Understanding How Sensory Changes Experienced by Individuals with a Range of Age-Related Cognitive Changes Can Effect Technology Use

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Clinical researchers have identified sensory changes people with age-related cognitive changes, such as dementia and mild cognitive impairment, experience that are different from typical age-related sensory changes. Technology designers and researchers do not yet have an understanding of how these unique sensory changes affect technology use. This work begins to bridge the gap between the clinical knowledge of sensory changes and technology research and design through interviews with people with mild to moderate dementia, mild cognitive impairment, subjective cognitive decline, and healthcare professionals. This extended version of our ASSETS conference paper includes people with a range of age-related cognitive changes describing changes in vision, hearing, speech, dexterity, proprioception, and smell. We discuss each of these sensory changes and ways to leverage optimal modes of sensory interaction for accessible technology use with existing and emerging technologies. Finally, we discuss how accessible sensory stimulation may change across the spectrum of age-related cognitive changes.

CCS Concepts: • **Human-centered computing → HCI theory, concepts and models**;

Additional Key Words and Phrases: Dementia, mild cognitive impairment, subjective cognitive decline, sensory changes, technology interaction

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1 INTRODUCTION

There are a variety of age-related cognitive changes, including subjective cognitive decline, mild cognitive impairment, and different types of dementia. Subjective cognitive decline is defined as "the self-reported experience of worsening or more frequent confusion or memory loss," which

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can be associated with a variety of conditions in individuals over the age of 45 [118]. Mild cognitive impairment includes a diagnosis of the presence of cognitive impairment in one or more domains of cognitive functioning without fulfilling the severity diagnostic criteria for dementia [138]. Mild cognitive impairment is often considered an intermediate stage of cognitive progression from subjective cognitive decline to dementia. However, subjective cognitive decline and mild cognitive impairment do not always lead to dementia [114, 138]. Dementia is an umbrella term for conditions which cause changes in cognitive, motor, and sensory functioning beyond what might be expected from "normal ageing" [141]. Dementia is typically described in terms of cognitive decline, affecting domains such as memory, thinking, comprehension, learning capacity, language, judgment, and ability to perform everyday tasks [141]. Based on this cognitive-centered definition of dementia and other types of age-related cognitive changes, it is not surprising that most technology focuses on cognitive support through task assistance (e.g., [13, 20, 29, 55, 76, 80, 93, 133, 134]) or memory enhancement (e.g., References [8, 86, 123]).

Researchers have shown people with dementia also experience changes in sensory and motor functions, which are different than typical age-related changes [58, 90] and are correlated with the progression of dementia [5]. Clinical researchers have begun to identify the sensory changes that people with age-related cognitive changes can experience that are unique to the normal process of aging [5, 53, 85, 96, 105, 107]. Our prior work, published at the 2020 ACM SIGACCESS Conference on Computers and Accessibility (ASSETS'20), described three strategies people with dementia and healthcare professionals who work with people with dementia used to overcome sensory changes associated with dementia, including stimulating at a desired level, adjusting technologies using built-in settings, and switching devices [28]. When these strategies were inadequate, participants ceased to use devices that were inaccessible [28]. The primary contribution of our past work included an understanding of technological accommodation strategies that are useful for people with dementia, evidence for the interrelationship between sensory stimulation and comprehension for those living with dementia, and new directions for technology design in this space [28].

This present article is an extended version of our past ASSETS'20 paper [28]. We expand on our initial paper by including an additional 11 interviews (4 with people with dementia, 2 people with mild cognitive impairment, and 5 with people with subjective cognitive decline). These additional interviews expand the scope of our work to include participants experiencing a range of age-related cognitive changes. In addition, we take a new analytical direction in this present article to uncover a spectrum of accessible sensory interactions for people with a range of age-related cognitive changes. This article makes three primary contributions. First, we provide an overview of the clinical literature concerning sensory changes people with age-related cognitive changes may experience that are distinct from typical age-related changes (see Section 3). Second, we detail the sensory changes participants in our study experienced and the effects of these sensory changes on their technology use. Finally, we discuss ways to leverage optimal modes of sensory interaction for accessible technology use with existing and emerging technologies across the spectrum of age-related cognitive changes. With this work, our aim is to take a step toward bridging the clinical research on the different sensory changes people with age-related cognitive changes experience and the body of research aiming to design technologies for accessible interactions for those experiencing age-related cognitive changes.

2 RELATED WORK

The following section describes research reporting on currently available technologies for use by people with dementia and mild cognitive impairment as well as the work that has been done to understand how these technologies are used in everyday life. Following this, we describe the main purposes of technologies specifically designed for use by people with age-related cognitive changes—to provide cognitive assistance or sensory engagement.

2.1 Technology Use for Those with Dementia and Mild Cognitive Impairment

There are nearly 1 billion adults over the age of 60 worldwide [140], with 6–12% of these adults diagnosed with mild cognitive impairment [104]. In addition, there are nearly 50 million people worldwide living with a diagnosis of dementia and a projected 10 million new cases each year [141]. With consideration for the number of people living with age-related cognitive changes, researchers are conducting studies to report on the assistive technologies currently available for use by people with dementia and mild cognitive impairment. One study projected technology trends for people who will be living with dementia in the future [142]. In terms of technologies that are currently available, Gibson et al. surveyed the landscape of available assistive technologies, dividing the resulting types of technologies into three categories: devices used "by," "on," and "with" people with dementia [42]. Lorenz et al. note how technologies are designed for use by people with mild cognitive impairment or those in the earlier stages of dementia and shift to targeting family carers and healthcare professionals as the condition progresses [69]. Despite this use, little research has focused on the usability of assistive technology that supports everyday life—how people can understand, use, and learn to use these technologies [74].

Some research has gone in depth on barriers to everyday technology use. Many studies discuss the importance of recognizing individuality for successful technology introduction, such as abilities, habits, attitudes, and environments [101]. Some research includes accessibility and usability issues in their accounts of barriers. While sensory barriers are sometimes mentioned, they have not been examined thoroughly. For example, in an analysis of the difficulties people with early-stage dementia have using everyday technology, Nygård and Starkhammar refer to weak vision in a section on the design of artefacts as one contextual condition that can be a hindrance to technology use or appropriate force (e.g., holding a remote volume button too long) as an example of communication difficulties in the use of technology [91]. In the present article, we directly study the sensory changes people with age-related cognitive changes experience, with a focus on how these changes effect everyday technology use.

2.2 Technologies to Provide Cognitive Assistance

Changing cognition has often been centered in technology design for people with dementia and mild cognitive impairment. One vein of work seeks to use technology to screen for age-related cognitive changes [49, 108, 119], prevent cognitive decline [79, 130], or improve cognition [6, 8, 125] using varying kinds of technologies. For example, Alves et al. developed a web application, Scrapbook, to support psychologists in performing cognitive therapy as well as reminiscence with people with dementia [6]. MemHolo, a mixed reality system, was developed as a cognitive training tool to practice short-term and spatial memory for people with Alzheimer's disease [8]. One project, MobiAssist, targets both physical and cognitive capabilities of people with dementia through exergames [123–126]. Virtual reality has been used as a cognitive training tool for people with mild cognitive impairments to simulate typical daily activities [129]. Other immersive technologies like PENCODER rely heavily on experiences and objects that are familiar to people with mild cognitive impairment and have positively influenced upward trends in self-esteem among participants [110].

Other research seeks to accommodate cognitive changes people experience in dementia. Much research has been done developing technologies to assist in navigation in case the person with dementia walks to places that the caregiver is not comfortable with [133, 134] or if the person with dementia forgets where they are and cannot get home [55]. Other technologies are designed to assist with cognitive barriers to task completion. These technologies often aim to stimulate thinking through step-by-step directions [20] and are targeted to support specific tasks such as hand washing [76], flushing the toilet [29], and cooking [26, 93]. Researchers used an augmented reality system called GhostHands to build upon similar types of task prompting tools, with the platform offering multi-sensory prompts that involved primary visual and auditory cues [136]. CoasterChat's designers, Diks et al., also found that the instructions accompanying the app pilot were most well received when they combined visual movements and auditory instruction [25]. This approach has also been taken in commercially available systems, such as MapHabit, which pairs visual with audio or written instructions to support everyday task completion [20, 72]. Muñoz et al. found that their touchscreen app called A Better Visit enabled interactions between caregiver–person-with-dementia dyads by curating content that specifically supported "pre-existing interests" [87]. This application created multi-sensory experiences in apps like Tic-Tac-Tango—which played familiar ballroom music and replaced typical X's and O's with visually stimulating dance moves—and sought to "support personhood" through personalization and familiar experiences [87]. Like MapHabit, both systems use multimodal prompts—the designers explain this design decision was made to ensure "interfaces that are highly adaptable to the cognitive support needs and any perception disabilities" [72].

The above examples that utilize multimodal prompts indicate that even when designing for cognitive support (rather than, for example, recreation), sensory abilities matter for the design of usable and accessible systems. Our past work introduces nuances to the relationship between sensory stimulation and cognition, such as that indiscriminate use of multi-modal stimulation can actually create anxiety and disrupt use and that people with dementia vary in their ideal mode of sensory input for comprehension [28]. The present article takes a systematic approach to understanding sensory changes people with dementia experience as they affect technology use.

2.3 Technologies Designed for Sensory Engagement

Human-Computer Interaction (HCI) technologies for people with dementia, particularly in later stages, and people with mild cognitive impairment, often recognize sensory abilities as ways to engage people with dementia. Design decisions that leverage sensory experiences are supported by research: a critical dementia perspective recognizes the importance of multisensory experiences and that physical and embodied experiences are ways of knowing [66]. The experience-centered design perspective attends to aesthetics and touch as both providing insights into the lives of people with dementia as well as creating opportunities for absorbing experiences [82]. Froehlich et al. posit that media has such an important role for people with dementia that there should be a new category of assistive technologies that involve media creation and consumption for well-being [39].

