Designing Tangible Technologies to Support Seniors Social Connections

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Abstract

As mobility and health decline with age, and as technology becomes more complex, many seniors face barriers to staying socially connected with friends and family at a distance. Games are a key way to create social connections, but online games often require complex interfaces that pose barriers to seniors' participation. Tangible interfaces that provide physical objects as input and output for interactive systems may provide an intuitive alternative, but their suitability for this demographic has not been well studied. To address this, we iteratively designed tangible interfaces for an online card game, moving from an initial AR-based system (limited by tracking issues) to a final e-ink playing card design that reduced accessibility barriers. Seniors believed the e-ink system was fun and could support remote play. Our work demonstrates how novel play interfaces can be designed and built to reduce the barriers seniors face in connecting with others around social play.

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List of Symbols, Nomenclature or Abbreviations

AR Augmented Reality

MR Mixed Reality

VR Virtual Reality

HMD Head mounted display

ICT Internet and Communication Technologies

NFC Near field communication

Chapter 1

Introduction

In 2020, one in three Canadian seniors reported feelings of loneliness, with an increased risk for those living alone, in social housing, or in retirement living [24]. Maintaining social connection can be difficult for seniors and is exacerbated by cognitive and physical decline associated with aging [4]. In turn, social isolation increases the risk of adverse mental and physical health outcomes, and is a predictor for the increased duration of hospitalization [38]. Reducing social isolation in seniors is important in addressing the complex triad of decline that comes with aging. Since seniors often rely on nearby family members to maintain social connectivity, seniors living away from family members can also be impacted, and it can limit family members' freedom of mobility to pursue careers, travel, and relocate [39]. Additional factors including rural living, lack of access to transportation, or lack of participation in community activities pose an additional challenge to maintaining social connection [16].

Games have been one of the ways that seniors have successfully used to stay socially connected, but online games for seniors have faced participation and accessibility barriers due to complex interfaces and interactions. While bridging the social barrier

for Canadian seniors can be made possible through technology, there is little variety in the technologies that have been explored and that are accessible to the greater population [16].

A report published by the Government of Canada shows a rise in social programs and telephone outreach for older adults across Canada [16]. On top of a recent global increase in internet availability, a recent survey reports 88 percent of seniors use the internet daily, and 54 percent use a smartphone daily [1]. Despite these statistics, many online services are hidden behind complex interfaces and ever-evolving technology that make using them challenging. Younger adults, and seniors who do use technology have had success using digital gaming for socialization [57] [56]. Co-located digital games with lower complexity like Wii Bowling [26] [8] and Bingo [54] have found similar success with older adults who identify as less tech savvy. Exactly how remotely played video games can be designed and/or adapted to support seniors' social connectedness remains understudied [18].

A range of physical and cognitive capabilities need to be considered when designing technologies for seniors, who might find remote connection through traditional video game interfaces challenging due to a variety of factors including lower visual ability, dexterity and familiarity [24]. As technology is ever-evolving, many seniors may have grown up alongside technology that looks and functions differently than their modern counterparts. Augmented reality is a promising solution to bridge this gap and provide intuitive and familiar interfaces for technology. Traditional analog games (including card or board games) already have the benefit of being familiar for many seniors. In most online card games, some that our participants reported playing digitally, the game and pieces of a traditional 52 card deck are well known to them, making knowing how to perform the actions that progress play easier. Following this notion, our study employs three iterations of a remote card game technology.

The remote-play enabled card game uses technological approaches to enable play with physical components (i.e., mixed reality and tangible computing technologies). Since the game and the method of playing is already familiar (a familiar card game using physical playing cards), each iteration of our study focuses on a qualitative analysis of the game play while using the technology, including its accessibility and usability for our targeted group (older adults).

Our starting point was to use mixed reality, which relied on a mobile tablet computer. This version of the system used the tablet's camera to track fiducial markers on physical playing cards and augmented the cards, which could be viewed on the screen. However, in brief, we found that the tablet had usability limitations similar to those of traditional mobile interfaces, but also related to the accuracy of camera tracking and the requirement to understand framing the cards in the field of view of the camera. Our next iterations instead used e-ink displays to address the usability and camera tracking issues with the tablet. Our participants found the physicality and direct nature of the e-ink displays be much simpler and more usable when compared to the augmented reality approach. By replicating traditional gameplay with tangible game pieces, this study demonstrates the successful adaptation of a tangible technology interface for remote digital gaming for seniors.

Chapter 2

Related Works

Seniors (aged 65 years and older) are particularly susceptible to social isolation and loneliness, with rapid changes during aging being one of many factors that contribute to this risk [24]. Social isolation and loneliness often go hand-in-hand but are themselves distinct concepts. The primary distinction is that loneliness refers to the subjective experience, while social isolation is measured by frequency, duration, and regularity of social connection [38].

