: 7.5)	77.6 (SD: 8.9)
Female	12 (80%)	17 (78%)	29 (78.4%)
Marital Status			
Single	6 (40%)	2 (9.1%)	8 (21.6%)
Married/Partnered	0 (0%)	8 (36.4%)	8 (21.6%)
Divorced	2 (13.3%)	3 (13.6%)	5 (13.5%)
Widowed	7 (46.7%)	8 (36.4%)	15 (40.5%)
Other	0 (0%)	0 (0%)	0 (0%)
Chose Not to Answer	0 (0%)	1 (4.5%)	1 (2.7%)
Education			
Less than high school	0 (0%)	0 (0%)	0 (0%)
High school diploma/GED	1 (6.7%)	2 (9.5%)	3 (9.3%)
Some college	1 (6.7%)	1 (4.76%)	2 (5.5%)
Bachelor’s degree	8 (53.3%)	8 (38.1%)	16 (44.4%)
Graduate or Professional degree	8 (33.3%)	10 (47.6%)	15 (41.7%)
Mean eHEALS* Score (SD, Range)	34.5 (4.5, 26-40)	30.0 (6.9, 16-40)	31.8 (6.3, 16-40)
Insurance			
Medicare	15 (100%)	22 (100%)	37 (100%)
Medicaid	0 (0%)	0 (0%)	0 (0%)
Private Insurance	6 (40%)	9 (40.9%)	15 (41.7%)
Other	2 (13.3%)	9 (40.9%)	5 (13.5%)

# of Chronic Conditions (self-report)			
0	3 (20%)	1 (4.5%)	4 (10.8%)
1-3	7 (46.7%)	18 (81.8%)	25 (67.6%)
4+	5 (33.3%)	3 (13.6%)	8 (21.6%)
# of Current Medications (self-report)			
None	4 (26.7%)	2 (9.1%)	6 (16.2%)
1-2	2 (13.3%)	9 (40.9%)	11 (29.7%)
3-4	5 (33.3%)	4 (18.2%)	9 (24.3%)
5+	4 (26.7%)	7 (31.8%)	11 (29.7%)
Use of Assistive Devices			
Yes	10 (66.7%)	10 (45.5%)	20 (54.1%)
No	5 (33.3%)	12 (54.5%)	17 (45.9%)

*eHEALS: The eHealth Literacy Scale, 8-40, higher scores representing higher self-perceived eHealth literacy.

In addition to demographic parameters, **Table 6** shows the self-reported health-related parameters measured at the baseline and exit and the pre-post trends of these parameters. In general, there were no statistically significant changes in any health-related variables between the 2-month study period.

Table 6. Health-related Variables at Baseline and Exit

	Phase 1 Baseline (n=15)	Phase 1 Exit (n=13)	Phase 2 Baseline (n=22)	Phase 2 Exit (n=22)	Combined sample at Baseline (n=37)	Combined sample at Exit (2-month) (n=35)	p-value (combined sample baseline vs exit)
IADL[1] (SD, Range)	7.5 (0.9, 5.0-8.0)	7.7 (0.9, 5.0-8.0)	7.7 (0.8, 5.0-8.0)	7.6 (1.1, 3.0-8.0)	7.7 (0.7, 5-8)	7.7 (1.0, 3-8)	0.57
LSA[2] (SD, Range)	52.9 (17.3, 27-82.5)	55.3 (14.1, 36.0-76.0)	64.2 (21.0, 28.5-100)	60.0 (22.7, 16.5-100)	60.5 (19.9, 28.5-100)	58.2 (19.9, 16.5-100)	0.32
SF-12 PCS[3] (SD, Range)	42.7 (8.8, 21.6-58.5)	43.3 (8.9, 25.7-56.8)	46.7 (7.5, 32.0-56.5)	52.9 (8.2, 31.4-56.1)	45.08 (8.2 ,21.6-58.5)	44.56 (8.4, 25.7-56.8)	0.35
SF-12 MCS[4] (SD, Range)	52.7 (8.7, 32.6-61.0)	50.7 (7.0, 33.7-58.9)	54.6 (6.6, 37.0-61.1)	49.4 (9.1, 22.4-60.0)	52.07 (7.4, 32.6-61.1)	49.85 (8.3, 22.4-60.0)	0.11

1. IADL=Instrumental activities of daily living: 0 (low function, dependent) to 8 (high function, independent); 2. LSA=Life-Space Assessment of Mobility: A composite score ranges from 0 (mobility restricted to the bedroom) to 120 (independence enabling travel to out of town); 3. SF-12 PCS = 12-item Survey Physical Component Summary Measure; 4. SF-12 MCS = Short form 12-item Survey Mental Component Summary Measure; Range 0 to 100, with higher score indicating better health

2.5 DISCUSSION

This pilot study evaluated the feasibility of using IoT smart home devices in real-world residential settings of older adults. The specific goal of this study was to assess some key aspects of trial design to inform future intervention study using IoT smart home devices in older adults' residences. Different from previous smart home research where the deployed system was often predetermined and prescribed to the participants, this study assessed the device preferences of older adult participants in the study design. Overall, most participants showed preference towards passive monitoring sensor devices and a smart speaker over IP-cameras. Most participants considered an IP-camera to be more intrusive and did not want it placed in their home environment. However, some participants who did not choose the camera themselves mentioned that they could see benefits of having a camera for frail home-bound older adults who might benefit from constant monitoring. Our findings suggest that perceived privacy concerns, perceived usefulness, and curiosity to technology were strong factors when considering which device to have it installed in their home. This is in alignment with some previous research which examined the acceptability of in-home sensor devices (Chung, Thompson, Joe, Hall, & Demiris, 2017; Reeder et al., 2013). Additionally, the results show that older adults have varying degrees of acceptability to the different types of IoT smart home devices in real world contexts. Future trials should consider older adults preferences to the different types of smart home devices to be installed in real world residential setting.

2.5.1 *Recruitment and retention*

In this study, we collaborated with local retirement facilities in the Puget Sound area and recruited 37 people from 6 different retirement facilities. Our recruitment results show that the recruitment information session held at the retirement facilities was an effective strategy among the different recruitment activities in our study. One key benefit of the group information sessions was the reduced burden on the research team in the facilitation of informed consent process. However, identifying local retirement facilities to collaborate with the research team to setup information sessions was a challenging process. Multiple contact attempts to most facilities often failed to result in return communication. To increase success of establishing contacts, the research team explored the networks and known contacts from previous research. In the end, we were able to recruit from 6 different retirement facilities in the area, 4 of them under same foundation which facilitated the contacts with each building administrators. Future research should explore research partnership with local retirement facilities and community agencies. The partnership could be mutually beneficial in that research teams could gain easier access to potential older adult research participants and the facilities could have increased access to innovative technology solutions and explore their potential applications in supporting their residents.

One barrier to participation was that some individuals who were interested in participating lacked Internet access at home. Due to limited funds and other practical constraints, we were not able to provide an Internet connection, and thus excluded those who did not have available access. This exclusion criteria could have turned away a group of participants who were not familiar with the Internet technology. No major challenges were noticed in our study procedures and all but one participant failed to complete the study. The high retention could be explained by low participant burden imposed by the study. In addition, engaging participants to choose the devices to evaluate at the start of the study may have eliminated any discomfort of having unwanted devices in their residence, in turn motivating them to remain in the study.

2.5.2 *Deployment management*

We identified some challenges to the maintenance of the deployed devices. We recorded total 22 additional visits to the participants' homes outside the regular study visits. Eleven additional visits were necessary due to unforeseen technical issue as we noticed that the memory overflow of the sensor data processing netbook required manual reboot of the system. This issue was resolved through replacement of the netbook with ones with larger memory for the study. The issue of reliability and stability of the system deserves to be highlighted. The home gateway system that manages and controls the interconnected IoT devices and the processing of the data received from the devices is an important central component of smart home infrastructure (Chang, Kuo, Chen, & Wang, 2015). The reliability and the stability of such home gateway system for long-term operation is essential for designing future intervention studies that use IoT smart home technologies.

2.5.3 *Limitations*

The primary study limitation is the generalizability of our findings due to a relatively small sample size recruited in a single metro area. Therefore, the opinions on IoT smart home devices may vary in other regions of the world. In addition, the two-month pilot deployment period may not be enough to understand the changes of perception and adoption behaviors over the long term. Furthermore, we only offer four different IoT monitoring devices for older adults to choose for this pilot study. The participants' opinions might have varied had there been additional kinds of devices available for them. Despite these challenges, the data presented in this study can inform future studies exploring the use of smart home devices with older adults in their residential setting.

2.6 Conclusions

Our study is particularly unique from previous studies, in that it assessed older adults' preferences of different sensor devices through a real-word testing of the IoT devices with older adults to address the literature gap. In addition, we combined environmental sensor data with motion sensor data to understand potential use cases of such integrated data in monitoring older adults' activities. Furthermore, to our knowledge, our study is among the first attempts to explore the use of smart speakers in a health context with an older adult population. We believe the finding from this feasibility testing of an IoT smart home sensor system may identify barriers and limitations of the technology features critical to rapid adoption among older adults. This work will inform the follow-up assessment of IoT technologies and their impact on health related outcomes, and advance our understanding of the role of IoT home-based monitoring technologies to promote successfully aging in place for older adults.

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Chapter 3. OLDER ADULTS' ATTITUDES, NEEDS AND PREFERENCES REGARDING IOT SMART HOME DEVICES

3.1 ABSTRACT

Background and Objectives: The purpose of this study was to examine older adults' perceptions of Internet-of-Things (IoT) smart home devices as part of a real-world feasibility study and describe what factors affect their adoption of these technologies.

Research Design and Methods: A total of 37 community-dwelling older adults residing in the Pacific Northwest enrolled in the 2-month feasibility study. Participants chose among different IoT devices to be installed in their home and test during the study period. Semi-structured interviews to explore perceptions of the technology were conducted twice (1 month and 2 month visits). Thematic analysis of the interview transcripts was conducted to meet study aims.

Results: Older adults have unique preferences for specific types of IoT devices and their functionalities. Similarly, there were different degrees of acceptability across devices. In general, older adults had a positive attitude toward IoT smart home technologies to support their health management. Emergency preparedness was a key benefit identified by many older adults in the study. Additionally, convenience of a voice-interface provided by a smart speaker were well liked among the participants. Older adults seemed to weigh the benefits and the actual need for having the devices against potential infringement on privacy.

Discussion and Implications: Our study findings broaden our understanding of older adults' perceptions of IoT smart home technologies. Researchers and system designers should consider ethical and practical challenges related to the interconnected services of the IoT domain.

3.2 Introduction

The ongoing growth of the older adult population is experienced worldwide, with predicted growth from 524 million people in 2010 to 1.6 billion people in 2050 (Suzman & Beard, 2011). As people age, sensory functions such as vision, hearing and motor perception normally decline (Carmeli et al., 2003; Mynatt & Rogers, 2001). With these and other aging-related changes, older adults are more prone to chronic health conditions, fall-related injuries, and limitations in memory and physical function (Gerteis et al., 2014; Shumway-Cook et al., 2009). The unprecedented demographic shift brings out new demands and challenges in many areas of society. Two domains that necessitate immediate attention are healthcare and caregiving. Older Americans are primary consumers of health care and receive more medical attention than any other U.S. demographic group. In fact, older adults 65 and older which make up 13 percent of the U.S. population, account for 34 percent of total healthcare-related spending in 2010 (Stanton, 2006). Health systems worldwide are finding it more challenging to support their aging populations and innovative solutions are needed to improve safety and positive outcomes while decreasing cost and demand on healthcare workers (Agoulmine et al., 2011).

‘Aging-in-place’ is a concept that has been proposed to address older adults’ needs and expectations of successful aging. It is a notion that describes older adults’ desire to remain and live in their own homes without having to relocate to support facilities such as nursing homes when health care needs change (Wiles et al., 2011). The importance of aging-in-place has been shown consistently across different surveys of older adults (Wiles et al., 2011). However, while older adults show a strong desire to stay independent without having to give up their own lifestyle as they age, aging-in-place can introduce some challenges including managing one’s own health, performing various activities of daily living, and maintaining a social connection.

Consequently, there is an increased need for interventions to support successful aging-in-place of older adults. Smart homes are a concept which define residences that integrate technology within the home to enhance residents' living by monitoring and supporting their health and wellness (Hensel, Demiris, & Courtney, 2006b). The Internet of Things (IoT), defined as the network of everyday objects equipped in internet connectivity, has broadened the possibility of smart homes. Current commercially available examples of IoT smart home devices include home automation tools such as the control of lighting and heating, and recording movement through motion tracking. Users can control such systems by using a smartphone app, accessing a web interface, or even with voice interaction with recent development of artificial intelligence (AI)-based personal assistant smart speakers. Such IoT "smart" residences equipped with connected devices could potentially make the lives of older adults easier, more convenient, and safer. For example, adults with limited mobility are able to control doors, window blinds, or light switches by simply giving voice commands. For these older adults, being supported to carry out these daily activities on their own may be the difference between being able to live independently or moving to an assisted living facility. In addition, the advancement in IoT sensor technologies along with advanced data analytics present an opportunity to support independent aging by identifying potential changes in health, detecting anomalous activities, and prompting early intervention to prevent adverse health events resulting from decreasing activity levels.