Researchers have used a variety of technologies to engage sensory abilities, often including multimedia. For example, the CIRCA project used touchscreens to present music, videos, and pictures to stimulate long-term memories to prompt conversations [4, 45]. More recent research may reflect an understanding of the importance of embodiment in dementia, adding haptics [60], gesture-based interaction [63, 111], and tangible objects to support multimedia engagement to support reminiscence [59]. Guan et al. also found that technology could act as a "communication modality" when adapted from embodied cues, noting that embodied cuing can be more successful than abstract verbal language when encouraging people with dementia to mimic activities or behaviors [46]. Further, embodied cues that stimulated several senses—such as a caregiver visually depicting the activity while humming—were particularly effective [46]. Another example leveraging embodied interaction alongside sensory modalities is in the Closer To Nature Installation, which used a display of a farm scene, old-fashioned water pump, and sensor-enabled, touch-responsive goat [36].

Audio has received particular focus. Researchers have investigated conversational assistances, such as through Google home and Amazon Alexa, to facilitate conversations between people with mild cognitive impairment and their care-partners [143]. Other researchers have focused auditory interactions due to the documented benefits of music therapy for people with dementia [128]. Researchers in HCI have designed technologies to facilitate musical creativity [83, 102, 103] and to give people with dementia more control over playing music [109]. When developing their application A Better Visit, Muñoz et al. found that embedding musical elements throughout the cooperative games encouraged engagement and concentration among people with dementia, especially if that music was familiar to them [87]. Houben et al. point out that music only represents a subset of the sounds that people perceive, and in contrast to experiences with music, experiences of everyday sounds for people with dementia are significantly under studied [57]. The authors explored the reactions of people with early and moderate dementia to generic, everyday sounds, finding not only that this provided opportunities for meaningful interactions but also that soundscapes could feel chaotic and overwhelming [57]. Muñoz et al. found similar success when using sounds to facilitate accurate guessing in the game Reveal, using animal sounds to help users recognize what animal was represented in a picture before they could see it fully [87].

3 BACKGROUND: SENSORY CHANGES UNIQUE TO AGE-RELATED COGNITIVE CHANGES

The aim of this present article is to better understand accessible sensory interactions with technology for those experiencing age-related cognitive changes. To provide supporting evidence for the sensory changes described in our findings, this section reviews clinical research investigating how sensory changes associated with age-related cognitive changes are distinct from typical age-related changes. Since the early 2000s, clinical research has begun to explore the unique sensory changes experienced by people with dementia when compared to the sensory changes experienced as a part of the typical aging process. Most of these studies have been done in regard to dementia, though some examine changes with mild cognitive impairment.

This past clinical work has shown the way a person with dementia interprets what they see, hear, taste, feel, and smell changes due to the condition [90] and that these changes may correlate with the progression of dementia [5]. Some of these changes are more common with specific types of dementia, (e.g., dementia with Lewy bodies [38, 43, 56, 97] or frontotemporal dementia [99]), but many sensory changes are common across various types of dementia [53, 85, 98, 105]. Below, we review some of these changes experienced by people with dementia and mild cognitive impairment based on clinical literature.

Vision loss is common for people as they age. However, there are specific aspects of vision that change differently than normal age-related vision changes. Individuals living with dementia often have significantly lower visual acuity, meaning less sharp vision (e.g., the ability to determine letters at a distance) compared to control groups [105]. People with dementia experience increased difficulty with contrast sensitivity—the ability to determine the foreground from the background—and color perception [105]. People often experience difficulty with visual integration, meaning the ability to look at an object and properly orient it in space [105]. Some experience surface dyslexia, meaning additional difficulty identifying words while reading and classifying stimuli as words or not as words [98]. Additionally, people may experience difficulty with "seeing" more than one thing at a time, which is referred to as "simultanagnosia," grasping the "big picture," and selecting something specific from among a cluster of items [15, 115]. Changes in vision are significant to the extent that differences in the retina are being explored as an option for early detection of neurodegenerative changes associated with mild cognitive impairment and Alzheimer's disease

[2, 14, 47, 68, 106]. Other visual changes may include visual hallucinations, which are more typical for dementia with Lewy bodies [97].

The loss of some hearing ability is also a typical aspect of the aging process. Researchers are finding that people with dementia experience changes in ability to process auditory input with dementia that are unique to typical age-related hearing loss [53]. One example is auditory agnosia, or impairment in sound perception, and identification of select types of sounds without any clinical hearing dysfunction [53]. Word deafness is one form of auditory agnosia, where individuals can comprehend written information drastically better than spoken information [61, 64, 94]. As another example, people living with Alzheimer's disease often have difficulty following conversations and other sounds when in a busy auditory environment [37]. Researchers have also documented people with dementia's difficulty with nonverbal sound recognition, including difficulty recognizing familiar voices even while being able to distinguish between voices [17, 43, 50, 51]. Other auditory changes unique to typical aging include auditory hallucinations, including muffled sounds, voices, and musical tunes [22, 43, 56]. Like visual hallucinations, auditory hallucinations are most often reported by people with Lewy bodies [22, 43, 56]. Researchers have also found that people with frontotemporal dementia and some people with Alzheimer's disease may have sound aversion, which is when certain sounds trigger emotional or physiological responses that some people may perceive as unreasonable given the circumstance [37], as well as increased sensitivity to sound [71]. Researchers are investigating hearing loss as a possible indicator and risk factor for cognitive decline and dementia [70].

Speech and language patterns can also change in dementia. Individuals living with dementia have been found to have distinct differences in "syntactic complexity, speech fluency, vocal parameters, and pragmatic language" as compared to control groups [85]. One study even found that measures of speech (e.g., reduced number of words spoken per minute) could be used to identify frontotemporal dementia [99]. Additionally, people who are bilingual and are in the more advanced stages of dementia often have difficulty maintaining their second language [75]. Researchers have not found a significant difference in speech and language patterns between control groups and people with mild cognitive impairments [85].

Olfactory (smell) dysfunction, where people experience changes in their ability to smell things, is a part of the normal aging process [30]. However, odor identification has been found to be more difficult for people with Alzheimer's disease or vascular dementia [5, 84, 100] as well as for those with mild cognitive impairment [40] compared to people without any known neurodegenerative condition. Changes in olfactory ability may influence taste and appetite for people with dementia, which can lead to a lack of nutrition and lower overall health [3].

Balance, gait speed, and stride length are also affected by dementia. Researchers have found people with dementia experience significantly less static balance, as well as lower gait speed and stride length, than the average person [107, 127]. The changes in balance and gait may be associated with different types of dementia. One study found participants with dementia with Lewy bodies and Parkinsonism dementias walked significantly slower, with shorter stride lengths and demonstrated less balance than people with Parkinson's without dementia or Alzheimer's disease [38].

Dexterity and fine motor skills are also affected differently for people with dementia. When comparing groups of individuals experiencing "normal aging," mild-cognitive impairment, and Alzheimer's disease, researchers found a progressive decrease in fine motor dexterity from those experiencing normal aging to mild cognitive impairment to Alzheimer's disease [96]. Past work notes differences in finger dexterity between individuals with different types of dementia, where people with dementia with Lewy bodies had less finger dexterity than people with Parkinson's or Alzheimer's disease [38].

Clinical research to understand the sensory changes people with dementia experience has started to gain public attention since the mid-2010s. With this being a relatively novel area of study, many general practitioners and the general public are still unaware of the sensory changes people can experience due to dementia. In this article, we provide findings related to some of the sensory changes that people with dementia experience in relation to technology use.

4 METHODS

Below, we present our approach to data collection, participant demographics, analytic approach, and limitations.

4.1 Data Collection

We recruited from four groups: people who self-reported subjective cognitive decline, people diagnosed with mild cognitive impairment, people diagnosed with mild to moderate dementia, and healthcare professionals with experience working with people across the spectrum of dementia. We include individuals with subjective cognitive decline and mild cognitive impairment in this study as a way to compare and contrast the effects of sensory changes on technology use to those diagnosed with dementia. Data from interviews with healthcare professionals were included to provide perspectives on technology use for a broader population of people with dementia, given the specifics of the sample of people with dementia (who were largely regular technology users) and to expand our understanding to those in the later stages of dementia.

We recruited people with dementia and mild cognitive impairment through large dementia advocacy organizations and snowball sampling. Initial contacts were made at a large dementia organization conference in 2019. These participants then shared our study information with other people they knew in their online support groups as well as on Twitter. We recruited a smaller number of people who experience subjective cognitive decline through personal contacts and snowball sampling. We recruited healthcare professionals through various professional societies Facebook pages (e.g., Therapeutic Recreation Directory) and snowball sampling.

For participants with cognitive impairments to qualify for the study, they first had to complete a screener call with the researchers where they were asked questions to determine their eligibility for the study as well as their capacity to consent. Capacity to consent was determined using the UC Davis Alzheimer's Disease Center procedures [121]. All participants gave informed consent before participating in the study.

To determine eligibility, we chose to rely on self-reporting a diagnosis of dementia, mild cognitive impairment, or experience with subjective cognitive decline rather than formal staging of the severity of cognitive impairment by a clinician (e.g., instruments such as the Mini-Mental State Exam or Montreal Cognitive Assessment). Relying on self-reported diagnosis is in alignment with accepted approaches in HCI that recognize that "It may be hard to get detailed information about the medical status of someone with a disability... because of the sensitivity involved in sharing personal health data" [67]. When participants with dementia did not know their stage, we asked them to self-assess their stage of dementia at the time of the study based on the categories we drew from the US Center of Disease Control and Prevention and National Institute of Aging's function-based stage classification [88, 89, 118]. These categories included subjective cognitive decline, mild cognitive impairment, mild, moderate, and advanced dementia, as well as vignettes of functional changes associated with each of these categories (see References [88, 89, 118]). Each category was read to participants where they indicated which best fit their functional abilities. Function-based stage classifications is a particularly relevant measure to technology use, as it indicates one's ability to carry out daily activities and tasks. Though we include the self-assessed stage in the table, throughout our findings we focus more on the self-reported diagnosis and not on the self-assessment of stage, as these self-assessments may not align with a clinical diagnosis of stage.

