Title

ACSAS: A Web-based Ambulatory Cognitive Self-Assessment System for Older Adults

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Publication Date

2019

UNIVERSITY OF CALIFORNIA
SANTA CRUZ

ACSAS: A WEB-BASED AMBULATORY COGNITIVE SELF-ASSESSMENT SYSTEM FOR OLDER ADULTS

A dissertation submitted in partial satisfaction of the
requirements for the degree of

DOCTOR OF PHILOSOPHY

in

COMPUTER SCIENCE

by

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June 2019

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List of Abbreviations

Abbreviation	Description
AAL	Ambient assisted living
ACA	Ambulatory cognitive assessment
ACSAS	Ambulatory cognitive self-assessment system
API	Application programming interface
CCT(s)	Computerized cognitive test(s)
CDC	Center for Disease Control
DOM	Document object model
EMA(s)	Ecological momentary assessment(s)
IoT	Internet of things
IRB	Institutional review board
JSON	JavaScript object notation
MCI	Mild cognitive impairment
MMSE	Mini-Mental State Exam
OOP	Object oriented programming
RAVLT	Rey Auditory Verbal Learning Test
SUS	System usability scale
UI	User interface
WCAG	Web Content Accessibility Guidelines
WHO	World Health Organization

Abstract

ACSAS: A Web-based Ambulatory Cognitive Self-Assessment System for Older Adults

by

Sean-Ryan W. Smith

We are at a moment in history for which the size and rate of growth of the aging population is the highest it's ever been, with 21% of the human population projected to be 60 years of age or older by 2050. The CDC reports that aging is the greatest known risk factor for developing Alzheimer's disease, which is the most prevalent form of dementia. Cognitive testing and assessments are traditionally used to aid in detecting cognitive impairment in older adults. However, conventional cognitive assessments can be expensive, time consuming, suffer from recall biases, and may neglect ecological and contextual factors pertinent to the assessment. Ambulatory cognitive assessment (ACA) methodologies provide an avenue to rapidly assess an individual in more naturalistic settings while maintaining ecological validity. Given the sensitive nature of cognitive assessments, traditional ACA studies have focused on its use in clinical psychology. However, studies have shown that older adults are active and interested in monitoring their own cognitive health and well-being. Little to no research has been done examining how ACA systems may be used as an end-to-end solution for self-monitoring cognitive well-being in older adults. Thus, using human-centered design principles, the contribution of this dissertation is fourfold. First, I explore stakeholder needs and requirements with ACA systems through observations and interactions. Second, I present the design of a novel, Web-based ambulatory cognitive self-assessment system (ACSAS) and evaluate its feasibility of use with healthcare social workers through formative usability testing. Third, I provide insight into the context of use surrounding the ACSAS for use by older adults through case studies and group discussions. Finally, I present design recommendations, including data visualization guidelines, for the ACSAS through a summative usability evaluation with older adults. Throughout these studies, I reflect on the lessons learned and design implications of developing the ACSAS or other ACA systems for older adults to self-monitor their cognitive well-being.

To dream well.

Acknowledgements

I would first like to thank my advisor, Dr. Sri Kurniawan, whose expertise and support were invaluable to my success as a doctoral student. This experience has been the most incredible experience of my life and I look forward to what comes next.

I would like to also thank Dr. Steve Whittaker for his guidance and input throughout my research.

I would like to thank my lab mates and colleagues for their help and collaboration throughout my academic career, in addition to their friendship.

I want to thank all the wonderful users and facilities I’ve had the opportunity to work with over the years for their time and support of my research.

Chapter 1

Introduction

1.1 Trends in the Aging Population

The 21st century will continue to see significant demographic movements and cultural shifts caused by the aging world population. The global percentage of older adults is expected to grow from 11.7% in 2013 to 21.1% by 2050 (Figure 1), with an expected population projection of two billion by 2050 [94]. It is estimated that by 2030, 20% of the U.S. population will be 65 years or older [17]. As the average overall life expectancy for individuals continues to increase, so does the need for accessible public healthcare solutions. This potential age gap lends itself to public health service disparities, such as a possible increase in cognitive issues related to aging [4]. It is reported that aging is the greatest risk factor for developing Alzheimer's disease [4], which is the most common form of dementia. This can result in severe cognitive impairments that interfere with an individual's daily life. A significant portion of cognitive health related issues and diseases, including mild cognitive impairment (MCI), can be successfully treated if detected early [17,91].

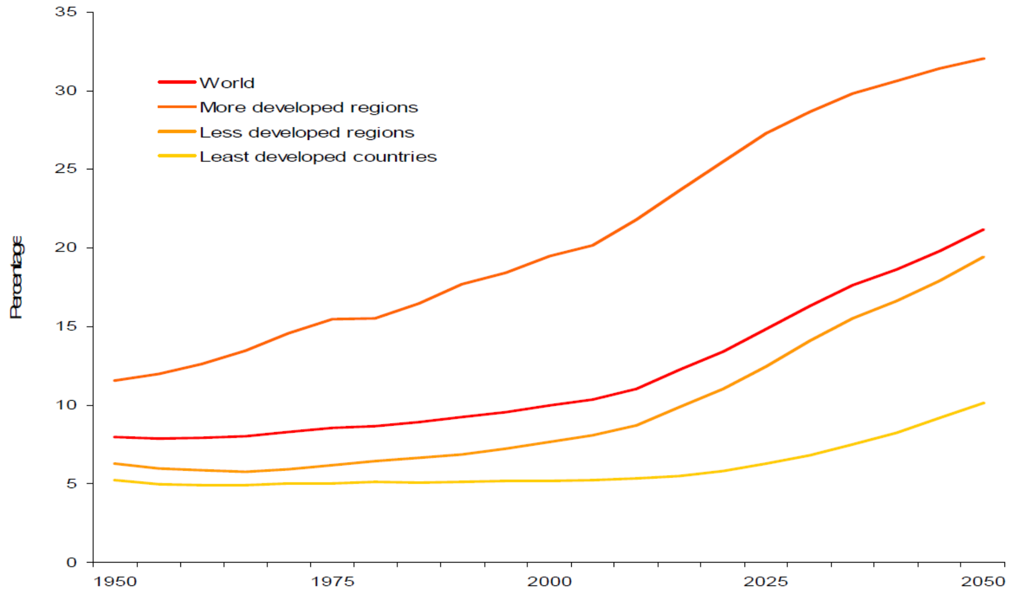


Figure 1. The World Health Organization (WHO) projected population size percentage of individuals 60 years of age or older between 1950 and 2050.

1.2 Aging Related Cognitive Decline and Impairment

Cognitive impairment in an individual can arise from many different factors and stages in life. The CDC defines cognitive impairment to involve difficulties with cognitive functions such as memory, learning, language, perception, concentration, and/or making decisions and carrying out tasks in everyday life [4]. The implications of cognitive impairment can be significantly severe and often require dramatic life adjustments. Daily activities that may have once required little to no assistance may now require substantial assistance. The severity and categorization of cognitive impairment can vary substantially from individual to individual. As a result, it is crucial to understand the specific needs of individuals with cognitive impairment and their cognitive abilities.

In the U.S., it is estimated that more than 16 million individuals are affected by some form of cognitive impairment, whether it be due to stroke, Alzheimer's disease, epilepsy, traumatic or acquired brain injury, etc. [2]. Furthermore, the percentage of households affected by cognitive impairment is approximated to be 16%. This percentage of households only highlights the quantitative effect of cognitive impairment and does not reveal the qualitative impact on families and caregivers. For example, individuals with cognitive impairment may require 24-hour care and may increase the responsibilities and workload of caregivers, many of whom are family members and/or have families of their own. These statistics show the impact cognitive impairment can have on families, highlighting the importance of being able to detect and treat cognitive impairment sooner.

The CDC reported that, in 2013, one in eight U.S. adults of age 60 or older experienced some form of progressive cognitive decline, including confusion and memory loss [17]. In 2013, the Alzheimer’s Association noted that Alzheimer's disease was the 5th leading cause of death among older persons aged 65 – 85 [4]. They reported that the likelihood of developing Alzheimer’s doubles about every five years after the age of 65. With a significant portion of the U.S. population reaching and surpassing this age, there is a greater initiative to investigate cognitive decline due to aging and develop effective solutions to detect and address cognitive impairment earlier.

It is said that a significant portion of cognitive health related issues and diseases can be successfully treated if detected earlier [17,91]. This is becoming increasingly important as the global and U.S. population percentage of older adults continues to rise.

Moreover, individuals affected by a stroke later in life may be at a higher risk for post-stroke onset of dementia or Alzheimer’s disease, which can lead to advanced cognitive impairment [62,63]. The ability to effectively screen and detect MCI earlier may help tackle this issue.

1.3 Cognitive Tests and Assessments

Given the complexities and variables that factor into cognitive decline and impairment, cognitive tests and assessments are the primary tools used to evaluate the cognitive functioning of an individual. In terms of cognitive assessments, there are numerous studies of a wide range of cognitive test batteries used for assessing different domains of cognitive functioning, such as attention, memory, language, etc. [6,39]. Some of the more widely used assessments include the Mini-Mental State Exam (MMSE) [30], the Montreal Cognitive Assessment (MoCA) [60], the Rivermead Behavioural Memory Test (RBMT & RMBT-E) [92], the Repeatable Battery for the Assessment of Neuropsychological Status (RBANS) [68], and the Cambridge Automated Neuropsychological Test Battery (CANTAB) [71], among many others [39,81,91]. Advances in computer and Web technology have allowed for new ways to test and assess.

1.4 Computerized Cognitive Tests and Assessments

Computerized cognitive tests (CCTs) offer many new avenues for practical applications and research into cognitive assessment methodologies [6]. By nature of

CCTs, the speed and cost of administration can be significantly reduced, allowing for rapid and adaptable deployment of assessments. This increases the availability of cognitive testing for individuals who may not otherwise have access to such assessments. Advances in device interface modalities allow for intuitive accessibility options for individuals with special needs. Moreover, the shrinking size of computers provides portability options for cognitive tests and assessments to be administered. Increased CPU speeds further incentivize the use of automated data acquisition algorithms [34] as well as data exploration [96].

With this continued trend of computerization, it’s no wonder that many standardized cognitive tests have been translated into computerized administration [6,91]. Some common CCT batteries include the CANTAB, the Computer-Administered Neuropsychological Screen for MCI (CANS-MCI) [85], and CogState [18], to name a few [91]. The use of personal computers and mobile devices has gained interest in the field of cognition and training [12,35,48,82]. The computational power, lowered cost of administration, interface and portability options, and accessibility capabilities of smartphones and tablets lend themselves well to cognitive research initiatives. In addition, high adoption rates of mobile devices strengthen the case for use of smart and mobile devices for CCTs.

1.5 Telehealth and eHealth

Advances in computer and Web technologies have enabled new forms of health services to be delivered to a broader population of people. Telehealth systems allow for information and communication technology to be used to remotely interact with, evaluate, diagnose, and treat individuals in areas where professional health care is limited. With this, it becomes increasingly feasible to utilize Web- and computer-based cognitive testing in telehealth solutions [78]. Technologies such as screen readers [57] and speech recognition algorithms [72] allow users with physical or cognitive impairments the ability to interact with digital interfaces in intuitive ways, thereby enabling broader impacts and accessibility for telehealth solutions. These technologies lend themselves well to the application of CCTs.

As we age, one’s mental, physical, and emotional functions are impacted. It’s not surprising that a primary area of interest for older adults is health and well-being, not only related to concerns, but also recommendations and guidance. Fortunately, with more and more information becoming readily available through the Internet, people can find health related information that might have otherwise only been obtainable through an in-person doctor or professional visit. It was estimated in 2013 by a Pew Internet Project study that 35% of U.S. adults have searched for health information online specifically to figure out medical conditions for themselves or others [32]. Not only are Internet users searching for information via health websites, but they are also engaging in health information exchange through social network websites. An earlier study reported that 18% of Internet users have used the Web to find other people with similar conditions [31]. Of these users, 23% of users who had chronic conditions reported using the Internet to interact with others online.

The ability to search and understand health information through digital sources for the purpose of applying said understanding to real-world health problems and decisions is referred to as eHealth literacy [61]. A telephone study in 2015 was conducted with 493 older adults living in Florida to investigate factors that influence eHealth literacy and use of Web 2.0 for health information by older adults [83]. The authors found that younger age and higher amounts of device usage were significant positive indicators of eHealth literacy and use of Web 2.0 for health information. Furthermore, higher education levels were shown to positively influence eHealth literacy, while being female was a significant positive indicator of use of Web 2.0 for health information. It was discovered that, though participants felt confident in their ability to search and find health information online, they found it challenging to discern the quality of online sources. The authors highlight a lack of interventions to increase the confidence and literacy of older adults in eHealth and suggest further investigations into improving older adults' confidence in eHealth literacy via training. Not only can Internet training increase the confidence of older adults, it has been shown to potentially improve their overall sense of well-being [77]. Moreover, the advances in Web tools and services afforded by social network websites (e.g., groups, events, marketplaces) will continue to create social opportunities for user health information and support.

As more and more of our world becomes digitally connected, so too does the permeation of Web-based applications. It is not uncommon to hear about internet connected homes [93] and wearable devices [69] these days. As such, the possibility space for development of internet- and Web-based applications will continue to expand. New Web standards and interaction paradigms allow for more users to use the internet [95]. With the number of internet users continuing to rise, the impetus for careful examination of Web interaction modalities and user accessibility issues becomes increasingly apparent.

1.6 Internet-of-Things

Internet-of-Things (IoT) is the concept of digitally connected devices sharing data to provide services and functionality to a user. Common examples of IoT technology include the Nest thermostat or smart speakers such as Amazon Alexa or Google Home. A prominent benefit of IoT devices for older adults include health monitoring and assistance. Through these connected devices and sensors, health related services, such as medication tracking through smart pill boxes [97], can be specifically tailored for the user. Moreover, guidance and assistance can be delivered directly to users via IoT devices such as smart speakers or activity trackers (e.g., smartwatches) [3]. As these technologies continue to blur the lines between the physical and digital worlds, new support opportunities for older adults will continue to emerge. It is imperative to include the ageing population when exploring the design space of IoT devices and applications.

An application of IoT devices that is gaining more exposure in the ageing population is ambient assisted living (AAL). AAL refers to a communication network of sensors and devices specifically aimed to help support and assist a user in their daily life while maintaining user safety and independence [22]. These technologies enable health monitoring [22,65], detect possible emergencies and falls [73], and offer guidance [65] to aid older adults living independently, or ageing in place. Though IoT and AAL technologies offer various benefits to potentially improve the quality of life of older adults, they don’t come without a tradeoff. For such technology to carry out the functions required for services, data must be acquired and shared through the communication network. This sharing of potentially sensitive data is not limited to IoT and AAL services but can apply to general Web-based services and tools. The issue of information privacy is a critical concern for most older adults when deciding to use Web tools and services.

1.7 Online Privacy, Trust, and Behavior

One of the biggest concerns for older adults when dealing with the Internet and Web-based technologies is privacy. In 2017, Zeissig et al. reported their findings in a German study of 200 older adults and their perceptions of online privacy [99]. Privacy of data and concerns of information security are among the top barriers for acceptance of online technology by older adults. Though there are similar levels of concerns over privacy between younger and older adults [41,99], differences in attitude come into play when taking into account the context of Internet usage. Bergström points out, for example, that older adults were more concerned with credit card and online financial security, whereas younger adults expressed concern over online social content [7].

Zeissig et al. (2017) report that privacy self-efficacy, awareness, and experience influenced the attitudes of older adults towards privacy as well as the protection behavior [99]. They found that protection behavior was higher in older adults than younger adults. This finding, however, is based on the self-reported measure of the user's perception of their protection behavior and may not fully represent the actuality of their behavior. They point out various issues that could potentially lead to low protection behavior in older adults, including possible complexities of online privacy protection tools and users' potential lack of awareness of which specific information is private and protected.

1.8 Usability and Accessibility Issues

The pervasiveness of the Web appears to be growing in line with the aging of the population. A report by Pew Research Center's Internet & American Life Project in 2012 estimated that more than half of adults age 65 or older were online [100]. Of these older internet users, 70% claim to use the Web on a typical day. Moreover, Zickuhr et al. note that seven out of every ten older adults across the U.S. own a cell phone of some kind. This is up from an estimated 57% in May 2010. Unfortunately, aging users face many challenges when trying to get access to the internet due to declines in vision, hearing, mobility and cognitive abilities. Advances in Web and mobile technology have allowed for improved accessibility capabilities of such technology, thereby aiding in usability for a broader range of users, including those with various disabilities. It is therefore important to take into consideration the special needs of an individual when developing Web interfaces.

Though both computerized and pencil-and-paper cognitive tests rely on proper interaction by the user, tests designed to be self-administered need to be particularly mindful of possible usability and accessibility issues. In a joint position paper on the standards for computerized neuropsychological assessment devices [6], Bauer et al. address the importance of issues faced by the examinee with regard to cultural, experiential, and disability factors. They stress the need to consider the user's background and status, i.e., examining the user's educational background and ability to interact with the system interface. The user's ability or inability to correctly interact with the computerized assessment may be compounded from numerous other factors, e.g., motor or sensory impairment, that should be taken into consideration when developing CCT systems.

For any cognitive test—computerized or otherwise—to be successful, it is crucially important that the testing activity be accessible to the user. The data gathered from the tests may no longer be valid if the test was not properly accessible [6]. Tests that gather reaction time may become invalid if the user has a physical impairment that impedes their motor skills, but not necessarily their cognitive functioning, thus producing erroneous test results. Moreover, tests requiring numerical or symbolic processing may cause errors in response for individuals with dyslexia, for example. This issue continues through to user feedback and data visualization techniques. In order to provide meaningful feedback to the user, it is crucial to consider accessibility in user feedback design. Such situations must be considered when developing cognitive tests, especially self-administered and/or computerized for older adults.

Bauer et al. also discuss the possibility of computerized testing missing important behavioral information of the user, such as display of emotion and perceived user motivation or engagement. For example, in an examiner-administered test, the examiner might notice that the user is making aural sounds indicative of frustration or boredom, which could then reveal insight into the interpreted results of the test and user. The user's computer experience and test results may further influence the user's display of emotions and ability to perform optimally. Additional factors such as mood, sleep, or external stimuli may also impact the user's test performance.

Hardware and software limitations of devices and systems must also be considered when developing CCT systems. Erroneous results may be produced if system speeds are slow or inconsistent, providing the possibility of exaggerated user response times [29]. With growing possibilities of interaction modalities of CCTs, the complexities of such interactions and cognitive load on the user must be considered for a CCT to be considered effective. As self-administered CCTs are continued to be utilized, the lack of presence of an examiner could lead to insufficient knowledge for proper data interpretation and understanding [6]. It is therefore important to consider possible issues and impactful factors of CCTs for use in real-world contexts.

1.9 Contextual Factors

Traditional methods of cognitive assessment involve a trained examiner conducting an in-person, one-on-one assessment of an individual in a controlled setting. These methods are usually costly (requiring a trained examiner, material, space, etc.), lengthy, take place in settings unnatural to the individual (e.g., laboratory), include long temporal gaps between assessments and follow-ups, can lack high precision due to recall biases and missing ecological validity, and may lack accessibility options for individuals with special needs (e.g., screen reader). Fortunately, newer forms of cognitive assessment have been established that emphasize rapid screening and sensitivity to cognitive decline while maintaining the reliability and validity of established assessments [27,60].

While most CCT systems have been shown to have sufficient data for validity and reliability, there are still concerns over the comprehensiveness of other test standards [91]. Moreover, without additional external information on user health and context, it can be difficult to properly gauge the effective validity of such assessment systems. With self-administered CCTs, there is the possibility of missing or neglecting important contextual, behavioral, and non-cognitive factors that might impact the interpretation of the psychometric data collected [6]. Contextual factors such as environmental noise [46] and time of day [74] have also been shown to have cognitive effects. It's been shown that temporal variations in cognition can happen not just over a period of months or years, but even weeks and days [20]. Given the variability of contextual factors at play during CCTs, it is important that new methods of assessment be explored that can factor such variables into the context of CCT.

1.10 Ambulatory Assessment

Ambulatory assessment is an umbrella term used to describe methodologies that seek to assess an individual within naturalistic contexts while trying to minimize retrospective biases and maintain ecological validity of data collected [86]. Ambulatory assessment methodologies provide an avenue to capture brief, rapid snapshots of an individual's experiential state at a given moment in a real-world setting. The concept of assessing an individual within their natural environment isn’t something new and has been studied through many different fields [14,27]. There are many different forms of such methodologies of natural assessment, either through self-reports, journaling, life-logging, or behavioral sampling. These methods can also be referred to as ecological momentary assessment (EMA) methods, experience sampling methods, real-time data capture methods, or electronic diary methods [86].

1.11 Ambulatory Cognitive Assessment

With ambulatory assessment methods, it is possible to assess an individual within ecologically valid contexts. This emphasis on accurate and rapid assessment makes it increasingly desirable to utilize ambulatory assessment methodologies in monitoring cognitive health and well-being [56,76]. Ambulatory cognitive assessment (ACA) is a subsection of ambulatory assessment methodologies that provide an avenue to capture brief, rapid snapshots of an individual's cognitive state in their daily lives. This is usually accomplished by delivering some form of cognitive assessment, either via questionnaires and/or brief cognitive tests [79]. Given the adoption of mobile and Web technology for use in clinical neuropsychology, ACA methods are also being adapted for digital interfaces.

1.12 ACA for Older Adults

Various studies have examined how ACA methods can be used to track and monitor cognitive well-being in older adults [1,66,75]. These studies demonstrate the potential benefits of ACA research for aiding in monitoring cognitive well-being for older adults. A benefit of ACA methods is the ability to more easily observe and monitor individuals for signs of cognitive decline or other ailments. Given the complex nature of aging, ACA methods allow for the inclusion of ecological and contextual factors that may otherwise be missed by traditional methods of assessment. Though the use of ambulatory assessment methods in aging research is nothing new [14,27], the proliferation of computerized and mobile interfaces has allowed such methodologies to be more easily deployed and accessible. As a result, the application of ACA methods in aging research is continuing to grow in popularity and application.

1.13 ACA for Self-Monitoring

Most ACA studies point out the usefulness of including ambulatory and ecological factors for psychometric data interpretation for research and clinical practices [16,27,56,86]. Most of these studies have looked at ACA through a clinical or professional lens, emphasizing the analysis and interpretation of ACA data by professionals. Unfortunately, no studies have examined how ACA tools and methods may be used by the end user to independently understand their ambulatory cognition over time. Most of the data collected through ACA systems is meant to be viewed and analyzed by a professional and not the end user. Studies have shown, however, that older adults are interested in their data and want to be involved in monitoring their well-being [23,83]. However, due to the complex and heterogeneous nature of multimodal ambulatory assessment data (i.e., data captured from various inputs such as device sensors) [16], the analysis and interpretation of raw ACA data can be difficult for older adults to independently assess. New general ambulatory assessment tools and systems are continually being designed [5], however, there is still a pressing need to make these tools more usable and accessible by the end user, while maintaining ecological validity and reliability.

1.14 ACA Information Communication and Visualization

ACA data can be complex and difficult to interpret [16]. Data visualizations are a useful tool for making sense of data. They can be used to simplify and convey potentially complex data if done effectively. Visualizations can be anything from traditional bar and line graphs to more complex or elaborate infographics [87]. They can be used to convey quantitative properties of an event or series of events in a compact visual summary. Studies have shown the value of data visualizations for self-monitoring health and well-being [24,55]. Meaningful data visualizations for self-monitoring can increase awareness of an individual’s well-being and empower them to make informed decisions based on their own data.

Chapter 2

Background

2.1 Mobile Technology for Older Adults

The emergence of smart mobile technology has given both technical and non-technical professionals new tools for exploring beneficial cognitive tracking strategies for individuals with cognitive impairment [19,36,101]. The development of assistive technology designed to help or be accessible to individuals with special needs continues to expand [59]. For older adults, Web interfaces and mobile devices can bring both difficulties and benefits [58,70]. Difficulties can arise from complex controls, unfamiliarity with the device/system, or lack of access, among other reasons. Despite such difficulties, some highlighted benefits for the use of mobile devices by older adults include portability, intuitive user interfaces (e.g., touch) and feedback (e.g., audio, visual, tactile), as well as positive social interaction (e.g., communication with family members) [70].

2.2 Computerized Cognitive Testing

A study was published in 2012 by Brehmer et al. that examined the potential effect of interruptions during CCTs [10]. The authors conducted a study with 36 users from 3 different age groups (young, pre-old, old) to see the effect of interruption (passive and active) on CCTs. They had each participant complete a set of CCT trials in which randomly selected trials for random participants had interruptions. They matched the trails and interruptions within participants for the three interruption types, i.e., uninterrupted, passive interruption, and active interruption. If a participant had a passive interruption for trial 2, 5, and 7, then that participant also received active interruptions for trials 2, 5, and 7 of the active interruption group trials. They ran various ANOVA tests with their 3x3x2 design (3 age groups, 3 interruption groups, and 2 interruption types). Overall, the authors found variations in interruption effects between participant groups but found that the overall accuracy of participants remained the same, that is, the interruptions didn't impede their participants' ability to complete tasks accurately. The authors point out various methodological and design implications for mitigating and dealing with potential interruptions during CCT. The method in which the authors delivered the interruptions involved an interruption lag period prior to the interruption. That is, their participants received a visual and text cue that informed them of an impending interruption, giving participants time to prepare. This itself is a form of interruption, but also may not be entirely representative of a naturalistic interruption. Additionally, the authors only examine immediate interruptions and not longitudinal factors that may cause internal interruption such as the participant’s mood, sleep quality, time of day, etc. Moreover, it is not indicated that the participants were given any form of feedback as to their own performance, let alone their performance in relation to the potential interruptions. This warrants further research into how to not only mitigate potential interruptions, but how to automatically detect them, how to inform participants of them, and how they might relate to or impact the participants’ performances.

In 2013, Lathan et al. introduced the Defense Automated Neurobehavioral Assessment (DANA), a cognitive assessment tool designed for use in field deployment military settings to provide enhanced battlefield concussion assessment [49]. DANA was designed to emphasize portability, durability, and usability. To test the system’s durability and feasibility of use within diverse and extreme environments, DANA was tested with 224 active duty service members across five different environments (i.e., arctic, jungle, high elevation, desert, and at sea). The authors report that the recorded scores from their preliminary deployment of DANA are consistent and stable across the varying test environments and batteries. Though DANA shows promise for CCTs usage in real-world settings, the authors do not address the potential interaction effects of external and environmental stimuli on cognitive assessment results.

In 2014, Canini et al. conducted a study with 38 healthy aging older adults (mean age 64) to investigate the relationship of age and different testing interface modalities with user efficacy and ecological validity [15]. They set out to test the efficacy of CCTs for attention and memory with respect to two different interfaces (audio and visual) and input modalities (mouse and touch). They found no significant differences in performance and interface, concluding that both interface modalities are feasible for use in CCTs for older adults. Canini et al. provide a compelling case for the broadening use of CCTs. However, the fact that the authors solely used healthy participants, excluding those with CI and low MMSE scores, warrants further investigation into the accessibility issues faced with CCTs. Physical impairment could also have an impact on the testing efficacy of the participant, thereby producing data that could alter their original results and conclusions. Moreover, the authors point out that their use of an experimenter in some of the trials may have made the task "not purely computerized" [15].

A study was published in 2015 by Jacova et al. in which a novel CCT (C-TOC) was prototyped and tested with older adults, both healthy aging and those with MCI, to investigate the usability issues potentially faced with unsupervised self-administered CCTs [43]. The authors ran multiple usability tests of the C-TOC to gauge its usability with older adults with and without MCI, as well as its validity against standard cognitive test batteries. They indicate that there is a lack of research on the quality of UIs for current CCT batteries, as well as usability regarding users' computer knowledge and skill that can impact CCT. They conducted a 3-cycle iterative development procedure with users and a panel of health and social professionals who interact with users of varying cultural and ethnic backgrounds. They used Microsoft PowerPoint to do rapid prototyping and testing, with researchers manually recording and evaluating users due to PowerPoint's limited functionality. They recorded participants' performances with and attitudes towards the prototype. They noted that a common perceived barrier to unsupervised self-administration was interruptions and distractions, along with participants’ lack of motivation, fear of getting stuck, and perfectionism. They don't comment on how interruptions and distractions might be mitigated or accounted for in their prototype or other similar systems. The authors found the prototype to be inadequate primarily in the length of instructions and understanding of specific tasks. Through the iterative development, they were able to minimize some usability issues, but not all issues. They note that making sure tasks are clear and that users receive appropriate prompts and reminders to stay on task are major challenges for optimizing the usability of CCTs. The authors don't show the prototype interface anywhere in the paper or present quantitative metrics of usability, i.e., success rates, time on tasks, or error counts. The prototype also doesn't seem to convey the user's performance measures back to them, instead taking a traditional approach of professional or administrative analysis.