Despite the recent surge of new IoT smart home technologies, there remain questions regarding acceptance and usage of these technologies among older adults. Previous studies demonstrate that older adults are generally positive towards adopting new technologies as long as they perceived them to be useful, effective and easy-to use (Hensel, Demiris, & Courtney, 2006a; Mccreadie & Tinker, 2005). There is however, a dearth of studies that examine older adults' perceptions of the IoT smart home technologies especially in a real-world setting as opposed to the laboratory simulation setting. Therefore, the objective of this study is to assess older adults' perceptions of IoT smart home devices over the course of a real-world 2-month feasibility study.

3.3 METHODS

This study was a 2-month feasibility study that enrolled community-dwelling older adults aged 65 years or older in the Pacific Northwest. Once enrolled in the study, participants were asked to choose from a list of available IoT devices which ones they would like to have deployed within their home. The available IoT devices included: a door and window sensor, a multi-purpose sensor, a voice operated smart speaker, and an IP video camera. **Table 7** summarizes these devices. The participants were recruited in two different phases. For Phase 1, a voice-operated smart speaker was not included in the available IoT devices and eligible participants had to be living alone. For Phase 2, we added the option of a voice-operated smart speaker and allowed interested couples who live together to enroll in the study together. All other inclusion criteria and study procedures remained the same. All study procedures were approved by the University of Washington Institutional Review Board.

Participants were recruited in collaboration with local retirement communities in the Pacific Northwest. To be eligible for the study, participants needed to be (a) community dwelling older adults (including those residing in assisted living facilities), (b) able to give informed consent, (c) able to read and write English, (d) have Internet connection at their residence, and (e) choose at least one or more devices for installation in the home. During the informed consent process, the subject chose the devices to be installed and indicated their choice on the form. We provided $25 gift cards after the midpoint and exit interview visits to compensate for participation.

Table 7. IoT Smart Home Devices Used in the Study

Device	**Description**
Door/Window Sensor 	The sensor generates ‘open/closed’ binary data.
Multi-purpose sensor 	This sensor collects two types of data. First is motion activity data. The other is environmental data including luminosity, temperature, and humidity.
Voice-operated smart speaker 	The smart speaker is equipped with a far field microphone that supports voice recognition. This allows for various hands free operations including playing music, retrieving information, and setting reminders and alarms.
IP web camera 	An IP web camera is connected to the Internet and enable monitoring of a room or area within the home through live or recorded video.

3.3.1 *Study procedures*

The research team conducted baseline, midpoint, and exit visits that each lasted 60-90 minutes with participants. An in-person appointment for the baseline visit occurred following written informed consent. During the baseline visit, we installed the participant-selected IoT devices in the subject's residence. After the installation was complete, we collected demographics data including age, gender, marital status, education, insurance status, history of chronic conditions and current medications, and the use of assistive devices. In addition, we administered the e-health Literacy Scale (eHEALS) (Norman & Skinner, 2006) to measure one's familiarity and experience in using electronic health information. Physical, psychosocial, functional, and mobility related parameters were collected using validated self-report instruments. For a complete description of instruments and the collection schedule, see *Chapter 2.3.5 Data Collection*. After all the baseline questionnaire data were collected, a semi-structured interview was conducted to assess initial participant perspectives on IoT smart home devices.

During the midpoint visit, we interviewed individuals to assess perceived usefulness of the installed IoT smart home technology, any challenges, privacy or other concerns as well as any recommendations or feedback subjects had at this point. During this visit, we presented participants with visualizations of their own sensor data collected during the first month, asking for their thoughts and feedback. After two months, we conducted the exit visit in subjects' homes. The installed devices were removed at this visit and a semi-structured interview was conducted to assess perceived obtrusiveness of the IoT smart home technology, any challenges, privacy or other concerns as well as any recommendations or feedback (pertaining to their overall experience) subjects may have as they conclude their participation. All baseline, midpoint, and exit interviews were digitally recorded. See **Appendix A** at the end of this chapter for interview guides used for this study.

3.3.2 *Thematic Analysis*

All interview sessions (at baseline, midpoint and exit) were audio-recorded and transcribed verbatim by the professional transcription service. We had 6 missing data due to audio file corruption (n=2 baseline), lost to follow-up (n=1 baseline, n=1 midpoint), and drop out (n=1 exit). Accounting for the 6 missing interview transcript data, we were left with 105 interview transcripts (34 baseline, 35 midpoint, 36 exit). All transcripts were verified for accuracy by listening to the recording and reading the transcript. Thematic content analysis (Hsieh & Shannon, 2005) was conducted to identify themes related to older adults' attitudes, needs, and preferences of an IoT smart home devices. The analysis was data-driven where data codes were inductively generated by the data collected. The initial codebook was created by the lead investigator after coding nine randomly chosen transcripts (n=3 baseline, n=3 midpoint, n=3 exit). With the initial codebook as a starting point, three researchers experienced with qualitative methods independently coded six randomly chosen transcripts (n=2 baseline, n=2 midpoint, n=2 exit). Once coded, researchers met to review the coding scheme and standardize codes and reconcile disagreements to develop a master codebook. We used Dedoose online qualitative coding software to facilitate coding and recoding of the transcripts. The master codebook was used to independently code about 25% (n=30) of the total 105 interview transcripts (n=34 baseline, n= 35 midpoint, n=36 exit interviews) which included 10 baseline interview, 10 midpoint interview, 10 exit interview. The remaining transcripts were coded by the lead investigator to check for validity. Recurrent and important themes were grouped together to identify key themes. Final results were summarized by the lead investigator. We believe that data saturation was reached following the guideline recommended by Guest et al. to code at least 6-12 transcripts to reach saturation (Guest, Bunce, & Johnson, 2006).

3.4 RESULTS

3.4.1 *Demographics*

There were total 37 participants recruited in this study. Fifteen participants were recruited during Phase 1 (12 female, 3 male) and 22 participants were recruited during Phase 2 (17 female, 5 male). Phase 1 and Phase 2 participants were similar in their demographic characteristics. **Table 8** summarizes demographics characteristics of study participants. Overall, the participants in the study had a mean age of 77.6 (±8.9), were likely to be female (78.5%) and have Bachelor's degree or higher (86.1%). Phase 2 included four couples living together (n=8 married individuals) and the rest of the participants (n=29) in the study lived alone. The majority of participants in the study had one or more self-reported chronic conditions (89.2%) and took more than three medications (54%). About half of participants used some form of assistive devices (54.1%) such as a cane, a walker, or a wheelchair.

During baseline interviews, participants were asked to discuss their prior experience or knowledge of IoT smart home devices. Outside the description given during the recruitment session, most participants did not have prior experience of using smart home devices. However, some stated that they had heard about the concept of smart home and discussed seeing some TV commercials about such devices or had friends or adult children already using similar devices.

Table 8. Demographic description of study participants

	Phase 1 (n=15)	**Phase 2 (n=22)**	**Combined (n=37)**
Age (years), M ± SD	77.2 ± 11.1	77.8 ± 7.5	77.6 ± 8.9
Female, N	12 (80%)	17 (78%)	29 (78.4%)
Marital status, N			
Single	6 (40%)	2 (9.1%)	8 (21.6%)
Married/Partnered	0 (0%)	8 (36.4%)	8 (21.6%)
Divorced	2 (13.3%)	3 (13.6%)	5 (13.5%)
Widowed	7 (46.7%)	8 (36.4%)	15 (40.5%)
Other	0 (0%)	0 (0%)	0 (0%)
Chose Not to Answer	0 (0%)	1 (4.5%)	1 (2.7%)
Education, N			
< High school	0 (0%)	0 (0%)	0 (0%)
High school graduate or GED	1 (6.7%)	2 (9.5%)	3 (9.3%)
Some college	1 (6.7%)	1 (4.8%)	2 (5.5%)
Bachelor's degree	8 (53.3%)	8 (38.1%)	16 (44.4%)
Graduate or Professional degree	8 (33.3%)	10 (47.6%)	15 (41.7%)
Chronic conditions (self-report), N			
0	3 (20%)	1 (4.5%)	4 (10.8%)
1-3	7 (46.7%)	18 (81.8%)	25 (67.6%)
4+	5 (33.3%)	3 (13.6%)	8 (21.6%)
Current medications (self-report), N			
None	4 (26.7%)	2 (9.1%)	6 (16.2%)
1-2	2 (13.3%)	9 (40.9%)	11 (29.7%)
3-4	5 (33.3%)	4 (18.2%)	9 (24.3%)
5+	4 (26.7%)	7 (31.8%)	11 (29.7%)
Use of assistive devices, N			
Yes	10 (66.7%)	10 (45.5%)	20 (54.1%)
No	5 (33.3%)	12 (54.5%)	17 (45.9%)

3.4.2 *Themes*

The thematic analysis of the 105 interview transcripts (34 baseline, 35 midpoint, 36 exit visits) resulted in the following four themes: perceived benefits, preferred features, perceived concerns, and perceived need.

Theme 1: Perceived benefits

Subtheme 1: Maintain independence

A majority of participants in the study expressed a strong desire to be able to stay in their home for as long as they can and mentioned that they appreciate the technological help. "*I mean this kind of stuff is definitely an important part of medicine and healthcare. You need to do this kind of research- to develop equipment and devices to help. Especially elderly people in their homes. Since staying in your home I think is very important, to stay in your home as long as you can*." (p2p2).

Subtheme 1.1.1 Emergency preparedness

Participants in general had positive views of the potential benefits of having IoT smart home devices installed in their home to help maintain their independence. Even when they did not see immediate benefits for themselves, participants were able to see themselves in the future or identify with other older adults benefitting from the technology in several ways. First of all, participants expressed how they would get 'a peace of mind' if the devices were there to monitor their activity and alert for help in case of an emergency. Several participants shared past stories about some tragic events experienced by other older adults. *"Being a building with old people, we find people dead after sometimes two or three days*" (p1p13). *"I had a friend who has gone on, now, who fell in her bathroom and she said she had to crawl on her hands and knees 'cuz she broke a leg. It would be just wonderful to be able to just tell a machine to quickly call 9-1-1. I* *would think that's the most vital thing you could do."* (p2p4). One participant also shared her story of falling and blacking out in their home several years ago. "*Yeah, it could [give more independence] because I do have some health problems, and if you were monitoring my health and I had an incident like I have fallen once and blacked out a couple of years ago, that could have been picked up possibly*" (p2p2). The same participant stated that arranging emergency contacts in the building to receive alerts from the IoT smart home technology could be helpful in those situations. "*Yeah, they could get a message text which would say so-and-so has not been responsive, and it'd be prearranged, this person would know that this is part of the healthcare check. [Name] is not responsive, please check. They could come over and do it right away. Then, that person could also call additional resources*" (p2p2). Another participant stated how the technology could make the home environment safer and reduce anxiety for some older adults. "*Well, I think anyone who is old and perhaps frail is afraid of falling or any kind of hazard around the home … and anything we can come up with to make it both safer and more pleasant is a plus. Yes and [it] will also decrease anxiety"* (p2p15).

Subtheme 1.1.2 Accessibility

A few participants who were mobility impaired and required a wheelchair in their home expressed that IoT smart home devices could create a more accessible living environment for them. *"It will be good because—yeah, because, a lotta times, I read. I'm sitting there reading in bed, and I want to turn off the lights as soon as I fall asleep, but then I fall asleep, and they're still on. If there was some way that it could sense, "Hey, there's no motion in here. Let's turn off the lights,"(p1p6).* One participant expressed that home automation feature such as using a smart speaker to control the door would be helpful. "*Especially for [name of mobility challenged spouse], instead of—when somebody rings a doorbell, instead of him having to get up out of the* *chair and take the walker over there. It would be nice if he could tell Alexa to open the door or to ask who it is or something like that*" (p2p18). One participant explicitly commented that smart home devices can help preserve physical energy levels by providing such accessible features. *"Because I am in a wheelchair. It means getting up, braking, standing, doing—reaching over to things, sitting down, braking again. It involves a lot of activity, whereas—in a way getting up is good, but limited. I feel that using the smart home would be—would save a lot of energy"* (p2p11).

Subtheme 1.1.3 Memory aid

Some participants acknowledged that a smart speaker could help with memory decline of older adults and help them stay independent. *"I can see perhaps in the future having a need for even conversations about something or reminders … I can see where if you have problems with memory of having a conversion. One of my best friends, my very best friend, brilliant woman calls me constantly for the names of people how we associated with in our life. I wanna go in the closet and scream. It's so awful. If I could put that information in [the speaker] I think it would be very helpful. " (p2p1).* Other participants expressed how they could benefit by having a smart speaker assist them with their daily medication routine or keeping their medical schedule. *"Alexa could say, "Well, it's time for your morning pill, " or she could play some music for me. That would be my reminder—music, not an obtrusive alarm*" (p2p21) . "*Well, I know that if I miss medications, it doesn't do me good, so really need to be closely reminded so that there isn't an up and down in the effects of the medication*" (P2P3). *"Some people might even need a reminder on the day because I have a friend that went to the eye doctor the other day, and her appointment wasn't that day. It was the next day. She really could use something like that. She knows she has memory problems, so there's a lot of things that people with severe memory* *problems—it really could help"* (p2p22).