All participants also had to self-report regular use of technology. We chose to include regular technology use as a criteria so that we could gain insights into experiences with technology—while recognizing that these participants may not be representative of the broader population of people with dementia (although there is a trend toward greater technology use by people with dementia: Research has found that 54.14% of people with mild cognitive impairment or dementia reported using their smartphones and tablets almost every day [48]). Inclusion criteria for healthcare professionals were that they had at least 3 years of experience working with people with dementia. All procedures were approved by the University Institutional Review Board.

Interviews were semi-structured, lasting approximately 1 hour. Nearly all of the interviews were conducted remotely via video-conferencing. Though several of the interviews were conducted in-person (prior to COVID-19 quarantine restrictions) when participants were located within a reasonable distance from our university. Each interview was audio/video recorded with the consent of participants, resulting in 40 hours and 40 minutes of recording used for analysis.

For the interview protocols, questions were structured to be very general concerning participants' technology use. The general nature of the questions and the semi-structured nature of the interview allowed us to ask further probing questions depending on the answers given by participants. This helped us to obtain data on a variety of ways technology was used to address people with dementia's unique sensory needs. In the first portion of the interviews, participants with dementia, mild cognitive impairment, and subjective cognitive decline were asked questions concerning their current use of technology, and healthcare professionals were asked about their professional strategies to engage people with dementia, with us probing for more detail on the strategies that involved technology. Examples of questions in this section included, "Have the changes you've experienced with dementia affected your technology use? If so, can you please explain in what ways your technology use has changed?" To healthcare professionals, we asked questions such as, "Can you tell me about strategies you use to make an activity accessible to people with dementia?" and "How have you modified technologies so that people with dementia can still engage with them?" With all participants, we asked in detail about their motivations for using technology and the challenges that technologies were used to address. We probed deeply into the answers where sensory changes were discussed, asking about how these changes were experienced, and how technologies were used to address them. Next, we asked all participants questions concerning their ideas for future technologies. The interviews with participants with dementia, mild cognitive impairment, and subjective cognitive decline concluded with a discussion of technologies that participants no longer used and why. Interviews with healthcare professionals concluded by giving them the option to review a website database of assistive technologies in terms of usability and usefulness to people with dementia. Please see supplementary materials for further detail. All participants received a $20 Amazon gift card after completing the interview.

4.2 Participants

This is an extended version of our accepted ASSETS paper [28]. As such, our analysis included the 30 participants from the previous version of this work (11 people with mild to moderate dementia and 19 healthcare professionals). In this extended version, we include an additional 11 participants. Four of these additional participants are individuals living with dementia, 2 are individuals living with mild cognitive impairment, and 5 are people who self-report subjective cognitive decline. In the findings section these participants are denoted with pseudonyms, with additional context of either their type of dementia or subjective cognitive decline. We use pseudonyms as a way to avoid dehumanization [10].

Table 1. Participant with Dementia, Mild Cognitive Impairment, and Subjective Cognitive Decline Demographic Information

Pseudonym	Age	Gender	Country	Type of Dementia or Cognitive Impairment	Stage of Dementia
Frank	63	Male	UK	Mixed vascular dementia/Alzheimer's disease	Mild/Moderate
Annette	65	Female	UK	Alzheimer's disease	Mild/Moderate
Bill	58	Male	US	Dementia with Lewy bodies	Mild
Sharon	60	Female	US	Vascular microangiopathy	Unknown
Helen	57	Female	US	younger-onset Alzheimer's disease	Mild
June	59	Female	US	Vascular dementia/white matter disease	Mild/Moderate
David	67	Male	US	Vascular dementia	Mild/Moderate
Linda	67	Female	US	Dementia (major neuro-cognitive impairment)	Mild/Moderate
Arthur	61	Male	UK	Dementia with Lewy bodies	Mild
Phillip	61	Male	US	Alzheimer's disease/semantic dementia	Mild
Andrew	59	Male	US	Alzheimer's disease/vascular dementia	Moderate
Joseph	71	Male	US	mild cognitive impairment[1]	N/A
Griffin	67	Male	Canada	Vascular Cognitive	Moderate
Ben	59	Male	US	early-onset Alzheimer's disease	Mild
Luke	61	Male	UK	Vascular dementia	Mild
Jade	73	Female	US	Vascular dementia	Mild
Everly	55	Female	US	mild cognitive impairment[2]	N/A
Alina	80	Female	US	Subjective Cognitive Decline	N/A
Ted	71	Male	US	Subjective Cognitive Decline	N/A
Chris	84	Male	US	Subjective Cognitive Decline	N/A
Peter	72	Male	US	Subjective Cognitive Decline	N/A
Margaret	72	Female	US	Subjective Cognitive Decline	N/A

[1]Joseph was originally diagnosed with mild dementia and has since been re-diagnosed as having mild cognitive impairment (MCI). [2]Everly throughout the interview referred to herself as being in the early stages of dementia, though when completing the demographics form, she reported being diagnosed with MCI.

The average age of participants with dementia was 62.5 years old (range 57–73). The average age of participants with mild cognitive impairment was 63 years old (range 55–71). The average age of participants with subjective cognitive decline was 75.8 years old (range 71–84). All participants with dementia, mild cognitive impairment, or subjective cognitive decline identified as Caucasian with the exception of Everly, who identified as African-American, and Margaret, who declined to self-identify her ethnicity. See Table 1 for more detail on participants age, gender, country of residency, type of dementia or cognitive impairment, and stage of dementia. Participants with dementia included individuals who identified as dementia advocates and others who were a part of advocacy organizations' peer-support groups but were not participating in active roles within these organizations.

We interviewed 19 healthcare professionals, with an average of 15 years of experience working with people with dementia (ranging from 3 to 46 years). All participants identified as female and Caucasian, with the exception of Esther, who identified as multi-ethnic, and Tiffany, who identified as Asian. All healthcare professionals were interviewed separately with the exception of two who were interviewed together to accommodate their time constraints. Healthcare professionals worked with a range of cognitive abilities from people with mild cognitive impairment through people with advanced dementia. Their average age was 47.8 years old (range 26–70). Throughout the findings, healthcare professional quotes are denoted with Pr# rather than pseudonyms as a way to distinguish their quotes from quotes by participants with dementia, mild cognitive impairment,

Table 2. Healthcare Professional Demographic Information

PID	Age	Country of Practice	Occupation	Years of Experience
Pr1	70	US	Occupational Therapist	4
Pr2	31	US	Occupational Therapist	5
Pr3	31	US	Occupational Therapist	8
Pr4	32	US	Occupational Therapist	8
Pr5	54	US	Speech Language Pathologist	30
Pr6	30	US	Activities Service Supervisor	7
Pr7	56	US	Activities Director	12
Pr8	61	US	Lifestyle Director	15
Pr9	56	US	Life Enrichment Associate	15
Pr10	58	US	Activities Service Provider	4
Pr11	26	US	Memory Care Activities Coordinator	4
Pr12	54	US	Gerontologist Consultant	30
Pr13	53	US	Occupational Therapist	20
Pr14	55	Canada	Executive Community Director	30
Pr15	40	Canada	Manager of Community Development and Engagement	12
Pr16	39	US	Director of Adult Day Care and Respite	20
Pr17	52	US	Dementia Consultant/Advocate	20
Pr18	62	US	Director of Quality Assurance and Education	46
Pr19	42	US	Dementia Care Educator	3

or subjective cognitive decline. To provide further context for healthcare professionals' quotes, we distinguish the type of healthcare professional when introducing their quote in the findings. See Table 2 for a summary of each healthcare professional's age, country of practice, occupation, and years of experience.

4.3 Analysis

For this extended version of our original paper [28], we took a thematic analysis approach [18]. This involved a secondary analysis of the data that were used for the ASSETS paper [28] and the additional data described above. We initially familiarize ourselves with the data by open coding six transcripts. These six transcripts included two transcripts from interviews with people with dementia, one transcript from an interview with a participant with mild cognitive impairment, and three transcripts from interviews with healthcare professionals. Our initial open codes from these six transcripts included codes such as "switching visual to audio," "dexterity affected," and "when visual is hard." This open coding process resulted in our interest in further understanding two aspects of the data: (a) the sensory changes people with age-related cognitive changes experience affecting technology use and (b) accommodation strategies that are used when changes in sensory abilities occur. We designed a codebook that was organized by sense, with open codes that seemed relevant to those senses. We then went back through all interview transcripts, including the six transcripts used for open coding, and categorized the data using this codebook, adding to it when new codes emerged. Codes reflecting accommodation strategies were added, such as "speech slowing," "mirroring," "embodied cueing," and "audio still too hard." By the 20th transcript, we reached data saturation, as no new codes were added. All transcripts were then focus coded using the established codebook. Following focused coding, through a collaborative and iterative process of considering the fit of each code with different sensory categories, each code was finalized in terms of where it was grouped within specific sensory categories, and the higher-level sensory categories were determined: visual, auditory, dexterity, proprioception, and smell. For example, we determined that the accommodation strategy of "embodied cueing" should be included under the sense "proprioception." We coded all instances, including where participants did not talk about technology directly. In our findings, we include instances that do not refer to technology use only when they reveal future opportunities for technical interventions to engage the changing sensory abilities of people with age-related cognitive changes. When quoting participants in the findings, we have removed false starts and filler words (e.g., "like") only when they affected readability.