In 2018, a study was conducted by Sliwinski et al. that examined the reliability and construct validity of ambulatory (in situ) cognitive testing as part of an EMA delivered on mobile devices [79]. They ran a study with 219 people between 25-65 years old. They performed standardized cognitive assessments for each person by a trained individual and delivered pseudo-random brief EMAs and CCTs via a mobile device 5 times a day for 14 days. The EMAs did not appear to account for environmental or detectable factors that may cause interruptions or distractions (e.g., sound or movement). The authors report high between-person reliability for the ambulatory tests. They report that there was a strong correlation between the ambulatory and in-lab tests, suggesting that the rapid ambulatory tests can be used to measure the functions measured by in-lab tests. They point out limitations to their study including the presumption that participants could effectively use their assessment protocol independently and that their study did not factor in potential external distractions or interruptions. The authors also don't mention any design decisions for the testing protocol.

2.3 Health and Well-being Monitoring

The use of health data is especially impactful for understanding aging related issues. Doyle et al. examined long-term adherence to a Web-based well-being self-reporting tool for older adults [25]. The tool (YourWellness) makes use of automated questions to inquire about the user's well-being and offers recommendations for how to improve, if need be. They conducted a longitudinal study investigating the attitude and behavior of older adults regarding the tool. They found the line graph data visualization was well understood by participants, more so than a traffic metaphor used to convey wellness (i.e., green means they feel well, yellow signifies relatively low wellness, and red indicates a very low score). Their participants pointed out that the usefulness of the system came from increasing one's awareness of their well-being. This increased awareness in one's wellness data was also a positive factor for improving adherence to the tool over time. There were also negative aspects to adherence and motivation. The authors noted that participants didn't like the repetitive and overly complex or “clinical” nature of the questions and feedback messages. The participants also pointed out that the activity of answering questions was not particularly fun. Additionally, they found that older adults were interested in tracking their wellness through aspects that are relevant to them (e.g., sleep was a more important factor than social wellness).

Boukhechba et al. explored the relationship between mental health of college students and ecological and contextual factors [9]. They used a psychological research mobile tool (Sensus) to measure passive, ambient data throughout a user's day and deliver ecological momentary assessments (EMA) through short questionnaires delivered through the mobile application. The authors first tested the participants in a laboratory setting. They administered standardized mental health self-reported questionnaires (SIAS, DASS, PANAS) to gauge the user's mental health levels. They also performed a stressor task in which the participant gave a speech in front of a mirror with the researcher(s) watching and measured the participant's stress level via questions. After the lab tests and training, each participant installed the Sensus app that delivered random and fixed EMAs to the participant every day for 2 weeks. Additionally, the installed app tracked passive sensor data at set frequencies (e.g., 150Hz for GPS) at seemingly all times of each day throughout the 2 weeks. After the in-the-wild tests, each participant went through a final lab test, consisting of self-reported questionnaires. The authors found positive correlations (Pearson) between low (physical) activity, increased isolation, low social interaction with depression, and social anxiety levels. They point out that their population was mostly homogeneous (college students) and that there wasn't a broad range of mental health conditions. The authors also highlighted app compliance rates degraded over time (to be expected). They demonstrate how such in situ data could be used to correlate contextual factors within the domain of mental health.

2.4 Visualizing Health Data

In one study, Meyer et al. investigated the requirements and design choices for visualizing complex, heterogeneous personal health data on mobile devices [55]. They gathered information from a group of users age 20 to 50 (n=12) and conducted surveys with current systems (Fitbit, etc.) to understand the user's preferences and attitudes towards data visualization techniques employed with said systems. They then designed their own visualizations based on two usage scenarios: "my health right now" and "my health in the past.” They found that there is a tradeoff between maximizing data privacy (i.e., using visual metaphors) and maximizing the user’s ease of understanding (i.e., graphs and charts) on mobile devices for personal health data. The authors point out that, despite limitations of mobile devices (small screen, etc.), they can still offer a means to explore complex health data through carefully designed data visualizations. This proves fruitful for Web applications running on mobile devices.

A study published in 2014 by Le et al. evaluated older adults' perceptions of hypothetical data visualizations for health and well-being [50]. The authors ran 3 focus group sessions and showed 3 different visualizations to participants in each session. The visualizations made use of Dunn's model of wellness [26], which breaks up wellness into 4 categories: physiological, social, spiritual, and cognitive. The 3 different visualizations they used were a bar graph, radial graph, and a light ball metaphor graph. Each hypothetical visualization displayed various subgraphs and charts conveying different aspects and categories of wellness. They found the bar graph to be preferred by most participants, as it was most familiar to them. The authors point out that these sorts of visualizations are useful to reveal potential issues between clinical visits but may still lack context as to what may have caused possible declines or inclines in the data. They note that different stakeholders may prefer different levels of granularity in visualization details, i.e., older adults may prefer broader high-level picture of wellness, whereas healthcare professionals may prefer more detailed information for smaller subsets of data. They also state that grouping all categories of wellness may not be meaningful to some users, as different users may value different aspects of wellness (e.g., some may place higher importance on spirituality than others). Overall, the authors recommend simple, clear, and easy to understand displays with minimal visual cues. They also recommend separating wellness categories as different user groups may prefer certain categories over others. They suggest that it might be beneficial for health visualization tools to allow for personalization and customization of visualizations and weights. The authors note that some of the limitations of their study were: the static nature of the displays, the single test facility (retirement community), limited user diversity, lack of user demographics, and the combination of wellness categories into a single visualization (albeit with multiple components).

2.5 Context-Aware Applications

The methodology of using embedded sensors to understand ambulatory health and well-being is something that continues to be explored as a subset of ambulatory assessment. Lee and Dey conducted a concept validation study in which they presented hypothetical scenarios of embedded assessment concepts to stakeholders to understand their needs with and limits of such conceptual systems [51]. They investigated the value that embedded assessment data on instrumental activities of daily living would provide to older adults, caregivers, geriatricians, and occupational therapists. The authors solicited feedback during interviews with stakeholders on the usefulness of three hypothetical “sensing” concepts, or use-case scenarios, and three types of data visualizations of varying granularity. From their study, Lee and Dey report that all participants found the data visualization of longitudinal data to be useful. Additionally, the authors point out that older adults found greater value in the short-term view (i.e., recent or immediate data) than the occupational therapists and geriatricians. Task completion and performance data were also found to be useful by all participants, as a way to provide valuable information on the individual's ability. From their study, Lee and Dey point out three main issues with the embedded assessment concepts: 1) the "why" behind the data is missing and could shed light on potential behavioral causes of data, 2) there is a lack of validation of critical points of significance in the data (i.e., what thresholds to use to know when a data point is critical), and 3) a lack of differentiation between user-generated "noise" and sensed "noise" in the data (i.e., irregular, but non-significant changes in user behavior can create noise in the data).

Harchay et al. proposed a framework for context-aware personalized mobile self-assessment for college students [40]. They investigated the use of ontologies to model aspects of the framework, including context, user (learner), and assessment objects, as well as the semantics used to personalize assessments. They describe their personalized mobile assessment framework and the layers, and sublayers, that compose it. The three primary layers that compose the framework are: The Assessment Context Layer that provides the graphical UI (GUI); the Semantic Layer which is composed of sublayers responsible for acquiring the user's context and selecting appropriate assessments based on these; and the Assessment Resource Layer which holds the ontological models and semantic rules. They outline a personalization algorithm that demonstrates how the system uses contextual and user information to filter, personalize, and weigh assessments from a database of possible assessments. An example walkthrough of the algorithm would be if the user seeks to self-assess their Object Oriented Programming (OOP) knowledge on their mobile device (detected through the system) in a public quiet location (specified by the user), the system would find matching assessments for OOP and filter out ones that have video or audio content, so as to avoid making noise (adapting to the user's assessing location and context). They developed a prototype of the system, mobiSWAP, using various web services and tested it with college students (n=40) split into two groups (beginner and intermediate) based on their score on an OOP pre-test. The authors appear to have evaluated the system on the user's "observation" or "perception" of the various aspects of the framework, i.e., the personalization and adaptation aspects, through different test scenarios, e.g., different devices and test locations. Additionally, they evaluated the usability and effectiveness of the framework with students. Overall it appears that the intermediate students "observed" the specific framework aspects more than the beginner students. Most students found the system useful and preferred to use the PC over a mobile device. The students recommend UI improvements (bigger buttons, etc.) and offer different use cases (in classrooms, etc.). The authors offer validation of their framework by developing and testing the mobiSWAP system with college students. They offer ideas for future work with more diverse users, more assessment types, and more test scenarios.

2.6 Telehealth and Machine Learning

Telehealth systems will also continue to see practical improvements in interaction and computational capabilities. Machine learning and data mining techniques offer novel approaches to behavioral data interpretation and exploration. A research study was conducted in 2014 that sought to investigate using machine learning algorithms for detecting cognitive impairment through subtle user behaviors during neuropsychological testing [21]. Davis et al. postulated the integration of AI technology with a digitizing ballpoint pen based neuropsychological test. By training on sample Clock Drawing Test user data composed of Alzheimer, dementia, and Parkinson’s disease patients, the authors reported linear support vector machines to outperform other techniques, such as random forests and boosted decision trees. Further, they use k-means and conditional random field classifiers to aid in digit isolation and identification. Overall, with 600 clocks from healthy users to train on, they report system results of more than 96% accuracy in digit recognition on clocks from healthy individuals [21].

Applications of mobile sensor technologies are broad and far-reaching. Advances in micro sensors and embedded chips [38] has opened the door for intelligent forms of sensing and computation. In 2010, Ganti et al. utilized Nokia smartphones to assess daily living patterns of users via microphones, accelerometers, GPS, and GSM [34]. The authors proposed a multisensor fusion algorithm for activity detection. They used a synchronous feature extraction approach that allowed them to capture and compute features from sensors independently at a constant time-frame rate. To better model each activity, they utilized hidden Markov Models (HMM) due to the time series nature of the human actions and activities. From 80 hours of tagged activity data with eight participants between the ages of 20 - 37, along with 45 hours of training data for their automated classification algorithm, the authors found high activity recognition accuracy when using a 3-state HMM, compared to a 1-state and 5-state model. They conclude with evidence from their results demonstrating the feasibility of using micro sensors on consumer smartphones for context identification. Ganti et al. point out the potential use of such technology for medical monitoring of older adults to support behavior management and rehabilitation.

2.7 Contribution

The major contributions of this dissertation include the following:

- I explore stakeholder needs and requirements with ACA systems through observations and interactions.
- I present the design of a novel, Web-based ambulatory cognitive self-assessment system (ACSAS) and evaluate its feasibility of use with healthcare social workers through formative usability testing.
- I provide insight into the context of use surrounding the ACSAS for use by older adults through case studies and group discussions.
- I present design recommendations, including data visualization guidelines, for the ACSAS through a summative usability evaluation with older adults.

Throughout these studies, I reflect on the lessons learned and design implications of developing the ACSAS or other ACA systems for older adults to self-monitor their cognitive well-being.

Chapter 3

Research Questions and Objectives

3.1 Research Questions

In this dissertation, I present a novel, Web-based ACSAS for self-monitoring cognitive well-being in older adults. Through the design and development of the proposed system, I address the following research questions:

RQ1. Is it feasible to use a Web-based ACSAS for self-monitoring cognitive well-being in older adults?

It is important to understand how feasible it would be to implement the solution and how stakeholders would perceive it. Traditional ACA systems are intended to be used by an end user whose data is then interpreted by a professional, leaving the end user in the dark about their own patterns and trends. By developing and evaluating the ACSAS as an end-to-end solution for self-monitoring and interpreting one's cognitive well-being using a Web interface, we can better gauge the feasibility of the system for use directly by older adults and stakeholders.

RQ2. What is the context of use surrounding the ACSAS for use by older adults?

The finding that older adults are interested in monitoring their well-being through contextual factors relevant to their personal experience, such as sleep or mood versus social interaction, provides an interesting research opportunity to explore further. Moreover, accounting for immediate contextual information surrounding self-assessment can provide a more accurate representation of an individual's ambulatory cognitive well-being. Through understanding the potential contexts of use by older adults, we can better design the system to include relevant contextual factors for ACA data interpretation.

RQ3. How can the ACSAS be designed to facilitate independent use of the system by older adults?

For the ACSAS to be adopted and used by older adults, it must be usable and learnable. The design space for Web and mobile technology has expanded significantly in the recent years, with the trend seeming to continue. As such, the opportunities for improved usability and accessibility continue to expand. It is thus important to carefully consider the design of the ACSAS situated not only in healthcare but also as a self-guided ACA solution for older adults, two design spaces with unique opportunities and challenges. Knowing that older adults seek engagement and interactivity with wellness monitoring tools, it is important to consider the specific needs of older adults when developing the ACSAS. Furthermore, given the quantitative and qualitative nature of the data proposed to be incorporated with the ACSAS, it is important to understand how best to communicate this heterogeneous cognitive well-being information back to the end user through a meaningful and intuitive interface.

3.2 Research Objectives

The primary research objects of this dissertation are the following:

RO1. Develop a Web-based ACSAS capable of capturing and tracking temporal variations in the user's ACA performance.

The system will administer an ACA via a Web application, in which the user will interact with directly. By taking multiple samples of user performance throughout the day and week, temporal variations in the user's cognitive performance can be assessed and analyzed with accompanying contextual data, both qualitative (via questionnaires) and quantitative (via sensors). The interface of the system will also be able to graphically output the user's performance in a data visualization that is easy to interpret by users and stakeholders.

RO2. Develop a Web-based system capable of capturing and analyzing ambient contextual data during testing.

By utilizing various embedded sensors present in off-the-shelf tablet devices, quantitative ambient data can be acquired and used in the assessment of performance data obtained from the ACA results. The system will simultaneously sample data from various sensors, i.e., microphone and camera, during the time of testing and fuse such data for contextual analysis of the user's performance and testing efficacy.

RO3. Adapt a single cognitive memory test for use in the developed system.

The system will employ a word list memory recognition test adapted from the Rey Auditory Verbal Learning Test (RAVLT). By focusing on a single cognitive domain and single test initially, we can gauge the feasibility of the simplified system to be used in the wild by users. This foundational framework can then lead to the inclusion of a wider range and variety of cognitive tests for similar and different cognitive domains.

RO4. Develop usability requirements for the ACSAS for use by older adults.

With the qualitative and quantitative information received from user testing, we will be able to generate a base set of usability requirements for future development of ACA systems for use by older adults. These requirements will help reveal insights into usability and accessibility issues faced by older adults and possible solutions to overcome them as validated by user responses and data.

3.3 Development Process Overview

The following table (Table 1) represents an overview of the research and development process of this dissertation. For Phase 0, we first conducted an exploratory investigation into the context of cognitive assessment and older adults with and without cognitive impairment. In Phase 1, we developed a low- and medium-fidelity prototype and conducted a formative usability study with healthcare social workers to gauge the feasibility and usability of the ACSAS prototype. With the feedback from Phase 2 and an updated prototype, we initiated Phase 3, which involved investigating the motivations, concerns, and contextual factors that might impact the performance and efficacy of ACA with older adults. Finally, for Phase 4, we iterated on the prototype and conducted a summative usability study with older adults to understand the usability and accessibility issues faced by older adults with the ACSAS prototype and ACA systems in general.

Table 1. An overview summary of the studies for this dissertation.

<table>
<tr><th colspan="2">Phase 0: Exploration and Ideation (N=25)</th></tr>
<tr><td>Healthcare providers and older adults w/ MCI (n=16)
• Exploration of stakeholder needs
• Nursing and transitional care facility
• Older adults with MCI and mid-level CI
• Nursing staff
• Fly-on-the-wall observations, contextual interviews</td><td>Healthcare providers and older adults w/ MCI (n=9)
• Exploration of stakeholder needs
• Assisted living facility for dementia
• Older adults with MCI (dementia)
• Contextual interviews, semi-structured focus group</td></tr>
<tr><th colspan="2">Phase 1: Prototyping and Feasibility (N=15)</th></tr>
<tr><td>Healthcare social workers (n=5)
• Gather initial feedback on the system prototype
• Adult day healthcare center
• Hands-on walkthrough, semi-structured focus group discussion</td><td>Healthcare social workers (n=10)
• Gauge general usability and feasibility of the system prototype
• Adult day healthcare center
• Hands-on usability tests, interviews, questionnaire</td></tr>
<tr><th colspan="2">Phase 2: Contextual Assessment (N=21)</th></tr>
<tr><td>Healthy-aging older adults (n=14)
• Investigate users' motivations and deterrents for using the prototypical system
• Senior activity center
• Community dwelling older adults (90+ years old)
• Focus group discussion, hands-on activity</td><td>Healthy-aging older adults (n=7)
• Understand what contextual factors older adults are concerned about for their experience of self-monitoring their cognitive well-being
• Retirement apartment community
• Healthy aging older adults (mean age=87, SD=7.2)
• Hands-on activity, focus group discussion, writing activity, questionnaire</td></tr>
<tr><th colspan="2">Phase 3: Usability Testing (N=6)</th></tr>
<tr><td colspan="2">• Understanding usability issues with the system for older adults
• Retirement apartment community
• Healthy aging older adults (mean age=86.8, SD=6.24)
• Hands-on usability tests, structured interviews, questionnaire</td></tr>
</table>

Chapter 4

Phase 0: Exploration & Ideation

4.1 Institutional Review Board (IRB)

Due to the nature of this project, it was important to obtain approval from our institution review board (IRB) for conducting human-subjects research. This involved completing various training programs to understand how to conduct human-subjects research as responsibly and safely as possible. I’ve completed 8+ hours of the Collaborative Institutional Training Initiative (CITI) Human Subjects Online Training course. It was composed of various modules explaining topics including ethics in research with humans, data security and privacy, responsibilities as a research scientist, as well as social impacts of scientific research. Congruent to this, I’ve completed a 2+ hour online HIPAA training course in understanding how to responsibly deal with sensitive subject information such as health and medicine. An additional 30-page protocol proposal was submitted, reviewed, and approved by our IRB.

4.2 Stakeholder Observations and Contextual Interactions

4.2.1 Stroke Center Observations

Early work at a local stroke and disability learning center was conducted to get a better understanding of cognitive assessment technologies that stakeholders felt were helpful, as well as examine the effectiveness and limitations of such technologies [90]. We worked with students, instructors, and facility staff. From observations and contextual interviews, we investigated the needs of stakeholders, i.e., older adults, stroke survivors, individuals with cognitive impairments, instructors, staff and administration, healthcare workers. We found older adults to be interested in the idea of a novel ACA system and expressed the usefulness of increasing awareness of one's cognitive well-being. It was also discussed that including other psychometric and contextual data (mood, ambient changes) could prove beneficial for understanding changes in one's cognitive well-being.

4.2.2 Transitional Care Facility Observations

With feedback from the previous location, we decided to shift our stakeholder focus to older adults with cognitive impairments as well as healthcare workers. We volunteered at a local nursing and transitional care facility. The facility had maximum resident capacity for 145 residents, with an occupancy of 138 at the time. Most residents (around 100) were short-term residents (7-90 days) and had varying physical and cognitive ailments. We helped with serving lunch, which involved passing out trays of food one at a time to each resident. Afterwards, our team led a regularly scheduled group activity (a group family feud game) with some of the residents, mostly long-term residents (n=16). During these activities we had the opportunity to observe and interact directly with residents. Given that most, if not all, of the residents who participated in the activity were long-term residents, there appeared to be a mixture of individuals with some form of cognitive impairment. This was later confirmed by one of the facility's nurses. Based on our interactions with the residents, it was surmised the ACSAS might pose significant difficulty for individuals with mid- to severe forms of cognitive impairment to use independently. Thus, we refocused our stakeholder definition to primarily older adults with and without MCI, excluding individuals with mid- to severe cognitive impairment.

We also observed the ambient setting of the facility. The layout of the facility was open and continuous. This design is beneficial in that it provides faster access and communication across the facility space, thereby possibly increase response time of the facility's staff to health-related events and emergencies. A byproduct of this open layout was increased audiovisual noise travel and interference. While leading the group activity, our team had to sometimes shout to convey activity related information to the residents, with background activities sometimes directly drawing attention away from the activity. The ambient nature of these types of health facilities do lend themselves to a potential increase in background noise interference with resident activities. This can be especially impactful during cognitive testing and assessment, given the sensitive nature of such activities.

4.2.3 Assisted Living Facility Observations

4.2.3.1 Overview

With our refocused stakeholder definition, we continued our exploration of user needs with older adults with MCI. We volunteered at a local assisted living and memory care facility. The facility itself was formed from a classic Victorian house near the ocean turned assisted-living care facility. Like the transitional care facility mentioned in section 4.2.2, the facility had an open, circular layout that allowed for easy flow of foot traffic and emergency services, if need be. Also, similar to the transitional care facility, the busy nature of the facility propagated sound and commotion, potentially impacting resident activities. The residents consisted of older adults with mild to severe forms of dementia. During our visits, we were able to interact with individuals considered to be in the early stages of dementia, whereby early signs of slight memory loss is symptomatic but constant supervision was not needed. I also had the chance to go through the facility's dementia care training orientation that they give their staff and volunteers. This was not only to learn more about dementia and dementia care, but to also understand more about the facility and its residents.

I led numerous technology education workshops for the residents. These workshops involved a short presentation on modern technology and its uses, followed by a hands-on activity in which residents got to interact with touch screen tablets and learn basics of touch interactivity and applications. Most of the residents who participated in the workshop had little to no experience with touch screen devices. Some of the participants pointed out difficulties with using touchscreen devices including difficulty reading and understanding the text and iconography. This led to frustration and embarrassment as one participant noted, “*I felt embarrassed because I can’t see the symbols on the device*.” However, all participants expressed their interest and excitement to learn how to use such technology.

4.2.3.2 Methodology

We focused on investigating the general attitude, comfort level, and familiarity of older adults with dementia with low-cost tablet devices. This was accomplished through the form of a workshop which sought to inform older adults about the benefits and features of tablet devices, as well as modern information technology in general, via hands-on demonstrations and interactions. Participants were residents of Sunshine Villa, a local senior living facility specializing in dementia care. Throughout the workshop, questions were asked to gain an understanding of some of the daily challenges faced by the Sunshine Villa residents, both cognitive and physical.

An interactive workshop was provided with a focus group of older adults (n=9, 7 female) recruited from Sunshine Villa. The average age of the group was 73. Each participant had been diagnosed with some form of dementia, the majority of which were in the “early to mid-stages of dementia,” as indicated by the Activities Director, with only one participant utilizing assistive technology for physical aid (medical walker). Of the group, 2 reported being comfortable with information technology (including mobile and/or tablet devices) and 8 reported to have used a touch interface within the past year (e.g., ATM or automated cashier).

A short overview presentation on information technology was given prior to the hands-on tutorial. The interactive tutorial was conducted on Android (4.2) tablet devices, one for each of the nine participants (Figure 2). Topics such as basic icons, device symbols, navigation and gestures, accessibility features, and applications (solitaire, word search) were demonstrated throughout the span of the workshop. Additional paper reference handouts outlining key symbols and icons were distributed to the participants.

Figure 2. Older adult participants interacting with tablet devices.

The first hands-on activity sought to introduce the participants to the basic symbols displayed on the physical hardware of the device. The participants were then instructed to power on the devices. This was followed by a walkthrough of basic touch gestures (i.e., tap, multi-tap, swipe, multi-finger drag, press and hold). These gestures were demonstrated with the task of having the participants change the background image on the device. In addition, the magnification accessibility feature was enabled and demonstrated, further utilizing slightly more advanced touch gestures (i.e., multi-tap and multi-finger drag). The workshop concluded with a short demonstration of different available applications (including solitaire and a word search game) and an open session in which the participants were free to interactively explore the devices. Short questionnaires were administered throughout the workshop to gauge the participants' attitudes towards the tablet devices.

4.2.3.3 Results

Most of the participants (n=7) reported to have had little to no experience with tablet devices. Despite this, all but one participant found the devices to be easy to use with little to no guidance. When asked about the issues they experienced with the devices, the consensus was on the difficulty of finding and reading the small physical symbols on the device hardware, as opposed to the device software icons. One participant abandoned the activity entirely, remarking that they felt "*embarrassed because I can't see the symbols on the device*." Echoing that sentiment, another participant pointed out that "*locating the buttons on the device was a little confusing*," but was able to complete the activity.

The second problem was the periodic device sleep (screen deactivation) activated upon detection of prolonged device inactivity (default 10 seconds). The automatic device sleep feature further reinforced the primary issue participants had with locating the power button to turn the screen back on. Some specifics of higher-level device functionality (e.g., applications and games) also contributed to some participant hesitation towards the device, though not regarding its perceived benefits for an individual. This is reflected from one participant claiming, "*I don't know how to play games, but I could see others liking them*."

Despite these issues, eight of the nine the participants were able to complete the activities, with one participant claiming that the "*[devices] are really fun*!" Another participant likened the process of understanding and interacting with the tablet devices to "*learning a new language*," which they found to be enjoyable. Upon completion of the activity, the remaining 8 participants indicated that they would "*want to learn more about information technology and tablet devices*," with 5 saying that they would "*likely use such technology*" if it were made available to them.

4.2.3.4 Discussion

The overall attitude of the participants toward information technology and specifically tablet devices was admittedly positive. This was reflected both in the feedback from the participants as well as the facility's staff. One aspect of the tablet devices that seemed to get positive attention was the ability to play games. Though research into games for older adults is continuously being pursued [88], the importance of specific design details (e.g., default device settings) should be considered throughout the entire design and marketing process. In some cases, individuals might have an incomplete or incorrect preconceived notion of how the technology should and could be used, leading to a lack of motivation to use such technology altogether because they might be unaware of how it might be able to specifically improve the quality of their lives. Moreover, they might feel embarrassed or off-put by the technology due to lack of understanding of the device capabilities, thereby making interaction with the device foreign or intimidating. Given the small-scale nature of this study, such insights are difficult to generalize to a larger population. Future studies will seek to address this limitation.

One overlooked aspect of information technology, as indicated by the Activities Director, is a lack of proper outreach to the community of older adults on the benefits of such technology from the onset. Though the percentage of older adults adopting information technology such as computers and mobile devices is increasing [100], there is still more work to be done on effectively educating older adults of the real-world benefits and applications of information technology [80]. One way this can be achieved is through positive emphasis and reinforcement of the user's importance and relevance to society. Applications that allow for social communication and news dissemination can aid in this regard by allowing users to publish and subscribe to content relevant to topics and communities important to them.

With information technology continuing to permeate throughout our society, a greater precedence must be placed on accessibility design features of information technology in order to reach a broader population of users. For older adults, design features such as larger physical buttons, larger hardware font and symbols, and non-distracting software interactions should be considered throughout the design phase. Detailed considerations such as default timing of interactions or device symbol size and placement can have a noticeable impact on the engagement of the user with the device. Improving the dialogue of information technology designers and developers with the community of older persons could possibly lead to greater overall user compliance by strengthening the user's comfort and trust towards the device.

4.3 User Groups and Personas

Throughout the stakeholder observations and interactions, we learned that there is a wide variance across user backgrounds and characteristics. However, as we combed through the observational and contextual interaction data, we found commonalities among stakeholders. These commonalities allowed us to group stakeholders into two user groups broken down into 3 separate personas: older adults with (Table 2) and without (Table 3) MCI as primary users, and caregivers and healthcare workers as secondary users (Table 4). Primary users consist of older adults (65+ years of age), both healthy aging and those with MCI, recruited from local residential senior centers and communities dedicated to improving the quality of life of older adults. Professional caregivers and healthcare workers were screened based on their direct interaction with primary users and prior experience with behavioral and cognitive assessments. Primary users with MCI were in the early stages of dementia, whereby early signs of slight memory loss are symptomatic but constant supervision is not needed. No primary user with middle, late, advanced, or severe stages of dementia, were included. The diagnoses of primary users with MCI had been ascertained for non-research purposes by the recruitment facility's staff a priori.