Subtheme 2: Utility of the 'generated' data

During the midpoint and exit visits, participants who selected a door/window sensor and a multi-sensor were presented with the display of their own sensor data collected in their home. Almost all but two participants seemed to agree that the display of their activity level data and environmental collected by the sensors accurately portrayed their average in-home activity patterns and home environment. These data were presented to older adults to help them think of ideas of how these 'generated' data could be useful for them. Similar to the previous themes, older adults foresaw the 'potential' utility of the generated smart home data. Some participants did not find the data to be useful enough in their current context for immediate adoption for themselves but discussed that the data could be more useful for those who are frail or have a medical problem that needs attention. Those who were comfortable with their health status did not find immediate usefulness.

Subtheme 1.2.1 Health management and monitoring

Some participants showed great interest in knowing their in-home activity level and discussed that having access to this smart home data can help them monitor their health status and manage their health. "*I think it will be very interesting when you come back and read them. Find out. I'm interested to know how much I actually move around*" (p1p13) Several participants mentioned that being aware of their objective activity level could help motivate them to improve their sedentary behaviors. "*I expect that I would be more aware of my activity, and I would try to be a little more active than before. … because sometimes I will sit in bed there reading a book, and sometimes I will sit as much as 10 hours just reading. It's not very good for the circulation if you stay immobile for so long*" (p1p6). "*Yeah, if I look on there and see that a day or two has gone* *by and I haven't gone out for my walk, an hour walk, then I'd be—I mean it's just a great way to track it….Then it would help me and I would pay attention to it.*" (p1p11) Several participants mentioned that they would like to receive an activity reminder from time-to-time to be more active. *"I think sometimes when we're not feeling too peppy or we're feeling depressed or down, we tend to hunker down in the apartment. Just a reminder that,* "*Hey, you're not getting outta here very much," might—I think might motivate us. I know it would motivate me to move around a little more. Even just in the building—just to get out. That is just very stimulating…." (p2p17).*

Subtheme 1.2.2 Sharing activity data with other stakeholders

Participants thought that the activity data could be shared with other stakeholder to generate additional benefits. One participant who were expected to receive a hip replacement treatment after the study mentioned that she wanted to share the activity data with her health care provider to help guide her recovery process. *"I would anticipate that my mobility is gonna greatly increase after I recover from that. That would be very useful. I could go to the doctor and say, "Hey, this is some real objective information…. This could definitely give some good information that they could then take to a healthcare provider. Same thing with me. I could tell my doctor, "Oh, it really shows that I've increased this much activity just around the house"* (p1p12). Another participant mentioned that she would like to share her sleep pattern data with her health coach because she has trouble keeping a sleep log. "*Yeah, I think it would be very helpful to them…rather than to rely on my memory….by sharing the information with the doctor and the health coach, then she can work with you to say, "Hey, you gotta go to bed earlier.*" (p1p15). Other participants mentioned that they would like to share the data with their family members to so that the family members can time-to-time check in their loved one's health status. "*Well, yes. Maybe for family members that would like to know more about what I'm doing. How*

I'm doing" (p2p16). "*In the future my health will eventually deteriorate. That would be a time that you might share this kind of information with your children*" (p2p15).

One participant noted that occasional discussion of health status with family members with the objective data collected through smart home devices can help older adults make important health transition. "*I can see the benefit of that, especially back to the fragile elderly. They're not quite ready to leave their home, but they're starting to notice mom's kinda slipping. … Well, it could be—yeah. Part of that can be an uncomfortable conversation, but if there have been conversations along, intermittently, before that about the [data] dashboard so that the older relative is already used to being aware that the daughter is watching, it may not be as uncomfortable as a cold call… rather than all of a sudden, "Dad, we're taking the keys away from you because you—we got reports about you."* (p1p9)

Theme 2: Preferred features

The theme 'preferred features' specifically covers the features of the IoT devices that the participants experienced during the study and perceived as desirable. Since a door/window sensor or a multi-sensor did not have a feature that participants can operate or interact with and not many chose an IP-camera, the features discussed here are pertaining to a smart speaker.

Subtheme 2.1 Convenience of a voice interface

The smart speakers are equipped with a far field microphone that supports voice recognition. Overall, participants found it easy and intuitive to operate and interact with the smart speaker's voice interface. Most participant did not experience problems executing basic voice commands such as setting up alarms or reminders and asking general questions. However, some people commented on learning to ask it the 'right' way to get an appropriate response. "*When it says, 'I do not have that information,' I can ask again in another way. I wasn't communicating properly* *to it. … I had to learn how to speak to it* (P2P1)”. Other participants mentioned that asking information to a speaker and retrieving the information in real time is convenient and useful compared to running search queries on a computer. “*It saved me a little time on—if I wanted a weather report before going out, or I wanted some anticipation of the next day, saved me from going to the computer.* (p2p21) *“ Well the thing is, I think of something and I can’t remember what it was, so I’ll go over there and I’ll turn on the computer, and wait for it to load, then by the time I get to Google, to ask the question, I’ve forgotten it. So I think that’ll be very useful, because when I have an idea, I can ask it.”* (p2p7). One participant commented on how voice interface and the traditional way of searching information on the web could compliment each other. *“Well, for one thing if I don’t know how to spell something but I know how to pronounce it— this [voice interface] is a lot better. I see them complimenting each other. On one I might get a more immediate response, but then I might wanna go more in-depth into the issue on the computer. I see them working together.”* (P2P17)

Subtheme 2.2 Setting up reminders

The most popular and desired feature of a smart speaker was a reminder function. Participants utilized the reminder feature to setup various reminders for daily routines such as picking up laundry or calling a friend. “*I use it a lot to remind me that it's time to go back and get the laundry cause it's a two-prong problem. First, it’s a half an hour, then it’s an hour, so it’s easy—one could get confused. That's been very handy*” (p2p1). One person expressed how she no longer keeps the hand-written reminder lists. “*‘Cause normally what I do, I make a list. I don’t know if you remember the apartment last time, there were tons of paper, piles of papers everywhere. I realized I was writing lists and throwing them in the pile. That wasn’t working. I* *have a whiteboard on the refrigerator and I find that I haven't been using it anymore. I just verbalize it*." (p2p7).

The most used health-related reminder feature related to medication use. One participant had been hospitalized in between the midpoint and exit visits. This participant reported that the reminder feature became handy for him when he had a new medication routine he had to follow after his discharge from the hospital. However, he noted that the basic reminder feature was not specifically designed for keeping complex medication routines, stating that he had challenges in setting up complex repetitive routine. "*Yes. It was the repetitive reminders that I couldn't get programmed. If the [reminder] feature, if that had more of a precise scheduling of every hour, daily… it would have been very useful*" (p2p3). There were several participants who purchased a smart speaker after the study because they became accustomed to using the reminder feature during the study. *"Well, I think we'd miss them….which is why I already bought one"* (P2P17).

Theme 3: Perceived concerns

In addition to the many perceived benefits of having IoT smart home devices, there were also significant concerns associated with their use.

Subtheme 3.1 Concern about privacy

At the beginning of the study most participants did not choose the IP camera which was included in the list of available IoT devices. When asked what prompted their decision, participants stated that they were concerned about potential privacy issues. Many said that the camera is too invasive and would make them uncomfortable in their own home. "*I would be very conscious of that. When I'm near it—I don't know if it's 360 degrees, when I'm near it, I might be cautious. There's certainly a sense of privacy that I feel invaded*." (p2p21). "*Privacy is an issue. I mean, you collect the data and it gets sent out somewhere, but you don't have control over it. In* *particular, like camera is a real issue— because there are reports of people hacking into such devices around the world and people are very paranoid"* (P2P5). Several participants mentioned that they will consider having a camera and giving access to a family member to monitor them only when they get much older and frail. "*Yes, probably, as I get older, if I become more infirm. I think about things like my son could check in on me—that kind of thing*"(p2p9). In contrast, most participants did not find a smart speaker to be invasive and were willing to use it in their home. However, there were a few participants who while noting the usefulness of a smart speaker expressed concerns it would be used to listen into private conversations. *"On the smartspeaker, well, I mean—if you want to save some sensitive information, I think it would be better to switch it off. You would assume that any device in your home would be monitored"* (p2p5). Some participants reported that they have no issues in using a smart speaker for its basic functionalities such as setting up alarms or reminders and asking general questions but did not want to use a smart speaker for sharing and receiving their personal medical information. *"Well, I guess that's where the privacy issue can come in. I guess I'd rather keep it the way I have it [using a computer]"* (P2P17). One participant expressed a concern about receiving unsolicited services through a smart speaker based on the user's health data. "*Seniors get enough unsolicited materials. I'm very – it bothers me very much about all the ads on television about drugs because I know it adds to the cost of the drugs. If the drug companies are paying to find out who might be interested in – that would bother me a lot"* (P2P12).

Participants in general did not regard a door/window and a multi-sensor to be invasive. Often, participants mentioned not caring or not noticing the devices after some time. "*Basically, once they were put, and ten minutes after you left, it was out of my mind. Every now and then I'd pass and look at it, but it really didn't affect me one way or the other. It's non-invasive. I didn't* *feel like it was invasive or anything*" (P1P12). Many were willing to share the presence of the devices among friends and family members visiting their home. Although the presence of a sensor itself was not much of a concern to many, some participants voiced their concern about the potential privacy risks related to their personal activity data being collected. "*I am kind of nervous about people knowing what my schedule is*"(P1P6). "*The whole notion of all this data being collected on everybody. I'm very uncomfortable with where we're going with that*" (P2P22).

Subtheme 3.2 Concern about reliability

Although only raised by a few participants, some did not agree that the smart home sensors were accurately capturing their in-home activity patterns. One participant expressed that the activity level data could be misrepresented by the presence of visitors coming in and out of the home. "*[It's] very inaccurate, because other people are in and out of the room, and there're various activities that change things*" (P1P2). Other participants questioned the accuracy of environmental data stating that it was off compared to their other devices. Some participants expressed dissatisfaction about the performance of a smart speaker stating that the speaker did not understand their questions correctly and failed to provide an answer or offered unrelated information. "*I didn't utilize it to the extent I thought I might. One reason, I think, is its limited database. It oftentimes would respond with no response*" (P2P3). "*Sometimes it said, "I don't have that information." I figured maybe I didn't ask it right or maybe there's a pre-set I have to do to get that information. I started asking it a lotta questions but she didn't have the answer to everything. That's the thing is I don't know why she didn't have it or what to do about it.*"(p2p21) One couple reported that they were having trouble shutting off the alarm. "*There were a couple of times when, for both of us, it didn't shut off when we said it correctly. There* *were times it just continued going*.” (p2p21) Several participants reported that the false alarm could be a huge concern. “*I suppose there could be false alarms. That could be something that, depending on how accurate and how sensitive the equipment was, it could register that there's either no movement when there was or there isn't—not pick up that there's no movement*” (p1p12). One participant also noted that factors such as lost Internet connection and the range of sensor devices can create system failure to respond to emergency. “*I think it may have trouble. I mean, it would make false alarms and make false calls to—again, it is again—it's not reliable enough. It depends on the Internet connection and other things like that. Also, its range is not very big. If somebody slips and falls in the bathroom, then you would not be able—I mean, how many—I don't know. What is the range of this thing?*” (p2p5)

Subtheme 3.3 Concern about affordability

When asked if they would like to use IoT smart home devices in the future, several participants raised issues related to the cost of an IoT smart home system as a barrier to its’ adoption. Participants discussed that the cost is a “big factor” saying that “*I think a lot of it would be dependent on cost, for seniors, because so many of us are on such a fixed income*” (P1P15). One participant expected that the technology would “*cost a fortune*” that they “*can’t afford the extra money*.” Several participants expressed that they are willing to make “*a one-time purchase of the devices*” but worried about possible monthly subscription fees to maintain the service or additional costs related to future upgrades to the software. “*I don’t know, because I don’t know what the cost of a service would be with these things. … If it’s a month-to-month additional service, I have to think about what that is*” (p2p9).

Theme 4: Perceived need

Based on their experience with IoT smart home devices for the duration of the study, the participants commented on what they expect from future smart home devices.

Subtheme 4.1 Access to data

For this study, the participants were not able to have access to their data real-time. The collected data were visually summarized and presented to participants at midpoint and exit visits to generate participants' insights into the value of the smart home data. Although participants found value in the periodic summary of activity data to be reviewed later, many participants expressed a desire to have real-time access to the data. When presented with an idea of an interactive website to view the data, many participants agreed that it would be useful for them. Some participants reported that they would want to view their activity pattern to guide their health management. "*Initially, it might be useful just to see my pattern. Right. To see if there was any major changes, especially with apnea incidents. Then, if I had a health crisis of some kind, it would be useful again because then I would want to see how I've regained my abilities and activity level and whatever else it records. Yeah*" (p2p2). Some participants wanted to share access to the website to their caregiver. "*That would be good to access this kind of information. Also for anybody responsible for taking care of me*" (p2p15). The desired frequency of access to a website varied among those who were interested in having access everyday out of curiosity upwards to every 6 months if there were no significant health changes.