The larger aim of our analysis was to explore how sensory changes experienced by people with a range of age-related cognitive changes effect technology use. To reach this aim, when writing the article we were intentional to include quotes in each section from all applicable participants in each participant group who described related sensory changes. We then structured our findings sections in a way that demonstrates the sensory changes experienced by participants from those experienced by all participant groups to those experienced by participants in the most advanced cognitive changes. Visual and auditory changes are included as the first and second findings section as these changes were described by all participants across the range of age-related cognitive changes. One participant with subjective cognitive decline described dexterity changes but these were largely described by people with dementia or healthcare professionals who worked with people with dementia, which is why it is the third findings section. Proprioception is described in the fourth findings section, as these changes were only described by people with dementia and healthcare professionals who worked with people with dementia. Finally, olfactory (smell) changes were only described by healthcare professionals in relation to their clients in the most advanced stages of dementia. These examples and organization of our findings serve to go beyond description of the data to illustrate sensory changes experienced by participants across the spectrum of age-related cognitive changes—which we discuss in further detail in the discussion.

4.4 Limitations

One limitation of this study is the reliance on self-reporting rather than requiring clinically confirmed diagnosis of dementia, diagnosis of mild cognitive impairment, or experience with subjective cognitive decline. We did not formally assess participants' cognitive abilities. And not all participants knew what stage of dementia they were in, so some self-assessed. Future work should consider partnering with clinicians to conduct these formal assessments of cognitive ability.

The average age of participants with dementia was 62.5 years. Dementia diagnosed under the age of 65 is considered early onset [1], representing 9% of diagnoses [139]. This relatively younger group of participants may be overrepresented in our research due to the hesitance of the general population to self-identify as a person living with dementia due to stigma [10, 116] that can lead to unwillingness to discuss experiences with researchers [112]. As many of our participants were active in various dementia advocacy organizations, these participants appear to be a part of the rise of the "young, active person with dementia" involved in publicly sharing information about their condition with researchers [21]. In addition, the recruitment requirement that participants had to use technology regularly may also have led to a relatively younger group of participants [11, 92]. Finally, recruiting participants with dementia using Twitter may have resulted in a sample of younger participants with dementia who are also dementia advocates, as has been found in previous work [117].

The limited racial diversity of participants is another limitation of our study. All but one participant with dementia, mild cognitive impairment, or subjective cognitive decline identified as Caucasian and one participant chose not to identify. Research shows a higher prevalence of dementia in the African American and Latinx communities in the United States [7], which was not represented in our participant pool. Additionally, the healthcare professionals who participated in our study were also primarily Caucasian. Researchers have suggested several barriers in research recruitment of different ethnic groups such as lack of trust in research due to a history of ethical issues [24, 34], institutional barriers to education [73], and stigma consciousness [73]. There is a need for further work to ensure that research includes more diverse demographics of people with dementia and healthcare professionals. Finally, our findings come primarily from participants residing in the United States, the United Kingdom, or Canada. Our findings are certainly influenced by these geographic and cultural settings.

Given our study utilized a single interview, the scope of the data collected is limited to the perceptions and accounts of participants that they shared within our 1-hour interview. Future work should consider using an ethnographic or longitudinal method to understand how sensory changes fluctuate and affect technology use as people progress with dementia. Further, most interviews were conducted remotely, which limited data collection to participants' verbal explanation, which can be arduous and suboptimal as an approach for some individuals. Future work should consider including observations and diary studies to further document sensory changes and their effect on technology use.

5 FINDINGS

Our past ASSETS paper [28] described technological accommodation strategies people with dementia and healthcare professionals who work with people with dementia used to overcome sensory changes associated with dementia as well as instances when no accommodations were available, which led to participants ceasing to use inaccessible technologies [28]. In this extended version of our previous work, we detail each of the different sensory changes participants with a range of age-related cognitive changes in this study described as well as ways these sensory changes effected the accessibility of technology use.

5.1 Visual

Participants described visual changes they experienced due to age-related cognitive changes that interacted with their technology use, including changes in visual acuity, color perception, ability to select an object out of a busy environment, ability to see the big picture, and surface dyslexia. Changes in vision have been associated with mild cognitive impairment and Alzheimer's disease in clinical research [2, 14, 47, 68, 106].

5.1.1 Visual Acuity. Many people experience vision changes as they age. Although everyone's vision changes with age, fluctuating changes in visual acuity, or sharpness of vision, are specifically linked to dementia [105]. Frank, living with mixed vascular dementia and Alzheimer's disease, said, "I struggle now, visually with reading and dealing with emails on the phone." He experiences a fluctuation in vision that is different than in typical aging, "because of vascular dementia causing sometimes hourly changes in my visual capabilities." In another instance, June, living with vascular dementia and white matter disease, described how she now uses the voice assistant on her phone to "voice text because for some reason my texting skills since my stroke[1] I don't know what that is but I'm just visually off a cog," meaning "If I type something really fast and send it, people will write back, 'What? Where are you? This is like a foreign language,'" because the letters June believes she is typing based on her visual abilities are not what she actually is typing.

Participants used several strategies to accommodate changes in visual acuity. One strategy was to use devices that supported larger text, as Pr13, an Occupational Therapist, described simply

[1] The strokes June experienced were linked to the development of vascular dementia and white matter disease.

"modify[ing] a TV screen by putting a magnifying screen on it" [Pr13]. Modifying the size of a device was particularly important, as Speech Language Pathologist Pr5, explains "the size of the piece of technology has to be relatable for their vision capabilities. So, the difference in the size between an iPhone, an iPod Mini, and a full-size iPad can have a substantial impact on the person's ability to read and receive the information." Phillip, living with Alzheimer's and semantic dementia, described a use that was consistent with Pr5's observation, where he uses a tablet as his phone, because it is larger and therefore makes it easier to see what is on the screen. An alternative accommodation was used by Frank, who is living with mixed vascular dementia and Alzheimer's disease, who "use[s] the phone to let me know I've had the emails... then when I get home I'll bring them up on the smart tv screen where it's big enough to see."

Another strategy participants used to accommodate visual acuity changes was utilizing other mediums for interacting with the phone rather than vision, such as voice to text dictation. For instance, Frank describes the necessity of using voice to text when "I need to be making a note, if I can't see clearly enough or operate the phone well enough… I can still dictate into it." Participants with dementia also described using voice recorded messages on their phones, which Frank refers to as "leav[ing] myself voice messages." Similarly, Arthur, who is living with dementia with Lewy bodies, regularly records "spoken" journal entries through his Alexa. In contrast, using voice to text was not described by participants with subjective cognitive decline with the same level of need as participants with dementia described. For instance, Alina stated "The only time I use voice to text is on my [phone]. When I'm texting sometimes" but not because she needed to use this feature to communicate via message due to visual acuity changes.

5.1.2 Color Perception. People with dementia can experience increased difficulty with color perception [105]. In our study, participants with dementia and healthcare professionals who work with people with dementia described the loss of the ability to distinguish visual features, where bringing in more color contrast was key to aid technology use. One participant living with vascular dementia explains intentionally choosing contrasting colors for his phone case "blue on black," because he often cannot visually distinguish his phone because "it's black. And so I got this case so that now I can see it. I'll recognize it" [Griffin]. Similarly, Pr13 and Pr1, both Occupational Therapists, described increasing color contrast to support everyday technology use. Pr1 describes, "For one person operating the CD player we used nail polish to highlight the buttons that he should push" where he "press[ed] the green button for go to start it." Pr13 would take "a really bright yellow or bright green duct tape and I'll cut like a little square to put over either the on button or a number button... So, this colored button on the microwave, it pops out. So, you're more apt to push that button. You may not remember what it's for but that bright color against that black microwave stands out and you just will automatically put your finger there to use the microwave." The need for color distinction to draw people with dementia's attention extends from physical devices to web-pages as Occupational Therapist, Pr3, describes web pages that are "white can be overwhelming," because it's "too much negative space." This is especially relevant for people in the "moderate or maybe mild [stages of] dementia," because with "all that white space… they don't know where to look" [Pr3].

Some participants actually used the attention-drawing properties of color, along with conventions of meaning assigned to different colors, to accommodate cognitive changes. Pr13 described the usefulness of the stoplight system to signal go or stop—though they did not note this specifically in regard to technology, participants with dementia described employing these colors in their own accommodations, with red signaling an urgent action. Helen, living with early-onset Alzheimer's disease, explains how she organizes her digital calendar system: "red is the absolutely, positively you have to do it. And if it has a time assigned to it, you have to do it at this time... darker green is just a recurring reminder for me to do something financial... if I'm expecting an action from someone else that's financially related... then that'll be a lighter green... just a regular navy blue is just an act. It's just an action that I need to take with no specific meaning… a lighter [blue] for things that are related to my health care… activities that are for people with dementia. Those are kind of a magenta, purplish, pinkish kind of color." Her intricate color coding system, "makes it easy for, easier for me to find a specific item on the calendar. Out of all the clutter" [Helen].

5.1.3 Selecting an Object from a Busy Environment. People with dementia can experience difficulty with "seeing" more than one thing at a time, which is referred to as "simultanagnosia" [15, 115]. Sharon, who is living with vascular microangiopathy, explains, "the world can feel very confusing and overwhelming when you have too much data to deal with. Sensory input. Too much, too many colors or flashing things in the eyes or noise." For example, Bill becomes visually overwhelmed with online forums because of "The way they're all laid out… first you have to try to search to see if somebody's already had that question before. Then try to find the question… It's just a mess, it's just a total mess" [Bill].