Table 2. Older adult with MCI persona description.

Name: Mary **Persona**: Older Adult with MCI	**Quote**: "*I know it's a good idea to use this, I just need to get better at it*."
Picture: 	**Background/Scenario**: Mary is a retired counselor who resides in an assisted living facility after being diagnosed with MCI. She engages in resident activities and enjoys playing games. She was gifted an iPad from her daughter and wants to get better at using it. She's heard there are brain exercise games and apps on there and wants to learn how to use them. Some of the nurses and staff have helped her setup some of the games for her on the iPad, but she has trouble navigating the apps independently.
Age: 91 **Occupation**: Retired counselor **Education**: College degree **Status**: Widowed, 4 children, 4 grandchildren **Ethnicity**: Caucasian **Technology**: Minimal familiarity with technology; has gifted iPad from daughter **Living**: Assisted living care facility resident **Cognitive Status**: Diagnosed with MCI **Assistive Devices**: Hearing aid and glasses **Hobbies and Activities**: Plays family feud with other residents; likes crossword puzzles	**Motivations**: • See friends and family • Be heard • Be remembered • Enjoy life **Frustrations**: • Complex apps and instructions. • Distracting images and moving things on the screen. • Forgetting how to do things.
Current Solutions Used: • Crossword puzzles • Family feud with friends and residents • Word search games **Questions**: • "*Are there any easy to use apps for me out there*?"	**Goals**: • Wants to retain her memory as much as possible. • Find fun and simple apps to play. • Independently use apps on her iPad.

Table 3. Older adult without MCI persona description.

Name: Peggy **Persona**: Older Adult without MCI	**Quote**: "*I'm tired of being bored. I want something fun and challenging for my mind*."
Picture:  **Age**: 78 **Occupation**: Retired teacher **Education**: Master's degree **Status**: Married, 3 children, 2 grandchildren **Ethnicity**: Caucasian **Income**: Middle class **Technology**: PC, smartphone, tablet; daily user of the internet **Living**: Homeowner; Scotts Valley, CA **Cognitive Status**: No diagnosed cognitive impairment **Assistive Devices**: Uses hearing aid and glasses for reading **Hobbies and Activities**: Active and social lifestyle; participates in organizations and clubs **Current Solutions Used**: • Crossword puzzles; Sudoku; Words-With-Friends • Reads newspaper • Intuition and social interactions **Questions**: • "*What apps are available right now that I can use to exercise my brain*?" • "*How well am I doing compared to others*?"	**Background/Scenario**: Peggy is a healthy aging independent older adult who is comfortable and experienced with technology. She lives in a local retirement community apartment complex. She has an active and professional lifestyle that occupies most of her time throughout the day. Peggy uses a smartphone, tablet, and PC. She uses these devices for communication, organization, and entertainment. She often attends community activities and learns new games. Peggy doesn't consistently keep track of her cognitive well-being but thinks about occasionally. This is particularly true when she plays games with and against friends.
	Motivations: • Enjoys fun and engaging experiences • Keep in touch with friends and family • Being healthy and active • Contribute to community **Frustrations**: • Boring app experiences. • Confusing apps and long instructions. • Too many ads in the app. **Goals**: • Have a go-to app that can occupy her time while keeping her mentally sharp. • Wants to maintain or improve her cognitive ability. • Wants to learn more advanced capabilities of her devices.

Table 4. Professional caregiver persona description.

Name: Lisa **Persona**: Professional Caregiver	**Quote**: “*I think it’s wonderful that my clients have something fun and beneficial for them*.”
Picture:  **Age**: 47 **Occupation**: Healthcare social worker **Education**: Master’s degree **Status**: Married, 3 children **Ethnicity**: Caucasian **Technology**: Owns iPad, iPhone, laptop, desktop; comfortable and familiar with technology; daily user **Living**: Homeowner; Scotts Valley, CA **Hobbies and Activities**: Reading; enjoys watching home decorating and landscaping TV shows; going to the movies with her husband some weekends; lunch dates with her daughters and friends **Current Solutions Used**: • Pen and paper cognitive assessments • Observations **Questions**: • “*Are there any alternatives to these assessment methods*?” • “*How can I account for possible distractions and personal issues that might impact assessments*?”	**Background/Scenario**: Lisa is an experienced healthcare social worker who works with older adults with MCI. She coordinates activities and programs for her clients to help keep them cognitively active and healthy. She has experience in cognitive and behavioral assessments and uses traditional methods of cognitive assessment to monitor the cognitive well-being of her clients. Given the complex medical conditions of her clients and busy nature of the facility, some of these methods have proven cumbersome, inaccurate, and not robust enough to understand her client’s cognitive state at times. Lisa’s open to the idea of using technology, but hasn’t found a solution that’s readily available, easy to use, and sensitive to the needs of her clients and facility.
	Motivations: • Give to her community • Help people • Apply her knowledge and skill **Goals**: • Create new activities and programs to help keep her clients with MCI cognitively active and healthy. • Find resources to help her deliver care to her clients. • Wants a more contextually sensitive solution for monitoring the cognitive well-being of her clients. **Frustrations**: • Noises and distractions that impact the cognitive assessments. • Lack of available resources for aiding in assessment. • Limited flexibility in assessment methods and tools.

4.4 Preliminary Requirements

Based on the observations, interactions, and feedback we received during the inspiration and exploration phase of this dissertation, we devised the following set of preliminary requirements for the proposed ACSAS. Table 5 lists the functional and non-functional requirements. Later studies have refined and added to this list of requirements.

Table 5. Preliminary functional and non-functional requirements.

Priority	Functional Requirement	Reason
High	The system must be able to deliver interactive cognitive games.	In order to assess a user, the system needs to be able to deliver cognitive games.
High	The system must have the capability to record and track a user's performance information (i.e., scores, reaction times).	User performance information will make the system more accurate for assessing a user’s cognitive well-being.
High	The system must be able to acquire contextual data (e.g., subjective mood, ambient noise) at the time of and/or during the cognitive game playthrough.	Understanding contextual information surrounding cognitive games can greatly impact the interpretation of performance scores (e.g., external noise and distractions).
High	The system should provide users with some form of record of their work and progress.	It is important users are aware of their cognitive well-being over time.
Medium	The system must allow a user to view past performance scores and contexts.	A user should be able to see quantitative feedback from the system to help inform the user of their cognitive performance with respect to the context at the time of testing and throughout.
Medium	The system must be able to store and retrieve user data.	To assess a user’s cognitive well-being, prior performance data specific to the user needs to be accessible.

Table 5 (continued)**.**

Priority	**Non-Functional Requirement**	**Reason**
High	The system should be easy to operate and navigate independently by a user.	Users should be able independently operate the system without help or guidance.
High	The system instructions should be clear and easy to understand.	Users need to be able to easily understand how to use the system independently.
High	The system should store user data securely.	Given the sensitive nature of the information collected, it is important the user's data is secure and private.
High	The system should be usable on common off-the-shelf devices with a Web browser (i.e., mobile, tablet, PC).	Making the system Web-based will allow it to be device agnostic.
High	The system should use large, well-spaced buttons and interactive elements.	Users may have varying levels of dexterity and physical ability to perform inputs.
Medium	The system should minimize the amount of extraneous information on screen.	Users might get distracted by extraneous information on a screen or experience cognitive overload.
Medium	The system should minimize the amount of input required by the user to operate and navigate.	Minimizing the number and complexity of input required by a user can maximize the efficiency of use of the system.
Medium	The system should be able to store user data locally.	A user's connection to the internet may be inconsistent or slow.
Medium	The system should use common iconography and layout.	Using common iconography and screen layout will maximize the intuitiveness of the system.
Medium	The system should be responsive and flexible in design.	Users may have different device, screen, and visual requirements.
Low	The system should minimize the amount of used client-side storage space and bandwidth.	Users might have limited storage space and bandwidth.
Low	The system should use lossy data compression for sampled data for fast and minimized storage usage.	The amount and frequency of samples taken should not impact the performance of the system.

Chapter 5

Phase 1: Prototyping & Feasibility

5.1 Concept Motivation Scenarios

To better motivate the concept behind the ACSAS, consider the following situation without the use of the system: a doctor might ask a client to complete self-administered cognitive tests using a traditional CCT system on a modern tablet device with embedded sensors once a month for six months, at which point they will meet to discuss the results. With traditional self-administered CCT systems, the primary variables measured throughout the tests are the user's scores, response times, and possibly application statistics, e.g., system usage, if such data is exposed to the users (client and/or doctor). In this scenario, the doctor would be able to see the client's performance on the CCT over the six months but would be missing contextual and ecological information as to why the scores are what they are. Was the client in a quiet setting while they were testing? Did the client get quality sleep the night prior to testing? Was the client in a properly illuminated room? The "why" behind the data is missing [51].

Now consider the previous scenario with the use of the ACSAS: the user is asked to perform the same routine of cognitive tests but now using the ACSAS on the same mobile device with embedded sensors. In addition to the traditional CCT variables measured, the system measures the average background noise, average environmental illuminance (brightness), location, and the surveys the user's perceived mood and comfort level. The doctor and client can then see the client's performance with respect to their environmental and behavioral attributes during the time of testing (e.g., did they perform well on the tests in a bright, medium-loud outdoor setting in the morning while feeling rested and happy, or test poorly at night in a dark, quiet indoor setting feeling tired and anxious).

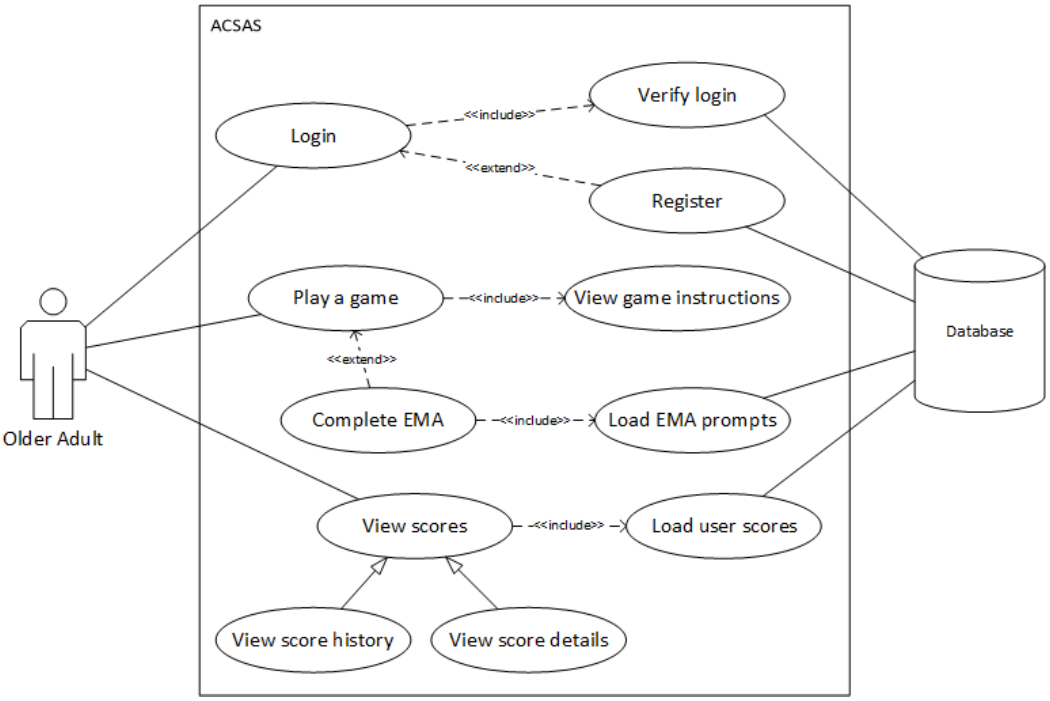


Figure 3. Initial use case diagram for primary user interaction with the ACSAS.

The ACSAS seeks to capture some of that missing data while the client goes through the self-assessment to give stakeholders more awareness into the context behind the ACA data. Given the self-guided nature of the system and context of use, an initial “Play Game” use case diagram (Figure 3) was created to convey the primary interaction between end user (i.e., older adults) and the ACSAS, including a backend database. The use case diagram captures the main scenario of the user going through a cognitive game in the ACSAS. It starts with the user logging into the system, playing through the game, and ends with them viewing their past performances. Throughout these interactions, there are other components that involve the database interfacing with the system to load or update information in the system.

By utilizing embedded device sensors and automated EMA surveys, the system can "observe" the contextual situation of the user during the time of testing and provide this contextual data complementary to the psychometric and application statistics. It can then aid in correlating the user's cognitive test performance with real-time contextual information pertinent to the interpretation and validation of the user's test results. The system will act as a tool for stakeholders by providing richer data on the contextual factors surrounding the self-assessment setting. It should be made clear, however, that the ACSAS is not meant to replace professional experience or intuition. The final interpretation and determination of the significance of results will ultimately be on the stakeholders.

5.2 Prototype Design

We employed an evidence-based approach [8] for the initial design of the prototype. We took established CCTs and adapted them as games for use in a novel Web-based ACSAS. We infused EMA and ambient data to display ACA results with contextual data. The initial CCT chosen for use in the system was a verbal recognition memory game adapted from the Rey Auditory Verbal Learning Test (RAVLT) [37,39]. The game primarily consists of a memorization task and a recognition task. The memorization task asks the user to remember a list of target words presented one at a time on the screen. This is immediately followed by a recognition task in which the user is prompted to recognize each target word in a new list of distractor words. This test was selected because of its validity and reliability as a psychometric indicator of memory impairment [39]. Like CNS Vital Signs [37], our adaptation of the RAVLT incorporates recognition tasks instead of recall tasks due to the in-the-wild nature of the ACSAS. This allows for easier self-administration and more discrete user interaction by not requiring the user to verbally recall the words in situ.

Based on our observations and interactions with stakeholders from section 4.2, in addition to reviewing literature on factors that influence cognitive assessment [6,10], we initially surmised environmental and behavioral information to be relevant in interpreting cognitive assessment results. For environmental data, we focused on real-world use-case scenarios and what the physicality of those scenarios would entail, i.e., what are the detectable characteristics of the physical space the user is assessing in. A detectable environmental characteristic shown to have cognitive effects on a user is background noise [46]. This matches our observational experiences with various older adult care facilities from section 4.2. To measure this, we chose to use the embedded microphone of mobile devices to measure the average loudness of the user's test environment in unweighted decibels (dB) [67].

For contextual factors that can be difficult to accurately detect using embedded sensors (e.g., mood, comfort), we designed the ACSAS to deliver brief, automated EMA surveys directly to the user to solicit such information. The qualitative responses to these surveys can reveal further insight into the context in which the user is testing that might otherwise be unattainable by the embedded sensors. With these heterogeneous sets of data being correlated with the user’s cognitive performance, it might be possible to get a more natural glimpse of the user’s cognitive well-being.

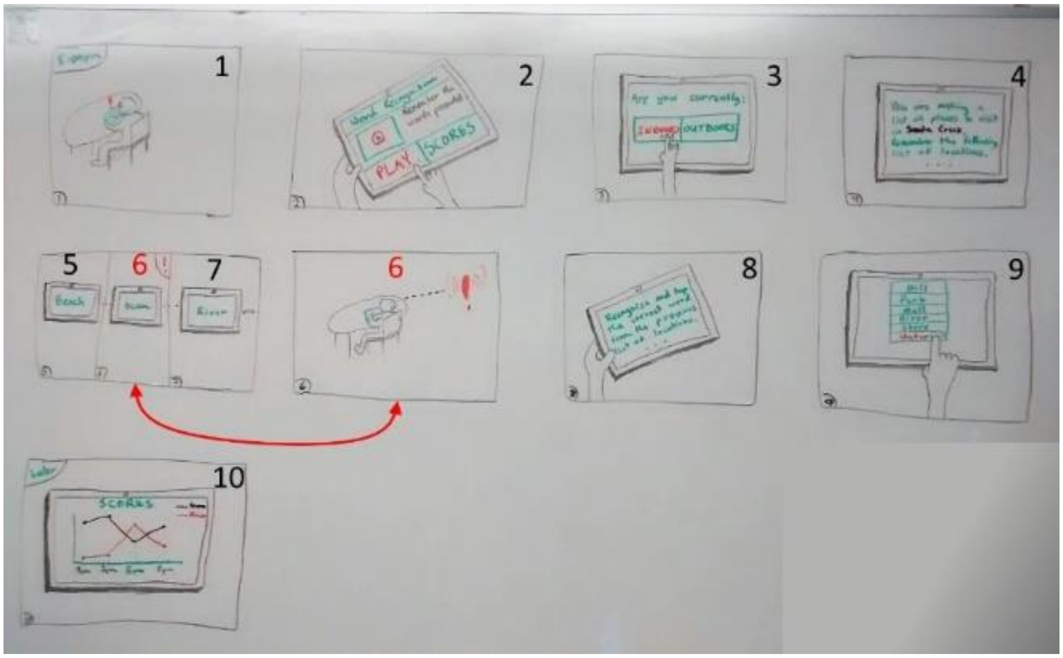


Figure 4. Storyboard of ACSAS prototype.

Given the motivation scenario in the previous section, we chose to storyboard the primary interaction of a user playing through a cognitive game in the self-assessment. An example storyboard highlighting possible external noise distraction can be seen in Figure 4. The storyboard is meant to highlight the novelty of the ACSAS as a Web-based, embedded ACA solution for self-assessment. The storyline progression of the storyboard is as follows:

1. An individual sits at a table in their living quarters at 5pm and is interested in playing a cognitive game in the ACSAS Web-app on their tablet device.
2. The person reviews the game instructions and presses the “PLAY” button to begin the RAVLT cognitive game.
3. The person taps through the brief EMA pre-game questionnaire to gain subjective context at the time of playing.
4. The person reads through the starting in-game instructions explaining the word memorization portion of the game.
5. The person is shown the first word(s) to memorize in the RAVLT game.
6. While a word is being displayed, an external element catches the person’s attention away from the game while memorization words are being displayed.
7. The memorization words are continued to be displayed until the last word is displayed.
8. The person reads the final set of in-game instructions explaining the word recognition portion of the game.

9. The person taps through the word recognition lists until they reach the end of the game.
10. Sometime later, the person is shown their past performance scores and corresponding ambient noise levels during those performances. They see a decline in their score at 5pm and an increase in the ambient noise level for that performance and recall when they were distracted by the external element.

Continuing from the storyboard, we iterated on various low-fidelity UI and interaction designs. We explored the primary tasks and interactions needed to progress through a single cognitive game for a given self-assessment session. The sketches in Figure 5 highlight initial UI designs that were used as the basis for our wireframes.

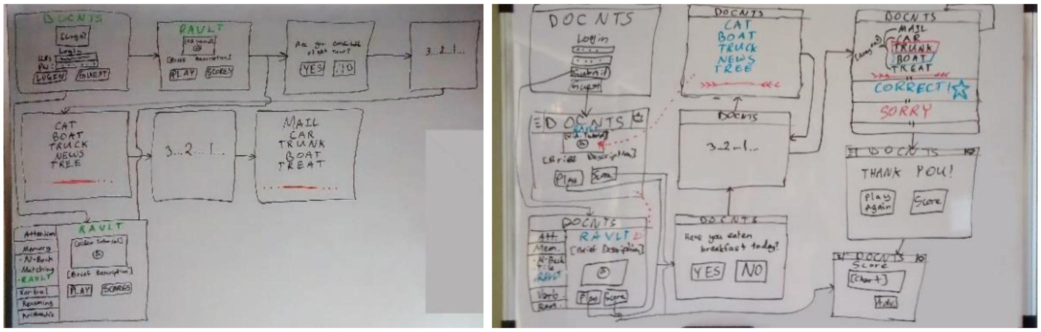
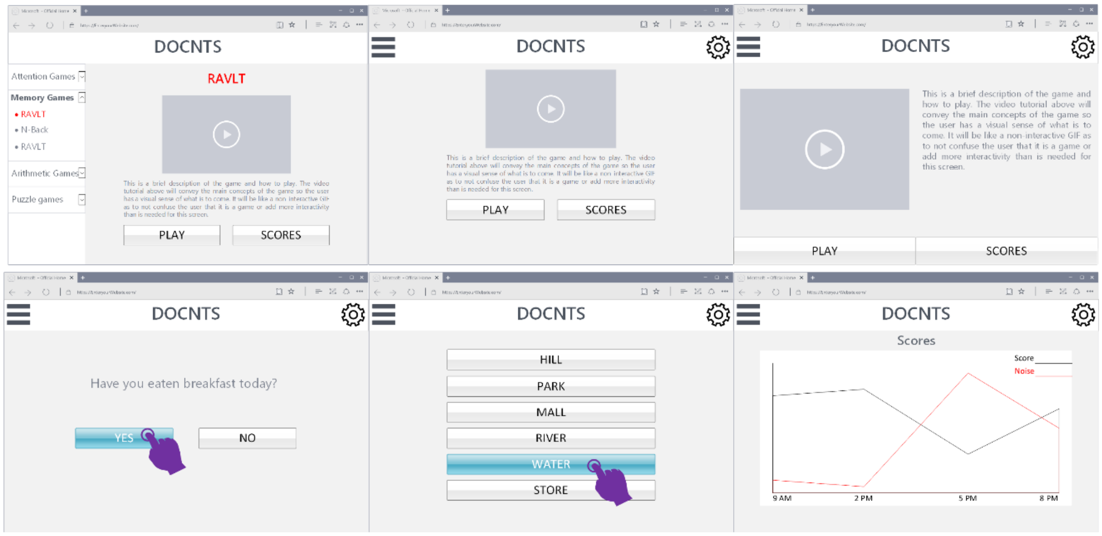


Figure 5. Initial low-fidelity UI and interaction design sketches.

After designing the basic interaction designs of the prototype, we moved on to create wireframe mockups of the system UI. We created wireframes for each major screen, i.e., game instructions screen, EMA screen, RAVLT screens, and score screen. A subset of wireframes of these screens can be seen in Figure 6.



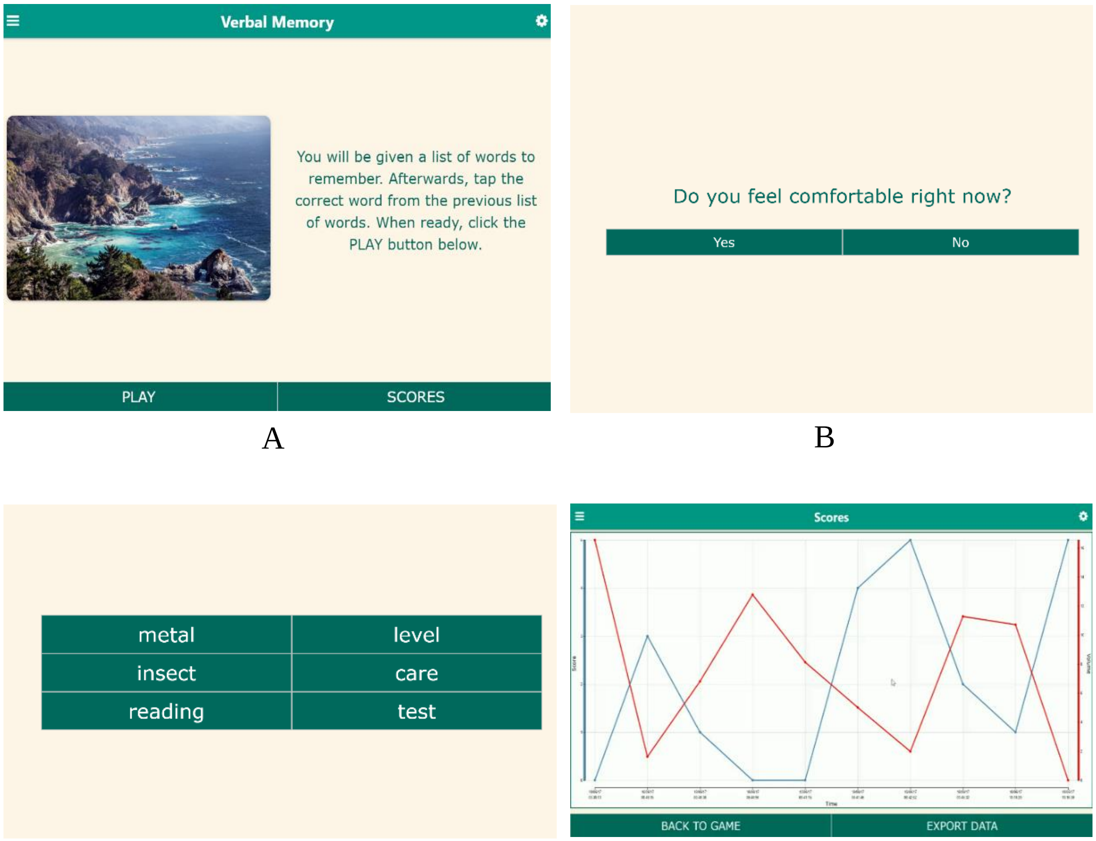
This is a brief description of the game and how to play. The video tutorial above will convey the main concepts of the game so the user has a visual sense of what is to come. It will be like a non-interactive GIF as to not confuse the user that it is a game or add more interactivity than is needed for this screen.

Have you eaten breakfast today?

Figure 6. Wireframe mockups of the UI design for the Game Instructions screen.

Once the wireframes were complete, we began the design of the medium-fidelity prototype (Figure 7). This medium-fidelity prototype included all the major UI and interaction design elements but didn’t include all the underlying logic and functionality of gameplay, scoring, and visualizations. The first version of the prototype used Microsoft PowerPoint as the driving engine, while later iterations, including the high-fidelity prototype, utilized HTML5. Chapter 0 provides specific details of the underlying system architecture and APIs used for the high-fidelity prototype.

We justify the design choices of the system prototype based on our preliminary system requirements. To address the functional system requirements, we: a) created the interactive cognitive game adaptation of the RAVLT (Figure 7, A and C), b) created the framework to allow the system to acquire contextual data at the time of self-assessment (Figure 7, B), and c) created the framework to allow users to view past performance scores and contextual data (Figure 7, D).



You will be given a list of words to remember. Afterwards, tap the correct word from the previous list of words. When ready, click the PLAY button below.

Do you feel comfortable right now?

A

B

C

D

Figure 7. Screenshots of the medium-fidelity prototype. (A) The initial visual design of the Game Instructions screen. The image of the ocean is a placeholder image for instructional media. (B) An example of an interactive EMA question display design. (C) An example of a word list during the recognition task. (D) The graph visualization of mock scores (blue line) and sound levels (red line) superimposed.

To address the non-functional system requirements, we designed the system to have two primary buttons at the bottom or middle of the screen for basic interaction and navigation. Simple text instructions were added to the system to ensure the system can be self-administered and easy to understand. Additionally, consistent colors, layout, and iconography were used throughout the prototype. This resulted in the medium-fidelity prototype that we then used to gauge the feasibility and initial usability of the novel ACSAS for use by caregivers of older adults, with the eventual goal of independent use by older adults directly.

5.3 Feasibility Study

5.3.1 Study Design

We developed a medium-fidelity prototype that included a working verbal memory game and fake sound level data. The prototype also included a mock graph displaying fake scores and sound levels (Figure 7, D) for concept validation purposes. In order to better approach testing directly with older adults, we first wanted to consult with healthcare professionals who work with older adults with MCI and individuals who are familiar with cognitive and behavioral assessments. For this study, the following primary system use case scenarios were defined: 1) the older adult sets up and administers the ACA independently and 2) a caregiver aids the older adult at the time of assessment. A use case diagram for these two primary use case scenarios can be seen in Figure 8.