Subtheme 4.2 Data monitoring service

For the scope of this study, the research team did not monitor the live stream data collected from the devices or provided automated real-time data monitoring service to the participants. However, as mentioned in the 'perceived benefits' theme, emergency preparedness was an important feature that older adults expected from a smart home system. "*but in a smart system,* *there would be some way of flagging the computer or the sensors that I'm in trouble*. [wouldn't it?]" (p1p9). Most participants acknowledged the importance of a real-time data monitoring service to analyze the data to detect abrupt changes or deviations from a normal pattern. "*Well, right now I'm fairly active, and so I think if my health was not as good as it is, and there were some sudden changes or something happened, then I think the monitoring would be very, very useful if there was a real change*" (p2p2). However, there were several participants who were living together with their spouses expressed that this type of monitoring service is more applicable for those living alone since they have their partner to check on each other. "*I might be [interested] in the future. Especially if, God forbid, I was living alone, but I'm not living alone, and so I don't feel it necessary*" (p2p17).

Subtheme 4.3 Devices that measure direct health impact

Participants were given four different IoT smart home devices to choose and evaluate from for this study. The devices were able to collect activity data, environmental data, and the video feed. Some participants suggested that they would benefit more from having smart medical devices that have direct health impact. A fall detection device was commonly mentioned by the participants as such an example: "*It might be beneficial to people if somebody knows they've collapsed on the floor right away. In a sense, if there is a system that could detect someone as fallen down.*" (p1p10) "In *case you fall down or something but they wouldn't know where I'll be, where I'll fall down cuz I'm so unpredictable. That way, they'll have instant contact and it'll always be monitored to some degree. So, perhaps that's the best kind of monitoring equipment*" (p1p7). Several participants noted smart devices that measure health indicators such as weight, blood pressure, glucose level, and cholesterol would be 'more helpful' to them and their health care providers. "*But, I can't see why he [health care provider] would care [about activity data]*.

He more cares about my blood pressure and the way my kidneys work and all that. He isn't asking me how many times I'm walking into my bedroom" (p1p2).

Subtheme 4.4 Connection with EHR/PHR

When asked, some participants expressed that they want the IoT smart home devices to be interconnected to their electronic health record or personal health record to easily log and retrieve their health information. For example, one participant discussed her trouble of keeping a paper record of medical information and bringing to a health care provider. This participant mentioned that it would be nice to be able to keep her medications list by "saying out loud my medication list". "*I have to write down all my medications during certain periods in the past, and it would be so nice to somehow have that information stored and just sent over so he can pick it up on the screen or something. It's very tedious writing that down…*" (p2p1). Another participant wanted a smart speaker to assist her logging of daily activity and diet information. *"I can ask Alexa to keep track of it, and I don't have to go turn my computer on and type stuff in. That's a pain in the butt….It would be nice if it could record, 'Went swimming ten laps' or 'Went to exercise, water exercise.' That kind of thing."* (p2p9). Some participants thought it would be *'handy'* to use a smart speaker to retrieve health information or receive a notification if their health record is updated by asking a smart speaker *'Do I have any new medical results?' … or it would be a good idea to remind you. 'Go check your e-medical—you have a new message, or you have a new blood result.'* (p2p20). One participant noted her concern for privacy for using a smart speaker for such purpose. *"But, then there's a big security concern. If you, I mean to access E-care, because it's got all these medical results in there."* The same participant stated that they would still use it out of convenience. "*Yeah. Because if it saves me the trouble of switching on my PC, connect internet and a login, I can't remember my password. I see, I mean* *if I can ask Alexa, tell me which is my next appointment at the medicine clinic and they can just look up… that would be quite useful*" (p2p5). Appointment scheduling with their care providers using a smart speaker was another commonly mentioned feature by the participants.

Subtheme 4.5 'Chat buddy' to relieve loneliness

After experiencing a smart speaker for this study, several older adults discussed the possibility of a future smart speaker to become 'intelligent enough' to be a 'chat buddy' to help older adults suffering from loneliness or social isolation. "*That should work out well because, if you're by yourself, you tend to become neurotic and stuff, but if you've got something that can provide a little music at some time—interactive discussions might be interesting*"(p2p3). Participants were open to the idea that a smart speaker would occasionally check in on those older adults and suggesting some activities. "*We have a lot of people that get lonely in their rooms. Somebody calling up and telling 'em a funny joke would be great. Or a story—a bit of the news, especially if it's exciting or good or bad or recommends on books to read*" (p2p20). Although one participant noted that such feature provided by a machine may not be appropriate. *"I don't think that's a job that you can give to a robot. I think that because if somebody is lonesome, what they need is people. I think the personal touch is really important, to have a neighbor knock on the door, or have somebody call. I think it needs to be a human being."* (p2p17)

Changes in the attitudes

Our interview protocol included similar items at different time points to identify potential changes in participants' perceptions. Overall, there were no substantive changes in the participants' perceptions on the previously discussed themes over various time points during the two-month study period. However, one participant who suffered from a fall-related injury in between the midpoint and exit visits had a change in her perception. She initially had a strong privacy concern for devices that record video or sound and did not see herself using such devices in the future. However, in her exit interview remarked that even though she still has the concern for privacy, her recent accident changed her mind to possibly using some devices in the future. "*Well, yes [it changed]. It's possible in the future that I will get over this paranoia, who knows, and use some of those devices, but not right now*" (p2p8).

3.5 Discussion

The concept of using an IoT technology to support health management of older adults is emerging as a potential tool to support aging. Unfortunately, little is known about how older adults perceive new IoT smart home technology. This 2-month feasibility testing in the real-world setting enriches current understanding of older adults' perceptions of IoT smart home devices.

Our data suggests older adults have favorable views toward IoT smart home technology and acknowledge that they may benefit from its use. However, many older adults did not feel the immediate need to adopt the smart home devices to support their health management as they were satisfied with their current health and health management routine. Similar to findings in previous research, most participants in this study seemed to assess benefits and the actual need for having the devices against potential infringement on privacy (George Demiris, Oliver, Giger, Skubic, & Rantz, 2009; Reeder, Chung, et al., 2013; Wild et al., 2008b). Aside from an IP-camera which can lead to severe privacy invasion, older adults were generally welcoming the IoT devices into their homes understanding their potential benefits in their health management. However, it is also important to note that some older adult population may not have a deep understanding about data security, control and ownership and may not be fully aware of where their data are stored, who owns the data, and how the data can be used and shared outside the original purpose. Clear communication about privacy practices and policies and even IoT data literacy education can foster trust and promote wider adoption.

Our findings indicate that those who regarded themselves limited in mobility and poor in health seemed to show a greater interest in the adoption of the technology barring cost issues. This is in alignment with some previous research which reported that older adults who thought they maintained good health show lack of perceived need for in-home sensors (Chung, Thompson, Joe, Hall, & sDemiris, 2017; Reeder et al., 2013) and that older adults who acknowledge being frail expressed a need for a telemonitoring device (Essén, 2008). Additionally, participants living together with their spouses expressed that this type of technology is more suited for those living alone since they have their spouses to check on each other. Future research could further investigate the relationship between older adults' health condition and living situation and technology adoption. This may help develop targeted adoption strategies based on older adults' living situations.

Additionally, the findings indicate that older adults have their own expectations on design of future IoT smart home devices to meet their health management needs. First, older adults expressed desire to access their data easily when they needed it. Older adults showed an interest in an interactive website to view their data and even share them with other stakeholders to guide their health management. We are not the first to report on older adults' willingness to access and share their data. Previous studies reported that older adults are interested in receiving data from sensor technologies that provide better insight into their health status (Lee & Dey, 2010; Reeder, Chung, et al., 2013). In addition to providing infrastructure for access to data, it is imperative that the data generated by the IoT devices presented in a comprehensible manner so that older adults themselves as an end user can easily interpret information about their health and activities of daily living. Future research and deployment of the IoT monitoring devices should include a medium for real-time access to data and investigate how it impacts older adults' acceptance and adoption of IoT smart monitoring devices as well as perceptions of other stakeholders (family, health care team).

Utilizing IoT smart home monitoring devices to respond to an emergency was an important feature identified by many older adults in the study. For this purpose, participants expected that a real-time data monitoring to be included with the devices. The advancement in data analytics present an opportunity to provide automatic real-time assessment of the health data. Such automated assessment will include prediction algorithms to identify potential patterns in health, detect anomalous activities, and prompt early intervention to prevent adverse health events. There have been numerous research studies to develop appropriate prediction algorithms that correctly model behavioral and physiological patterns of the residents in the home setting (X. H. B. Le, Di Mascolo, Gouin, & Noury, 2007; Li, Chen, Yang, Zhang, & Deen, 2017; Rashidi & Cook, 2013; Xu, Wang, Wei, Song, & Mao, 2016). Diverse methodological approaches are exploited ranging from traditional machine learning techniques such as support vector machine (SVM) and K-Nearest Neighbors (KNN) to more recent deep-learning approach. The older adult participants expressed desire for such monitoring service to make automated contacts to 9-1-1, the community staff, or family and friends in case of emergency. However, practical challenges such as reliability of the service and potential false alarms must be addressed to implement data monitoring services with high precision. Finding the acceptable thresholds for specificity and sensitivity of the smart monitoring system is critically important to capture the emergency while minimizing the false alarms. Follow-up studies that involve system designers, emergency department representatives, and facility administrators could further the development of such services.

Older adults in the study also wanted to see future IoT systems that would facilitate measurement of health indicators such as glucose level or blood pressure. The need for specific monitoring needs was also reported by prior research conducted by Wild et al. (Wild, Boise, Lundell, & Foucek, 2008a). In their focus groups, older adults placed higher value on disease -specific measures compared to the non-medical measures such as general activity level. Additionally, the expectation for broader interconnection of services were expected to be included in the future IoT smart home system. For example, older adults desired smart home devices to be able to connect to their medical record to both log and retrieve data as well as provide more personalized services. A convenience of a voice-interface provided by a smart speaker seemed to also facilitate this desire by older adults. Some older adults welcomed the idea of using a smart speaker to log and retrieve their health information. On the other hand, some explicitly stated that they would not want to use a smart speaker to handle their personal health data out of privacy concerns. Future research should further investigate the interconnected functionalities IoT smart home devices and determine what solutions best fit with older adult's health management need.

Limitations

Limitations of the study include a relatively small sample of participants, who were racially homogenous, having a higher level of educational attainment than the general US population of adults 65 years of age and older. Thus, the perceptions of IoT smart home devices may not generalize to larger populations of older adults in other regions of the world. Additionally, the two-month pilot deployment period may not have been enough to understand the changes of perceptions and adoption behaviors over the long term. Finally, we only offered four different IoT smart home devices for older adults to choose for this pilot study. The participants' opinions might have been different if additional types of devices were available to evaluate.

3.6 Conclusions

The IoT smart home devices have a significant potential to help older adult's healthy aging-in - place. Our study is among the first to assess older adults' perceptions of different IoT smart home devices through a real-word deploying in older adults' residences. In addition, to our knowledge, our study attempted to explore the use of smart speakers in a health context with an older adult population. The findings of this study provide directions to follow-up assessment of IoT technologies and their impact on health-related outcomes and inform the design of future systems that meet older adults' unique needs.

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3.8 APPENDIX A FOR CHAPTER 3

Semi-Structured Interview Guide (Baseline)

- We would like to first hear about your general thoughts on sensor technologies. Prior to this study, have you been introduced to smart home devices before?
    - What are some examples of smart home devices that you have seen or heard of?
    - What did you think about those devices? What did you like or dislike about them?
- How do you think smart home devices might play a role within your residence, if at all?
    - Would you have any concerns with having smart home devices within your home?
    - What are some benefits that you might find in having smart home devices within the home?
    - What are some drawbacks that you might have with having smart home devices in the home?
    - What are your thoughts on the potential intrusion of smart home devices within the home?
- How might you use the information generated from smart home sensors?
    - What types of information would you be willing to share with others?
    - Who would you share this information with?
- Is there anything you currently do to keep track of your health?
    - What do you do with that information?
- Of all the things that we have discussed, what to you is the most important?
    - Is there anything else that you would like to add regarding smart home devices ?

Semi-Structured Interview Guide (Midpoint)

1. Here we have created a few rough sketches of data generated from sensors within your home. (Explain the graphs). What are your thoughts on the graphs shown?
    a. What do you find interesting about the displays?
    b. What do you find confusing about the displays?
    c. How accurate are the displays a reflection of your activity and well-being?
    d. Are they helpful in anyways?
    e. How might you use these displays, if at all?
    f. How frequently would you look at this information?
2. What information would you like as feedback on the visual display?
3. What suggestions would you have for improving the displays?
4. Are there alternative ways in which you would like the sensor information to be presented?
5. Would this information be useful to share with others? With whom would you share the information?
6. Do you have any further comments to make about the sensor data and the graphs?
7. Conclusion
    a. Thank the participant for the time, give a gift card and adjourn the interview.