In these overwhelming sensory environments, participants describe not being able to pick out certain objects they may be looking for. For example, Griffin, living with vascular dementia, explains how "I have visual problems… [an object] could be right in front of me. I wouldn't recognize it because it might blend in with everything else" [Griffin]. Similarly, Helen, who was in the early stages of Alzheimer's disease at the time of the study, explains her common experience with not seeing something that is directly in front of her. This visual change affects her engagement in both the physical and the digital world where "even though my eyes still work perfectly fine, the brain doesn't process. [I] wouldn't see" whatever it is she's looking for [Helen]. Margaret, living with subjective cognitive decline, experiences similar moments when using her computer where "I don't know where all my documents are." For Helen and Margaret, using visuospatial organization by positioning documents on their desktop computer in a particular way helps accommodate moments of not seeing by helping them know to look "specifically [at] that area of the screen or image" [Helen]. Margaret uses regions of the space and layering to support organization, where "if it's [a document] on the left, it means I've been working on that one longer. If it's on the right, it's an older a draft of an older piece. So if I move it with that left side it's closer to being finished" [Margaret]. Related documents are "even superimposed on top of each other… That way they don't take up too much room" [Margaret]. This strategy may not work for all people with age-related cognitive changes as June, who is living with vascular dementia and white matter disease, did not arrive at a visuospatial approach to accommodating simultanagnosia—she mentioned the challenges she experienced when she had "four hundred notes all over the place." Instead, June has switched to an online calendar and reminder system as "a way to stay organized" and not become overwhelmed with busy visual environments.

5.1.4 Seeing the Big Picture. People with dementia may have difficulty grasping the "big picture" [15, 115] when everything needed for a task is not visible at one time. Pr16, a Director of Adult Day Care and Respite, explains when there are "a ton of options" such as in "drop downs" menus, this creates "areas for them to get lost," because people can't see everything at once [Pr16]. Phillip, living with Alzheimer's disease and semantic dementia, describes his "difficulty knowing which is which, when I got to go down the bottom and click the tab. So I might click the wrong tabs multiple times till I find my way where I want to be." To avoid becoming disoriented when working on multiple tabs, Phillip describes how he now uses split screen on a 24-inch monitor where he "tend[s] to open up multiple screens at a time," which is "much easier on a desktop versus utilizing a laptop to do that," because he needs the surface areas to see all that he is working on at once. Jade, living with vascular dementia, also utilizes a split screen to keep everything needed for a task visible. For example, when "read[ing] some kind of directions while I'm doing something else" like "filling out a form, for example."

5.1.5 Surface Dyslexia. People with dementia can experience surface dyslexia, meaning it can be difficult to read irregular words and classify stimuli as words or not words [98]. Bill, living with dementia with Lewy bodies, explains his difficulty with restaurant menus: "There's just these big long words, it's just descriptions of things," which causes him to "have a hard time making a decision… for me that was never a problem" before dementia. Difficulty reading irregular words likely contributed to Occupational Therapist, Pr3's observation that a website with a paragraph describing an assistive technology was "too hard to follow" for many people with dementia, because "the words for these products have been standard across the industry" but included a lot of technical jargon.

Participants also discussed limiting the text on interfaces as an accommodation. Information needs to include only "very brief descriptions of what something is" to not be "overwhelming" because of "too much text" [Pr2]. Pr5, a Speech Language Pathologist, provides an example of how she would change text descriptions over time with the progression of dementia, "perhaps the person is able to read, sentence level material. I might label a photograph that that person has that says, 'This is my son, Allan, and his wife, June, visiting London, England.' Then, over time, that might be too much information for that person, so I might change the label, you know, 'My son, Allan, and his wife, June.' Then, so on, until it gets to 'Son, Wife,' because those pieces of information are able to be understood by that person."

Some participants preferred pictures and icons as helpful accommodations when they experienced difficulty reading irregular words. For example, Bill describes how restaurant menus are much more accessible to him when they have "pictures of things" on the menu rather than just word descriptions of menu items. Pr17, a Dementia Consultant and Advocate, notes how visuals become increasingly important with the progression of dementia. Where when working with people in the moderate to later stages of dementia, "if you're cueing them, that it's done both with words and with pictures of some sort... it's got to be more than words" [Pr17]. In Sharon's experience living with vascular microangiopathy "I think that words are going to go before the icons are going to go." Though Sharon sees the value in computer icons, she critiques them as being "so abstract that a lot of them are meaningless to me." To address the abstractness of many icons, Pr4, an Occupational Therapist, uses "Visual guides like putting a picture of the toilet or the bathroom" on the bathroom door, rather than just the standard icons for bathrooms. Luke, living with vascular dementia, proposes a future device to verbally describe icons to address abstractness "If you were to hover over the icon and there was something on the computer there that could be spoken as to what that icon is."

Other participants with dementia described the need to switch to receiving information auditorily from technology to address surface dyslexia. As Sharon describes, when she reads she "mix[es] up information because something gets crossed in my brain. So, when I look at words the way I used to scan and speed read... I get things wrong." But when she "hear[s] it, and I can see it… I can triangulate the information to be sure I got it right" [Sharon]. Annette, who is living with Alzheimer's disease, explains: "These days, I much prefer to hear what it is I'm doing really. I do emails and everything else, yes, but sometimes I get a little bit muddled" with the written information.

Participants with subjective cognitive decline and mild cognitive impairment also described audio as currently useful, or potential useful in the future, as alternatives to reading text. Alina describes experiences where she reaches mental fatigue: "I get to the point in the evening where I don't want to look at things. I still have things I'd like to do on my computer. But I can't, my brain is tired... I think that is related to the cognitive strain." At that point, she uses audiobooks rather than printed books or reading eBooks. Margaret, also living with subjective cognitive decline, describes preferring to listen to poems. However, she chose to read the poem text alongside as a way to "try to control" and "maintain" her ability to read, because "I don't want to just become where I rely on listening." In this example, Margaret is choosing to read along as a way to stimulate her brain, where people with dementia may no longer have the ability to take in information through reading. When asked if he uses audio functions on his eBook, Chris, living with subjective cognitive decline, said that "I just haven't got there yet," indicating that he might see a need for this function in the future if his cognitive changes progress. Everly, living with mild cognitive impairment, describes how she "want[s] something that's going to be able to read to me… I just need something like that [Audible], to do everything to read everything," including everyday things like recipes or how much food to feed her dogs as this is more accessible for her than reading text-based content.

Videos were another way to accommodate difficulty with reading irregular words, by supporting individuals in receiving information auditorily as well as visually without having to read. As Frank describes his preference for "YouTube, how to guides" rather than "try[ing] to read somebody's supposed detailed instructions on how to do something. That might be reams and reams of it, miles and miles of it. Where you can go and look at a thirty-second video of it, and oh, yeah, that's it." Similarly, Ben, living with early-onset Alzheimer's disease, preferred video "little mini tutorial[s]... where you can actually watch the person do what you need to do. So instead of seeing instructions."

5.2 Auditory and Speech

Participants described auditory changes they experienced that interacted with their technology use, including fluctuating sensitivity to sound, changing speech and language patterns, and perceiving and identifying different sounds. Clinical researchers have identified hearing loss as a possible indicator and risk factor for age-related cognitive changes and dementia [70].

5.2.1 Fluctuating Sensitivity to Sound. Individuals living with dementia experience changes in their sensitivity to sound [71]. For instance, Frank, who is living with mixed vascular dementia and Alzheimer's disease, describes his decreased auditory sensitivity, where "Sometimes I need things louder and louder and louder." The need for louder audio was attributed to the progression of the day as well as "what's been happening in the day [which] will have a massive effect on the speed at which the change takes place" [Frank]. So, "as the day wears on the levels go down and down and down" [Frank] in relation to the amount of activity during the day. Pr13, an Occupational Therapist, suggests to her clients with decreased auditory sensitivity assistive devices such as "a pocket talker or a pocket magnifier so that they can hear music or have conversations." Pr5, a Speech Language Pathologist, describes using an app called Bla, Bla, Bla that includes a "face [which] changes as your voice gets louder" for people with dementia who need others to speak more loudly to hold a conversation due to their decreased auditory sensitivity [Pr5]. In other instances, as Frank describes, he can have increased auditory sensitivity where he "can't handle anything."

During conversations, participants reported having difficulty concentrating on the conversation while blocking out other noises from the environment. For example, during the remote interview session with Bill, who is living with dementia with Lewy bodies, he remarked, "I'm working extremely hard trying to stay focused talking to you because right outside the window are these guys doing their things [construction]. And, out of my eye I can see them, but not only that, I can hear them. And it's really hard for my brain to stay engaged and focused on just you." When interviewing Helen, living with early onset Alzheimer's, in person at a local coffee-shop, she explained how "the music that you hear playing and the conversations and the dishes clanking and the people moving and the trucks driving by, that's all stimuli." This caused Helen's "brain" to be "maxed out," making interacting with the interviewer much more difficult. These environmental conditions "can have a fluctuating effect" [Frank] on auditory sensitivity. As Frank describes: "I can go off to a crowded shopping center... and it's fine. Another time, I can go to exactly the same place, possibly with even less people there and within five minutes I'm so stressed out I need to leave." Further, Frank describes how these fluctuations are "not really predictable," because "I don't know what causes the same thing one day to appear totally different and have a completely different effect on you another day." In response, Frank sometimes put on headphones on the noise cancelling setting or with music. He sometimes even listens to music while interacting with others: "when I'm having a conversation with somebody, I might just slip the headphone back or the earphones."