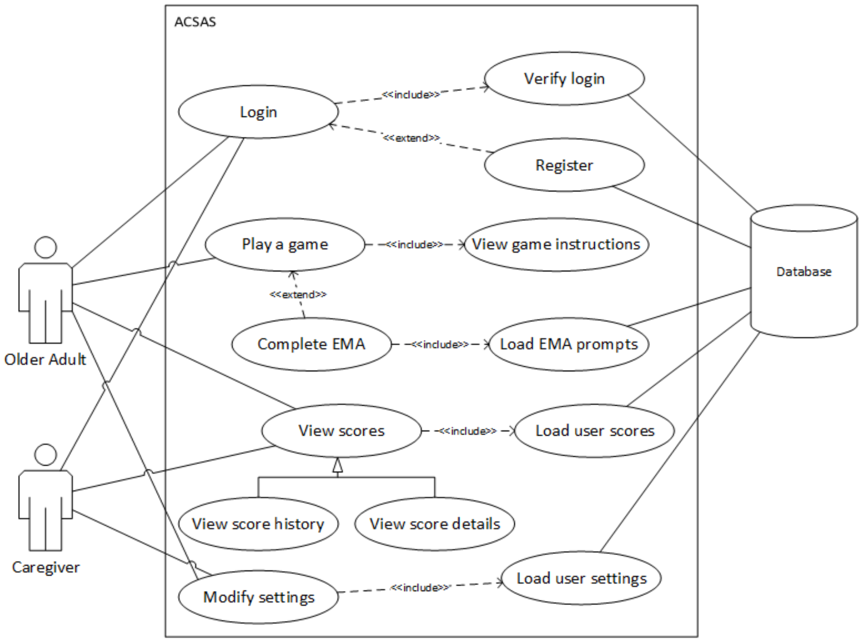


Figure 8. Primary use case diagram for the ACSAS, including older adult and caregiver use cases.

For this study, we chose to focus on use case scenario 2, i.e., a caregiver sets up the ACSAS for an older adult. Due to the sensitive nature of aging and MCI, we found it beneficial to work first with healthcare professionals to get expert feedback on how best to approach the design of the ACSAS for use by older adults. We devised two consultation sessions with healthcare social workers at a local health center for older adults. We deduced that the healthcare social workers' direct experience with older adults, both with and without cognitive impairment, would prove invaluable for our research purposes. Healthcare social workers were screened based on their direct interaction with older adults and prior experience with behavioral and cognitive assessments. The aim of Session 1 within this study was to gather initial feedback on the prototype. Session 2 involved a hands-on formative usability test with the prototype to find usability issues and recommendations to further improve the system prototype. The goal of Phase 1 was to address RQ1 and gauge the feasibility of using the ACSAS for use by older adults.

5.3.2 Session 1: Expert User Focus Group

5.3.2.1 Session 1 Methodology

After the development of the medium-fidelity prototype, we solicited feedback on the design of the prototype with healthcare social workers (n=5) at a local adult day health care center. We explicitly recruited healthcare social workers with experience in behavioral and cognitive assessment as participants for Phase 1. We ran a focus group with participants to gather initial feedback and recommendations for improving the system. This consultation session consisted of a short presentation and demonstration of the prototype to participants, followed by a think-aloud walkthrough of the prototype, concluding with a semi-structured focus group discussion. The think-aloud protocol allowed for explicit feedback from the participants regarding the system requirements and functionality. This information was complimented with deeper explanations and new insights through the focus group discussion. The focus group discussion topics included participants' attitudes and thoughts toward the prototype design, functionality, and its feasibility as a Web-based ACSAS for use by their clients, i.e., older adults with MCI.

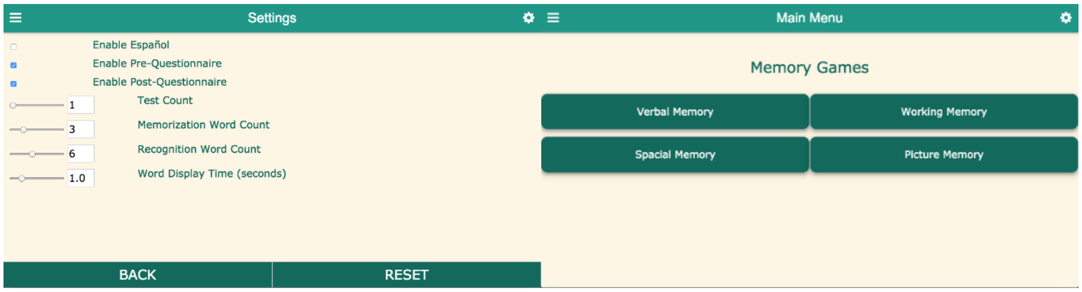
5.3.2.2 Session 1 Feedback

Some of the themes acquired from the think-aloud protocol included: a desire for the inclusion of specific automated contextual questions (e.g., "Have you eaten?", "Have you taken your medication?"); the need to use simple words; and the removal of distractions. Participants also complimented the simplistic design and interaction with the system. Based on feedback, participants most wanted a language selection feature (i.e., Spanish), more game customization (i.e., difficulty settings), and simpler overall UI design (i.e., simplify terminology used in the system and remove unnecessary images). As a result, the prototype was improved by removing visual distractions (i.e., unnecessary images and icons), and simplifying the system language (e.g., "scores" instead of "performance"). New system requirements were then established from participant feedback. The new functional and non-functional requirements can be seen in Table 6.

Table 6. New functional and non-functional requirements resulting from the focus group session.

Priority	Functional Requirement	Reason
High	The system should include a translation feature adapted to the user's native language.	Users of different backgrounds and cultures should be able to use the system in their native language.
Medium	The system should allow the user to navigate to a chosen cognitive game.	As more cognitive games are added to the system, it is important the user can locate a chosen cognitive game.
Low	The system should give users the option to change and modify system and game settings.	Allowing modification of system and game settings will increase the personalization options available to users and can aid in accessibility.
Priority	**Non-Functional Requirement**	**Reason**
Medium	The system should offer a selection of cognitive games.	To improve engagement and encompass more cognitive functions, the system should offer more than one cognitive game.
Medium	The system should use simple words and sentences.	Users may have different reading and educational backgrounds.
Low	The system's contextual questionnaires should be dynamic in content and flexible in administration.	Different contextual content may be relevant to specific users (e.g., specific medication intake or behavioral habits may need to be accounted for).
Medium	The system should be easily modifiable and dynamic in structure.	Given the dynamicity and flexibility required for system requirements, it is important the system architectural structure be modular and easy to modify.

The following features were then based on the additional recommendations by the participants: a settings screen that allows for manipulation of game settings and properties (Figure 9, Left); settings option to allow for English or Spanish language; settings options to allow automated questionnaires to be enabled or disabled; and slider options to allow for manipulation of game difficulty. Additionally, a main menu screen was added to allow the user to select their desired game (Figure 9, Right), thereby allowing for more cognitive games to be deployed within the system.



☐ Enable Español
☑ Enable Pre-Questionnaire
☑ Enable Post-Questionnaire
1 Test Count
3 Memorization Word Count
6 Recognition Word Count
1.0 Word Display Time (seconds)

Figure 9. (Left) The new Settings Screen that allows for customization of test properties. (Right) The new Main Menu screen to allow for more games to browse and choose from.

5.3.3 Session 2: Expert User Evaluation

5.3.3.1 Session 2 Methodology

For Session 2, a formative usability study was designed to test the updated prototype with a new group of healthcare social workers (n=10), 8 female and 2 male, at the same healthcare facility. The objectives of Session 2 were to: a) gauge the formative usability of the prototype and b) gather any additional feedback to further improve the system prototype.

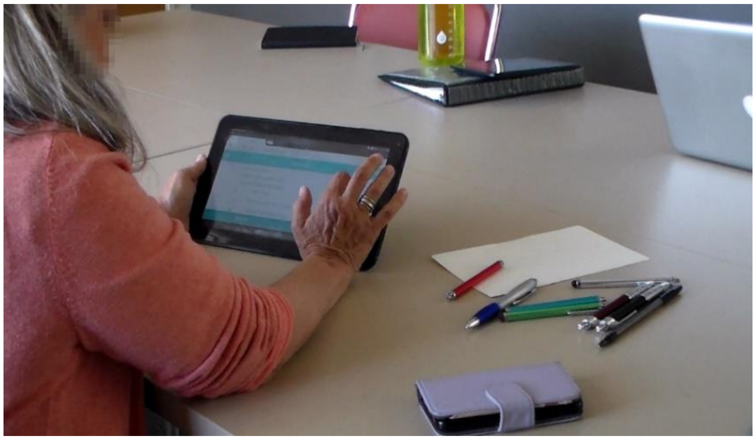


Figure 10. Healthcare social worker interacting with the ACSAS prototype on a tablet device.

Since most cognitive assessments for older adults are currently administered by professionals, it was important to get professional feedback on the usability of the proposed ACSAS. Hence, a usability study was conducted with ten healthcare social workers at a local adult day healthcare center. All participants were screened to have had prior experience with behavioral and cognitive assessments with older adults. Additionally, all participants had experience with touchscreen devices, indicating their ownership of a smartphone and/or a tablet device. After obtaining approval from our institutional ethics review board (IRB), participant consent to capture audio and video recordings was collected prior to the study. Some participants asked to not be recorded. Only researcher observational notes and summaries were collected for those participants.

The usability study consisted of a series of one-on-one usability test sessions that included two interviews (pre- and post-test), a hands-on usability test with the system, and a brief post-test satisfaction questionnaire. During the hands-on usability test sessions, participants were asked to complete a series of predefined tasks with the system on a provided tablet device (Figure 10). The tasks aimed to test the general usability of the system with medical professionals. Tasks involved navigating through the system screens, modifying system settings (e.g., enabling / disabling system features, modifying game variables), and completing the cognitive tests (i.e., games) to verify successful modification of the game settings. This was followed by the final post-test interview session in which explicit feedback on the usability of the system was targeted. Specifically, participants were asked to complete the following tasks:

T1. Complete 1 memory test with the default settings.

T2. Complete 2 back-to-back memory tests with both pre- and post-test surveys disabled, keeping all other settings to default.

T3. Complete 1 memory test in Spanish with 4 memorization words and 4 recognition word choices with both pre- and post-test surveys disabled.

T4. Complete 1 memory test in English with 3 memorization words, 2 recognition word choices, pre-test survey disabled, and the post-test survey enabled.

Following the hands-on test session, the participants were given a short survey to evaluate their overall attitude toward and satisfaction with the system. The Unified Theory of Acceptance and Use of Technology (UTAUT) model was utilized due to its usefulness in assessing the likelihood of success for new technology within an organization, in addition to its aid in understanding the motivations for acceptance in populations of users that may be less inclined to adopt and use a new system [89]. We explored the following items from the UTAUT: performance expectancy, effort expectancy, attitude toward using technology, facilitating conditions, self-efficacy, and anxiety. The survey was composed of the following eighteen questions derived from the UTAUT model:

Q1. My interaction with the system is clear and understandable.

Q2. The system behaves in the way that I would expect.

Q3. I find the system easy to use.

Q4. Learning to operate the system is easy for me.

Q5. Using the system to aid in cognitive testing is a good idea.

Q6. Working with the system is fun.

Q7. I have the knowledge necessary to use the system.

Q8. I feel apprehensive about using the system.

Q9. I hesitate to use the system for fear of making mistakes I cannot correct.

Q10. The system is somewhat intimidating to me.

Q11. I find it easy to remember how the system works.

Q12. I like working with the system.

Q13. I find the system difficult or annoying to use.

Q14. I feel comfortable using the system.

Q15. If I were to use this system in my job, I would find it useful.

Q16. If I were to use this system in my job, it would be easy for me to become skillful at using the system.

Q17. I could complete a job or task using the system if there was no one around to help me.

Q18. I could complete a job or task using the system if given enough time to complete the job or task.

This was followed by the final post-test interview session in which explicit participant feedback on the usability of the system, including ease of use, was targeted. The questions asked during the post-test interview were the following:

O1. How easy/difficult was it for you to use and navigate the system?

O2. How easy/difficult do you feel the system would be for your clients to use?

O3. How do you feel about the look/design of the system?

O4. **4.1.** What was your favorite aspect/feature of the system?

4.2. Least favorite?

O5. What features/functionality do you feel would be most important to include in the system (e.g., Spanish version)?

O6. Do you have final comments or feedback?

Responses to the UTAUT-based survey were captured using a 5-point Likert scale. The responses to the survey can be seen in Figure 11. Additionally, open-ended responses to the post-test interview questions were captured and qualitatively analyzed. The interviews of all recorded sessions were transcribed and analyzed using inductive thematic coding by two independent coders and revised by a third researcher. The results of these sessions are summarized in the following section.

5.3.3.2 Session 2 Results

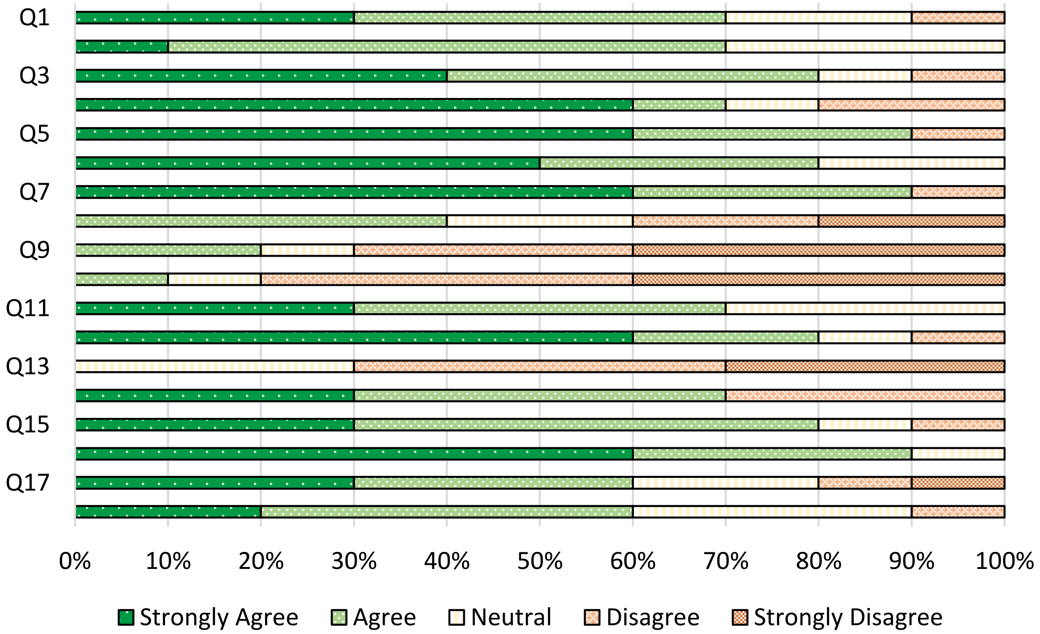


Figure 11. Summary of usability survey responses.

Of the 10 participants, only one needed assistance in completing the tasks. The remaining 9 participants successfully completed all the tasks without assistance or external guidance within the allotted time of 15-minutes. Nine out of 10 of the participants agree that using the system to aid in ACA is a good idea (Q5), they have the knowledge necessary to use the system (Q7) and could become skillful at using the system professionally (Q16). The one participant who disagreed with the statement went on to say that it would depend on the individual using it, specifying some of their clients (older adults) would benefit from it. Overall, 8 out of the 10 participants found the system to be easy (n=5) or somewhat easy (n=3) to use or navigate for themselves (Q3), found the system fun to use (Q6) and enjoyed working with it (Q12).

When asked about the system usability regarding their older adult clients, 4 out of 10 participants believe the system would be easy to some degree for their clients to use independently. They agreed that the usability of the system would depend on the cognitive ability of the individual client. As P10 indicated, "*I feel like independently depends on the level of cognition that they have currently... if it was [healthy aging] people... I think they can use it by themselves*." The system was also said to be easy to use because "*the [system] instructions were clear, and you don't have to touch a lot of stuff*," (P7). In contrast, 6 out of 10 participants believe the system would be difficult or somewhat difficult for their clients with MCI to use independently. However, with some practice, participants believed that the system could be used by their clients. "*They would have to practice a lot. A lot of [clients] had difficulty initially with iPods, but could learn this [system] with practice*," (P9). P8 states that: "*They probably need…*

a fair amount of training. Most of them. But I think, you know, the thing is, touch screens are very intuitive."

Additional feedback received by participants also pointed out the usefulness of including contextual and ambulatory information in traditional cognitive assessment. "*It's something that, you know, an aspect of this cognitive testing that we hadn't thought of. You know, when we do our assessments of our participants, how are they feeling? Are they in pain? Is there something going on outside the window that can be, you know, distracting from us being able to get a more accurate sense of their cognitive abilities? It's great!*" (P7). Referring to the automated EMA questions, P4 states, "*I like the questions. Um, I feel like it's good information and context to have for [clients].*"

Table 7. Improvement themes emerging from O3.

Improvements	Count	Participants
Improve color scheme and contrast	4	P5, P7, P8, P9
Simplify options / choices / settings / terminology	3	P2, P4, P6
Provide meaningful summary of user scores	1	P8
Make text entry via slider or keyboard easier	1	P5
Minimize number of menus the user must navigate	1	P2

When asked about the look and design of the system, six out of 10 participants explicitly stated they liked the system design. They pointed out specific reasons such as the simplicity of the design (n=6), it was not distracting (n=4), and the font is good (size, color, layout, etc.) (n=3). Participants' responses to O3 – O6 are summarized in Tables 7 – 11.

Table 8. Summary of participant responses to O4.1.

Favorite Feature	Count	Participants
System customization	4	P1, P2, P5, P8
Ease of use	4	P3, P7, P8, P9
Spanish/English option	3	P2, P6, P8
Score graph	2	P1, P10
Self-assessment capability	2	P6, P10
Inclusion of contextual information	1	P4
Timing and pacing of game	1	P10

Table 9. Summary of participant responses to O4.2.

Least Favorite Feature	Count	Participants
Unintuitive interface	3	P2, P4, P8
Difficult to use slider elements	3	P5, P7, P8
Poor color scheme	3	P5, P8, P10
Complicated wording	2	P4, P6
Small font size	2	P1, P10
Difficult to navigate	1	P2
Not enough direction/instructions	1	P4
Learning curve	1	P3
Discouraging scores	1	P9

Table 10. Summary of participant responses to O5.

Recommended Feature	Count	Participants
Audio dictation/guidance	5	P3, P4, P5, P6, P7
Music and sound	2	P1, P6
Increase/improve visual aids	2	P3, P9
Improve interface consistency	2	P2, P10
Increase/improve user engagement	1	P6
Improve accessibility options	1	P8
Increase/improve system instructions	1	P10

Table 11. Themes extracted from participant feedback to O6.

Themes	Count	Participant(s)
System is a good idea for use with older adults	4	P1, P6, P7, P8
Context is important for understanding cognitive ability with older adults	2	P7, P9
Touch interaction is a good idea for older adults	1	P3
Game-like interface is a good idea for older adults	1	P4
Positive reinforcement is a good idea for older adults	1	P4
Beneficial to introduce clients to technology	1	P6
Technology for good is good	1	P8
Would require assistance for some	1	P9
System runs smoothly	1	P10

5.3.4 Feasibility Discussion

The feedback received during these studies highlighted some important aspects of the ACSAS requirements. One insight that stood out was the importance of understanding and considering the cultural and educational experience of the users when designing ACA systems. This sentiment reinforces the conclusions made in previous studies [6]. By implementing a language selection option and simplifying the system terminology, the system prototype was designed within the cultural and educational experience of primary and secondary users, thus enhancing the overall accessibility of the system for older adults and caregivers.

Considering system use case scenario 2 (Figure 8), it was important to include caregivers early in the design process. The feedback from these participants during the focus group discussion brought to our attention to the need for easily customizable system options and settings. It was decided that a dedicated settings screen would allow secondary users to easily modify and setup specific testing settings for end users, thereby improving the personalization capabilities of the system for older adults. Additional system requirements were established based on participant responses to O3-O5 (Table 12).

Table 12. New functional and non-function requirements resulting from the Session 2.

Priority	Functional Requirement	Reason
High	The system must allow for audio dictation of on-screen text.	Not all users may be able to read.
Medium	The system should provide visual instructions.	Written instructions may be too lengthy and insufficient for understanding tasks.
Priority	**Non-Functional Requirement**	**Reason**
High	The system should use a simple and consistent high-contrast color scheme.	Users may have different visual experiences and may require high contrast.
High	The system should use large font sizes.	Users may have varying levels of vision.
Medium	Navigation should be easy and straightforward.	Navigation buttons and icons should behave as expected by the user to mitigate confusion.
Medium	Interaction with settings should be simple and easy to use.	Users must be able to quickly and easily change system and game settings.
Low	The system should provide a meaningful summary of user scores	User should be able to quickly see an overview of their performance scores.
Low	The system should include music and sounds in the cognitive games.	Additional audio fidelity could improve user engagement.

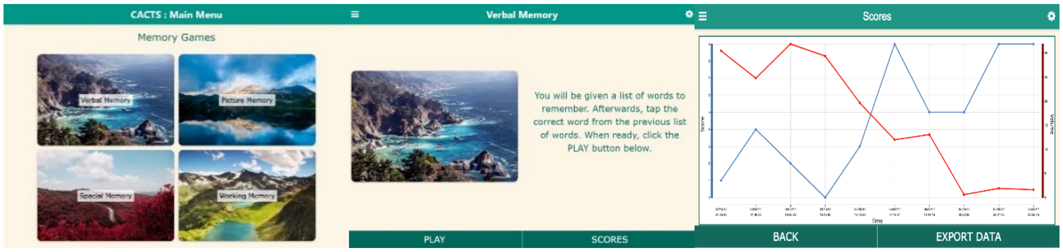
Though most participants felt the system would be difficult for their clients to use independently, 9 out of 10 agree that using the system to aid in cognitive assessment is a good idea. Moreover, the sentiments of the participants indicate that with assistance, the system could be used by older adults with and without MCI, further justifying the feasibility of the ACSAS. Based on the feedback from participants, we decided to update our primary user group to focus on healthy aging older adults. It was also stated that their clients could learn to use the system with training and practice, emphasizing the system’s learnability. These results address RQ1 by indicating that, with some training and simplifying of the system user interface, there is a reasonable degree of feasibility in using the ACSAS for self-monitoring cognitive well-being for healthy aging older adults.

5.4 High-Fidelity Prototype Iteration

Based on the compilation of system requirements, a high-fidelity prototype of the ACSAS was developed and implemented as an HTML5 Web-based application that supports the use of device sensors and automated surveys to infer user context (Figure 12). The data supported in the high-fidelity prototype includes the user’s test performance (i.e., score, reaction time), the user’s responses to the automated surveys, audio data (i.e., average level of sound in the environment), and temporal data (i.e., time of tests).

A recommended design feature that stood out from participant feedback was the importance of including the support for audio dictation. Given the advances in computer and Web accessibility [95], numerous tools exist for aiding in audio dictation of Web content, including built-in accessibility features in operating systems and Web browsers. Rather than implementing a specific audio text to speech synthesizer in the

ACSAS, the prototype capitalizes on WCAG guidelines by using semantic HTML markup for on screen text content and UI elements (e.g., alt text, headers, paragraphs). This allows for built-in and third-party audio accessibility tools to function with the ACSAS Web app, thereby providing dynamic support for audio dictation through the system.



You will be given a list of words to remember. Afterwards, tap the correct word from the previous list of words. When ready, click the PLAY button below.

Figure 12. Screenshots of the high-fidelity ACSAS prototype.

The system is composed of four primary modules: Administration Module, Sensor Module, Context Module, and Data Module. The Administration Module is primarily responsible for administering the cognitive tests to the user. The Sensor Module is responsible for capturing and processing raw sensor data for context analysis. To complement this data, brief, automated surveys will be utilized through the Context Module to gather additional data on the user’s testing context. For instance, short binary response questions (e.g., “Did you sleep well? Yes or No”) will be delivered to the user either before or after a cognitive test. For the system to track user performance and context over time, the Data Module is designed to store and query all system data. Currently, the Data Module utilizes lossy compression for storage of raw sensor data, thereby decreasing the overall storage size. This compression also aids in user privacy since the audio clips themselves are not stored; instead the numeric value of the processed input signal (i.e., volume).

5.4.1 Contextual Factors

5.4.1.1 Embedded Sensors

We investigated the affordances and capabilities of modern consumer mobile devices. Most modern mobile devices come with a wide array of embedded sensors and software capabilities. Our aim was to maximize the amount of relevant contextual information gathered while minimizing the number of required sensors and features, and thus cost, of a mobile device capable of running the system. Based on literature for factors that affect CCT [6], we initially surmised environmental and behavioral information to be relevant in interpreting psychometric test results.

For environmental data, we focused on real-world use-case scenarios and what the physicality of those scenarios would entail, i.e., what are the detectable characteristics of the physical space the user is testing in. A detectable environmental characteristic shown to have cognitive effects on a user is background noise [46]. To measure this, we chose to use the embedded microphone of mobile devices to measure the average loudness of the user's test environment in dBA (A-weighted decibels) [67]. Though there have been problems identified with A-weighting [64,84], we chose to measure the average loudness in dBA based on literature citing it as meaningful measure of perceived loudness by the human ear [46,67]. Various sampling and calibration techniques will be explored from literature to find an optimal measurement of ambient noise. Additional ambient and behavioral measurements that are detectable through embedded mobile sensors, such as the quality environmental lighting via a front facing camera, were investigated but not implemented.

5.4.1.2 Interactive Surveys

For contextual factors that can be difficult to accurately detect using mobile sensors (e.g., mood, comfort), the system can deliver brief, automated surveys through the system directly to the user to solicit such information. The survey content can be dynamically created and modified within the system via UI elements to personalize the gathered information. The qualitative responses to these surveys can reveal further insight into the context in which the user is testing that might otherwise be unattainable by the device sensors. With these heterogeneous sets of data being correlated with the user's cognitive performance, it might be possible to get a better glimpse as to true state of cognition of the user.

5.5 Phase 1 Discussion

The feedback received during the prototype development highlighted some important aspects of ACA system design considerations. One insight that stood out was the value ecological and contextual information can bring to cognitive assessment. By nature of ACA methods, these contextual factors can enhance cognitive assessment by giving a more accurate sense of cognitive well-being. This reinforces conclusions made in previous studies [1,66,75]. Furthermore, the results point out the importance of understanding and considering the cultural and educational experiences of users when designing ACA systems. This further supports findings from Bauer et al. [6]. Implementing a language selection option and simplifying the system terminology can enhance the overall accessibility and usability of the system with older adults. These findings further motivate the need to investigate and understand the potential contexts of use for the ACSAS by older adults.

From this study, we gathered feedback and design recommendations to improve the system prototype for direct testing with older adults. Given the nature of ACA for self-monitoring, we found it important to not only include contextual factors that have been shown to have a cognitive effect (sound, sleep, mood, etc.), but also those that older adults themselves find important. Moreover, a novel component of the prototype is its capability to communicate this ACA information back to the end user for interpretation. We chose to use data visualization techniques, as they can provide a quick summary of sometimes complex data in a clear and concise manner [55]. With the complex nature of aging, it is increasingly important to situate the interpretation of ACA data within the context of individual experiences. When thinking about information communication, it was important to consider what information to communicate to the end user, i.e., what factors are older adults most concerned about regarding their cognitive well-being and how do we visualize that for them? We move forward to address RQ2 in Chapter 6.

Chapter 6

Phase 2: Contextual Assessment

From the previous chapter, we learned that healthcare social workers believe that, given some practice and training, the ACSAS has the potential to be used by older adults. Additionally, we learned that contextual factors can have an influence on cognitive assessment based on feedback from healthcare social workers. This latter conclusion serves as motivation to further explore what types of contextual factors should be considered for independent use of the ACSAS by older adults. As a result, we sought to address RQ2, that is, what is the context of use for the ACSAS with older adults?

6.1 Senior Activity Center Workshop

We first started by investigating user motivations and deterrents for using the ACSAS in the daily lives of older adults. We led an interactive workshop with a group (n=14) of healthy aging, community dwelling older adults above 90 years of age at a local senior activity center. The objective of the workshop was to explore and gain insight into the following questions: 1) what would deter or prevent older adults from using the ACSAS and 2) what would motivate users to use it?