Semi-Structured Interview Guide (Exit)

- Physical dimension
    - Did you become dependent on the device?
    - If yes: What features or aspects of the device did you rely on?
    - If no: What features or aspects of the device did you not like?

- Privacy
    - How do you feel the device keeps your information private or not private (i.e., passwords, permission to share information with who and what information to share)?
    - How did the device interfere with your home environment or personal space?
- Function
    - What types of issues did you experience when wearing or interacting with the device?
    - What types of functions did you expect the device to do?
    - What needs did the device meet or not meet?
- Human Interaction
    - How did the device impact your interactions with others (i.e., family and friends, healthcare providers, caregivers etc.)
- Self-concept
    - How did the device influence your independence (i.e., give you more independence or less)?
- Routine
    - How did the device impact your daily routine?
- Sustainability
    - How do you see yourself using the device in the future? (i.e., cost, usefulness)
- Would you continue using it? Why or why not?

Chapter 4. OBTRUSIVENESS OF IOT-SMART HOME TECHNOLOGIES AS PERCEIVED BY OLDER ADULTS IN RESIDENTIAL SETTING

4.1 ABSTRACT

Objective: The development of non-obtrusive technologies is important to increase adoption of technological solutions to support healthy aging. The purpose of this study was to apply a previously-tested obtrusiveness framework to analyze older adults' perceptions of numerous Internet-of-Things (IoT) smart home devices that were implemented in residential settings as part of a real-world feasibility study.

Participants: A total of 37 community-dwelling older adults residing in the Pacific Northwest enrolled in the 2-month feasibility study. Participants chose among different IoT devices to be installed and deployed within their homes. One participant withdrew, leaving 36 who completed all procedures.

Methods: We performed thematic analysis of exit interviews using a codebook developed based on a previously-tested obtrusiveness framework.

Results: We found that interview data contained examples of each dimension (physical, usability, privacy, function, human interaction, self-concept, routine, and sustainability) and 12 of the 22 subcategories proposed by the obtrusiveness framework. The findings highlight the importance of privacy and perceived usefulness for adoption of IoT smart home technology by older adults.

Conclusion: As smart home technologies advance and new IoT tools emerge, it is important to assess the users' perceptions of technology obtrusiveness appropriate for IoT context which will determine successful adoption of the technology.

Keywords: Internet-of-Things, smart home, older adults, aging, obtrusiveness

4.2 INTRODUCTION

4.2.1 *Internet of Things smart home technology and aging*

The older adult population is a rapidly growing demographic group worldwide. With the increase in the aging population, developing innovative ways to promote healthy aging of older adults and helping them maintain independent living in their own homes are important focus areas. To this end, many initiatives are exploring the use of "smart home" technologies for older adults, including those that can support health monitoring in their residence to support aging in their own homes. Recent advancements in the Internet of Things (IoT) technology, defined as the network of everyday objects equipped with internet connectivity that facilitates interconnectedness, has broadened the possibility of smart homes. An IoT smart home system has the potential to automate processes of care and enhance remote monitoring and provide more intelligent care services to a resident. For example, activity pattern data gathered through IoT sensors can be analyzed to detect unexpected events such as falls and slips. Furthermore, an artificial intelligence (AI)-based voice operated smart speaker can routinely check in on a recently discharged patient to follow up and improve medication adherence. Such IoT "smart" residences equipped with connected devices and sensor technologies could support independent aging of the older adults by identifying potential patterns in health, detecting anomalous activities, and prompting early intervention to prevent adverse health events resulting from decreasing activity levels. Additionally, a recent development of artificial intelligence (AI)-based voice assistant smart speakers may provide an easier interface to operate an IoT system. Despite the potential for helping older adults, the adoption and usage of IoT smart home products among older adults is low. Previous research has documented technology adoption barriers as wells as unique challenges associated with older adults' technology adoption and use. Factors such as complexity of technological devices, technology anxiety and lack of experience has been pointed out as a barrier to adoption by a number of studies (Czaja et al., 2006; Heinz et al., 2013; Mitzner et al., 2010; Steele, Lo, Secombe, & Wong, 2009). In addition, older adults are less inclined to adopt new methods when they believe older methods work for them (Akatsu, 2004). The stigma associated with aging and dependency is another important barrier identified by previous research (Gooberman-Hill & Ebrahim, 2007). Even when older adults wanted assistive technologies to help them live independently, some were reluctant or outright rejected some health monitoring devices because they thought others would perceive them as frail and having limited autonomy in need of special assistance (George Demiris et al., 2004; Steele et al., 2009). Therefore, design of IoT smart home devices intended for use by older adults to support their health management must give special consideration into the unique challenges of older adults in relation to the adoption and use. Unfortunately, little research has been done to understand older adult's perceptions in the context of IoT smart home technology and this study was conducted to address this gap.

4.2.2 *Obtrusiveness Framework*

IoT Smart home devices could bring forward unique privacy and obtrusiveness concerns to older adults. Therefore, it is important to understand the unique concerns of older adults and design appropriate IoT smart home systems that minimize their obtrusiveness to end users (Hensel et al., 2006a; Rialle, Duchene, Noury, Bajolle, & Demongeot, 2002). Hensel et al. defined obtrusiveness in home-based monitoring technologies as "a summary evaluation by the user based on characteristics or effects associated with the technology that are perceived as undesirable and physically and/or psychologically prominent." (Hensel et al., 2006a) (p. 430)

Within this definition, there are four underlying assumptions. First, obtrusiveness is a summary evaluation. This evaluation may be based on the cumulative obtrusiveness of a number of characteristics or effects associated with the technology or on a single characteristic or effect that is especially important or prominent to the user. Second, the obtrusiveness of a given technology is subjectively assigned by each user. Technology that one person perceives as obtrusive may not be perceived as such by another. Third, “user” refers to not only the older adult, but also any other resident in the home. Fourth, there is a different psychological dynamic operating in the home environment than in an institutional facility. With these underlying assumptions, Hensel et al. developed a conceptual framework of obtrusiveness that includes eight dimensions, namely physical dimension, usability, privacy, function, human interaction, self-concept, routine, and sustainability (Hensel et al., 2006a). **Figure 1** summarizes these 8 dimensions and the 22 subcategories of the obtrusiveness framework. This framework has been validated in follow-up work by the authors and other investigators (J. Chung, Demiris, & Thompson, 2016; Courtney, Demiris, & Hensel, 2007; KL & Courtney, 2006; Meulendijk, Van De Wijngaert, Brinkkemper, & Leenstra, 2011; Reeder et al., 2016).

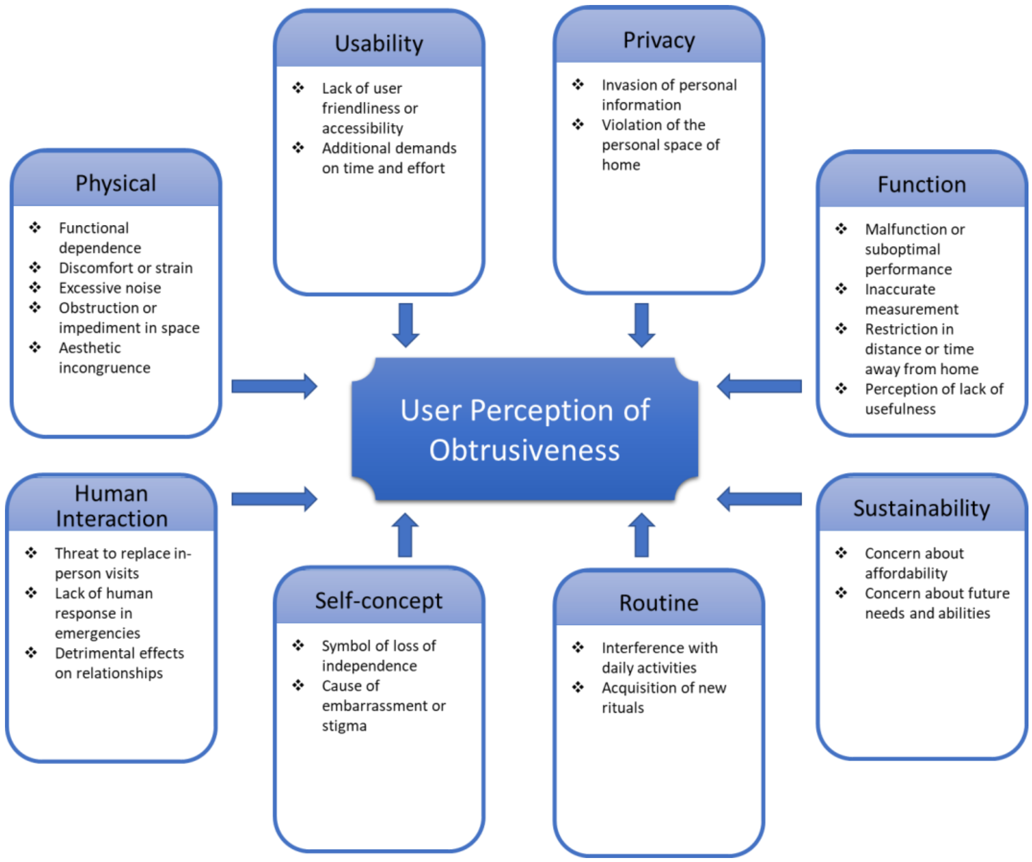

Figure 1. Obtrusiveness Framework

Courtney et al. conducted a secondary analysis to explore the presence of the dimensions of the obtrusiveness framework on the older adults' responses to information-based assistive technologies in two residential care facilities. (Courtney et al., 2007) Similarly, Reeder et al. validated the framework with community-dwelling older adults regarding the obtrusiveness of in-home activity monitoring sensors installed in their residences.(Reeder et al., 2016) Building upon the previous work, this study explored older adults' perceptions of obtrusiveness of new smart home interconnected solutions using a different set of commercially available IoT smart home devices, and examined if the dimensions and sub-categories of the obtrusiveness framework were represented in older adult's responses collected at exit interviews of an IoT feasibility study.

4.3 Methods

4.3.1 *Study Design*

This study was a secondary analysis of interview data collected as a part of two-month feasibility study to investigate the use of IoT smart home devices in real-world residential settings of older adults. The study participants were recruited from retirement communities in the Pacific Northwest. Recruitment occurred in two different phases in this study. For Phase 1, inclusion criteria required participants to be living alone; a voice-operated smart speaker was not one of the available IoT devices in this phase. For Phase 2, a voice-operated smart speaker was made available and inclusion criteria were changed to include interested couples who live together to join the study together. Otherwise, the recruitment process and the study procedures remained the same between two phases.

To be eligible for the study, participants needed to be 65 years of age or older, be able to give informed consent, be able to read and write English, and have Internet connection at their residence. Once enrolled, participants were allowed to choose which different IoT smart home devices would be installed in their homes for the 2-month study period. The IoT devices included a door/window sensor, a multi-purpose sensor, a voice-operated smart speaker, and an IP-video camera. The function and activity of each device was explained to the participants during recruitment information sessions.

4.3.2 *IoT smart home devices*

Four different IoT smart home devices were made available for the participants to choose from. A door/window sensor records a binary on/off signal when the magnetic switch is activated. The multi-purpose sensor collects data on motion, temperature, luminosity, and humidity. The smart speakers are equipped with a far field microphone that supports voice recognition. This allows for various hands-free operations including playing music, retrieving information, and setting reminders and alarms. An IP video camera allows for synchronous monitoring of a room or other area in the home by the participants. The research team did not monitor the live feed from the camera but the participants could choose to share the access to the camera with someone in their life by sharing the web address of the secured camera dashboard and accompanying id and password.

Participants were interviewed at three different time points: baseline, 1-month, and 2-month to understand older adults' attitudes, needs, and preferences, and perceived level of obtrusiveness of an IoT smart sensor system. All interviews were recorded with a digital audio recorder. A full description of the study protocol, semi-structured interview guides, instruments administered and data collection schedule for each instrument is available in "Chapter 2". The study procedure was reviewed and approved by the University of Washington Institutional Review Board.

4.3.3 *Data Analysis*

A theory-driven qualitative analysis was conducted on the exit interview transcripts. The coding template was based on the existing obtrusiveness framework (Hensel et al., 2006b). Exit interview transcripts were specifically chosen because part of the interview protocol was informed by the obtrusiveness framework. A version of this coding template has been previously used to analyze interview data of older adults living in residential care communities and community-dwelling older adults regarding information-based assistive technologies and in-home sensors (Courtney et al., 2007; Reeder et al., 2016).