5.2.2 Changing Speech and Language Patterns. Participants with dementia described experiencing changes in their verbal communication abilities. For example, Helen, living with early onset Alzheimer's disease, explained how due to dementia, she started to "stutter severely," including long "pauses" when she speaks and "slowness of the speech." Due to similar changes, Phillip, living with Alzheimer's disease and semantic dementia, now speaks more slowly and has to "stop to think about something" before he says it—a strategy Helen also employs. Phillip describes how his speech pattern changes makes interacting with his voice assistant "aggravating," because "I got to repeat it [what he is asking] three times because it doesn't understand what I'm saying." For this reason, Phillip proposes his idea for his Google Assistant to recognize who is speaking so that "when I speak, that it allows for more time in between my speaking so it doesn't stop in the middle."

Some participants appreciated that voice enabled smart devices make it so that voice commands could be in natural language—using "our simple language" [Frank], where "If I don't say it exactly correctly, she can still figure it out" [Sharon]. Other participants experienced difficulty with forming commands for voice enabled smart home devices. For example, Annette, who heavily uses a Google Assistant, reported increased difficulty using syntax that matches the system's requirements, making it difficult to use Google Assistant, because "the commands must be asked in a certain way because otherwise she's not understanding what I'm trying to say." Frank and Linda, living with mixed vascular dementia/Alzheimer's disease and major neuro-cognitive impairment, respectively, compared voice assistants and favored Google Assistant, because it is "the best listener" [Linda]: "Alexa... is too specific with its vocabulary… Google [voice assistant] is a bit more forgiving. And for somebody with dementia... That's critical" [Frank]. Pr11, a Memory Care Activities Coordinator, indicated that in later stages, people can be supported in prompting commands that could be understood by the voice assistants: "we have a script that says, 'To turn on light say this. To turn off light say this."'

5.2.3 Perceiving and Identifying Different Sounds. Some people with dementia experience auditory agnosia, which is impairments in sound perception and identification for select types of sounds without any clinical hearing dysfunction [53]. For example, researchers have documented people with dementia's difficulty recognizing sounds that are not words [17, 43, 50, 51]. Frank, living with mixed vascular dementia and Alzheimer's disease, describes how the "musical" sounds that different apps make "wouldn't register." In response, he's used an app (Zedge) so that "absolutely every kind of notification, I've changed to have an audible word that tells me what it is." So, when he gets a WhatsApp message his phone will audibly notify him by saying "WhatsApp."

In other instances, people with dementia may experience difficulty perceiving and identifying sounds in the form of "word deafness," where individuals have difficulty comprehending spoken information [61, 64, 94]. For example, David, who is living with vascular dementia, describes how he now has trouble interpreting information from others when they talk: "for myself…every eight words you miss like three to four of those." Similarly, Phillip describes "when you talk to me. I don't even get everything... I literally have to piece together in my mind what you're saying and try to kind of make sense of it because I'm not getting every single word that you're telling me." He elaborates, "that's just a disease. I mean, I used to be such a good listener." Joseph, living with mild cognitive impairment, describes situations where "if I'm in a store and someone is explaining something to me going too fast... I got in the habit I'd say, 'Could you slow down a little bit? I have Alzheimer's' or 'I've got some cognitive issues. Could you slow down a little bit?'" This difficulty with listening transfers to the use of Google Assistant, where he needs it to speak, "slower in speed when it talks" [Phillip]. He suggests, "set[ting] it up to have a dementia mode. So under dementia mode, you can set the delay of speaking." Linda, living with major neuro-cognitive impairment, also suggested voice enabled smart speakers speak "slower" and "pronounce better" what they are saying. Pr19, a Dementia Care Educator, emphasizes the importance that voice interactive technologies are "sensitive enough to be able to slow down and if the person says, 'Can you repeat that?"' rather than requiring the person with dementia to ask the device to slow down.

Healthcare professionals described modifying the way they interact with people with dementia when they experience difficulty with comprehension of verbal communication due to the progression of the condition. Pr2, an Occupational Therapist, describes how her interactions with people change: where she "starts out primarily just verbal and fades into needing some visual, maybe tactile, and then more tactile in the end [stages]." This is because "if you just say move your right hand this way, they may not know what that means" [Pr2], because they may no longer understand words. Often this is because as people progress with dementia "verbal, it gets lost, they stop understanding verbal things sometimes" [Pr3]. Some healthcare professionals take people's inability to understand words to mean their clients can't hear them. However, Pr12, a Gerontologist Consultant, noted how it's "not necessarily louder; you don't have to always rely on noise" to get your point across. Instead, when people with dementia exhibit difficulty understanding verbal communication, Pr3, an Occupational Therapist, described how "they really need the physical prompts versus the verbal prompts." This could include physically motioning the actions they would like someone with dementia to follow or mirror to complete a task. Pr3 describes this as "do[ing] a lot of miming… most people I worked with really the physical miming prompts rather than the verbal." For example, Pr8, a Lifestyle Director, explained that with shuffleboard, "You'd have to put it in front of them and make the motion of pushing the puck so that they could do it. Every time it was their turn." In these instances, the healthcare professional would be "mirroring them or standing in front of them and actually physically motioning what to do" [Pr8]. Pr2, an Occupational Therapist, described utilizing a virtual reality simulation to give people visual feedback on how well they were mirroring the physical movement. Pr2 explains, "If people have trouble just following verbal instructions, there was a way to put on the screen an image of them moving. It was like a mirror image so they could then see what they were doing was reflected back to them."

5.3 Dexterity

People with age-related cognitive changes can experience changes in dexterity or fine motor ability that are unique to the experiences of "normal aging" [38, 96]. Dyspraxia, a condition that partially limits motor function [41], was described by participants. For example, David and Annette, living with vascular dementia and Alzheimer's disease respectively, explained their difficulty "getting dressed" due to dexterity changes: "I'm no longer able to do zip up buttons and fiddly garments" [Annette]. Healthcare professionals in our study even use dexterity and tactile skills as determinants of progression of dementia, with Pr3 using a "box and blocks" test that involves sorting blocks quickly. Though changes in dexterity due to aging are not unique to those living with dementia. As Peter, living with subjective cognitive decline, describes how precise or accurate movements were increasingly difficult to accomplish: “I sometimes hit something which I’m not expecting to.” In activities composed of “slight” movements, like unloading the dishwasher and “taking out the glass or the cup” he sometimes “hit[s] the edge of the countertop” because of disruptions in his dexterity and tactile abilities.

Participants described a variety of dexterity changes that made using technology challenging. This included difficulty with mice, trackpads, and keyboards while using their computer. When using a mouse was difficult, Pr6, an Activities Service Supervisor, suggests “a laptop would be better for them to use,” because they could use the trackpad. But, some people, such as Phillip, prefer desktops with a mouse, because “I have trouble with laptops. I have trouble coordinating the mouse [through the trackpad] using my finger.” Still others described difficulties with computer keyboards due to “massive pains in my hands” because of a medication, which makes typing on a keyboard difficult [Arthur] or other comorbidities which caused “a tremor” [Pr13].

Touchscreens require some precise motor movements or selection between options that can be close together, which were challenging for some participants. Frank found sliding a button on his phone to answer a call difficult due to the precision and sustained movement required. When using his phone, Phillip often “send[s] them the text by accident rather than call them, you know, because I hit the wrong thing.” Peter experienced something similar, explaining how he “minimize[s] composing” emails and surfing online using his phone, because he hits “two keys at same time” or “the wrong key.” Because of the challenges he encounters with precisely typing on his phone, he chooses to only surf or send emails on his computer where he can utilize the keyboard. Phillip, living with Alzheimer’s disease and semantic dementia, explained the interplay of memory and dexterity required to operate touchscreens and how this was impacted by his changing abilities: “And I don’t remember how to do the right amount of pressure and feel to do the swipe.” In contrast, Ted, living with subjective cognitive decline, said “I’ve learned how hard and long to press a button to make it actually work most the time.”

In response to the mismatch between dexterity abilities and what was required to operate the touch-screen devices successfully, participants switched to larger devices (Arthur and Phillip), and envisioned solutions like a single press physical button in a consistent location for their phone (Phillip) or auditory input to answer the phone rather than swiping (“then I haven’t got to touch anything” Frank). As Sharon, living with vascular microangiopathy, noted her desire for a computer to “alternate between modes of inquiry” by “use[ing] a linguistic and touch interface” where one could visually use icons, tactilely press on the screen, and have an audio interface, so that someone wouldn’t have to rely solely on interact with the device through touch.

5.4 Proprioception

Participants described changes in proprioception or their ability to move their bodies, which affected their daily lives, including fluctuations in motor memory, and changes in balance.

5.4.1 Fluctuations in Motor Memory. Pr3, an Occupational Therapist, describes how over time, someone with dementia’s ability to do tasks changes “because they lose that motor memory and they just lose the memory portion of how to perform those tasks at times.” In these instances, one strategy healthcare professionals use is to physically move their clients bodies in the motion of the activity, where the client would then be able to follow the motion on their own. Healthcare professionals described using Teepa Snow’s (a Dementia Care Educator [144]) “hand-over-hand guiding” (also known as “hand-under-hand”) where “I’m moving her body for her in a way” to provide “tactile” interactions [Pr3] “use[ing] the person’s hand so they’re not surprised” [Pr18]. Pr8 described an application of hand-under-hand where one of her clients with dementia “was struggling” to complete a coloring activity “and they loved to color.” So, Pr8 “put the pencil in their hand and put my hand over their hand and color[ed] with them until they started doing it themselves." Though Pr8 does elaborate that their ability to color is "all short-term as well. It doesn't last as long." The goal of using body movement is to "make the most of somebody's procedural memory, which is preserved longer into the disease process" [Pr5].