6.1.1 Methodology

The workshop included a short video presentation on the ACSAS prototype, followed by a co-discovery activity in which participants worked in pairs to complete tasks with the system prototype, and concluded with a group discussion on the activity and system prototype. The hands-on activity consisted of participants breaking into groups of two to cooperatively explore the system prototype. In each pair, one participant was instructed to take on the role of the guide while the other participant performed the tasks instructed by the guide (Figure 13). All instructions were provided ahead of time to the participants. Once the performing participant finished all the tasks, they would switch roles and continue through a different set of tasks with the system until both participants had a chance to take on both roles. Following this activity was a group discussion exploring participant motivations, deterrents, and attitudes toward the ACSAS prototype. We observed participants throughout the hands-on activity and during the focus group discussion. The session was transcribed and independently by two researchers and verified by a third.

Figure 13. Participants at the senior activity center working cooperatively in pairs for the hands-on activity.

6.1.2 Activity Observations

Observations during the hands-on activity revealed that most participants felt confused with the activity and apprehensive towards mobile and Web technology in general. Most, if not all, participants had never partaken in such an activity with tablet devices (i.e., instructed cooperative use of a Web app on a tablet device) and expressed confusion as to what they were supposed to do. Verbal and written instructions were given to participants prior to the activity, but left participants confused as to the overall purpose of the activity. Despite this, most participants had a chance to directly interact with the application prototype or observe the application prototype being interacted with. Two of the participants explicitly chose not to participate in the activity.

When asked what issues participants had with the activity, some participants pointed out the lack of proper instructions or explanations within the system. "*When you're* *asking all these simple (EMA) questions, and you're answering them, right, then all of a sudden you put up three words, then all of a sudden that's the end. There wasn't enough [explanation],*" (P5). Prior to the hands-on activity, a short video demonstration of the ACSAS was presented on a TV to participants. Though the video walked through the basic flow and features of the system, it was not interactive and gave little preface as to the intention of the system specific to the activity. In fact, the researchers involved found it necessary to provide individual instructions and guidance to each pair of participants throughout the activity. P6 noted that instructions given by research was what was missing in the system, "Y*eah, well, you finally gave it to us by talking to us*."

6.1.3 Group Discussion

6.1.3.1 Deterrents and Motivations

In addition to the observations of the hands-on activity, we ran a group discussion tackling some of the deeper questions of adopting the ACSAS regarding participant motivation, deterrents, and other concerns surrounding the use of the ACSAS and similar technology. We first began by asking participants what issues they had with the system during the activity and what would prevent them from using the system on their own in their daily lives. One of the main themes participants discussed was a lack of resources needed to use the system, i.e., computer or tablet or Internet access, "*Well I don't have a computer at home. So I'm not computer friendly at all. So that's the problem.*" (P1). As a result, participants felt intimidated by the system, as P9 highlights, "*It's harder to open your mind to something that's challenging. And this is certainly challenging to me because I don't have a computer, I don't have access to the internet.*

So this is intimidating.” This sentiment of lack of resources or intimidation by the system was reflected across most participants.

Some participants expressed their specific apprehension towards the Internet. “*I don’t like to get on the Internet. I stay off of it, because I don’t like to expose myself or whatever. I just stay off of it because I can stay out of trouble that way. That’s my own opinion. I just don’t do Internet or anything like this*,” (P7). The issue of Internet privacy and trust is a topic that participants felt was an important factor that might deter them from adopting the system. More specifically, there may be a lack of awareness of what data of theirs is being exposed and how they could minimize or mitigate that. This reflects what was discussed in section 1.7 regarding older adults and online privacy and trust. P1 points out that their feeling of security and training might improve their willingness to adopt the ACSAS, “*I would really have to feel more secure about what I’m doing. And get some training*.”

Participants also commented on how they felt the ACSAS would not “fit” into their daily lives. P8 points out that the ACSAS may have to compete with more compelling activities for them to be motivated to use it, “*You know if we didn’t have television or newspaper, which I certainly use much more than I ever did, then that would be a motivation. But I think that the day goes by so fast and I’m not bored by what I’m doing, so why get something that’s going to frustrate me*.” Some participants added to this by noting their apprehension towards mobile and Web technology and its appeal towards a younger population. “*I think age-wise, we’re just beyond... taking on, I don’t know, maybe everybody else is different, but I just don’t need it, let’s put it that way. I just* *don't need this. I'd rather bake cookies or whatever. It's just a personal feeling. I'm not into that type of thing. I think that at our age—maybe from 80 to 90 it would be a lot more interesting for people at that age, or 70 to 80. I think there are so many more people who are into computers and Internets and tablets*." (P7).

Some positive feedback and comments on motivation towards using the system included it being fun and engaging as well as its ease of use, i.e., large buttons and easy to read text. "*I think this was fun, what we did! Maybe I could learn this, possibly. So I think it's a good thing we have this here*." (P8). The learnability of the system was something mentioned by other participants, indicating that with some training, participants might be able to use it independently. P6 also made a comment about how they might be motivated to use the system, "*If I could talk to my doctor this way*." This supports similar reports of patient-doctor communication through Internet enabled devices [31].

6.1.3.2 Attitude Towards Self-Monitoring Cognitive Well-Being

In addition to participant deterrents and motivations for using the ACSAS, we asked participants about their opinion of self-monitoring their cognitive well-being. Some participants expressed it would be appealing to self-monitor their cognition over time. When asked how they would go about doing that, P8 pointed out the difficulty in doing so, "*It's very difficult. I wouldn't know. Because I think you can tell, one day is better than another and... but it's important to know or think why*." One participant (P6) shared taking their "*blood pressure. That's how I see [how] I'm doing*."

When asked about how they prefer this information communicated to them, P6 followed up, "*it's numbers. Because I have a Fitbit. Tells me how many beats per second, because I was up to 120 and now I'm in 60. So I have to take it every morning*." P1 did note, however, they dislike of numeric feedback, "*I'd just like it to tell me. I don't want numbers. And if it doesn't talk out-loud, I guess it has to be written [on the screen]*." Another participant countered the idea of written performance feedback, "*That would piss me off, frankly. I don't want a computer telling me, that lividly, what I'm doing. I love the [idea of the] cartoon. I can deal with that, but—especially if it's a complement—but I don't think I like the computer talking to me or texting me*," (P14). This discussion points out the difficulty of providing feedback on an individual's cognitive well-being in a meaningful and appropriate manner. This is especially true of older adults with different backgrounds, experiences, skills, and preferences.

We followed up this discussion by asking participants about other factors they felt might affect their cognitive well-being. The primary theme participants mentioned was age and the act of aging. "*We have to face it every day. I mean you're either good or one day you get up and you don't feel good. You just have to deal with it.*" (P7). This highlights the complexities of aging and the difficulty of categorizing its specific effects on daily life. Moreover, the awareness of decline in older adults compared to their younger selves can impact mood and thus cognitive ability. "*For me, being on a walker, trying to do what I used to do 5 years ago… Some days are good, some days are not good*." (P10).

6.1.4 Reflection

Perhaps not too surprising is the finding that a barrier to adoption of the ACSAS by older adults is an individual’s level of familiarity and comfort with technology. This workshop has shown that, though older adults are among the highest adopters of mobile and Web technology across the U.S. [100], this statistic may not hold true for smaller populations. Given the sample size of this workshop, the findings may not be generalizable but instead provide contextualized insight into the hesitation to use such technology by older adults. Moreover, it may be the case that older adults over the age of 90 may be more reluctant to use mobile and Web technology than younger older adults. The subgrouping of older adults may be a more fruitful perspective to take when investigating the technological familiarity and comfort level of older adults with mobile and Web technology.

An individual’s perception of their own familiarity with technology also plays a role in their decision to use the ACSAS. If an individual feels intimidated by the ACSAS, they will not want to use it. Furthermore, if the system does not provide enough information and guidance for self-administration, the individual will become frustrated choose not to use the system. It is important that training and guidance be given to users prior to using any ACA system. However, for unsupervised self-monitoring, this training and guidance must come from within the system itself.

Participants mostly felt that the ACSAS did not integrate naturally within their daily lives. However, as they also mentioned, the younger subgroups of the aging population may be more inclined to adopting the system for use their daily lives. Though the participants of this workshop did not believe the system would fit in their lives, they did express the usefulness and importance of the concept of self-monitoring. It is also hinted at that, in addition to improving system instructions, increasing the variety of engaging interactions within the system could improve user enjoyment and motivation to use the ACSAS.

6.2 Retirement Community Case Study

We volunteered to teach a short, 4-week class on the basics of tablet devices at a local retirement community. The community consists of 206 individual apartments to maintain resident independence and privacy. It includes numerous services and activities for residents to use at their discretion. The residents were healthy aging older adults (average age = 85), a requirement established by the community administration. During our partnership with the community, we had the chance to interact directly with residents and staff through presentations, classes, workshops, and research activities we put together. Through these activities, we learned valuable insights into the experience of older adults and their needs for independent living.

We iterated on the design of the system and developed a high-fidelity prototype. The prototype included a fully functioning verbal memory game which recorded user performance data (i.e., score and reaction times) and ambient sound data (i.e., average sound level in the environment via the device microphone). All collected data is time stamped by the system and stored locally on the participant's device as well as a back-end database. A login feature was also implemented to store and retrieve participant data to and from the database. For this case study in Phase 2, the automated EMA questionnaires were disabled and replaced with a writing prompt activity with participants that solicited feedback on the types of contextual factors participants believed to be most relevant to monitoring their cognitive well-being.

6.2.1 Study Design

We ran a case study with a group of healthy aging older adults in a local retirement community to understand what contextual factors older adults are concerned about for the purpose of self-monitoring their cognitive well-being. The results of this assessment would then be used to guide the design of the system and information visualizations relevant to the end users themselves. In addition to understanding participants' perceptions and concerns, we sought to test the functionality of the ACSAS to capture ambient sound during self-assessment. Motivated by prior observations (Phase 0), feedback (Phase 1), and literature [6,46], we designed an experiment to investigate whether commonplace ambient sounds have an impact on healthy aging older adults' ACA performance.

As stated previously, most ACA studies focus on clinical research outcomes rather than end user experience for self-monitoring ambulatory cognition. We decided to take an end user approach to ACA and focus on what ecological and contextual factors older adults find most important to include in *their* interpretation of their cognitive well-being. This end-to-end exploration of ACA tools for self-monitoring by older adults is something that has not yet been explored in literature.

6.2.2 Methodology

We recruited 7 healthy aging, English monoglot older adults (mean age = 87.4), all female, at a local retirement community (Table 13) to participate in a group hands-on test and discussion with the system prototype. After obtaining approval from our institutional ethics review board, participant consent to capture audio and video recordings was collected prior to the study. The study session consisted of: a brief introduction and practice with the system prototype, an ACA consisting of a series of back-to-back CCTs delivered through the ACSAS prototype in a group setting, a brief usability and opinion questionnaire, a writing activity soliciting explicit feedback on contextual factors important to participants, and finally concluding with a group discussion. The ACA involved participants independently playing through a series of verbal memory games back-to-back while various common background sounds (i.e., English and non-English conversations, traffic noises, classical music) were played on the room speakers to see if there was any noticeable impact on their performance.

Table 13. Phase 2 retirement community case study participant demographic information. ACA indicates whether the participant participated in the ACA portion of the study. Participants rated their hearing on a scale from 1 (worst) to 10 (perfect).

PID	Age	Gender	ACA?	Hearing Aid?	Hearing Rating	iPad Usage
P1	94	F	Yes	Yes	7	Never
P2	93	F	Yes	No	9	Often (2+ times a week)
P3	93	F	No	Yes	6	Daily (1+ times a day)
P4	83	F	Yes	Yes	6	Often (2+ times a week)
P5	91	F	No	Yes	5	Often (2+ times a week)
P6	83	F	Yes	No	8	Daily (1+ times a day)
P7	75	F	Yes	No	9	Daily (1+ times a day)

Due to unforeseen device issues, 2 of the 7 participants were unable to participate in the ACA. The remaining 5 participants then participated in a series of 24 verbal memory CCTs delivered through the ACSAS whereby different types of pre-recorded sound clips were played in the background. Three of the 7 participants used hearing aids, but it was confirmed that all participants could hear the sounds being played from the room's wall-mounted TV clearly. The test progression proceeded as: 4 tests in silence, 5 tests with instrumental music (no lyrics), 5 tests with English speech and conversations, 5 tests with traffic and city sounds, and 5 tests with non-English (foreign) speech and conversations. Within each sound type, 5 unique sound clips were created, whereby each of those unique clips had 6 variations of pre-calibrated sound levels (i.e., output volume) ranging from -15dB (lowest volume) to 0dB (full volume) at intervals of 3dB [44]. A random ordering of clips and sound levels within sound types was applied. During each test, the individual system instances on the users' devices sampled the background sound level periodically (100 milliseconds) to capture the auditory volume throughout the tests.

The 5 participants who participated in the ACA were then asked to complete a short usability and opinion questionnaire. Following the survey and a short break, all 7 participants were instructed to write down contextual factors they perceived to be most impactful for self-assessing their cognitive performance and well-being. Each participant independently generated a list of at least three factors and gave a rating of importance to each. The ratings ranged from 1 (least important) to 5 (most important). This activity was followed by a group discussion to gain deeper insight into the participants’ experiences and reasoning behind their lists, in addition to their thoughts on the session and system prototype. All but 1 participant participated in the group discussion (Figure 14).

Figure 14. Older adult participants engaging in the group discussion.

For each individual game playthrough, we captured participant performance scores (number of correct responses), their reaction times for each response, and the average sound levels recorded by the system throughout each individual game. A post-test questionnaire was given to gauge the usability of the system and participants' opinions. The System Usability Scale (SUS) questionnaire was administered to evaluate the usability of the system [11]. The group discussion was recorded, transcribed, and coded by two independent researchers and verified by a third. The themes are highlighted in the results section.

Due to the small number of participants, it was important to complement the quantitative data with qualitative data. In addition to the video observations of participants, we ran a group discussion addressing questions related to the context of use surrounding the ACSAS or similar systems for use by participants in their daily lives. The discussion was recorded, transcribed, and coded by two independent researchers and verified by a third. The themes are highlighted in the results section 6.2.3.4.

6.2.3 Results

6.2.3.1 Participant Performance

The primary variables examined for participant performance were the scores (i.e., correct responses) and reaction times within each test. Due to the nonparametric nature of the data, a Spearman's correlation test was run to assess the relationship between participants' scores and average sound levels (unweighted dB) per test. There was no significant correlation for participants' scores and average sound level, r_S= 0.1824, p= 0.3936. Another Spearman's correlation test was used to evaluate the possible correlation between sound levels and participant reaction times. No correlation was found between unweighted sound levels and participant reaction times, r_S=0.0267, p=0.5594.

Table 14. Contingency table for the percentage of correct and incorrect responses per sound type.

Contingency Table		
	Correct	Incorrect
Silence	80%	20%
Music	77%	23%
English	82%	18%
Traffic	84%	16%
Foreign	83%	17%

To evaluate the relationship between scores and sound type, i.e., silence, music, English speech, traffic, and non-English speech (foreign), a chi-squared test was run on the data. No significant association was found between participant scores and sound type, $\chi^2(2, N=5) = 2.5845, p = 0.6296$. The contingency table for the percentage of correct and incorrect responses is shown in Table 14.

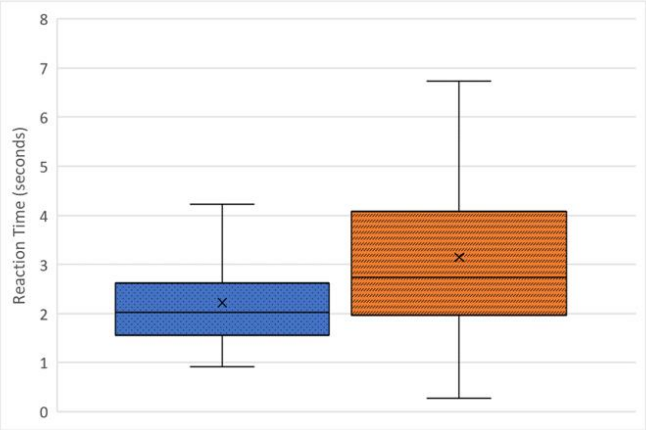


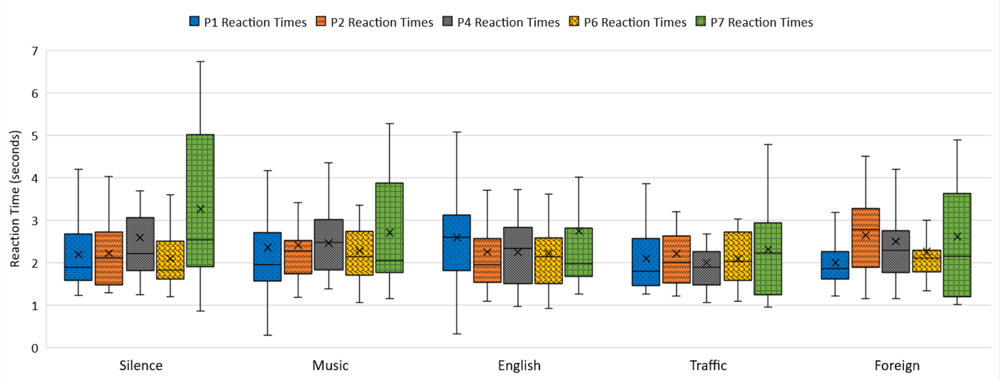
Figure 15. Comparative distributions of all reaction times for correct (left) and incorrect (right) responses.

A Kruskal-Wallis test was run to examine reaction times between correct and incorrect responses. There was a statistically significant difference between reaction times for correct and incorrect responses, $\chi^2(1) = 36, p<0.01$ (Figure 16). A final Kruskal-Wallis H test showed that there was a close to marginal, but not statistically significant difference in reaction times across the different sound types, χ^2 (4) = 7.713, p = 0.1027.

Table 15. Kruskal-Wallis medians and ranks for reaction times across sound types.

	Silence	Music	English	Traffic	Foreign
Median	2.1	2.133	2.149	1.932	2.149
Rank Sum	31751.5	39226	38001.5	32907.5	38413.5
Count	100	125	125	125	125

Table 15 shows the medians and ranks for corresponding sound types. Individual Kruskal-Wallis tests were used for each participant to see if there was within-subject variation in reaction times across sound types. There was found to be no statistically significant ($p<0.05$) difference in reaction time and sound type within participants. P4 had marginally significant differences in reaction times across the sound types ($p<0.1$). The results are summarized in Figure 16.



	P1	P2	P4	P6	P7
χ^2	7.1335	5.3015	8.2393	1.3142	7.1417
df	4	4	4	4	4
p-value	0.1290	0.2577	0.0832	0.8590	0.1286

Figure 16. Distributions of reaction times across the different sound type per participant. Participant p-values are displayed below the chart.

6.2.3.2 SUS and Opinion Questionnaire

To measure the usability of the system, the SUS questionnaire was used. The SUS uses a scale from 0 (low usability) to 100 (high usability). The average SUS score across participants was 76. A score above 68 is considered above average. The summary of responses to the SUS questionnaire are shown in

Table 16. Additional questions specific to the system were included in the questionnaire. The responses are summarized in Table 17.

Table 16. Mean SUS responses and standard deviations by question. Responses were scored on a 5-point Likert scale, strongly disagree=1 to strongly agree=5.

SUS Question	Mean	SD
I think that I would like to use this application frequently.	3.6	0.55
I found the application unnecessarily complex.	1.8	0.45
I thought the application was easy to use.	4	0.00
I think that I would need the support of a technical person to be able to use this application.	1.6	0.55
I found the various functions in this application were well integrated.	4.2	0.45
I thought there was too much inconsistency in the application.	2	0.71
I would image that most people would learn to use this application very quickly.	4	0.00
I found the application very cumbersome to use.	1.8	0.45
I felt very confident using the application.	4	0.00
I needed to learn a lot of things before I could get going with this application.	2.2	1.10

Table 17. Mean opinion responses and standard deviations by question. Responses were scored on a 5-point Likert scale, strongly disagree=1 to strongly agree=5.

Opinion Question	Mean	SD
I found the application to be appropriately challenging.	3.2	1.30
I don't think the application would help me track my cognitive health.	2.6	0.89
The application was enjoyable to use.	4	0.00
I would not like to keep track of my cognitive health.	2.2	1.10
I would use this application if my doctor told me to use it.	4.2	0.45
I would not use this application independently on my own.	3	1.00
I liked the overall appearance of the application.	3.8	0.45
I think this application is less enjoyable than other cognitive health applications or games.	2.2	0.84
I plan to use the application in the future if possible.	3.6	0.55
I don't like that the application "listens" to my environment while I use it.	1.8	0.45
I think this application is easier to use than other cognitive health applications or games.	3.4	0.55
I don't feel motivated to use the application.	2.2	0.45
I feel the application is secure and safe to use.	3.8	0.45
I don't like the amount of data the application collects.	2.4	0.55

6.2.3.3 *User Generated Contextual Factors*

We collected participants' written responses to the writing prompt for contextual factors they believed to be most impactful on their ability to perform well on the cognitive test. The written responses were analyzed and grouped by theme. The results are summarized in Table 18. Ranking weight was calculated by the following equation: $Weight = \sum Rating_i \times (Number\ of\ Ratings)$.

Table 18. Participant-generated list of contextual factors participants found most relevant to their cognitive ability and/or assessing their cognitive well-being sorted by rank, including individual ratings and total weights.

Rank	Theme	Rating 1	Rating 2	Rating 3	Rating 4	Rating 5	Weight
1	Health	2	5	4	2	2	75
2	Auditory Distraction	5	4	5	3		68
3	Comfort Level	3	5	5			39
4	Audiovisual Distraction	5	4	2			33
5	Energy Level	4	2	2			24
6	Sleep Quality	3.5	3				13
7	Sense of Privacy	5	1				12
8	Time of Day	2	3				10
9	Ambient Temperature	3.5	1				9
10	Ambient Lighting	3					3
11	Feelings	2					2
12	Weather	1					1

6.2.3.4 *Focus Group Themes*

In addition to the writing activity, we conducted a focus group discussion with all remaining participants. The focus group questions were centered around the context of use of the ACSAS. The discussion questions are arranged below. The inductive themes identified and the number of participants who contributed to those themes are displayed in Table 19 through Table 22.

Q1. What contextual factors do you feel would most impact your ability to perform well on the cognitive test(s) of this system or similar systems?

Q2. What would motivate you to use this system or similar systems?

Q3. What would prevent you from using this system or similar systems?

Q4. Where and at what times would you most likely use this system or similar systems?

Table 19. Main themes identified for Q1 of the focus group discussion.

Contextual Factors Themes	Count
Audiovisual Distraction (Unexpected Event)	7
Health (Physical/Mental/Emotional)	7
Auditory Distraction	5
Sense of Privacy	4
Feeling	3
Mood	3
Energy Level	2
Technology Experience	2
Lighting	1
Sleep Quality	1

Table 20. Main themes identified for Q2 of the focus group discussion.

Motivation Themes	Count
Improve Cognitive Ability (Cognitive Health Concerns)	5
Entertainment	5
Track/Assess Cognitive Ability	2

Table 21. Main themes identified for Q3 of the focus group discussion.

Deterrent Themes	Count
Time Availability	3
Potential Negative Side Effects (Sleep Interference, Overstimulation)	2

Table 22. Main themes identified for Q4 of the focus group discussion.

Context of Use Themes	Count
When: Free-Time	4
Where: Living Room	2
When: Watching TV (Boredom)	2
When: Afternoon	2
When: Mid-Morning (After Breakfast)	1

6.2.4 Discussion

6.2.4.1 Performance and Sound

In examining the results of the effect of environmental sound level on the participants' test scores, there doesn't appear to be any significant impact. The sound clips played during the tests were chosen to represent common sounds that one might expect to hear in everyday experiences. The question we sought to tackle was whether there would be a detectable effect of these types and levels of sounds on a participant's performance (score and reaction time) in self-administered ACA. Based on the results, there didn't appear to be any noticeable impact on participants' performances.

One of the main variables we measured for participant performance was score, i.e., the number and instances of correct responses. Each test had 5 words to remember and thus 5 possible points. Previous pilot tests with social workers and caregivers suggested that

5 words was a good balance between difficult and easy for older adults to remember in a given timeframe. However, most participants received high or perfect scores throughout the tests. Though most participants (3 out of 5) agreed the tests were appropriately challenging (Table 17), it appears the test was in fact too easy or didn't provide enough difficulty to see a significant effect on performance. One solution to this would be to implement a difficulty scaling feature that can adjust the test to the participant's performance.

Reaction time has been shown to be an important measure of cognitive performance, especially for older populations [42]. In addition to correct responses, the system recorded participants' reaction times per individual response as well as averages across tests. The results seem to indicate that regardless of prerecorded background sounds, the participants' reaction times were significantly shorter for correct responses than for incorrect responses. There was no significant difference between participants' reaction times and either sound level or sound type. This is most likely in part due to the nature of the sounds being "*everyday sounds,*" as P6 said, thus potentially easily ignored or not distracting. Most of the participants (5 of the total 7) agreed with P4's statement that the sound clips "*weren't that bad*". P5 points out that had there been "*a big bang*" or "*people distracting [us] or somebody coming in*," there might've been a more noticeable effect on participants' performances. P6 goes on to say, "*Yeah…the fire alarm going off or something. That's what I meant about outside distractions*."

6.2.4.2 Context in Sound

Given the complexities of sound, it makes sense to reason that different types of sounds affect people in different ways. At the start of this study, we sought to examine common sounds older adults might be prone to hearing on any given day based on firsthand experiences volunteering and working with various local older adult communities. Music was a common sound type that fell into two main categories: instrumental and lyrical. We chose to use instrumental classical and orchestral music, as it was perceived to be a more common form of background music. As the results show, instrumental music had little effect on the participants' performance. When discussing this more with participants, some noted that music with lyrics might have proven to be impactful on their performance. "*Well I was thinking when I heard the music, that didn't bother me to speak of. Um, because it was just sort of generic. But if I would have been hearing music with lyrics, it would have just thrown me off.*" (P4).

We expected to see a possible change in reaction time and/or score for English and non-English speech, when in fact there was none. One possible reason for this is that the prerecorded audio clips consisted of many different audio tracks played simultaneously, thus creating a form of "white noise". Though the content of these audio tracks were from common sources, i.e., podcasts, radio, and TV, the overlapping of content might have proved easier to ignore as it becomes more difficult to focus on one audio track over the other. Moreover, the relevancy or familiarity of the content to an individual might have stronger effects than unfamiliar or irrelevant content.

6.2.4.3 Usability and Participant Opinions

The results of SUS indicate that the participants who participated in the hands-on exercise with the ACSAS found it to be easy to use and learn. All participants said that they felt confident using the system and that they image it would be easy for others to learn how to use it quickly. As promising as these results are, it should be noted that participants were given training with the system prior to the hands-on portion of the session. Additionally, the tests themselves were guided and only involved participants completing sequential CCTs. Participants did not test independent navigation or explore other system screens, such as the Score screen or Settings screen. With that said, it is promising to see that the CCTs within the ACSAS are easy to use by older adults. This aids in maintaining high user testing efficacy and further justifying its use as an end-to-end solution for self-monitoring cognitive well-being.

The opinion questionnaire revealed mostly positive attitudes toward the ACSAS by participants. The two prominent opinions were that participants found the system enjoyable to use and would be motivated to use the system if their doctor recommended it. This falls in line with what one participant pointed out as a motivating factor for using the system in Section 6.1 during the group discussion with older adults. This isn’t too surprising given the precedence of a doctor’s recommendation over an individual’s intrinsic motivation to self-assess. One approach to addressing user motivation to adopt such systems is through fun and engagement. This is discussed more in Section 6.2.4.5.

There was a split among participants on whether they would use this system independently. This is different than most participants indicating that they would not need the support of a technical person to be able to use it. This seems to indicate that though some participants felt they have the technical capability to use the system without a technical person, they may not be motivated or inclined to use it independently. It may be the case that participants don’t believe the system is entertaining or fits well within their daily lives and thus have minimal desire to use it on their own.

6.2.4.4 Relevant Contextual Factors

Participants were asked to discuss the reasons behind their generated lists of important contextual factors. Based on the themes discussed, two categories of contextual factors emerged: internal and external factors. Internal factors are those that are internal and dependent to the participant's being. The subset of factors that participants noted included health (physical, mental, and/or emotional), feelings or mood, energy and comfort levels, as well as experience with technology and sleep quality. For external factors, or those factors that are external to and independent from the participant, the main themes discussed were audiovisual and auditory distractions, ambient lighting, and sense of privacy. The two most prominent themes of these factors discussed were health-related factors and unexpected audiovisual distractions.