All exit interviews (n=36) were transcribed using a professional transcription service. Fifty percent (n=18; phase1 n=7, phase2 n=11) of the exit interviews evenly proportionate across two different phases were randomly chosen and independently coded by two research team members (YC and SL). Disagreements were reconciled through discussion during in-person meetings of coders until consensus was reached about application of codes. We independently coded 18 transcripts to meet the recommendation of 6-12 interview transcripts to reach saturation following Guest et al.'s publication (Guest et al., 2006). The rest of the exit interview transcripts (n=18) were coded by the primary investigator (YC) for validation after the consensus conference and the final results were summarized by the primary investigator.

4.4 RESULTS

The study enrolled a total of 37 older adults including 15 participants in Phase 1 and 22 participants in Phase 2. Among the participants, only one participant withdrew participation before completing the exit visit. Therefore, total 36 exit interviews were conducted. Participants in the study had a mean age of 77.6 (SD 8.9), were more likely to be female (78.5%) and have Bachelor's degree or higher (86.1%). Four couples living together (n=8 individuals) enrolled in the study jointly in Phase 2 and the rest of the study participants (n=29) lived alone. The most frequently selected combinations of IoT devices by the participants for Phase 1 was Door/window + Multi-sensor (60%). For phase 2, with addition of a smart speaker in the available devices to choose from, the majority of the participants chose the combination of Door/Window + Multi-sensor + Smart speaker (50%). An IP camera was significantly less desired choice among participants in both phases (Phase 1: 13.3%, Phase 2: 13.6%) due to expressed privacy concerns.

Table 9 shows the dimensions and subcategories of the obtrusiveness framework that were represented in the exit interviews among Phase 1 and Phase 2 participants. The check marks under the ‘presence’ of obtrusiveness represent cases where participant explicitly indicated the dimension or subcategory was a concern. The check marks under the ‘absence’ of obtrusiveness indicate the dimension or subcategory was explicitly stated as no concern by the participants. Overall, the results were similar among the two group of participants and minor differences were noted. The obtrusiveness concerns related to Functional dependence, Aesthetic incongruence, Lack of user friendliness, Lack of human response in emergencies, and Acquisition of new rituals were only represented in Phase 2 group. Additionally, the concerns related to the subcategory Inaccurate measurement was only represented in Phase 1 group.

Table 9. Representation of presence and absence of obtrusiveness dimensions and subcategories at 2-month exit interview among Phase 1 and Phase 2 participants

		Phase 1		**Phase 2**	
Dimension	**Subcategory**	**Presence of obtrusiveness**	**Absence of obtrusiveness**	**Presence of obtrusiveness**	**Absence of obtrusiveness**
Physical	Functional dependence	N/R	(✓)	(✓)	(✓)
	Discomfort or strain	N/R	N/R	N/R	N/R
	Excessive noise	N/A	N/A	N/A	N/A
	Obstruction or spatial impediment	(✓)	(✓)	(✓)	(✓)
	Aesthetic incongruence	N/R	(✓)	(✓)	(✓)
Usability	Lack of user friendliness or accessibility	N/R	(✓)	(✓)	(✓)
	Additional demands on time and effort	N/R	N/R	N/R	N/R
Privacy	Invasion of personal information	(✓)	(✓)	(✓)	(✓)
	Violation of the personal space of the home	(✓)	(✓)	(✓)	(✓)
Function	Malfunction or sub-optimal performance	(✓)	N/R	(✓)	N/R
	Inaccurate measurement	(✓)	(✓)	N/R	(✓)
	Restriction in distance or time away from home	(✓)	N/R	(✓)	N/R
	Perception of lack of usefulness	(✓)	N/R	(✓)	N/R
Human Interaction	Threat to replace in-person visits	N/A	N/A	N/A	N/A

	Lack of human response in emergencies	N/R	N/R	N/R	(✓)
	Detrimental effects on relationships	N/R	(✓)	N/R	(✓)
Self-concept	Symbol of loss of independence	N/R	(✓)	N/R	(✓)
	Cause of embarrassment or stigma	N/R	N/R	N/R	N/R
Routine	Interference with daily activities	N/R	(✓)	N/R	(✓)
	Acquisition of new rituals	N/R	(✓)	(✓)	(✓)
Sustainability	Concern about affordability	(✓)	(✓)	(✓)	(✓)
	Concern about future needs and abilities	N/R	N/R	N/R	N/R

N/R: Not Represented in the data, N/A: Not Applicable in the study

4.4.1 *Physical Dimension*

Participants in the study in general did not find the IoT smart home devices installed in their home to be physically obtrusive. Often, participants mentioned not caring or not noticing the devices after some time. "*Basically, once they were put, and ten minutes after you left, it was out of my mind. Every now and then I'd pass and look at it, but it really didn't affect me one way or the other. It's non-invasive. I didn't feel like it was invasive or anything*" (P1P12). A small number of participants noted that they did not like the shape or look of the device and mentioned it was aesthetically incongruent to their residence as illustrated by the following quote. "*I would prefer a more attractive piece of equipment, something that almost look like it belonged on a table… Maybe look like a candle holder, or something like that, something aesthetically prettier*" (P2P12). Functional dependence was not a concern for most participants. This may be because many joined the study out of curiosity as they wanted to know about smart home devices, and not necessarily out of the need. A few participants who chose and experienced a smart speaker mentioned that they became accustomed to using the speaker to set up reminders and alarms that they decided to purchase one for themselves. "*Well, I think we'd miss them. Yeah, I think we would, which is why I already bought one*" (P2P17). Interestingly, though not something need any time soon, most participants expressed that they might rely on the smart home devices in the future when their physical and cognitive health declines. "*I hope I don't need it. … If I become impaired physically or in some way cognitively, especially if I'm alone, yeah, then I could see a use for it*" (P2P21). Some participants mentioned that family caregivers might become dependent more so then themselves. *"I don't know what use I would have for them. I know my activity. I think it would be more of use to family members, if you were monitoring someone's isolation, those kinds of things"* (P2P8). *"Well, I see some usefulness down the line. yes. probably more for others than for me. Maybe for family members that would like to know more about what I'm doing. How I'm doing"*(P2P16). Physical discomfort or strain and excessive noise was not represented in this dimension.

4.4.2 *Usability Dimension*

The usability dimension is applicable to only those who used a smart speaker and an IP camera because participants did not interact or operate a door/window sensor or a multi-sensor after they were installed and therefore, did not have a "user experience" operating these sensors. Since only a few participants chose an IP camera, usability comments were mainly about the smart speaker. Overall, participants found it easy to operate and interact with the smart speaker by giving basic voice commands such as setting up alarms or reminders and asking general questions. However, some people commented learning to ask it the 'right' way to get an appropriate response. "*When* *it says, 'I do not have that information,' I can ask again in another way. I wasn't communicating properly to it. ... I had to learn how to speak to it* (P2P1)".

4.4.3 *Privacy Dimension*

Overall, mixed opinions emerged in participant's responses that represented both the presence and the absence of the subcategories 'Invasion of personal information" and "Violation of the personal space of the home" in the privacy dimension. Some participants voiced their concern about the potential privacy risks related to their personal activity data being collected. "*I am kind of nervous about people knowing what my schedule is*"(P1P6). "*The whole notion of all this data being collected on everybody. I'm very uncomfortable with where we're going with that*" (P2P22). On the other hand, some did not regard it as much of a privacy issue. "*I'm not concerned about anybody finding out how much I'm moving around my apartment. I mean that's just not a big privacy issue for me.*" (P2P17).

The majority of the participants commented that an IP camera is too invasive to have at their home saying that "*We don't want a Big Brother eye here*" (P2P21). "*Camera is an issue because we're not always dressed. To put it very bluntly and—I don't know. It's a little creepy*" (P2P17). Even though many expressed that the camera poses a great privacy risk, some described that they would be willing to accept it in their home if they became more frail in the future. "*You get to a certain point where—do you wanna be by yourself and live alone or do you wanna be private? You kinda have to weigh it. If you go to an assisted living, you're not gonna be private anyway. Yeah, as long as you trust the people that have it, I have no problems with that in the future*" (P1P12).

Overall, participants did not find a smart speaker to be invasive when using it for basic uses such as setting up reminders and retrieving general information. and were willing to use it in their home. However, when prompted whether they would want to use a smart speaker for sharing and receiving their personal health information, some showed an elevated level of concern. "*Well, I guess that's where the privacy issue can come in. I guess I'd rather keep it the way I have it* [using a computer]" (P2P17). One even worried about receiving unsolicited services through a smart speaker based on user medical data. "*Seniors get enough unsolicited materials. I'm very – it bothers me very much about all the ads on television about drugs because I know it adds to the cost of the drugs. If the drug companies are paying to find out who might be interested in – that would bother me a lot*" (P2P12). Some participants saw the benefits of a smart speaker but did not want to have one at home worrying that it could listen into private conversation. "*Well, I think those devices are great, to be able to talk to them, get answers to questions, and things like that. It's just I'm too paranoid to have one in my house. I can see a lot of uses for it. I'm just too paranoid to have one....I don't trust that when you turn it off, it turns off. It's bad enough they can hear everything we do on our phones"* (P2P8).

4.4.4 *Function Dimension*

Almost all participants seemed to agree that the display of their activity level data accurately portrayed their average in-home activity patterns. There were few cases where participants did not agree that the sensors were accurately capturing their in-home activity patterns. One participant expressed doubts about the sensor accuracy and worried that the activity level data could be misrepresented by the presence of visitors coming in and out of the home. "*[It's] very inaccurate, because other people are in and out of the room, and there're various activities that change things*" (P1P2). For some participants, the accuracy of environmental data was a problem. "*Gosh, that's so much colder than my temperature shows*" (P1P13). Some participants noted suboptimal performance of a smart speaker stating that the speaker did not understand their questions correctly and did not provide an answer or offered unrelated information. "*I didn't utilize it to the extent I thought I might. One reason, I think, is its limited database. It oftentimes would respond with no response*" (P2P3). The subcategory 'Perceived lack of usefulness' category generated numerous coded responses. Overall, the participants did not find the smart home technologies to be useful enough for immediate adoption for themselves. Participants thought that activity level data could be more useful for those who are frail or have a medical problem that needs attention. Those who were comfortable with their health status did not find much usefulness. "*Again, I'm not nearly as – ill is the wrong word, but I don't have as many ailments as everybody else. It means I don't need this as much as, maybe, somebody else does*" (P2P12). "*Not to me personally, but I feel that the ability to detect sleep patterns and all through this type of monitoring could be helpful to someone who needed assistance sleeping."* (P1P3). However, many participants expressed that they see the potential of the technology and the usefulness of activity monitoring in the future when their health may decline. "*As I get older, I think there will be more value in that. I mean right now, I'm just active all the time. As I get older I want to be sure that I'm still active. That's where that would come in. I would want one of those in every room. If I look on there and see that a day or two has gone by and I haven't gone out for my walk, an hour walk, then I'd be—I mean it's just a great way to track it. I could track it another way too, but I don't."* (P1P11). Some people noted that the activity level data are more useful to their family caregivers or heath care providers than themselves. "*Well, I don't know what use I would have for them. I know my activity. I think it would be more of use to family members, if you were monitoring someone's isolation, those kinds of things, but for me personally—I don't like people knowing my business to begin with*" (P2P8). One participant mentioned the benefit of using a smart speaker to setup detailed medication reminders to adhere to new medication routine after hospitalization. "*Oh, it would have been very useful. That medication reminder feature, if that had more of a precise scheduling of every hour, daily.*" (P2P3).

4.4.5 *Human Interaction Dimension*

The technology used in the main feasibility study did not provide real-time monitoring of data. When participants were asked about potential continuous data monitoring of activity level data, some acknowledged that such service could be helpful in taking preventive measures in case of an emergency. "*If they noticed a sudden drop off in activity that might be a cue to them to check and see what's going on*" (P2P17). Participants indicated that the use of smart home technologies did not have a detrimental effect on relationships and interactions with friends or family members. Some noted that their family members might be interested in the activity level information and several participants indicated that they have shared their experience with family members and friends visiting their home.

4.4.6 *Self-concept Dimension*

Participants did not perceive using smart home devices to be a symbolic loss of their independence. On the contrary, some participants described how the devices can potentially empower older adults to be more independent and help stay healthy in their homes. One participant mentioned how activity monitoring by the sensor devices could help older adults with sedentary behavior. "*Yeah. It would increase your independence, I think, if the motion detectors told you that you weren't doing anything…* [it] *would be a great comfort to people*." (P2P4). One participant described how using a smart speaker as a memory aid made her feel more independent. "*[I feel] more independent because I don't have to rely on anyone else to remember anything*" (P2P1).

4.4.7 *Routine Dimension*

Overall, participants did not feel that having the smart home devices changed their daily routine. Some participants who tested a smart speaker expressed developing a new habit of using it daily to benefit them. One participant mentioned asking for the current weather information every time she went out to wear appropriate clothing for the weather. "*it[weather] was more accurate than the newspaper. I'm always conscious of that in terms of what I will wear*." (P2P11). Another participant discussed how she have gotten used to using the speaker to set reminders for her daily routines. "*I did mostly timing with her[smart speaker]. Timing everything. Timing the wash, timing my pills, timing my programs, timing when I have to leave here. It's been great*." (P1P15).