A second strategy healthcare professionals used is to provide physical objects as embodied cues to spark motor memory. For example, utilizing objects from "somebody's previous profession or routine" is one way to access procedural memory [Pr5]. So, "If somebody was an electrician, I might engage them in activities where they're sorting the little tiny wire caps that they would have used in their profession as opposed to a stay at home mom, a homemaker, who I might engage in clipping coupons or something of that nature." As another example, Pr12, a Gerontologist Consultant, shared the following:

> We put the Wii on, and one of the ladies, I read in her background that she had played tennis.... All of a sudden, this woman got out of her wheelchair, got the typical tennis stance because she was a lifetime tennis player, and started swinging the Wii [remote] with the tennis racket. We used the Nerf attachments that you can put on so it looked like a tennis racket and started playing tennis. It was beautiful... she actually got up and played like a professional tennis player.

Participants living with dementia also described utilizing physical objects as embodied cues to help them in their daily lives. For example, though Helen uses a complex reminder system with her Google Calendar on her phone, she explains how sometimes she has to use a "physical post-it note" that she "will physically keep it in my hand" as a "tactile reminder" of where she is going when she leaves her house. Although the post-it note is one example of an embodied cue, Helen takes embodied cues one step further by "either stick[ing] it [the post-it note] on the purse" or "on the phone," which are the two items she has ingrained in her routine to take as she leaves the house. Thus she "makes sure it [the post-it note] goes with me." She described how "even sticking the post it note on the door doesn't work. There has to be something to force me to touch it" in order for the embodied cue of the post-it note to be effective [Helen]. In these instances, people in the earlier stages of dementia may experience changes in ability to engage in many everyday activities of daily living. But by utilizing objects and routines they know well, they are able to surface procedural motor memories and continue to participate in everyday activities.

The key to the embodied cueing strategy was finding objects that facilitated ingrained motor movements. For example, embodied cueing with technology only works "if the person was a technology user, like I often think when I get older and experience dementia perhaps a telephone with a calendar is going to be the habit or routine that I am used to. If you're talking about my mom, her technology is a television with a remote control" [Pr5]. When there is not a match between embodied cues and ingrained behaviors, this can "make them a little bit more confused" [Pr4], for instance, having clients "sign off on the home health tablets with their finger" where "they're looking for the pen and they're trying to give us their finger back thinking it's the pen," because "they're not used to that technology" [Pr4]. To sign a document with their finger was not a motor movement that was ingrained in their everyday procedural memory prior to dementia.

5.4.2 Fluctuations in Balance. People with dementia may experience unique changes in balance [38]. For example, Bill, living with dementia with Lewy bodies, explains how he cannot drive anymore "because I have my balance issues." Changes in balance can fluctuate throughout the day, where Andrew, living with Alzheimer's disease and vascular dementia, described how: At "8:30 this morning, there was there wouldn't be no way for this to take place because I was in a very, very thick fog where I was not able to get words out... [and] my balance was off." However, by the afternoon when the interview was scheduled his balance had changed again and had gone back to normal. Pr3, an Occupational Therapist, describes how balance can fluctuate from day to day: "Every day is going to be different. If mom got up yesterday and walked beautifully to the bathroom and you guys had a great day, it might not be that way tomorrow." "Balance assessment[s]" are even included in "cognitive assessments" given by healthcare professionals, where they "check how someone does getting up, turning around, eyes closed, eyes open" as well as "assess[ing] someone's strength or range of motion" to check the progression of the condition over time [Pr2]. Pr2, an Occupational Therapist, used virtual reality to assess motor ability, asking patients to perform a series of movements: "Move your arm up, reach this way, move that way, lean this way or step to the side." While patients were doing these tasks, the computer would assess how precise these movements were and provide Pr2 with real-time feedback.

Healthcare professionals used various accommodation strategies for their clients with dementia experiencing changes in balance. For example, Pr11, a Memory Care Activities Coordinator, utilizes Alexa with her clients with difficulty balancing to turn on and off the lights because this can "be so much easier than them trying to stand up, causing more fall risk and leading to hospitalization." Pr2 tries to include exercises that "not only support someone's goals and strength and whatever they're working on but also can be enjoyable to someone." For example, she uses "a little set of flowers, so people can garden if they want to at least get their upper body going, [and] work on balance" [Pr2]. Taking a similar approach focusing on enjoyment, Pr8, a Lifestyle Director, has found "Dancing... If you stood someone up, even if they had trouble with balance they could dance and walk to the music where ordinarily they couldn't." In other instances, healthcare professionals had to focus on more functional activities of daily living and working with ingrained procedural memory. For example, Pr3 describes how "recently I had a lady with multiple cognitive diagnoses, so when you interplay those together it's always a mixed bag... so this particular lady just was not able to get up and really move to the bathroom safely." When Pr3 tried to implement a new "route to the bathroom that I deemed as safer" this client would not use it. So, Pr3 "put grab bars everywhere she put her hands" on her typical route to the bathroom to support her "patterns, instead of trying to break them."

5.5 Smell

Clinicians have documented the unique changes in olfaction (smell) that people with age-related cognitive changes experience [5, 84, 100]. Regardless, healthcare professionals in our study point to smell as one of the remaining ways to engage the senses of people with even in "the very end-stage dementia" [Pr2]. As Pr2, an occupational therapist, described "the only thing I could do with them is, like, we had this sensory bin, and we have different scents and aromas that they could smell." Specifically, one of her clients, "who had really just looked like she was not engaged in anything. She suddenly would smell something, and she would look up and make eye contact and smile" [Pr2]. Similarly, Pr6, an Activities Service Supervisor, uses "sensory stimulation" through "scents or lotions, hand massages, that kind of thing" to engage with "residents who are unable to verbalize." Pr7 and Pr8, an Activities Director and Lifestyle Director, respectively, utilize flower arranging activities for the tactile and scent engagement but also as a way to "bring back memories... You know a flower for happy occasions. Even though it could have been sad occasions, it's something that will trigger, mostly a good memory" [Pr8]. In other instances, Pr8 described, "put[ting] on a pot of soup in a crockpot and just the aroma of the food would help increase their appetite" and provide a stimulating experience. Aromatherapy was used by some healthcare professionals as an engaging sensory experience, because "when they breathe it in, they don't have to do anything your body knows what to do. It just reacts." This instinctive reaction to aromatherapy was used by Pr11, a Memory Care Activities Coordinator, when "someone who, let's just say they're in hospice care, they're at their end stage. One of the things we can have Google Assistant to play music, to set some aromatherapy for them to set the scene with the lights… So, that would help advance the quality of life for that individual going through that last journey of life." Healthcare professionals were the only group of participants to describe changes in olfactory ability. All instances were described in relation to provide engaging or enjoyable experiences for those in the very end stages of dementia.

6 DISCUSSION

Our analysis of interviews with 15 people with mild to moderate dementia, 2 people with mild cognitive impairment, 5 people with subjective cognitive decline, and 19 healthcare professionals describes how sensory changes experienced by people with a range of age-related cognitive changes affect technology use. Clinical studies have demonstrated each of the sensory changes participants in this study described: visual [15, 98, 105, 115], auditory [17, 44, 50, 52, 61, 64, 71, 94], dexterity [38, 41, 96], proprioception [38, 107, 127], and olfaction [5, 40, 84, 100]. Therefore, the contribution of our work is not to surface these sensory changes, but to bridge the clinical research with the body of research aiming to design technologies that are accessible and useful for people experiencing age-related cognitive changes. The present article takes a step back from our previous paper [28], which focused on the technological accommodation strategies people with dementia and healthcare professionals use to overcome challenges with technology use due to sensory changes to provide an understanding of the effects of sensory changes people with age-related cognitive changes experience on technology use. Below, we first discuss each of these sensory changes and ways to leverage optimal modes of sensory interaction for accessible technology use with existing and emerging technologies. Finally, we discuss how accessible sensory stimulation may change across the spectrum of age-related cognitive changes.

6.1 Interacting with Technology Using the Senses

Participants described changes to vision like lowered visual acuity, color perception, and surface dyslexia, which affected reading, texting, and finding documents, resembling those described in the clinical literature [98, 105]. For visual changes, participants benefited from changing font size, as well as from existing accessibility features that have been designed for people with visual impairments, such as utilizing voice to text dictation or voice recording messages (as noted in our previous work [28]). Participants also emphasized how changes in color perception made it important for technology to include adjustable color, intensity of brightness, and color contrast on their devices [28]. Some participants used the attention-drawing properties of color, along with conventions of meaning assigned to different colors, to accommodate cognitive changes. For example, they color coded tasks of a digital calendar, using red to signal urgency [Helen]. We can also learn from the barriers and workarounds participants described, such as difficulty selecting something from a cluster of items, needing everything for a task to be visible at one time, as well as from their experiences with surface dyslexia. Designers may attempt tactics such as leveraging visuospatial organization and split screens to keep all documents for a task visible at one time, as well as simplifying text phrases, using images or short video tutorials instead of or in addition to words, and utilizing auditory read-aloud settings either independently or to "triangulate" auditory information with written information.

Though auditory interaction was described by many participants as their preferred mode, some participants described experiencing fluctuating sensitivity to sound—as described in the clinical literature [71]—meaning in some instances they needed increased volume and in others they needed to utilize noise canceling headphones to block out all sound. Other participants described difficulty perceiving and identifying sounds. Clinical research shows people can experience this in the form of "word deafness" [61, 64, 94] or in the form of difficulty distinguishing musical tones [43, 56], which can affect the way audible notifications on devices are perceived by users with more significant age-related cognitive changes, such as dementia. This work also has implications for the design of voice enabled smart speakers, as some people with age-related cognitive changes may need smart speakers to speak "slower" and "pronounce better" if they are experiencing "word deafness." Additionally, participants describe changes in speech and language that affect their use of voice-enabled smart-speakers. For example, some participants described developing a stutter and experiencing slowed speech. To accommodate these changes, participants describe wanting voice-enabled smart speakers to be able to adjust based on the auditory and speech needs of the user. Though the nuanced needs of users with dementia and age-related cognitive changes in voice interactions with technology is a topic beginning to be investigated [19], further work is needed in this area.