Given the study population, it's not unreasonable to expect health to be a primary contextual factor. P6 points out various factors related to health that could be impactful: "*I think the most impact would be how I felt that day. Do I have a headache? Am I feeling good? Am I depressed? Am I... how I physically, emotionally, mentally feel. How do I feel that day?*" This response highlights the importance of including such information in helping one understand their cognitive performance over time and possible interactions of such factors.

Unexpected audiovisual distractions also seemed to be an obvious contextual factor that could affect one's performance or ability to perform well in CCT. However, these distractions can take on many different forms in different contexts. It was therefore important to understand the specifics of the kinds of audiovisual distractions participants might expect to encounter in their daily lives. P6 highlights specifics about living in the retirement community, "*because we live in this community, there's commotion that goes on, ambulances coming in, and emergencies happening, you know, and all that kind of stuff affects what you're trying to concentrate on*." The noises that these types of unexpected events would produce could possibly be captured through the user's device at the time of testing and be used to give otherwise missing context to the user's performance at the time of testing. Some of the more prominent words mentioned throughout the discussion can be seen in the word cloud in Figure 17. The words we found to stand out the most were words relating to distractions and privacy.

Figure 17. A word cloud generated from the most prominent words mentioned during the group discussion on contextual factors participants believed to be most impactful on self-monitoring their cognitive well-being.

6.2.4.5 Participant Motivation

When asked about what would motivate participants to use the system independently, the main responses participants discussed were their desire to improve their cognitive ability (sometimes in response to real-world cognitive health concerns), wanting to use the system for fun or entertainment during down-times, and the importance of being able to track and assess their cognitive ability. Some participants discussed real-world instances in which they might have cognitive health concerns, warranting the use of the system to improve their cognitive ability. "*With me it would be if I had met somebody and couldn't remember their name. Then I'd think to myself, 'I better start, you know, exercising the brain cells.' And that would motivate me to want to play it*," (P2). Participants also pointed out that viewing the system as a game would be a motivator to get them to use it: "*I like to play games, so anything involved with the game I like to* *do. So here's an educational game that might help me to start remembering these things more,*" (P6). Rather than seeing the system as a testing application, participants preferred to view the system as a serious games system for use during times of leisure. This reflects other findings and avenues being explored in literature [33,45,52]. Figure 18 highlights this sentiment via a word frequency cloud, with some of the more prominent words being "game", "play", and "time".

Figure 18. Focus group discussion word clouds for the motivations to use the system.

6.2.4.6 *Obstacles and Deterrents*

Converse to understanding what would motivate participants to use the system, we also asked what would prevent or deter participants from using it. The two primary deterrents participants discussed were time availability and possible negative side effects of using the system. Given the nature of the retirement community in which numerous activities are scheduled, let alone health and personal appointments, it makes sense that time availability would be among their obstacles for using the system. When discussing the possible negative side effects of using the system, P5 talks about the potential for it interfering with their sleep in the sense that it might foster overstimulated use: "*Well if it keeps you from sleeping... if you get involved in this stuff... I wouldn't want that.*" P2 echoes this sentiment, "*No, I wouldn't want that kind of overstimulation either*." This concern of overstimulation is one that appears to be tied more with mobile technology in general rather than a specific deterrent for using this system.

6.2.4.7 Usage Contexts

When considering contextual factors that might prove useful in understanding users' self-administered ACA performance results, it is useful to know when, where, and how users would use the system. Participants indicated that they would primarily use the system while in their living room, sometimes while watching TV. "*I'd play it in the living room, number one. And I'd play it when the news got so boring that I couldn't stand it anymore, and I wanted to fill my time. So I'd just sit down and play it because it's entertaining*," (P2). This sentiment further supports the finding that participants would prefer to use the system for educational entertainment. P2 highlights the importance of understanding the situational context during the time of testing to better interpret the user's ACA results (e.g., did they miss points because of their cognitive ability or because they were distracted by the TV).

Time of day was also an important factor for participants. Participants noted mid-morning or afternoon were the ideal times they would choose to use the system. P1 states, "*Probably midmorning. Around 11. I find if I do crossword puzzles in the* *morning when I'm having my breakfast, maybe 8 [or] 8:30, I miss some that later on in the day, if I go back, I can *snaps finger* pick up like that. But my brain hasn't gotten into gear or something, early on*." P1 highlights how time of day can affect one's cognitive ability [74].

6.2.4.8 Preference for Performance Feedback

Most participants indicated that they would prefer some form of numerical score feedback on their performance, noting that "*it would be nice if [the system] had a numerical score*," (P1). Some participants expressed their preference for graphs and visualizations, "*The graphs are easy to interpret, you know, the visual tells you the whole thing*," (P2). P6 takes this one step further and points out a want for fine-grained details of their performance, "*At the end of each [Verbal Memory game]…you put the numbers…and say, 'You got 5 right or 4 wrong,' and show me which ones were the ones I got wrong. And then that would tell me ah ha! So next time I go to do it, I try to be sharper on remembering those*." Participants noted that they wanted immediate feedback on their performance as opposed to longitudinal performance feedback, "*I'd like to view mine immediately*," (P2). When asked how often they would want to view their performance results, P6 said they prefer to view their results "*every time I play*." This supports the findings from [51].

6.2.4.9 Attitude Towards Self-Monitoring Cognitive Well-Being

All participants expressed the value in self-monitoring their cognitive well-being in some way. Most participants indicated that they would want to keep track of their cognitive health and felt that the system would help them keep track of it. They believe it to be valuable for themselves, “*I’d like to know my score… I’d like to know what I’m at fifty or sixty percent*,” (P4). One participant noted the value in monitoring cognitive well-being for professional reasons, such as “*if you see a therapist or some specialist*,” (P2). Some individuals only feel the need to monitor or assess their well-being, cognitive or otherwise, if they or their doctor sees a “radical” change in their health. This is not an uncommon mindset for individuals to follow, i.e., assess if something warrants the assessment. With physical health, it is sometimes more direct in identifying symptoms to address a health issue. However, with cognitive health and well-being, subtleties in cognitive decline can be difficult to detect and diagnose [60], and thus may require a more sensitive and continuous form of monitoring.

6.2.4.10 Efficacy and Privacy

An interesting byproduct of this study was the discussion on participants’ efficacy and sense of privacy. Due to technical issues, 2 of the 7 participants could not participate in the system test and instead watched the others test. As P5 noted, "*I was sitting next to [P6] ...And when we’re all through, [P6] said 'I felt you,'...and I thought back the minute [P6] said that. That would affect me. If somebody was sitting here looking over my shoulder, that would really affect me*." This finding supports the claim that third party presence, including that of an examiner, has the potential to impact an individual's CCT performance [98], also known as the Hawthorne Effect [53].

Despite this, participants indicated they were okay with the system “listening” to their environment as they assessed. “*For me, it’s a no-brainer. I don’t even think about it*,” (P2). One reason for this is the passive and “invisible” nature of embedded sensors, hinting at an “out of sight, out of mind” attitude by participants towards the system’s ambient sensing. It is still important to make sure users are aware of the fact the system is passively sensing their physical environment. Transparency will be crucial to not only protecting users’ privacy, but also to maintaining user trust.

6.2.4.11 Limitations

Due to the limited number of participants, it shouldn’t be said that the data presented is representative of the study population. User recruitment at the facility was limited to secondhand recruitment through the facility’s staff in addition to participant willingness to volunteer to take part in the study without compensation. Moreover, due to logistical constraints, we were unable to conduct individual tests with participants and instead had to test in a group setting. This itself brought additional technical and logistical challenges regarding facilitation, including between participant interaction. However, it also led to an interesting finding regarding participant efficacy and the Hawthorne effect on ACA.

Another limitation of this study was the seemingly easy difficulty level of the verbal memory CCT. It was suggested from stakeholders during previous work that 3 to 5 words for the verbal memory CCT would be challenging for older adults with MCI. As a result, we chose the upper bound of this recommendation for testing with healthy aging older adults. Future studies could utilize a practice and training phase in which the difficulty of the CCTs are either dynamically or manually set based on participant initial performance. This could also allow for participant performance benchmarking.

Additional CCTs (or cognitive games) are in development and will be utilized in future user studies. The next cognitive games to be implemented into the system are the N Back test, reaction inhibition test, and Stroop test, all standardized neuropsychological tests [37]. These additions are to expand on possible cognitive domains to assess, as well as increase user engagement through variety and novelty in experience.

It was anticipated that the participants' devices (iPads) would work for the study from previous interactions and demonstrations. However, due to the wear-and-tear and variety of participant devices, unforeseen technical issues prevented some participants from participating in the hands-on user test. These issues are under investigation, but one possible solution to this is to use low-cost tablet devices that have been tested to work with the system.

6.2.4.12 Design Implications

Despite these limitations, it is important to note that this study highlights the context of use surrounding the ACSAS for use by older adults (RQ2). By first examining the types of factors that are relevant to the study population, we can then iterate on the design of the ACSAS to incorporate such information. Future studies will make use of the automated EMA surveys of the system to solicit meaningful feedback on the contextual factors found to be relevant in this study. The following design implications reflect on what we have learned from this study:

- Participants prefer to view the ACSAS as a game rather than a test or assessment. This reframing of the system as a possible cognitive gaming platform may prove more attractive and thus more motivating for participants to actively use the system.

- Background sound level does not necessarily imply external distraction. Though there are objective sound levels that can cause physical discomfort or pain [46], subjective sound qualities may prove more useful in understanding distractions during the time of testing. In this regard, audio frequency spectrum analyses could be used to classify background noise and provide a better understanding of the types of situational contexts at the time of testing.
- In addition to internal contextual factors, such as health, mood, and feelings, participants' perception of their surroundings should be considered when interpreting cognitive performance results. If a participant doesn't perceive their surroundings to be distracting, despite what is recorded, it may be the case that it will have no effect on the participant's performance.

Based on the findings from this study, new system requirements were established and are shown in Table 23. The requirements focus on user engagement and performance feedback recommendations. The input from participants regarding their preference for performance feedback has shed light on the importance of providing the user with fine-grained details on their immediate performance.

Table 23. Functional and non-functional requirements derived from Phase 2.

Priority	**Functional Requirement**	**Reason**
Medium	The system will display the user's immediate performance details after each game.	Users want to see their immediate performance after each session.
Low	The system should give users the option to view performance details for a past date.	Users may want to see their performance details for a previous date.
Priority	**Non-Functional Requirement**	**Reason**
High	The system should be game-like and engaging for the user.	Users prefer entertainment to testing or assessing. This will aid in user motivation and compliance with the system.
Medium	The system should display numerical scores for the user's immediate performance.	Users want to see a numerical representation of their performance.

6.3 Next Steps: Visualizing ACA Data

Based on the writing responses of participants, the most prominent factors users found important to their cognitive well-being was health. This is not surprising considering the experiences of older adults and the process of aging. However, given the variability and complexity of health issues between users of the same population, it can be difficult to pinpoint the top health factor to include in the initial design of the data visualization. Moreover, in order to collect objective measurements of such health data, additional external equipment and devices would be needed (e.g., heart rate monitor), thus increasing the complexity of the system at hand. Instead, we chose to capitalize on the external sensory capabilities of mobile devices and focus on the second most important factor users expressed to impact their cognitive performance, which is external auditory distraction. There have been studies that point out the effect of auditory noise level on cognitive performance [46]. Furthermore, given the unsupervised nature of ACA methods, various ACA studies have pointed out the possibility of external distractions as a potential limitation to ACA data validity [79].

Though the results of the common background sound levels and participant performance were not significant, direct feedback from participants indicate that auditory noise or distractions can influence their efficacy and performance in ACA. Similar research has been done exploring recording sound in an individual's daily life to look for patterns of depressive symptoms [54]. It has not been the case, however, that a study has examined the context of use of ACA tools regarding ambient noise level and user cognitive performance. Furthermore, little to no research has been done in displaying fine-grained details of ACA performance data back to the end user for self-awareness, evaluation, and interpretation. From this, we iterated on the system prototype score screen to include a score details screen that displays the fine-grained results requested by the participant (Figure 19, Right).

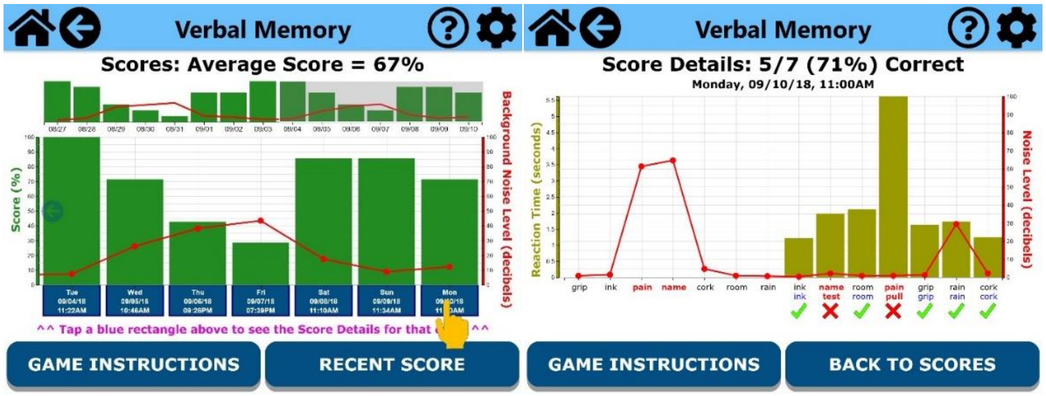


Figure 19. (Left) Score history screen displaying overall scores at the top and a subsection in the middle. (Right) Score details screen that displays fine-grained details of the participant's score.

These findings from Phase 2 helped us address RQ2 within the context of older adults living in a local retirement community. We decided to continue to explore how the ACA system prototype could be further used within this sample population to help tackle RQ3, i.e., how can the ACSAS be designed to facilitate independent use of the system by older adults? In order tackle this question, we chose to conduct a usability study with participants from the same community and an updated version of the ACSAS aimed at optimizing independent use of the system by users.

Chapter 7

Phase 3: Usability Testing

With the feedback from Phase 2, we again iterated on the prototype design. The initial score history screen's double line chart (Figure 12) was replaced with a bar graph for scores and a superimposed line graph for background noise level (Figure 19, Left). This same score history screen was updated to display scores over a longer period and added interactivity to the chart, allowing the participant to horizontally scroll and pinch-and-zoom the graph. Additionally, an interactive display of all scores was added to the top of the score history screen to give the participant a snapshot of their overall scores. A new interactive feature was added to allow participants to click on the date of the score to see the score details of the selected score entry. This score details screen (Figure 19, Right) was added in response to participants' desire to see the details of their immediate scores (i.e., words missed). Numeric scoring was added to the top of the score details screen as was requested by participants. This score details screen also included the noise level at the time of each key event during the game (i.e., display of words and participant input) and the participant's reaction time for each input. Along the x-axis, the correct responses are displayed above the participant's chosen response, along with a green checkmark or red X to denote correct and incorrect responses, respectively. The final major update to the prototype was the inclusion of a video demonstration in the game instructions screen (Figure 20, Left). This was to further aid in usability by improving the system instructions.

7.1 Study Design

How To Play

- You will be shown a sequence of **7 individual words** to memorize one at a time.
- Afterwards, a sequence of **7 word lists** will appear, one for each memorized word.
- Each word list will contain **1 word you memorized earlier** and 3 other distractor words.
- A **video demonstration** of this can

How To Play

- You will be shown a sequence of **7 individual words** to memorize one at a time.
- Afterwards, a sequence of **7 word lists** will appear, one for each memorized word.
- Each word list will contain **1 word you memorized earlier** and 3 other distractor words.
- For each word list, tap the **individual word** you

Figure 20. (Left) Game instructions screen for the first session of usability testing for Phase 3. (Right) Updated game instructions screen for the second session of Phase 3.

The aim of this study was to address RQ3, i.e., how can the ACSAS be designed to facilitate independent use of the system by older adults? It is imperative that the system be usable by users in order facilitate independent use. Given the issues participants faced in Phase 2, we found it important to focus more formally on the usability of the ACSAS before moving further with user studies and field tests. We designed a usability study with older adults to more deeply understand the usability issues faced by older adults when independently using the prototypical system. In designing the usability study, we sought to include an explicit focus on testing the understandability of the ACSAS score screens for independent data interpretation by older adults. We improved upon the design and functionality of the score screens, including the addition of the score details screen and numerical text as requested by participants from Phase 2. Motivated by [25] and participant feedback from Phase 2, we maintained the inclusion of graph data visualizations. Now with numerical text and graph visualizations, we wanted to investigate how effective these visualizations methods are in conveying ACA data to older adults.

Table 24. Participant demographics.

PID	Age	Sex	Education	Internet Time per Week
P1	94	F	Graduate Degree	“More than I’d like”
P2	83	M	College Degree	“At least once a day”
P3	93	F	College Degree	“More than an hour a day”
P4	89	F	Professional Degree	“A lot. Let’s say 10 hours a week”
P5	78	F	Professional Degree	“Quite a bit. 10-12 hours a week”
P6	84	F	Graduate Degree	“Multiple times a day. Maybe 4”

To accomplish this, we ran a summative usability study with healthy-aging older adults to see how participants interacted with the ACSAS and understand how to improve the understandability of data visualizations of ACA data for end users, i.e., older adults. We recruited 6 participants (mean age = 86.8), 5 female and 1 male, from the same retirement community indicated in Chapter 0. This study consisted of two separate usability test sessions. Each individual usability test session was conducted with a single participant at a time and two researchers to moderate and observe. Due to recruitment constraints, we conducted the study with 4 overlapping participants across the two test sessions. Five participants participated in the first session and 4 of those 5 participated in the second session, with 1 new participant joining the second session for a total of 6 participants across the sessions. The demographics of the participants can be seen in Table 24.

7.2 Methodology

Each usability test session consisted of: a consent explanation and acquisition step, a short demographic and background interview, an introduction to usability testing and think-aloud protocols, a short participant-guided exploration/walkthrough of the system, a series of usability tasks (4 main tasks), a post-test interview upon completing all the usability tasks, and a short questionnaire to fill out. A focus for the Phase 3 usability study was to see how participants would use the system with little to no guidance, i.e., independently. This was done to mimic the real-world usage scenario in which the participant would independently self-assess. Based on participant feedback on the contexts of use of the system from Phase 2 and use case scenario 1 from Figure 8 (i.e., older adult sets up and administers the CCTs independently), we designed 4 high-level usability scenarios and tasks for participants to carry out independently with the ACSAS. We administered and observed each participant with 4 usability scenarios and tasks. The scenario and tasks are summarized in Table 25.

For the data visualizations, approximately two weeks of mock data was generated for the usability tasks. The mock data was designed to highlight key features of the system as well as aid in framing the task scenarios. Participants were instructed to interpret the mock data as their own and proceed with the task as though they themselves had produced the mock data presented to them in the system.

Table 25. A summary of the usability tasks and scenarios administered.

Task	Scenario	Task
1	You have some free time in the morning after breakfast. You feel alert and want to test your brain. You decide now would be a good time to exercise your memory with the application on your tablet.	Try and score above 50% in the Verbal Memory game. Play the game as many times as you need to achieve the desired score.
2	Sometime in the afternoon, you are thinking about your scores for the Verbal Memory game. You decide to see how you've been doing for the past 2 weeks.	Find the date you scored the highest and the date you scored the lowest for the Verbal Memory game. Also, find the scores for those dates, respectively.
3	You've just recently played some Verbal Memory games on your tablet while there was some commotion happening outside. Looking at your scores for the Verbal Memory game, you see that you missed some points in yesterday's score and you're curious about why you might have missed them.	Find which words you missed in yesterday's game and what might have caused those misses.
4	You've had some time to play a few memory games throughout the past few weeks. You are interested to see what patterns you might find in your Verbal Memory game scores.	Try and find a pattern(s) in your scores.

7.3 Results

7.3.1 Pre-Task Interview Responses

When asked whether the participant tracks or monitors their cognitive health, a major theme that emerged was that participants did not formally or informally keep any form of discrete measurement of their cognitive well-being. Instead, most participants inferred their cognitive well-being through the quality of interactions and events in their daily lives. "*Only by recalling that I can't remember what I used to know (chuckles)! I* *don't keep any kind of record about it. You know, it's something that I just recall that, you know, a few years ago I was able to remember certain things much more easily than I can now.*" (P5). Two participants commented on using other cognitive or brain games as a relative gauge of their cognitive health and well-being. For example, P4 notes, "*I think about it. Who am I beating at Scrabble? (chuckles)*!" One participant specifically noted that they do not self-monitor their cognitive health, citing that "*I've done it all my life, I'm tired of doing it,*" (P1). Only 1 participant (P2) indicated that they monitor their cognitive well-being with a health professional in the form of individual discussions, "*I've hired a gentleman who comes uh, about once a week and we just generally discuss things.*"

A follow up question was asked about how satisfied or not satisfied participants were with their current method of self-monitoring their cognitive well-being. Most participants indicated being satisfied overall with their passive forms of self-monitoring. P2 mentioned their satisfaction with using meditation and mindfulness, "*So mindfulness class and that seems to help quite a bit as well. I'm not sure why, but I always feel much better after I have taken the mindfulness class and... meditation. And uh, I used to do a little meditation years ago and they are training me to get back into it again and it seems to be very satisfying for me*." P5 indicated they were unaware that were tools available for self-monitoring cognitive well-being, "*Um, I guess I don't realize that there is any way of recording it, truthfully. I didn't realize that there would be any accurate way of keeping track of it*."

If the participant indicated they did not self-monitor, we followed up by asking them what would motivate them to do so. P1 stated that they would consider self-monitoring their cognitive well-being “*If it's not working too well*.” One participant noted their “fear of knowing” as a deterrent to self-monitoring, “*I'm not sure I would be motivated, truthfully. I feel like it’s going to be a natural extension of my life to lose some cognitive abilities and whether or not I want to be frightened into, you know, keeping track of it or not. I'm not sure I would. The fear of knowing how much you don't. When the Alzheimer's is hitting*.” (P5).

7.3.2 Task Completion Rates

The moderating researcher recorded the participant’s ability to successfully complete the tasks without aid. The success rate for each task was equal to the number of successful completions of the task divided by the number of participants who attempted it. The task success rates for Session 1 are summarized in Table 26.

Table 26. Success rates by participant and task for usability session 1.

Task	P1	P2	P3	P4	P5	Success	Attempted	Success Rate
1	1	0	1	0	1	3	5	60%
2	0	0	0	1	0	1	5	20%
3	-	0	1	1	0	2	4	50%
4	-	-	0	1	0	1	3	33%
Total	1	0	2	3	1	7	17	**41%**

For the first usability test session, participants had an average success rate of 41%. Three of the 5 participants were able to successfully play through the specified game in the prototype (Task 1). Two participants were able to accomplish Task 3, while only

1 participant was able to accomplish Tasks 2 and 4. P1 was unable to attempt task 3 and 4 due to a time conflict. P2 was unable to attempt Task 4 for similar reasons.

The average success rate for the second session of usability tests was 45%. All participants successfully completed Task 1 (play through the game). Two of the 5 participants were able to accomplish Task 3 without assistance. As with session 1, only 1 participant was able to successfully complete Tasks 2 and 4. The results of the second usability test session are summarized in Table 27.

Table 27. Success rates by participant and task for usability session 2.

Task	P1	P2	P3	P4	P5	Success	Attempted	Success Rate
1	1	1	1	1	1	5	5	100%
2	0	0	0	1	0	1	5	20%
3	0	0	1	1	0	2	5	40%
4	0	0	0	1	0	1	5	20%
Total	1	1	2	4	1	9	20	**45%**

7.3.3 Task Error Counts

In addition to success rates, we also counted the number of errors participants made while trying to complete the tasks. Errors were marked when a participant made an incorrect input into the system or device relative to the task, or verbally indicated incorrect information regarding the system and task. These errors were categorized by error type via a deductive coding scheme adapted from [47], shown in Table 28.

Table 28. Video coding scheme for each type of usability error type.

Error Type	Description
Understanding data visualization(s)	The user indicates difficulty understanding/interpreting the data visualization(s).
Touch gesture(s)	The user indicates difficulty with touchscreen input (i.e., invalid/incorrect touch screen gestures).
Understanding UI elements and interaction	The user indicates difficulty understanding the overall UI elements and input options (e.g., doesn't recognize UI buttons, incorrect UI interaction).
Understanding system instructions	The user indicates difficulty understanding system instructions/explanations (e.g., instructions screen or help tour).
Understanding usability test procedure	The user indicates difficulty with understanding the usability test procedure (e.g., confusion with tasks/scenarios).
Navigation	The user indicates difficulty with navigation (e.g., confusion of place in system).

The total number of errors by participant for usability test session 1 is displayed in Table 29. For Session 1, Task 1 (i.e., play through game) had the most overall errors, at 214 total errors across participants. Task 2 (i.e., interpret past high and low scores) came in second with 109 errors. Tasks 3 and 4 had the fewest total errors, at 49 and 23, respectively. As noted in the previous section, P1 was unable to participate in Task 3 and 4, and P2 was unable to participate in Task 4. This is a contributing factor to consider when examining the low error counts for Task 3 and 4.

Table 29. Total error counts by participant for each task within usability test session 1.

Task	P1	P2	P3	P4	P5	Total
1	57	29	45	50	33	214
2	49	24	9	6	21	109
3	-	20	5	11	13	49
4	-	-	4	6	13	23
Total	106	73	63	73	80	395

Table 30 shows the total number of errors for usability test session 2. Across Session 2, Task 4 (i.e., find patterns in their data) had the most amount of errors (56) by users. This is followed by Task 2 with 51 total errors. Task 3 (i.e., interpreting score details) had 49 errors, while Task 1 now had the fewest amount of errors, at 39 total.

Table 30. Total error counts by participant for each task within usability test session 2.

Task	P1	P2	P3	P4	P6	Total
1	10	8	4	4	13	39
2	23	8	5	0	15	51
3	25	10	1	9	4	49
4	11	22	4	17	2	56
Total	69	48	14	30	34	195

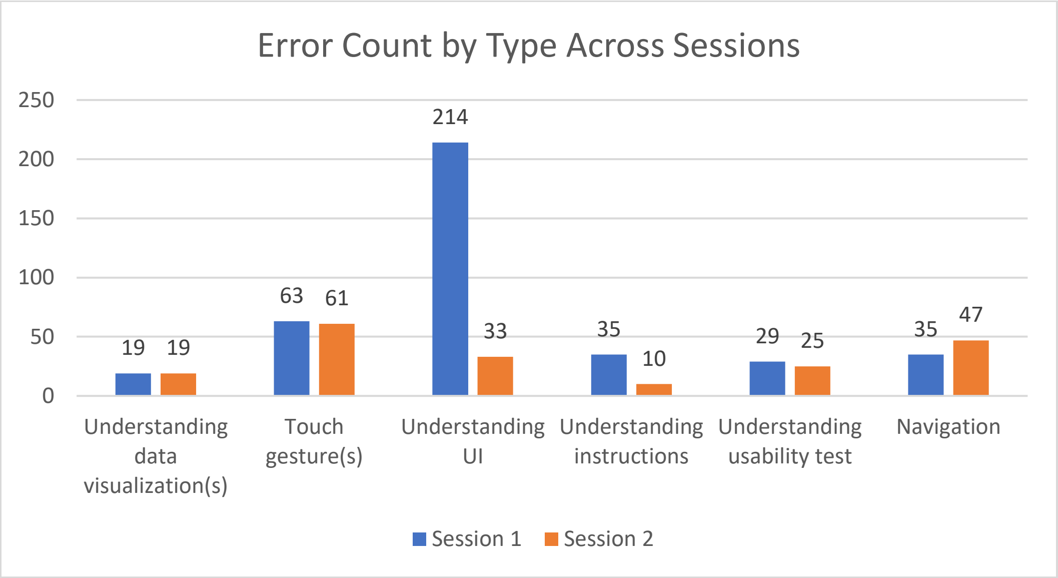


Figure 21. The error counts by error type across the two usability test sessions.