4.4.8 *Sustainability Dimension*

Issues related to affordability were raised by several participants when asked about having their own smart home devices as illustrated by the following quote. "*I think a lot of it would be dependent on cost, for seniors, because so many of us are on such a fixed income*" (P1P15). Another participant was okay with making a one-time purchase of the devices but worried about possible monthly subscription fees to maintain the service. "*I don't know, because I don't know what the cost of a service would be with these things. … If it's a month-to-month additional service, I have to think about what that is*" (P2P9). For many others, sustainability was not their concern as they did not see the immediate need for smart home technology with their current health status and living situation. "*Well not in my current state of health. Maybe if I had some medical needs and stuff and I needed to keep track for the most optimal health wise for my* *wellbeing*" (P1P7). "*For my particular needs, and my situation in a small, confined apartment, and healthy for my age, it's not something I would benefit from as much as others may*" (P1P8). The subcategory "Concern about future needs and abilities" were not represented.

4.5 Discussion

This study examined the dimensions of the obtrusiveness framework with older adults who participated in a real-world feasibility testing of IoT smart home devices. In contrast to the previous study that validated the obtrusiveness framework with a single type in-home motion sensor (Reeder et al., 2016), our study tested several different types of commercially available IoT smart home devices including motion sensor devices, an environmental sensor, an IP camera, and a voice-operated smart speaker. Although the IoT smart home devices used in the study do not fully represent the full variety of devices in the growing IoT smart home market, the inclusion of several different types of devices widen our understanding of older adults' perception of obtrusiveness of IoT smart home technology and provide insights into assessing obtrusiveness of such technology.

First, a varying degree of obtrusiveness concerns based on the type of devices were apparent especially in the 'Privacy' (Invasion of personal information) and 'Function' (lack of usefulness) dimension of the framework. As an example, most participants did not choose an IP-camera at the beginning of the study as they were intimidated by potential privacy concerns related to the sensitivity of the data it collects. In contrast, older adults preferred devices which in their understanding collected 'insensitive' data. Our findings suggest that there are mixed opinions on the notion of 'sensitivity' of data. Some expressed that they were completely free of privacy concerns because they did not care about somebody knowing their in-home activity data, whereas others voiced a strong concern about how the data can potentially be misused or wrongfully used against them. The diversity in opinions may be impacted by previous experience with the technology and/or preexisting idea of the technology as suggested by the Golant's model of elderly consumers' smart technology adoption behaviors (Golant, 2017). Our findings also suggest that the 'usefulness' of the data the device collect is an important factor to older adults' privacy concerns. The privacy concerns were mitigated if older adults deemed the data collected is valuable information for maintaining their health and independence. This is similar to past studies that documented the older adults' privacy concerns are weighed against the perceived need and benefits (George Demiris et al., 2009; Reeder, Chung, et al., 2013; Wild et al., 2008b).

Secondly, future investigators must consider the interconnected functionalities when assessing the perception of obtrusiveness of IoT smart home devices. IoT devices are different from traditional in-home health monitoring technology in that each of the devices are Internet-enabled and able to transmit and aggregate data in a central repository in real-time to provide more intelligent services. As an example, a data monitoring app installed in a smart speaker can monitor the activity data recorded by motion sensors in real time and check in with and request a voice response from older adults if an abnormal activity pattern is detected. It can also be programmed to send a notification to emergency contacts if there is no movement detected for a predetermined period of time. In the era of IoT, the functionalities of a device are not tied to a single device alone and therefore assessment of obtrusiveness must consider this composite nature of services provided by multiple devices.

Finally, multiple roles of IoT smart home technology must be considered when understanding the perception of obtrusiveness. Hensel et al.'s conceptual framework of obtrusiveness of smart home technology was created considering technology primarily used in a clinical context or solely for health related purposes. However, commercial IoT smart home systems are designed to serve multiple purposes including home automation, home safety, and entertainment in addition to its use in the health context. Although we initiated this study to primarily understand older adults' perception of IoT smart home technology used in a health context, it is unlikely that the future users of the technology will only use it for that purpose. Our data also suggest that different roles of the technology provoke different levels of obtrusiveness concerns. For example, almost all participants who chose a smart speaker liked the convenience of a voice interface and expressed satisfaction when using it for entertainment such as playing music and asking practical questions such as weather information. However, the participants noted elevated privacy concerns when using a smart speaker for health purposes such as recording and sharing their personal medical information. This confirms the importance of assessing obtrusiveness concerning technology use and adoption based on different roles of the technology. Future work to assess obtrusiveness of IoT smart home devices should consider expanding the existing Hensel et al.'s framework to capture differing levels of obtrusiveness based on their uses in a non-health context such as entertainment and home safety as well as their uses in the health context.

4.6 CONCLUSION

Overall, the dimensions and subcategories of the conceptual framework for obtrusiveness were represented in older adults' interview data collected for an IoT smart home feasibility study. However, in analyzing our data, it became evident that the conceptual framework to measure obtrusiveness of smart home technology may need to be re-examined to include multiple contexts and roles in which the technology is used in addition to the health purposes to more appropriately assess perceptions of obtrusiveness of IoT smart home interconnected solutions, Such holistic assessment of obtrusiveness is necessary to fully understand the obtrusiveness concerns that might negatively impact the adoption behaviors of older adult users.

This work was limited in terms of recruiting a small sample of participants, who were racially homogenous, having a higher level of educational attainment than the general US population of adults 65 years of age and older in the Pacific Northwest. Thus, the perceptions of obtrusiveness may not generalize to larger populations of older adults in other regions of the world. In addition, the two-month pilot deployment period may not have been enough to understand the changes of perception and adoption behaviors over the long term. Furthermore, we only offered four different IoT smart home devices for older adults to choose for this pilot study. The participants' opinions might have varied had there been additional kinds of devices available for them. Even with these limitations, the study provides insight into older adults' perceptions of obtrusiveness regarding IoT smart home devices.

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Chapter 5. CONCLUSION

5.1 OVERVIEW

The recent developments in the Internet of Things (IoT) connected smart home devices present a unique opportunity to support successful aging of the older adult population. In the past, there has been research investigating the use of in-home sensor technologies to passively monitor activity levels of older adults (Chen et al., 2014; Kaye et al., 2011; Rantz et al., 2013; Reeder, Chung, et al., 2013; Sixsmith et al., 2007; F. Wang et al., 2013; Wild et al., 2008b). However, these projects used systems with hardware components that capture and transmit data, but do not have ways to interact with other devices and aggregate the data in a central repository as would be the case in an IoT-based smart home system. In addition, most prior research did not perform real-world evaluation with older adults, did not assess older adults' preferences of different types of devices, or used non-commercially available sensors. To our knowledge, there has been little research on real-word testing of the IoT smart home devices with older adults. In addition, little research has been conducted to understand older adults' perceptions and concerns related to the use of IoT smart home devices. The papers presented in this dissertation addressed the identified gaps in research by exploring the feasibility of using of IoT smart home devices with older adults and understand their acceptability of these tools within their home.

The first paper resulting from this work (Chapter 2) presented findings from a feasibility study in which various IoT smart home devices were deployed within older adult participants' (n=37) homes for 2 months. In this work, I described the feasibility of the study, examining several key aspects, including 1) recruitment and retention, 2) participants' preferences regarding device choices, 3) device deployment and maintenance, 4) feasibility of data collection and 5) acceptability of the selected health outcome measures. The results demonstrated successful implementation of IoT smart home devices within the actual living environment of older adults. Unexpected challenges related to recruitment and maintenance of the deployed devices were identified. Based on the identified challenges, the paper provided insights to how future assessment of IoT technologies with older adults should be designed.

The second and third papers resulting from the dissertation (Chapters 3 and 4) presented qualitative findings from the dissertation study. In order to understand older adults' attitudes, needs, and preferences, and perceived level of obtrusiveness of an IoT smart sensor system, interviews were conducted at three different time points: baseline, 1-month, and 2-month. The second paper identified themes related to older adults' attitudes, needs, and preferences of IoT smart home devices. The analysis was data-driven where data codes were inductively generated by the data collected. In general, older adults had a positive attitude toward IoT smart home technologies to support their health management. I identified 4 major themes from the analysis which included perceived benefits, preferred features, perceived concerns, and perceived need. Emergency preparedness was a novel key benefit identified by many older adults in the study. Additionally, the convenience provided by the smart speaker's voice-interface was well received among the participants. Older adults in our study weighted the benefits and the actual need for having the devices against potential infringement on privacy. The participants also expressed desires regarding what features they expect from future smart home devices. These include easy access to data and interconnected services by network of IoT smart home devices with their electronic health record (EHR). For example, older adult participants wanted to use a smart speaker to be able to connect to their EHR to retrieve health information or receive a notification if their health record is updated.

The third paper focused specifically on older adults' perceptions of obtrusiveness of IoT smart home devices. I performed thematic analysis of exit interviews using a codebook developed based on a previously-tested obtrusiveness framework. The interview data contained examples of each dimension (physical, usability, privacy, function, human interaction, self-concept, routine, and sustainability) proposed by the obtrusiveness framework. Therefore, this work provides further evidence to support this framework, extending it to use with IoT. The findings highlighted that older adults have a varying degree of obtrusiveness concerns based on the type of device. The older adults in our study seemed to prefer devices, which in their understanding, collected 'insensitive' data, a term they used to describe data that they were okay even if made public. This study suggested that the interconnected functionalities and the multiple roles of IoT smart home devices should be considered when assessing the perception of obtrusiveness of IoT smart home devices. Based on the findings from these studies and the fieldwork experience conducting the study, I generated recommendations to improve the overall design of IoT smart home systems aiming to support older adults' health and independence.

5.2 DESIGN RECOMMENDATIONS

The complete list of the recommendations can be found in Appendix A at the end of this chapter. The recommendations below are grouped into five categories: interactive data web portal, data visualization, data monitoring, interconnected and interoperable services, and social support.

5.2.1 *Interactive Data Web Portal*

Provide easy access to data: IoT smart home devices will generate vast volumes of data that include multitudes of behavioral and physiological data. I recommend future designers of a smart home system include an interactive web portal that provides older adults with easy access to data generated by the smart home system. For the scope of this study, the participants were not provided with real-time access to their data but received the visual summary of their activity data at midpoint and exit visits. Although the periodic visual summary of activity data was found of value, many older adults desired to have real-time access to the health-related data themselves so that they have more direct control and review their data whenever they desire When presented with a prototype of an interactive website that provides access to their data, many were willing to use it if it was made available to them. In addition, older adults discussed that they would like their data from different smart home devices pooled together so that they can review them in one place, ranging from activity level, blood pressure readings, environmental readings and even utility consumption data if available. Further work needs to be done in order to fully understand the extent of data integration that older adults prefer and to implement interoperable smart home data standards.

Include customizable data sharing options: Additionally, I recommend the design of such a data portal should include customizable data sharing options so that older adults have control over what types of data and with whom to share. Participants in the study reported that they would want to view their activity pattern to guide their health management, but also wanted to share access to the website with their health care providers and family members.

5.2.2 *Data visualization*

Provide data visualization to facilitate interpretation of data: In addition to providing infrastructure for easy access, it is imperative that the data generated by the IoT devices are presented in a comprehensible manner so that older adults themselves as an end user can easily interpret information about their health and activities of daily living. Mere access to unprocessed raw data will have limited value. On the other hand, appropriately designed data visualizations can help users to identify trends and patterns and synthesize meaningful information from data. Additionally, a well-designed visualization can be valuable resources for older adults' health care providers and family caregivers that can facilitate communication among the care team. Previous work in human computer interaction in designing ambient displays for the home environment such as the Digital Family Portrait (Mynatt, Rowan, Jacobs, & Craighill, 2001), the CareNet Display (Sunny Consolvo, Roessler, & Shelton, 2004), and DigiSwitch (Caine et al., 2011; Huber et al., 2013) paint a picture on how the information collected by different IoT sensor devices can be combined and integrated into the visual interface to help coordinate care-related activities for older adults.

In addition, some previous research has been conducted to understand appropriate visual representations, metaphors, and timeframe for smart home sensor data. Wang and Skubic visualized motion data from a smart home through density maps (Shuang Wang, Skubic, & Yingnan Zhu, 2012; S. Wang, Wang, & Skubic, 2008). The number of motion sensor hits was recorded and aggregated along a 2D grid representing hours within the day by days within the month. O'Brien et al used a similar grid visualization approach, however the grid was spatially overlaid on a floor map (O'Brien, McDaid, Loane, Doyle, & O'Mullane, 2012). This provided spatial information on motion sensor activity from room to room. The DigiSwitch system (Caine et al., 2011) incorporated a feedback data visualization interface within the system and evaluated user preferences on visual metaphors and representations of data. Work by Le et al. highlighted the value older adults place in viewing longitudinal trends of data, in particular to identify gradual differences in health (T. Le, Reeder, Chung, Thompson, & Demiris, 2014). Smart home data visualization with focus to health management for older adults is a field that warrants further research. Future work is necessary to explore what graphical representations and metaphors are best suited for diverse smart home data and their ease of use in terms of insight generation.