Dexterity changes, as described in the clinical literature [38, 41, 96], affected touchscreen use, as these devices require precise motor movements for selection between options and the use of the right amount of pressure, which was challenging for some of our participants. These findings provide a more nuanced understanding that advances previous work [35, 62, 120, 135] on the effects of dexterity changes people experience on the accessibility of touchscreen devices and how they imagine future accommodations. To accommodate their dexterity changes, some participants switched to larger devices. Others envisioned solutions like a single press physical button in a consistent location for their phone or utilizing auditory input to answer the phone rather than swiping. Previous work with people with dementia has shown the effectiveness of auto-snap on touchscreen devices as one accommodation for dexterity changes [135]. Further work is needed to expand our understanding of future technical adaptations to address dexterity changes for people experiencing age-related cognitive changes.

Similarly to Guan et al.'s work [46], our findings point to the usefulness of miming actions for people with dementia to mirror when people are no longer able to understand verbal communication. This finding supports Bouvier, Hinz, and Schmidt's concept of a "virtual coach in a mirror" for people with dementia [16]. This finding also provides further justification for extending research efforts in Augmented Reality (as in References [8, 137]) and XBOX Kinect (as in Reference [32]), as our findings demonstrate the potential of these tools to provide accessible sensory prompting when verbal interactions become less accessible. Additionally, with changes in proprioception, participants described the importance of motor movement to trigger procedural memory. This finding points to the potential of using technology to prompt motor movement. For example, future work should consider testing the use of haptic gloves [78] to prompt motor movements for people with dementia.

With the changes in balance that people with dementia experience [38], this opens up new opportunities for voice-enabled smart speakers to facilitate everyday tasks such as turning on and off devices without having to stand up, which could put someone in jeopardy of falling and hurting themselves. However, this brings up debates over agency vs. safety in dementia technology design [27, 54, 55, 65, 113], which are of critical importance for technology designers in this space to consider.

Our findings also indicate using physical objects as embodied cues to spark motor memory for people with dementia. This finding links efforts to designing accessible interfaces for dementia with the extensive research designing for embodied interactions with people with dementia [12, 31, 66, 81, 131, 132]. For example, one participant described using a Nerf tennis racket attachment to their Wii remote to engage with a client. This person primarily uses a wheelchair due to changes in physical abilities. However, when the client touched what looked and felt like a tennis racket, they were able to stand up and play Wii Tennis, because they were prompted with a personally meaningful embodied cue. This finding implies the potential of including embodied cues in virtual environments (as in Reference [63]) but specifically to facilitate exercise and movement for people with dementia and mild cognitive impairment (as in References [33, 77, 123, 124, 126]). This finding also points to the potential for designing Internet-of-Things environments, providing embodied cues through a sense of touch with familiar objects that are interconnected with technical environments for use by people with dementia.

Embodied cues were also used to assist with focus and comprehension for people in the mild to moderate stages of dementia, such as described by Helen's use of Post-it notes as "tactile reminder[s]" for assistance with navigation. In particular, the permanence and continuous presence of physical objects appear to be beneficial (as noted in our previous work [28]). Uhlig et al.'s concept of designing digitally augmented everyday reminder objects to "break down and communicate complex information via sensory input and output" [122] serves as inspiration for future work that aims to provide embodied reminders for people with dementia. At the same time, it is key to consider how embodied cues are only useful if the object held meaning or was a part of daily routines for someone before they developed dementia.

Smell also changes as a result of dementia [5, 40, 84, 100]. Participants described using aromatherapy, the smell of slow cooking food, and sensory bins to engage with people in the most severe stages of dementia. In these instances, smell actually facilitated reminiscence and positive feelings. This finding points to the potential of incorporating smell into multi-sensory environmental therapy for people with dementia [23] and including the use of smell in combination with virtual reality [9, 95] to support reminiscence and enjoyment for people with dementia.

6.2 Accessible Sensory Interaction across the Spectrum of Age-related Cognitive Changes

In this section, we provide preliminary evidence for accessible sensory interactions with technology for a range of age-related cognitive changes, as described by participants in our study. Our intention is to support HCI researchers and technology designers in investigating a continuum of accessible sensory interactions for people with age-related cognitive changes and thus be better equipped to design adjustable, multi-modal devices to adapt to a range of abilities and changes in abilities. Further, we intend to help researchers and technology designers distinguish between sensory changes people with different age-related cognitive changes may experience, which can assist in designing for more targeted groups of end-users with age-related cognitive changes. These distinctions will also assist technology designer and developers in making technologies adaptable with the progression of age-related cognitive changes, which is particularly useful when considering the often unique changes in ability each individual with dementia can experience.

Participants with subjective cognitive decline, mild cognitive impairment, and mild to moderate dementia described how visual changes they experienced affected their interactions with technology. For example, many participants described having to use voice-to-text due to changes in visual acuity or auditorily listening to text-based information be read aloud to accommodate surface dyslexia or mental fatigue. In addition, healthcare professionals noted how verbal communication and interaction is best for people in the very mild stages of dementia. Participants across the range of age-related cognitive changes also described their increased difficulty with dexterity, specifically with fine-motor skills required for using touchscreen devices and computers. To accommodate changes in dexterity participants described their desire for a single button system or always using voice to interact with their devices. Based on these findings, we posit that verbal interactions with technology may be more accessible for some people with more mild age-related cognitive changes, such as subjective cognitive decline, mild cognitive impairment, and mild dementia.

Participants in our study described changes in speech and language patterns, such as developing a stutter, slowed speech, and word deafness, which affected people's ability to interact with others and technologies through verbal communication. When these verbal and auditory changes occurred, participants noted the use of visual stimulations as the next best mode of interaction. As one healthcare professional noted, her interactions with clients start with primarily verbal interactions, and as her clients progress she uses more visual interactions [Pr2]. But not all forms of visual stimulation were considered equal. As several participants described, written information was more difficult for people to understand than visual images (e.g., Bill, Sharon, Pr17). Healthcare professionals also described how color perception changes for people shifting from the mild to moderate stages of dementia [Pr3]. Though providing visual prompts through miming and asking people to mirror their actions was one strategy that healthcare professionals described when verbal or auditory interaction was less accessible.

When visual prompting became less accessible, people with dementia and healthcare professionals described using embodied cues (e.g., Helen's sticky notes) or for those who were in the more advanced stages of dementia interacting using hand-over-hand prompting (Pr8's coloring exercise). Specifically, healthcare professionals described the use of more tactile or physical interactions in the end stages of the condition rather than visual or verbal, such as in the example Pr12 gave of the woman who was a life-long tennis player. This is an especially accessible form of interaction for those in the later stages of dementia, as these embodied cues may spark procedural or motor memories that are preserved much longer into the progression of dementia. Though, when designing technical interactions triggered by embodied cues for those in the later stages of dementia, it is important to consider changes in balance that people may experience that could make certain activities, such as playing Wii tennis, difficult and potentially hazardous.

Interacting using one's sense of smell was only described when participants referred to people who were in the very last stages of dementia who were approaching end of life. For example, one healthcare professional even associated sensory prompting through aromatherapy with hospice care for people with dementia in their last days of life. Therefore, based on these findings, we posit that technical interventions that include interactions with users' sense of smell may be particularly useful for interacting with those in the latest stages of dementia, although clinical research has shown odor identification can be more difficult for people with Alzheimer's disease, vascular dementia [5, 84, 100] and mild cognitive impairment [40]. Future work is needed to investigate the olfactory abilities that remain and the potential of technical interactions that utilize the sense of smell for people with various types of dementia as well as across the spectrum of age-related cognitive changes.

Although our findings provide some evidence for accessible sensory interactions for people with different age-related cognition changes, our findings also demonstrate instances where participants' visual, auditory, and proprioception abilities fluctuate day to day or even throughout a day. Thus, accessible sensory interaction may fluctuate within a day or even within an hour. With this understanding of the fluctuations of the condition and the wide variety of ability changes, we urge future researchers to conduct longitudinal studies with people with various age-related cognitive changes to better understand how sensory abilities change over time and how these sensory changes affect technology use. Future work in this area should also consider systematically testing different sensory modes of interactions with technology to better understand how to provide accessible interactions with technology for those experiencing age-related cognitive changes.

It is particularly important for future research to investigate the varying effects on the sensory ability changes people experience with different types of dementia [38, 43, 56, 97, 99]. While we provide an overview of these sensory changes, this article does not comprehensively break down sensory changes by different types of dementia (e.g., dementia with Lewy bodies, vascular dementia, and Alzheimer's disease). One direction for future work in HCI is linking specific accessibility features and building accessibility profiles for each of the different types of dementia. Though we recognize dementia is complex and even those with the same type of dementia may experience differences in sensory changes, this mapping would help technology designers and developers to make adaptable and customizable accessibility options to accommodate the spectrum of sensory changes with dementia.

7 CONCLUSION

This work provides a first step toward bridging the gap between the clinical literature describing sensory changes due to age-related cognitive changes and understanding how these sensory changes effect technology use. Through interviews with people with subjective cognitive decline, mild cognitive impairment, mild to moderate dementia, and healthcare professionals who work with people with dementia, findings from this study describe how changes in visual, auditory, dexterity, proprioception, and olfactory abilities effect engagement with technology. Together these findings demonstrate ways to leverage optimal modes of sensory interaction for accessible technology use with existing and emerging technologies. Finally, these findings provide preliminary evidence for accessible sensory interactions with technology across a spectrum of age-related cognitive changes.

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