Figure 21 shows the number of errors within each error type across the two usability test sessions. By far the most errors were with understanding the system UI for Session 1. Most of these errors were caused by the confusing video demonstration UI element, for which most participants mistook as the actual game. Second to that was touch gesture errors, i.e., errors with general touch screen input. Such errors included accidental touch gestures and incorrect gestures, such as tap-hold instead of tap. The fewest number of errors by type was for understanding the system instructions for usability Session 2.

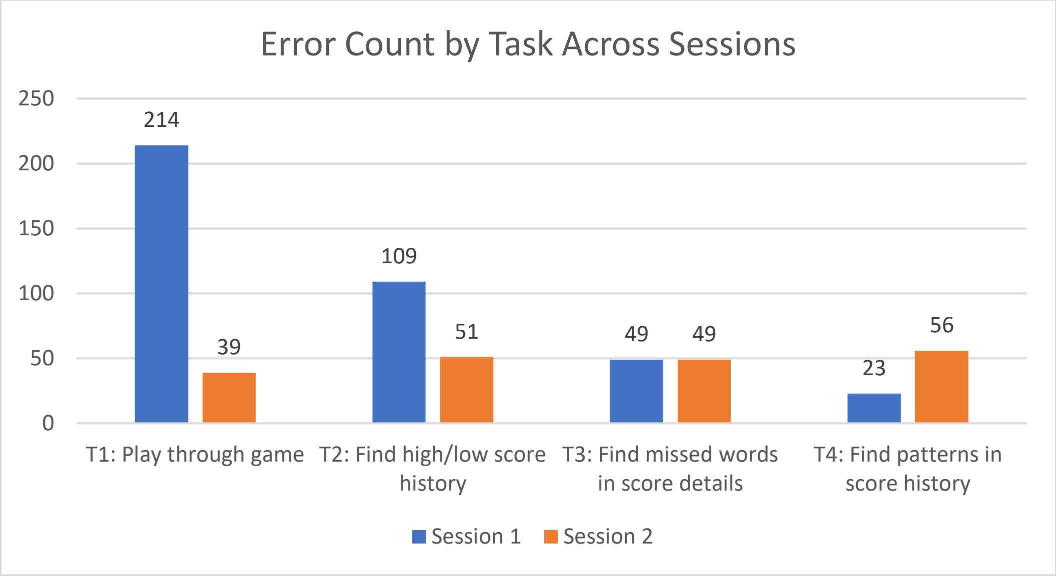


Figure 22. The error counts by task across the two usability test sessions.

Figure 22 shows the number of errors grouped by usability task across the two usability test sessions. Task 1 (play through game) for usability Session 1 had the largest number of errors at 214 errors total across all participants. Second to that was Session 1 Task 2 errors with 109. Beyond that, the remaining task error counts were below a total of 60 errors per task, with Session 2 Task 4 having the next largest error count at 56. The smallest number of errors was for Session 1 Task 4 at 23 errors total. A summary of total error counts by error type and task across the two usability sessions can be seen in Table 31.

Table 31. Number of errors for each error type per task across sessions.

	Task 1		Task 2		Task 3		Task 4		Total Errors	
Error Type	**S1**	**S2**	**S1**	**S2**	**S1**	**S2**	**S1**	**S2**	**S1**	**S2**
Understanding data visualization(s)	4	3	11	8	0	7	4	1	19	19
Touch gesture(s)	47	21	12	9	1	4	3	27	63	61
Understanding UI	118	1	58	11	29	14	9	7	214	33
Understanding instructions	22	4	9	2	2	3	2	1	35	10
Understanding usability test	13	5	11	7	4	7	1	6	29	25
Navigation	10	5	8	14	13	14	4	14	35	47
Total Errors	**214**	**39**	**109**	**51**	**49**	**49**	**23**	**56**	**395**	**195**

7.3.4 Time on Tasks

The time each participant spent on individual tasks was recorded throughout the usability test sessions. The individual times for Session 1 and 2 can be seen in Table 32 and Table 33, respectively.

Table 32. Time per task for each participant in seconds for usability test session 1.

Task	P1	P2	P3	P4	P5	Average
1	262	415	233	392	304	321.2
2	426	200	91	150	323	238
3	-	219	125	125	260	182.25
4	-	-	72	100	128	100
Average	344	278	130.25	191.75	253.75	210.36

Table 33. Time per task for each participant in seconds for usability test session 2.

Task	P1	P2	P3	P4	P6	Average
1	155	148	64	66	116	109.8
2	620	231	189	31	286	271.4
3	573	669	100	356	152	370
4	194	584	240	50	79	229.4
Average	385.5	408	148.25	125.75	158.25	245.15

Along with the total times, the average times are calculated for each participant as well as for each task and the total average time across tasks. For Session 1, Task 1 (i.e., play through a game) took the longest on average to complete (mean=321.2 seconds), with all participant completion times above 260 seconds (more than 4 minutes). For Session 2, Task 3 (i.e., identify missed words and reason for missing for previous game) had the longest average time at 370 seconds, with a range of 100 seconds to 669 seconds. Additionally, Task 1 for Session 2 had the smallest average time on task at 109.8 seconds.

7.3.5 Usability Results Summary

Table 34 shows a summary of success rates, average time on tasks, and error counts for each task across usability test sessions. The totals for each evaluation metric are indicated in the last row of the table. The numbers in the last row for average time on task represent total averages for each usability test session.

Table 34. Summary of results across usability test sessions, S1 and S2. * Indicate overall average times on task per usability test session.

	Success Rate		**Avg. Time on Task**		**Error Count**	
Task	**S1**	**S2**	**S1**	**S2**	**S1**	**S2**
1	3	5	321.2	109.8	214	39
2	1	1	238	271.4	109	51
3	2	2	182.3	370	49	49
4	1	1	100	229.4	23	56
Totals	7	9	210.36*	245.15*	395	195

7.3.6 SUS and Opinion Questionnaire

In addition to the task analyses, the System Usability Scale (SUS) questionnaire was used to gauge the overall usability of the system [11]. Table 35 shows the participant responses to the SUS for usability test session 1 and 2. Overall, the SUS scores for session 1 and session 2 were below the standard average of 68, with scores of 65 and 58, respectively. This is a decrease in overall SUS score compared to the SUS score of 76 from Section 6.2.3.2.

All participants disagreed that they would need the support of a technical person to use the system in session 1. However, 40% of participants agreed to the contrary during the second session. All but one participant consistently disagreed that there was too much inconsistency within the system. Most participants (80%) consistently agreed most people would learn to use the system very quickly. Most participants (60% and 80%) agreed that the various functions in the system were well integrated across the sessions. Most participants (80%) agreed that the system was unnecessarily complex during the second session. This is a 40% increase in agreement compared to the responses from the first session. Consistently, 60% of participants agreed that they would use this system frequently. More than half (60%) of participants agreed they felt confident using the system during Session 1. There was a 40% decrease in agreement of confidence in the second session. There was a 20% decrease in agreement that the system was easy to use across the sessions, going from 60% agreement to 40% agreement.

Table 35. Mean rating and agreement percentage of SUS responses by question across both usability test sessions. Responses were scored on a 5-point Likert scale, strongly disagree=1 to strongly agree=5. Percent agree (%) = agree and strongly agree responses combined.

#	SUS Question	Session 1		Session 2	
		Mean (SD)	**Percent Agree**	**Mean (SD)**	**Percent Agree**
1	I think that I would like to use this application frequently.	3.6 (1.14)	60%	3.8 (0.84)	60%
2	I found the application unnecessarily complex.	3.2 (1.30)	40%	3.6 (1.52)	80%
3	I thought the application was easy to use.	3.8 (0.84)	60%	3 (1.58)	40%
4	I think that I would need the support of a technical person to be able to use this application.	2.0 (0.0)	0%	2.8 (1.64)	40%
5	I found the various functions in this application were well integrated.	3.6 (1.52)	60%	3.8 (1.10)	80%
6	I thought there was too much inconsistency in the application.	2.2 (1.10)	20%	2 (0.71)	0%
7	I would imagine that most people would learn to use this application very quickly.	4.2 (0.84)	80%	3.8 (1.10)	80%
8	I found the system very cumbersome to use.	2.6 (1.14)	20%	2.8 (1.30)	40%
9	I felt very confident using the application.	3.4 (1.34)	60%	2.6 (1.52)	20%
10	I needed to learn a lot of things before I could get going with this application.	2.6 (0.89)	20%	2.6 (1.52)	40%

An opinion questionnaire was also administered to acquire participants' attitudes towards the system. Participants' opinions are summarized in Table 36. During Session 1, most participants (80%) agreed that the system was useful and felt motivated to use the system in the future. Only 40% of participants agreed that the system was fun to use and liked the inclusion of contextual information such as background noise.

Table 36. Mean rating and agreement percentage of opinion responses by question across both usability test sessions. Responses were scored on a 5-point Likert scale, strongly disagree=1 to strongly agree=5. Percent agree (%) = agree and strongly agree responses combined.

#	Opinion Question	Session 1		Session 2	
		Mean (SD)	Percent Agree	Mean (SD)	Percent Agree
1	I found the application useful.	3.8 (1.64)	80%	3.6 (1.34)	40%
2	I don't think the application would help people understand their cognitive health.	2.4 (0.89)	20%	2.0 (0.71)	0%
3	I felt there was enough instructions and guidance throughout the application.	3.4 (1.34)	60%	3.8 (1.10)	80%
4	Navigating through the different screens of the application was difficult.	2.8 (1.10)	40%	3.2 (2.05)	60%
5	Learning to use the application was easy.	3.4 (1.34)	60%	4.0 (1.41)	60%
6	The information in the application was difficult to understand.	2.6 (0.89)	20%	3.0 (1.41)	60%
7	The application was fun to use.	3.4 (1.14)	40%	4.2 (1.30)	80%
8	I was not satisfied with the overall appearance of the application.	2.4 (1.14)	20%	1.2 (0.45)	0%
9	I feel motivated to use the application in the future if possible.	3.8 (1.64)	80%	4.2 (0.84)	80%
10	I feel that the score screens were difficult to understand.	2.8 (0.84)	20%	2.8 (1.64)	40%
11	I like the inclusion of contextual information such as background noise.	3.6 (0.89)	40%	3.8 (1.10)	80%
12	The application was not user friendly.	2.8 (0.84)	20%	1.8 (0.45)	0%

During Session 2, all participants agreed the ACSAS was user friendly, would help people understand their cognitive health, and were satisfied with the overall appearance of the system. Most participants (80%): agreed there was enough instructions and guidance throughout the system, felt the application was fun to use, liked the inclusion of contextual information, and continued to feel motivated to use the system in the future if possible. Across the sessions, 40% fewer participants agreed that the system was useful. There was a 40% increase in agreement that: the system was difficult to understand, the system was fun to use, and participants liked the inclusion of contextual information.

7.4 Discussion

7.4.1 Self-Monitoring Cognitive Well-being

When asked whether participants monitor their cognitive well-being, it was found that most participants did not use any form of formal tracking. Participants instead primarily use informal and passive methods of self-monitoring their cognitive well-being and were mostly satisfied with these methods. As some participants pointed out, they would be motivated to track if they saw a change in their ambulatory cognition through retrospection (P5), reflection (P3), or self-comparison to peers (P4). This reflects the findings from section 6.2.4.9, i.e., participants are motivated to self-assess if something noticeably warrants the assessment. However, as discussed, it can be difficult to detect subtle cognitive declines that might be indicative of MCI [60], a precursor to Alzheimer’s disease. It is important that older adults be aware of the benefit and possible need to self-monitor their cognitive well-being despite a lack of noticeable shift in cognition. It may be the case that improving cognitive health literacy could be used to motivate older adults to actively self-monitor their cognitive well-being [28].

One participant pointed out the usefulness of meditation and mindfulness for not only self-monitoring their cognitive well-being, but also as a method to improve it. This hints at the nature of assessment as a form of exercise for improvement. Just as a physical assessment for endurance can measure strength in an individual, the assessment can also exercise strength and contribute to improving it. Periodic and regular cognitive assessment may also help in maintaining or improving cognitive well-being.

7.4.2 Usability Test Performance

During the first usability test session for this study, we found that all participants incorrectly interpreted the video demonstration on the Game Instructions screen as the actual game. Three of the 5 participants were still able to successfully play through the specified game in the ACSAS (Task 1). The primary reason for this issue was that video interactivity was disabled and automatically played on a loop. As a result, participants believed the video demonstration was the actual game progressing as they touched it. The video demo was included in the system based on prior feedback and literature stating that video instructions can be effective [29]. It was surmised that the inclusion of both text and visual instructions would complement one another and improve understanding of the game. However, we found the opposite to be true. In fact, despite the written instructions explicitly pointing out the instructional video as a demonstration, and a “Video Demo” header text above the video, the simultaneity of both instructions caused confusion and distraction in participants. One participant realized this issue and pointed out the error wasn't necessarily with the video demonstration, but rather the simultaneous presentation of both instruction formats, "*the two sides of the screen seemed to be fighting each other... when I have this little thing on the left side that kept bouncing around, it was distracting for me*," (P5). From this observation, we found it necessary to iterate on the system prototype to address this issue and attempt to re-test with the same participants to see if the changes would improve task success rates. We iterated on the system design and removed the video demonstration entirely to see how a baseline of only written instructions would suffice. Based on the usability task success rates of the second session for Task 1 (100% success rate), it appears the written instructions were enough for all participants to understand the game instructions.

For both usability sessions, only 1 participant was able to successfully identify the high or low Score History scores (Task 2) and make a correct correlation between chart axes in the Score History screen (Task 4). These two tasks were designed to evaluate the understandability of the Score History screen's ACA performance data visualizations. Given the success rates of these tasks, it appears the understandability of the Score History data visualizations is low. Two participants were able to successfully navigate to and interpret the Score Details screen of the ACSAS (Task 3). Though only 2 participants fully completed Task 3, there was an additional participant who was able to find the words they missed in the Score Details screen but were unable to interpret the noise level line graph. The performance results of this study indicate that participants appeared to understand the Score Details better than the broader picture of well-being presented in the Score History screen. This supports findings from [51] while slightly differentiating from the findings of [50], which found that older adults may prefer a broader picture of wellness, whereas health care professionals might prefer more detailed information.

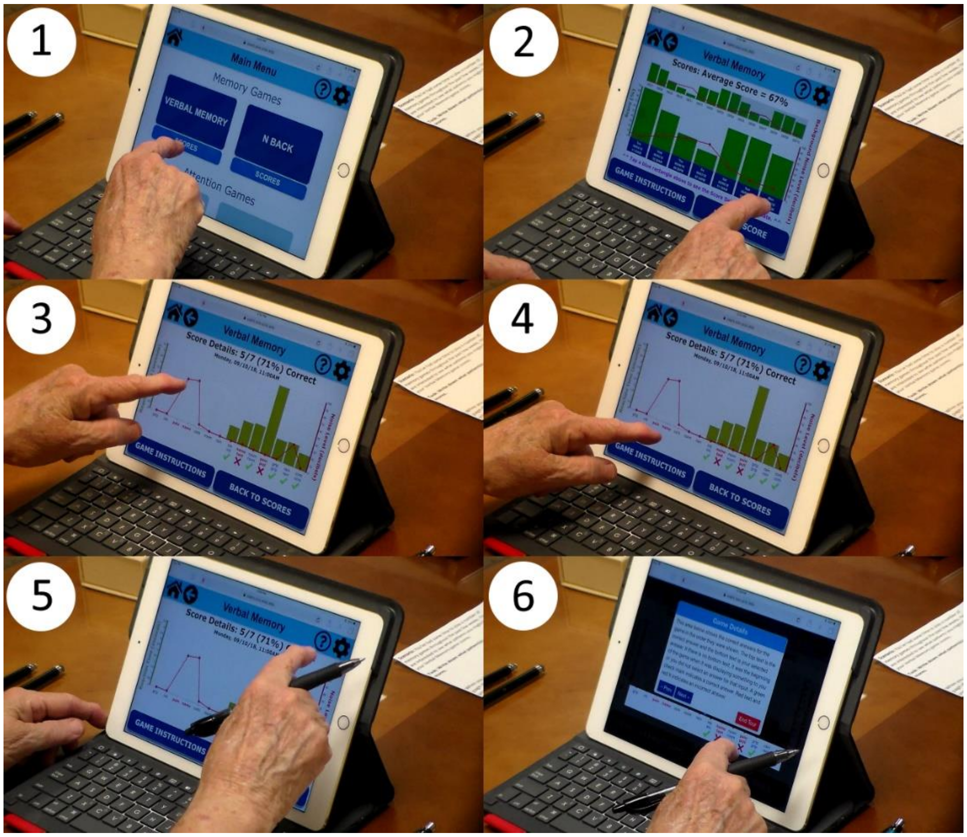


Figure 23. A series of steps (1 through 6) a participant took to successfully complete Task 3 independently.

Given RQ3, we sought to examine how participants would independently use and navigate through the system. For the second usability test session, a Help feature was implemented in the system that would provide participants with information relevant to the current screen they were at. This feature was represented as a commonly used question mark icon at the top of each screen in the system (Figure 23, step 5). When pressed, it displays an interactive walkthrough of the elements of the current screen the participant is looking at. It visually highlights and explains each major UI element on the screen (Figure 23, step 6). The Help functionality was added to better facilitate independent use and address issues participants from Phase 2 had regarding a lack of instructions in the system. Figure 23 shows the sequential steps a participant took to successfully accomplish Task 3 independently by making use of the Help feature.

In Task 3, the participant is tasked with finding out what words they missed in their most recent playthrough of the Verbal Memory game and what might have contributed to those misses. In the first 2 steps, the participant navigates to the correct score details screen. Steps 3 and 4 show the participant noticing high peaks in the data visualization graph (i.e., noise level line graph) and where those peaks happen relative to the x-axis (i.e., the words being displayed during that time in the game). The participant then notices and taps the Help icon in step 5. The Help feature walks the participant through each component of the screen they are currently at, highlighting elements of focus and visually dimming extraneous screen elements. The participant taps through the Help guide and reads through the Help explanations of what the data visualization elements and x-axis mean and how to interpret each element (step 6). They then successfully complete Task 3 by correctly identifying the words that were missed (red highlighted words) and what might have caused them (peaks in the noise level data visualization during those missed words). This highlights the benefit of the added Help feature to improve independent use of the ACSAS by older adults. However, it is still imperative that this and similar features be more apparent and intuitive to use by all participants. Specific issues regarding this feature are discussed below in sections 7.4.5 and 7.4.7.

7.4.3 System Usability and Opinions

The results of the SUS questionnaire revealed that there was an overall decline in participant opinion on the usability of the ACSAS. Both SUS scores (65 and 58) were not only below the score from Phase 2 (76), but also the generally accepted average of 68. This indicates that the ACSAS is generally perceived to be difficult to use independently by older adults in its current state. However, participants' opinions on the learnability of the system (SUS question 7 and 10) remained mostly positive across both sessions. This supports prior our findings from Phase 1 and 2 indicating that, with some training and practice, older adults could learn to use the system independently.

Despite the low usability ratings, the overall opinion of the ACSAS by participants was relatively positive by the end of the second usability session. Most participants felt that the system was fun to use and user friendly. This was found to be an important motivator in Phase 2 for using the system. By designing the ACSAS to be playful and interactive, we seek to satisfy participant motivations for fun and engaging experiences. "*I would love that kind of memory [game], kind of playing around with that kind of stuff and get a little harder and a little easier and fun. Yeah, I think that would be fun,*" (P6). There were still negative opinions towards the usefulness of the system and difficulty of understanding the information presented in the system. This could be indicative of the complex nature of ACA data and the difficulties involved with conveying such data to older adults in a meaningful way.

7.4.4 Issues with Data Visualizations

Most of the participants had difficulties in understanding and interpreting the ACA data visualizations in the ACSAS. However, only 20% and 40% of participants (Session 1 and 2, respectively) agreed that the score screens were difficult to understand. Though the graphs were meant to provide a compact visual summary of ACA data, they came across as overly "*academic*" or "*mathematical*" to some of the participants, thus discouraging and distracting them from interpretation. "*This, um, really seems more mathematical and, um, much more academic,*" (P5). A particular issue participants had with the data visualizations was the fact that multiple variables (i.e., performance and sound level) were displayed superimposed on a single graph (Figure 19). This multivariate graph hindered participants' understanding of the data visualizations. As P6 stated, "*if it was separate and not the noise and the reaction [time] and all the stuff at one time*," they may have been able to interpret the graph appropriately. P6 goes on to recommend, "*maybe just first show me one thing and give me numbers or whatever, rather than the graph*," to aid in their understanding of their ACA data. One participant reflected on the idea of using graphs versus the reality of using them. "*Charts and graphs are efficient. I know they work, you know. I mean that's how we get data. So, um, I guess in terms of feedback… I'm more accustomed to feedback that's more gentle… and [is] a little more word oriented and not quite so graphic*," (P5).

Despite the difficulties associated with interpreting the graphs, participants understood usefulness of such data visualizations within the system. As P5 states, "*[the graphs] gave you the opportunity to check on your, um, improvement or, you know, decline over* *time. So that's something good also*.” P4 points out the learnability of the data visualizations, “*I actually did like the, um, the graph at the end. Well, at first I was confused because it had all the dates along the top and you had to move it along. And I didn't at first realize the red line was there… but once I saw the red line then, yeah, I liked the graph*.” Another participant noted that the data visualizations may provide motivation for continued use, “*I like the way it tells you here (pointing at the Score Details screen), it has the score that inspires you to go on*,” (P1).

One recommendation to address difficulties in understanding ACA data visualizations might be to allow for more flexibility in the display of user data. The data visualizations could be displayed on a requested basis, that is, allow the end user the option of seeing detailed information on their performance at their request (e.g., a “See More Details” UI button). By only showing simplified relevant information first (e.g., the user’s most recent numeric score), the cognitive load on the user is significantly reduced and can improve their understanding of the ACA data presented to them in more manageable sizes. Simple solutions to information communication should be employed first wherever possible. From there, more complex visualizations can be utilized to convey detailed ACA data as requested by the end user.

7.4.5 Issues with UI

Some participants were unaware of some of the UI buttons and interaction options available to them in any given screen of the system’s Web interface. When asked what buttons they see on the Game Instructions screen, one participant pointed out the icons at the top of the screen but failed to mention the bottom two buttons (“Play Game” and

"Scores"), despite the "Play Game" button being critical to Task 1 (i.e., play through one game). Additionally, though some users were able to identify the icon buttons at the top of the screen (e.g., the Help icon), some were unaware as to what their purpose was or had forgotten. For example, P4 stated, "*I wasn't sure what was behind the question mark [icon]*." P6 expressed their confusion with the iconography and uncertainty of interaction options available, "*I don't think it was clear about whether I was supposed to press these buttons on the top or what else I was supposed to do*." This highlights an issue with the system relying on participants to recall the purpose of icons rather than having participants recognize their purpose. One way to address this issue would be to include text below the icons that conveys the icon's purpose, thereby not relying on participants' recall.

For some participants, the distinction between the ACSAS (i.e., Web app) and the Web browser (e.g., Safari) was unclear. For example, when told to go back to the Main Menu, one user pressed the Home button of the iPad to go back to the device Home Screen. Another user tried to tap the Web browser's Back button to go to a previous screen in the Web application rather than tapping the Back button in the Web application itself. A benefit of a Web interface is that it has the potential to be consistent across various devices. By being device agnostic, the ACSAS can be used on a device familiar to the end user, further reducing the learning curve of the system. However, it is important the end user understands what Web applications are and how they differ from the Web browser. This is especially true for mobile devices, as it may be confusing for some users to understand they are using a Web application inside of a system application. Without developing a native application, one recommendation would be to design the Web system with the Web browser in mind, i.e., make it clear to the end user that they are on an interactive website. For example, rather than adding a Back button in the Web application, allow the user to use the browser’s Back button or explicitly instruct the user to not use the Web browser’s Back button as some applications do. However, if possible, developing a native, or native-like, application may mitigate such Web application and Web browser discrepancy issues.

7.4.6 Issues with System Navigation

Another issue participants faced was navigating to specific screens in the system. One participant pointed out the difficulty in navigating to the Score History screen from the Game Instructions screen, “*I needed to get to the score sheet and I couldn't figure out how to get back to the score sheet form the instructions. And I did that two or three times and I took a very long time to try to figure it out and I think you gave me a hint as of what to do so that helped me but… I had great difficulty*,” (P2). They go on to suggest, “*maybe have a title or something that would refresh your memory of what these things (pointing to the icons at the top of the screen) on the main menu are, in order to try and get back to as I said, I had trouble getting back to the score sheet*.” Converse to that opinion, another participant found navigating easy and enjoyable, “*The navigation is great, navigating is great, the explanations are very good too*,” (P3).

The balance between effective information communication and information overload can be difficult. We chose to focus on minimizing the amount of UI elements to prevent information overload on participants. For older adults, this can be especially critical, as too much information can cause confusion and fear of accidentally causing an unintended event to occur. However, given the navigation issues some participants faced, it may be beneficial to include a UI representation of the system navigation. Utilizing site breadcrumbs to indicate navigation location may alleviate navigation issues older adults face with the ACSAS.

7.4.7 Issues with System Instructions

For the ACSAS to be used independently by older adults, the instructions within the system must be understandable. Given the sensitive nature of ACA, it is crucial that the individual understand how to complete the tasks within the system for the data to be accurate and thus meaningful. We initially designed the Game Instructions screen to convey visual and textual information simultaneously to complement one another and reinforce understanding. However, we found this caused confusion and distracted from understanding. In response to this, P5 recommend, "*it might have been easier for me to do this in sequence. Like, give me the instructions and then I would learn the instructions, one, two, three, and then do the demo where the words were addressed.*" Conveying information in a logical, linear format will prove beneficial for improving one's understanding of ACA systems for self-monitoring. Moreover, based on observations of participants trying to interact with the video demonstration, it was clear that a major factor in increasing one's understanding of how to play was through direct practice with the games themselves. Incorporating interactive tutorials or hands-on practice runs of each game should be utilized to increase an individual's self-efficacy and understanding [29].

Between the two usability test sessions, a Help feature was added (via a question mark icon) to the top of each screen in the system. In addition to explaining system and UI elements, the Help feature would explain where the participant is relative to the site. Some participants used this feature but stopped midway through the walkthrough due to the length of the explanations and information overload. "*The explanations seem a little more complicated then maybe they need to be. Yeah, it could be maybe simpler*," (P4). Reducing the length of the Help explanations could help address this issue. Additionally, providing a mechanism for the user to choose what area or component they need help with could reduce the amount of information the user must go through to get to the desired help text.

7.4.8 Issues with Touch Input

Some participants had difficulties with touch gestures. These issues included performing an incorrect touch gestures (e.g., touch-and-hold instead of tap), accidental multi-touch gestures (e.g., skin contact in multiple places on the screen), unawareness of successful touch input. For incorrect tap gestures, some participants would press too hard on the screen and trigger a "right-click" action. Others accidentally would perform a touch-and-drag gesture, sometimes triggering an imperceptibly small scroll action. In the latter case, this would cause confusion and frustration in the participant because they believe their touch gesture to be correct. For example, one participant had the thumb of their left hand (holding the device) accidentally making skin contact with the touchscreen while they attempted to tap the recognition words they remembered with their right hand. The participant was in fact making the correct choices but because the system was not responding in the way they expected, the participant selected an incorrect word, believing that system was preventing them from making choices. These touch input issues appear to stem from the participant's unfamiliarity with touchscreen interfaces rather than an explicit usability flaw with the system prototype. However, these forms of issues must be considered when developing mobile and Web-based ACA systems for older adults.

7.4.9 Design Recommendations

Based on the findings of this study, we present the following design recommendations for the ACSAS as indicated in Table 37.

Table 37. Design recommendations from Phase 3.

Priority	Recommendation	Reason
High	The system should convey performance information in a flexible manner.	Users may prefer to view past performance information via written text or graphics or charts.
Medium	The system should include a descriptive label for each system icon displayed.	User's may not be familiar with icons or remember their purpose. It is better to rely on user recognition rather than recall.
Medium	The system UI and buttons should be easily distinguishable from the Web browser's UI and buttons.	Users may mistake the Web browser buttons for system UI buttons.
Low	The system should indicate where the user is in the system in terms of navigation.	Users may forget where they are in the system and how to navigate to specific screens relative to each other.
Low	The system Help feature should prioritize brevity and allow users to see more information if requested.	Long, complex explanations can confuse users and prevent them from understanding the information provided.