Make it easy to detect longitudinal patterns: The visualization should be made so that the users can easily detect longitudinal patterns in the data. Our interviews with participants after showing their visual data summary confirms the previous findings that older adults want to be able to detect longitudinal changes over time from their data (T. Le, Chi, Chaudhuri, Thompson, & Demiris, 2018; Reeder, Le, Thompson, & Demiris, 2013). However, older adults' opinion varied when asked about appropriate timeframe and visualization methods to show the changes. Future research is warranted to assess ideal graphical representation of data and the appropriate time intervals to capture the changing health status of older adults.

Add elements of interactivity to data visualizations: I recommend that the visualization of the smart home data be interactive. The interactive visualization is essential because it allows users to easily customize the graph and facilitate the comparison of data. Feedback provided by the older adult participants supports this recommendation. For example, they desired to have the options to interact with the graph and easily choose specific days of activity they want to review and to also easily compare the activities of weekdays and weekends.

5.2.3 *Data monitoring*

Provide real-time data monitoring: I recommend that future IoT smart home system provide a real-time data monitoring function. The continuous real-time monitoring and assessment of data can be automated with the appropriate machine learning algorithms. The use of computer algorithms for real-time data monitoring may provide a high-quality remote monitoring of older adults that can detect both emergencies as well as longitudinal patterns at a lower cost and with minimal error. The importance of such real-time monitoring was highlighted by the older adult participants in the study. For this study, the research team did not monitor the live stream data collected from the devices or provided automated real-time data monitoring service to the participants. However, most older adult participants mentioned that emergency preparedness is an important feature that they expect from a smart home system. Most participants acknowledged the importance of a real-time data monitoring service to detect abrupt changes or deviations from a normal pattern for emergency detection at a reasonable cost. At the same time, privacy concerns were common among older adult participants. Therefore, the designers of IoT monitoring solutions should find a good balance between protecting privacy and system functionalities.

Provide automated health-related assessments: The advancement in data analytics present an opportunity to provide automatic real-time assessment of health related data. Such automated assessment should include prediction algorithms to identify potential patterns in health, detect anomalous activities, and prompt early intervention to prevent adverse health events. There have been numerous research studies to develop appropriate prediction algorithms that correctly model behavioral and physiological patterns of the residents in the home setting (X. H. B. Le et al., 2007; Li et al., 2017; Rashidi & Cook, 2013; Xu et al., 2016). Researchers are exploring diverse methodological approaches to develop the prediction algorithms including traditional machine learning techniques such as support vector machine (SVM) and K-Nearest Neighbors (KNN) to more recent deep-learning approach.

Minimize false alarms: The prediction algorithms in the IoT smart home system may generate alerts and notifications based on the data and provide timely interventions and emergency response in case of an adverse event. For example, the system with fall detection devices and motion sensors can detect falls or no activity and automatically call for assistance to emergency contacts or local emergency medical services (EMS). Therefore, the algorithms must be robust and have a high degree of precision and accuracy to avoid problems caused by false alarms as it was noted to be a concern amongst our participants. The false detection of falls set off by ordinary activities like sitting down can be annoying, cause disruptions in daily activities and thereby reducing the usability of the system. On the other hand, the consequences can be disturbing and dangerous to older adults if a fall event occurred and the algorithm was not able to successfully detect it. Such occurrence due to inadequate sensitivity and specificity undermines the confidence of users in the system, cause emotional distress and potentially lead them to reject the system. Additionally, false alarms can be a substantial societal cost in which local EMS resources are wasted and not able to attend to real emergencies. Therefore, I recommend that the system minimize false alerts and also provide means to easily cancel emergency assistance to avoid negative consequences of false alarm activations. Successful implementation of real-time data monitoring and automated health assessment with high sensitivity and specificity will lead towards increased adoption of IoT smart home by older adults.

5.2.4 *Interconnected and interoperable services*

The interconnection of devices, services and systems is at the core of emerging IoT technology. IoT devices differ from traditional in-home health monitoring technology in that each of the devices are Internet-enabled and able to communicate with each other to transmit and aggregate data to provide intelligent services. Therefore, IoT smart homes for older adults' health management are expected to be equipped with variety of devices and services to meet each resident's unique health needs. Unfortunately, there is lack of scientific evidence to support that the current IoT smart home infrastructure can provide personalized health services. For example, several participants desired having IoT smart devices that measure health indicators such as weight, blood pressure, glucose level, and cholesterol, as they found information generated by such devices would be helpful to them and their health care providers. These participants further expressed that they want such devices to be interconnected to their electronic health record to easily log and retrieve their health information.

Potential applications for interconnected IoT health services are endless. Several participants wanted to use a smart speaker to manage and query their own health data collected by different smart devices. One participant wanted a smart speaker to assist her logging of daily activity and diet information. Some participants thought it would be 'handy' to use a smart speaker to retrieve their lab results or receive a notification if their electronic health record is updated. One participant mentioned that it would be nice to be able to use a smart speaker to manage her medications list by simply "saying out loud" the medications. In other studies, medication support has also been a theme. Moshnyaga et al. (Moshnyaga, Koyanagi, Hirayama, Takahama, & Hashimoto, 2017) developed a smart system for people with dementia that used the data collected by sensors and actuators to monitor the patient's activities and adjust the medication dosage in medicine dispenser, providing vocal reminders on the time of intake and steps of medication intake. The smart pillbox system developed by Abbey et al. integrated with a mobile app that manages the medication schedule and generate reminder alarms for adherence tracking and monitoring (Abbey et al., 2012). Practical challenges related to standardizing different service protocols and data standards must be addressed for such interconnected services to be implemented. However, this is necessary work that needs to be addressed by future designers IoT smart homes to support health.

5.2.5 *Social support*

Include intelligent chat 'buddy' to provide social support: Loneliness and social isolation among older adults pose a significant societal problem and health risks (Dickens, Richards, Greaves, & Campbell, 2011). After interacting with a smart speaker for this study, several older adults discussed the possibility of a future smart speaker to become 'intelligent enough' to be a 'chat buddy' to help older adults suffering from loneliness or social isolation. Participants were open to the idea that a smart speaker would occasionally check in on those older adults, engage them in 'small-talk' and suggest activities.

Efforts have been made to develop a 'virtual relational agent' to provide social support for older adults. The concept of a relational agent was proposed by Bickmore and colleagues, describing s an autonomous computer system designed to form long-term, social-emotional relationships with its user by building trust, rapport, and a therapeutic alliance over time (Bickmore, Caruso, Clough-Gorr, & Heeren, 2005). The Bickmore research group subsequently developed computer-animated, humanoid conversational agents that simulate face-to-face dialogue with their users. The results from an exploratory pilot study demonstrated that an 'in-home' conversational agent was deemed acceptable by isolated older adults (Ring, Barry, Totzke, & Bickmore, 2013). In the IoT context, such conversational agent could be serviced via a smart speaker platform and utilize data from other smart home devices in order to provide more personalized social support to older adult users. For example, the agent could initiate conversation to promote physical activity if the sensor data suggest sedentary behaviors for a prolonged time. Furthermore, if data suggest isolation and/or the older adult expressed feelings of loneliness, the agent could suggest recreational and leisure activities or facilitate communication between the older adult and their social network. Features such as that of a 'virtual conversational agent' incorporated within the IoT smart home system may encourage adoption of IoT smart homes among older adults.

5.3 Limitations

The feasibility study had some limitations. First, we recruited a relatively small sample of participants, who were racially homogenous, and had a higher level of educational attainment than the general US population of adults 65 years of age and older. Thus, the perceptions of IoT smart home devices may not generalize to the larger population of older adults in general. Second, the two-month pilot deployment period may not have been enough to understand the changes of perceptions and adoption behaviors over the long term. Third, we only offered four different IoT smart home devices for older adults to choose for this pilot study. The participants' opinions might have been different if additional types of devices were available to evaluate. Despite these limitations, this dissertation addresses a gap in the literature by providing insights into older adults' opinions based on their actual experience with IoT systems over a longer period of time, and highlighting suggestions to improve a future IoT smart home system targeted for older adults.

5.4 Implications for future research

The findings from this study present the opportunity for future work.

5.4.1 *Gather perspectives from other stakeholders*

The results presented in this study focused on the perceptions of older adults themselves as an understudied group. Future studies could explore the perspectives of various stakeholders involved in older adults' health such as adult children, residential facility staff or health care providers. This would enable better understanding of how IoT smart home devices impact their roles and responsibilities related to supporting health and well-being of the older adult. . Furthermore, further investigation is necessary to explore ethical issues pertaining to sharing smart home data with other stakeholders and how that impacts the shared decision making process related to older adults' health management.

5.4.2 *Validate design recommendations*

The design recommendations (Appendix A) are generated solely based on the older adult users' feedback and my field experience with the IoT smart home devices. These recommendations can further be validated and refined by experts and system designers.

5.4.3 *Conduct long-term efficacy testing*

It is necessary to provide evidence of the efficacy of interventions utilizing IoT smart home devices before further issues related to integration into standard practice and reimbursement can be discussed. Future research should involve trials that recruit more diverse and larger sample of older adults across different socioeconomic status. Additionally, future real-world testing of these devices should be conducted for a longer period of time to more accurately gauge the changes of perceptions and adoption behaviors over the long term. Furthermore, such testing should integrate other smart devices such as the glucose meter, the weight scale, as well as the conversational agent serviced through smart speakers.

5.5 Conclusions

The growing older adult population calls for innovative technology solutions to support older adults' health management and independence. IoT is emerging technology that creates a network of interconnected devices to provide intelligent services. IoT smart home systems can potentially revolutionize health management and care delivery in the home environment for older adults. This dissertation showcases that IoT smart home devices are generally acceptable to older adults. Additionally, this dissertation provides an insightful look into older adults' attitudes, preferences, and perceptions of obtrusiveness regarding the IoT smart home devices. Findings from these studies provide actionable insights for future designs of IoT smart home system while outlining several directions for future research.

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5.7 Appendix A For Chapter 5: Design Recommendations

1. Interactive Data Web Portal

1.1 Provide easy access to data: IoT smart home devices will generate vast volumes of data that include multitudes of behavioral and physiological data. An interactive web portal should be able to provide easy access to data generated by the smart home system.

1.2 Include customizable data sharing options: Give older adults control over what types of data and with whom to share the data.

1.3 Include privacy policy document: Making the privacy policy document available and transparent on the data website could increase the credibility and trust to the system.

1.4 Smart home data types for supporting aging-in-place:

1.4.1 Activity monitoring data: Motion sensor data to obtain quantitative information about activity pattern

1.4.2 Sleep monitoring data: Include data that tracks sleep patterns that could estimate the quality of sleep.

1.4.3 Key health parameters: Include key health parameters such as blood pressure, glucose, and weight.

1.4.4 Emergency planning data: To prepare for emergency situations, the system should include information such as emergency contacts list, current medications list, and known allergy list.

1.4.5 Environmental data: e.g. indoor/outdoor temperature, humidity, air quality

2. Data visualization

2.1 Provide data visualization to facilitate interpretation of data: Data generated by the IoT devices should presented in a comprehensible manner so that older adults themselves as an end user can easily interpret information about their health and activities of daily living.

2.2 Make it easy to detect longitudinal patterns: Longitudinal patterns can generate insights in to the health status of older adults. The visualization should be made so that the users can easily detect longitudinal patterns in the data.

2.3 Add elements of interactivity to data visualizations: The interactive visualization is essential because it allows users to easily customize the graph and facilitate the comparison of data. For example, users should be able to interact with the graph and easily choose which weekdays of activity they want to review and also easily compare the activities of weekdays and weekends.

2.4 Provide adjustable font sizes and contrast: Vision impairment is common among older adults. The system should be able to provide older adults with adjustable font sizes and contrast.

3. Data monitoring

3.1 Provide real-time data monitoring: The real-time monitoring is important to be able to detect abrupt changes or deviations from a normal pattern for emergency detection.

3.2 Provide automated health-related assessments: The automated assessment should include prediction algorithms to identify potential patterns in health and prompt early intervention to prevent adverse health events.

3.3 Provide automated emergency call: The system should be able to monitor the status of the home environment along with the physiological parameters of the older adults and automatically contact local emergency response team in case of an emergency.

3.4 Minimize false alarms: The predictive algorithm must have a high degree of precision and accuracy to avoid problems caused by false alarms as it was noted to be a concern amongst our participants.

4. Interconnected and interoperable services

4.1. Connect with EHR/PHR: The IoT smart home system should be able to connect with older adults' EHR/PHR and able to log and retrieve their health information. Additionally, it should be able to receive notifications such as lab results update.

4.2 Increase voice control integration: The voice control interface supported by Artificial Intelligence smart assistant can support older adults navigate various IoT smart home devices.

5. Social support

5.1 Include intelligent chat 'buddy' to provide social support: Loneliness and social isolation among older adults pose health risks for older adults (Dickens et al., 2011). Intelligent conversational agent can be serviced via a smart speaker platform and utilize data from other smart home devices to be able to provide more personalized social support to older adult users.