These recommendations reflect solutions offered to address the main issues participants faced throughout the usability tests. The priorities were derived from observations on the number of participants that experienced related issues, i.e., 1 participant is Low priority, 2 – 3 participants are Medium priority, and 4+ are high priority. The design recommendations shed light on how to improve the design of the ACSAS to better facilitate independent use of the system by older adults (RQ3).

7.4.10 Limitations

Due to the limited number of participants (i.e., mostly the same participants across the sessions) and homogeneity of participant characteristics (i.e., older adult females living in a retirement community), it shouldn't be said that the data presented is representative of the primary study population, i.e., older adults in general. Facility recruitment limitations were a contributing factor to the small number of participants and had to be conducted through a secondary user (i.e., facility staff) who had direct contact with primary users. As was the case in Phase 2, some of the ACSAS functionality was disabled or limited. This included no EMA survey being given and a primary focus on playing the Verbal Memory game. Though some participants had the chance to play one of the other implemented games (i.e., N Back), there is still a need to test more cognitive games and see what information communication techniques would most benefit them. Moreover, one participant had the opportunity to explore the Settings screen of the app before and after the usability test sessions. They noted their interest in being able to customize the system to best fit their needs. This customization feature has yet to be fully evaluated by primary users.

The study presented was conducted in a semi-controlled environment (i.e., facility activity room) and not fully representative of natural ambulatory states of the participants (e.g., living room). It should be stated again that the purpose of this study was to investigate the usability issues faced by older adults independently using the ACSAS and how data visualizations of ACA data are perceived by older adults. In order to simulate independent use of the system, participants were not given initial explicit training as offered in Phase 2 and were not given guidance throughout the usability test sessions. Instead, participants were instructed to explore the ACSAS in a self-guided manner prior to the start of the usability task sessions. Though participants could ask questions and were given answers by researchers, the process did not offer any external guidance or training, as expected in an independent use context. This lack of training and lack of proper instructions within the system are a contributing factor to the low usability scores and ratings. However, this study provides a baseline for which future usability studies of the ACSAS can be evaluated against. Future studies will examine compliance in real-world usage contexts and understand how those usage contexts factor into the participants' interpretation of their cognitive well-being.

7.5 Conclusion

For the proposed ACSAS to be adopted and used by older adults, it must be usable and learnable. We ran a usability study to understand what issues older adults face when independently using the ACSAS for self-monitoring. Many usability issues were due to poor system instructions and a lack of understanding of interaction capabilities.

Some recommendations to improve understanding include user training, providing information in logical, linear steps, and including UI elements that inform the user of where they are in the system and what actions are available to them. Additionally, it was important to assess how effective traditional graphs are for conveying ACA data in a meaningful way to older adults. The results of Phase 3 show that, though traditional bar and line graphs can convey information effectively, they may be intimidating to older adults who wish to self-monitor their ambulatory cognitive well-being. It may be more beneficial to display ACA performance results in a written and numerical format at first. Individuals who feel more comfortable with graphs can then have the option to see the data in graphical form, rather than requiring it upfront. These findings shed light on how ACA information can be better communicated to older adults for self-monitoring cognitive well-being.

We present the findings from a usability study with the novel, Web-based ACSAS for self-monitoring cognitive well-being in older adults. It has been found that older adults are active in monitoring their cognitive health and well-being. ACA tools provide an effective way to aid in monitoring cognitive well-being. However, traditional ACA methodologies neglect the end user in the data interpretation and reflection process. To the best of our knowledge, there has been no studies examining how an ACA system could be used as an end-to-end solution for older adults to enable self-monitoring of their cognitive well-being. We argue that a carefully designed ACSAS can be used independently by older adults to monitor their cognitive well-being.

Chapter 8

System Architecture

Throughout the course of this dissertation, the underlying system architecture has evolved and expanded to include additional functionality to address emergent system requirements based on user needs. The architecture model used to diagram the ACSAS architecture was the C4 (Context, Container, Component, Code) model [13]. This model was chosen due to its flexibility in presentation and granularity of abstraction. The C4 model was created by Simon Brown and takes an "abstract-first" approach to system architecture diagramming. It allows for diagraming various levels of granularity, similar to how Google Maps allows zooming-in for more details. The model is composed of persons (or actors), the software system, containers making up the software system, and components that make up the various containers. The following sections outline the most up to date version of the Web-based system architecture for the ACSAS.

8.1 System Context Diagram

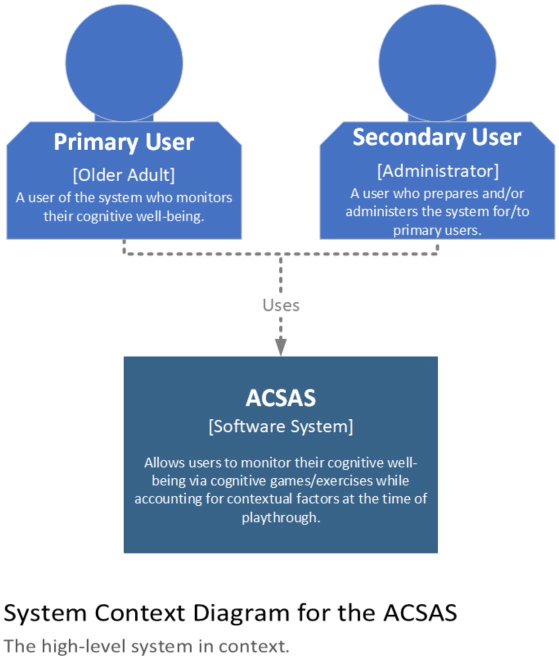


Figure 24. The system context diagram of the ACSAS.

The system context diagram (Figure 24) shows a high-level representation of how the system relates to users and potentially other systems. The diagram shows the two representative user groups (primary users and secondary users) interacting with the main software system, i.e., the ACSAS. The system will be used independently by primary users (i.e., older adults) or cooperatively with a secondary user (e.g., caregiver, clinician, researcher). No external or third-party hardware or devices are required other than the user's primary device and an internet connection.

8.2 Container Diagram

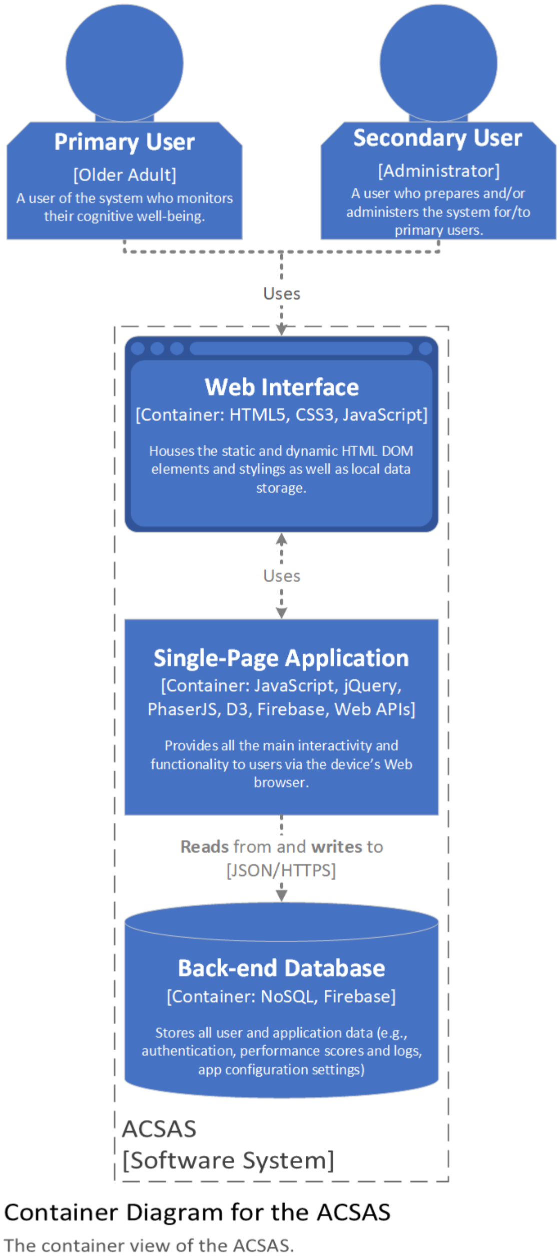


Figure 25. The container diagram of the ACSAS.

The container diagram (Figure 25) shows an overview of the containers that make up the software system. Each container of the diagram represents a separate contained portion of the software system that hosts code or data.

- **Web Interface**: Represents the hosted HTML5 website that is loaded and rendered to the user's device browser. It houses the static and dynamic HTML DOM elements and stylings of the website. Additionally, it holds a local data storage for individual user data and settings.
- **Single-Page Application**: Acts as the primary source of logic and interactivity of the system. It provides all the functionality and interactivity between the user and the system. It is composed of various JavaScript libraries and APIs to manage rendering, interaction, device sensing, and data communication. It connects to the client-side storage in the Web Interface and the Back-end Database.
- **Back-end Database**: A NoSQL Firebase real-time database that stores all user and system data. It uses a JSON structure to organize and update content, making it flexible in the type and organization of data stored.

8.3 Component Diagram

The component diagram view shows a more detailed look at the components that make up the containers of the software system. The current models represent the most up-to-date version of the software system.

8.3.1 Web Interface

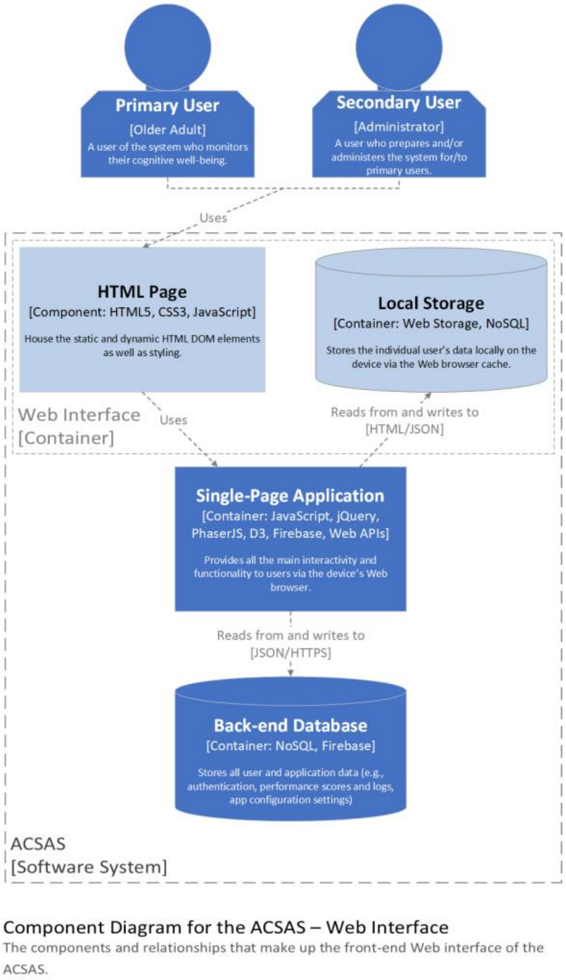


Figure 26. The component diagram of the Web Interface of the ACSAS.

Figure 26 shows the component view for the Web Interface container. The Web Interface is composed of the following two components:

- **HTML Page**: Houses the static and dynamic HTML5 DOM elements for the website as well as the page CSS3 styling.

- **Local Storage**: Stores the individual user's data on the client-side device via the Web browser cache. It uses a NoSQL JSON structure to organize data and is accessed via the Web Storage API.

8.3.2 Single-Page Application

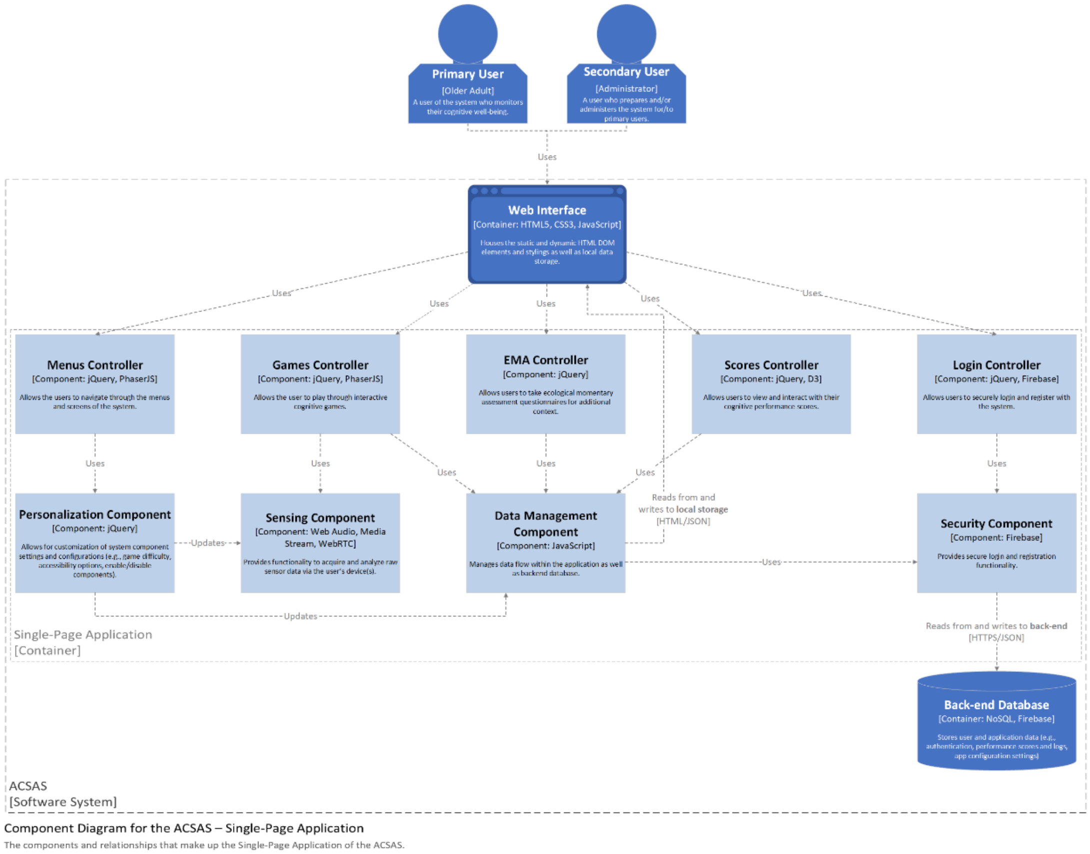


Figure 27. The component diagram of the Single-Page Application of the ACSAS.

Figure 27 shows the component view for the Single-Page Application container. The Single-Page Application is composed of the following components:

- **Menus Controller**: Allows users to navigate through the menu states (i.e., screens) of the system. It uses the Personalization Component to modify the display of menus (i.e., language translation). This is primarily managed through jQuery DOM manipulation and event listeners, as well as PhaserJS state manager to navigate states (i.e., screens).

- **Games Controller**: Allows the user to play through interactive cognitive games/exercises. User interaction is handled both through jQuery event listeners and the PhaserJS game engine. It uses the Sensing Component to actively sense the user's context (i.e., background noise, lighting, etc. via the device's sensors). It communicates with the Data Management Component to store and retrieve data (i.e., save scores, load settings).
- **EMA Controller**: Allows the user to fill out interactive EMA questionnaires for additional context. Interaction is primarily managed through jQuery event listeners. It uses the Data Management Component to store and retrieve data (i.e., save user responses, load questions and content).
- **Scores Controller**: Allows users to view and interact with past cognitive performance scores and logs. It uses the D3 visualization library to generate and render interactive data visualizations based on the user's performance and contextual data. There is the Score History screen that displays an overview of the user's past performance scores and a snapshot of the context corresponding to each performance log (e.g., noise level for a given score). The user can select a specific score and see the Score Details for that score. The Score Details screen displays the detailed performance and contextual data for that score (i.e.,

reaction time for each input, noise level throughout the playthrough, and correct/incorrect responses with answers).

- **Login Controller**: Allows users to securely login to and register with the system. It uses features from jQuery and the Firebase API to generate a secure login page.
- **Personalization Component**: Provides the functionality of customization of system component settings and configurations (e.g., game difficulty, accessibility options, enable/disable components). This component is accessed via a Settings screen through the Menus Controller and uses jQuery to modify and update the system's dynamic DOM elements. The Personalization Component offers functionality to select the language of the system, modify specific game settings, and enable or disable components. Additional work is being done to add more accessibility features to the component, such as font size and color scheme manipulation for individuals with low vision or visual impairments.
- **Sensing Component**: Provides functionality to acquire and analyze raw sensor data via the user's device(s). It uses the WebRTC (Web Real-Time Communications) and related APIs to access the device hardware and sensors, such as the Web Audio API to access the microphone and Media Stream API to access the camera. Further work is being explored to enable data stream captures from additional internal (GPS, accelerometer) and external sensors (wearables) for improved contextual assessment.

- **Data Management Component**: Manages the data flow within the application as well as to and from the client-side storage and back-end database. It receives data from other components, timestamps data packages, and prepares and sends data packages to the corresponding storage or database. It interfaces directly with the client-side local storage and communicates with the Security Component to securely access the back-end database.
- **Security Component**: Provides authentication and verification functionality between the front-end components of the system and the back-end database. It uses the Firebase Authentication API to authenticate users and verify packages (i.e., size and timestamp).

8.4 State Machine Diagram

The state machine diagram in Figure 28 outlines the overall flow and state interactions of the most up to date version of the ACSAS. The system's state machine is represented as a directional graph. The colored boxes represent the underlying states of the system. The lines represent transitions between states. The state machine diagram displays primary navigation pathways and transitions for the overall system, including primary state functions. State transitions are triggered either manually by the user or automatically by internal triggers.

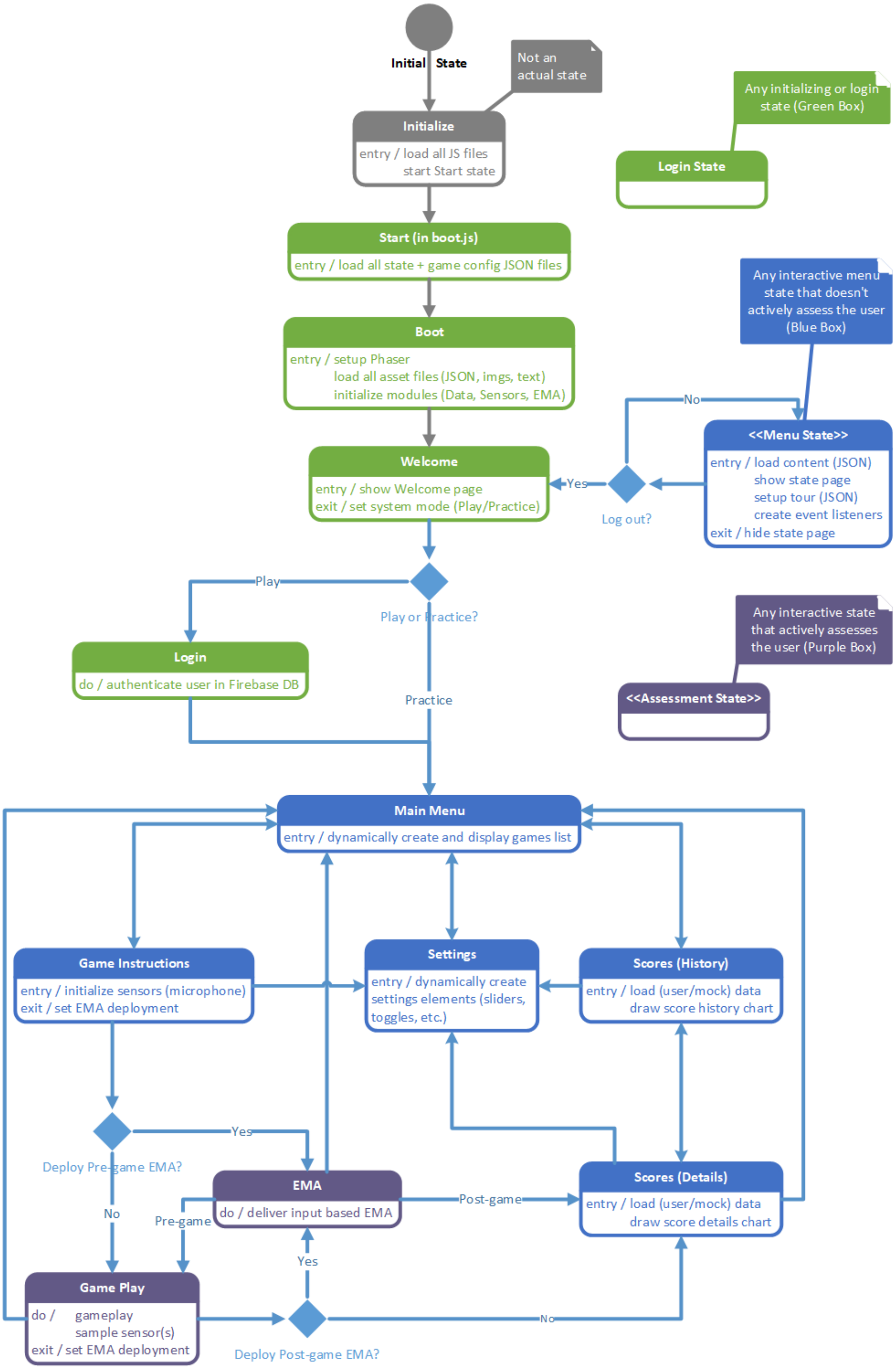


Figure 28. State machine diagram of the ACSAS.

The login states (green boxes) indicate initial states for loading initial data and user login. Past the initial login states, the menu (blue boxes) and assessment (purple boxes) states represent the primary interaction and navigation of the ACSAS. Blue boxes represent interactive menu states within the system that do not actively or passively assess the user, i.e., no assessment is taking place and the device sensors are disabled. Assessment states (purple boxes) represent interactive states in which the user is actively (i.e., through interactive CCTs and EMAs) and, if enabled, passively assessed. Passive assessment (i.e., device sensors) can be manually enabled or disabled within the settings state.

The directional links represent the transitions between states. Unidirectional transitions are triggered from the tail-end state through passive events (grey lines) or active events (blue lines). Passive event triggers are independent of user interaction, whereas active event triggers are activated by user interaction and input. Bidirectional transitions indicate bidirectional navigation between states. Every menu and assessment state can transition to the main menu state through user input, allowing for easy navigation back to the default state of the ACSAS.

Chapter 9

Meta-Discussion

We started this project with RQ1, asking how feasible it would be for older adults with and without MCI to independently use the novel ACSAS for self-monitoring their cognitive well-being. The findings from Phase 1 suggest that it is feasible for healthy aging older adults to use the system independently but would require practice and training. Given the adoption rates of mobile devices by older adults, it seems plausible that the general familiarity with mobile applications will increase. Moreover, older adults can benefit from the multimodal nature of mobile devices, thereby decreasing the barrier to entry. For the ACSAS to be adopted, it would require appropriate introduction and training. The same, however, is true for any new mobile or Web application. Therefore, it is not unreasonable to expect a learning curve with the application. By simplifying the user interface and including guidance within the application itself, the ACSAS has the potential to be used independently by older adults.

We found that older adults are in fact interested and invested in monitoring their cognitive well-being independently. Given the dynamic nature of aging, it would prove beneficial to include contextual information pertinent to the end user for their interpretation of their cognitive well-being. We postulated RQ2, which asked what the contexts of use are surrounding the ACSAS and older adults. We explored health aging older adults' motivations, obstacles, opinions of self-monitoring their cognitive well-being, and the possible contextual factors most impactful for self-monitoring, in addition to ACA data feedback and communication preferences. Phase 2 resulted in the findings that older adults living in a retirement community are most concerned with both internal (physical health) and external (environmental stimuli) factors. When considering self-monitoring, participants noted how they felt in their daily lives was a significant factor for assessing their cognitive well-being. They also pointed out that external factors, such as environmental stimuli in the form of auditory distractions and emergencies, can impact their ability to assess effectively, thereby potentially affecting their understanding and interpretation of their cognitive well-being. Being able to capitalize on mobile device sensors and multimodal input could allow for individuals to customize the types of contextual factors they want to monitor and include in their ACA information. For example, a minimal interface could be implemented that allows users to enter in the name of a contextual factor pertinent to them and assign a type of monitoring method, e.g., text input, camera input, microphone input, or even location input. Furthermore, with the possibility of including information captured from IoT and context aware devices, fine-grained patterns of contextual information could be recorded and correlated with ACA information to aid individuals in deeply understanding their own cognitive well-being situated in their daily lives.

For these possibilities of improved self-awareness of cognitive well-being through use of the ACSAS to take hold, it is imperative that the system be usable by older adults. The information of these systems must be communicated in a way that is meaningful and effective for the end user. Given the rich and temporal nature of ACA data, it was important to consider what visualization techniques could and should be used to convey such data to older adults for independent monitoring of cognitive well-being. This realization helped us form RQ3, how can the ACSAS be designed to facilitate independent use of the system by older adults? Through Phase 3, we learned that, though bar and line graphs have their place in understanding ACA data, it may be advantageous to convey such data through simple numeric and written output modalities. Given the study population of older adults, having basic written interpretations of their ACA data generated for them by the system could prove beneficial for their understanding of their cognitive well-being. With the processing power of mobile and Web technologies, it is possible to train a machine learning algorithm to learn patterns in an individual's ACA data and convey the assessment results in a manner appropriate for the end user through natural language processing.

Chapter 10

Conclusion

Throughout the course of this dissertation, I've had the opportunity to observe and work with a wide array of individuals, including older adults with and without MCI and caregivers, all with diverse background and experiences. In Phase 0, I explored stakeholder needs and requirements with ACA systems through direct observations and interactions with older adults and caregivers. Through Phase 1, I iteratively designed a novel, Web-based ACSAS and evaluated its feasibility of use with healthcare social workers through usability testing and interviews. Moving on to Phase 2, I provide insight into the context of use surrounding the ACSAS for use by older adults through case studies and group discussions. Wrapping up in Phase 3, I investigated usability issues and design recommendations, including data visualization guidelines, for the ACSAS through a summative usability evaluation with older adults. I reflect on the limitation and lessons learned throughout these studies in developing the ACSAS for older adults to self-monitor their cognitive well-being. The findings from this dissertation suggest that the ACSAS may have a place in independent use by older adults but needs to be designed carefully and take into consideration the needs of the prospective end users. With continued improvements to the proposed system, I believe the ACSAS can enhance awareness of cognitive well-being and empower older adults to self-monitor their cognitive health independently.

10.1 Appreciation and Reflection

The aging population is a demographic that is isn't always included in the conversation of designing technology. I'm glad to have had the opportunity to give voice to an underserved population that may lack a voice in computation and design. The following quotes highlight the importance of including users with special needs throughout the design process.

> "*Our participants are sort of, kind of, forgotten people in a way, you know. They're kind of people who, you know, have various sorts of problems, they're getting older, and, you know, there's not a lot of energy put into this group of people. I think it makes everybody feel so good to just know that there's [this] kind of thought and this kind of energy going into trying to do things to help our kind of participants. And it's just, it kind of, like, makes everybody feel good*." (Section 5.3.3, Healthcare social worker)
>
> "*I think what you're doing is wonderful. I feel so inadequate when I'm with a younger group of people because they are constantly talking on their little machines. And this concerns me because I think generations coming up are losing personal contact with each other and that concerns me. But we have to adapt. We don't have a choice. So what your research is doing is giving us a choice, if we choose to take it. That's helpful*." (Section 6.1, Older adult)

This dissertation represents the culmination of my research and contribute to the field of cognitive health and aging through the lens of computer science and human-computer interaction. Motivated by real-world implications of cognitive health and aging, I began with questions and ended with experiences, knowledge, and opportunities. Throughout this dissertation journey, I’ve had the opportunity to engage directly with a multitude individuals with rich, diverse backgrounds and experiences. The glimpses into the lives of older adults with and without MCI, as well as caregivers, has provided me with invaluable insight into the everyday experiences of these diverse populations. I have the utmost respect and gratitude for the individuals I’ve had the honor of interacting with. Just as there are innumerable atoms within us all, there is an immeasurable amount of experience and wisdom the aging population has to share with the world. As the late Carl Sagan once said, “*We are, each of us, a multitude*.” I am humbled by this journey and look forward to what’s to come.

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