To address social isolation among older adults, we first look at the factors that contribute to social isolation and then identify the research currently being examined to support seniors' well being. Although research in technologies supporting healthy aging is abundant, it has primarily focused on supporting physical and cognitive well being. The technologies that are being studied to support the well being of older adults are diverse. One study evaluated cyclotourism - a stationary cycling machine that controls a virtual reality 360 tour experience [40]. Another study employs custom AR game tables (eldergames) set up in community homes to enable playing digital games with real world objects like pens [20]. Identifying the factors that make technologies such as cyclotourism [40] and eldergames [20] successful in these cases is

key to adapting technologies to support seniors' social well being. These studies also highlight the continued challenges of senior-tailored solutions. Negative attitudes towards technology and complex systems with invisible infrastructure contribute significantly to the challenge of adapting these systems [37] [51]. Mixed reality technologies can afford the advantages of intuitive tangible interactions, which can reduce the accessibility challenges in using an interactive system [30].

2.1 Social Isolation Amongst Seniors

Social isolation is a growing concern in the senior (>65 year-old) population in Canada. As of 2021, one in five Canadians are aged 65 or older, and this proportion is increasing year to year [48]. In the midst of an aging population, studies show around one in three Canadian seniors reported feeling lonely, while one in four reported less than weekly participation in social activities [24]. Seniors are living longer and enjoying a higher quality of life, but are also increasingly at risk of social isolation and associated health issues throughout those years [23]. Aging is often accompanied by chronic conditions and other declines in mobility, cognitive health, and physical health [50]. In turn, social isolation is cyclically associated with adverse mental and physical health outcomes, many of which themselves are risk indicators for social isolation; including cognitive challenges, vision and hearing problems, and loss of independence [38, 17, 4]. Social isolation is ultimately associated with an increased length of time in hospitals and overall mortality [17, 24].

While 93% of the 65-plus population live at home, that percentage declines to 72% among those 85 years and older [49, 48]. Seniors still at home are at an increased risk as they face the loss of loved ones, families moving away, and loss of transportation as they age [24]. The risk does not decrease as seniors age and move into commu-

nity living; disability, depression, and other conditions that limit independence all increase the risk of social isolation [17, 9, 38]. These factors that accompany aging pose challenges to participation in social activities and reduce seniors' ability to stay socially connected [24, 17]. Addressing social isolation in seniors could be a key component in increasing lifespan and the quality of life during those years [17, 23].

2.2 Designing Technology for Seniors

The co-morbidity of social isolation and other age related decline makes addressing social isolation challenging but crucial for decreasing overall health risks of the senior population. The internet and communication technologies have been increasingly studied as a response to social isolation since the COVID-19 pandemic [16]. The reduction in social activities, limited access to freedom of travel and movement, and lower number of social contacts associated with social isolation during the pandemic are similar to factors that older adults face as they age [16] [24]. Surveys taken during this time highlight that 88% of Canadians aged 65 years and above access and use the internet daily [1] but the rate at which seniors use technology declines as they face certain changes brought on by aging, like moving to a nursing home or facing dementia [33]. Although all seniors are vulnerable to social isolation, those living alone or living in care homes are at increased risk [4] [17]. Institutionalized seniors who lack independence rely on family members and friends to keep socially connected by visiting them. For these seniors, geographic distance can pose a greater impact on their ability to maintain connectedness to family and friends.

Despite the prevalence of challenges with in-person connection, seniors have diverging attitudes when it comes to using technology to stay connected [4]. Seniors with low social participation may require a social introduction to learn and engage with

technology [4] [2]. Older adults also value technology differently, with seniors over 75 preferring telephones and TVs over mobile phones and computers [29]. In healthcare and technology systems, accessibility is one key to successful adoption by seniors, some of whom still live at home while others require a larger degree of assistance. Many programs aiming to engage seniors socially opt for telephone based or virtual call (Zoom, Skype) based solutions to improve outreach [16]. For seniors that use communicative technologies to remain connected, time zone differences, perceived availability, and poor usability contribute to reduced effectiveness [2].

Designing technology for seniors requires considerations beyond the core factors proposed by the Technology Acceptance Model [41]. Ease of use and perceived usefulness are particularly unique for individuals in this age demographic. Social influence, the need for the technology, and existing alternatives to what the technology does are all important factors [41].

The seniors system usability survey by R. Holden identifies the need for a different approach in evaluating technology for this demographic [27]. Many seniors still struggle with basic digital literacy in modern technology [51]. The lack of basic digital literacy that many seniors struggle with impacts their ability to accurately relate their experiences with a system. Holden identifies the need to tailor these tools to the context of the system and user evaluating it. These tools use vague wording like "the system", which make it hard for less-technologically savvy seniors to relate their experience to the actual technology they used. Holden proposes an alternative wording to the System Usability Survey to ensure seniors can better evaluate the technology systems within the context of their needs and use. While maintaining positive and negative valence balance, as well as the well-tested Likert-scale response style, Holden also identifies wording within the questions themselves. Seniors may struggle to relate their frustration with the system to the five-item

agreement responses on “inconsistency” in “the system”. Senior friendly wording – like replacing ”inconsistency” with ”confusion” – can alleviate the confusion and allow for responses to more accurately reflect seniors’ experiences. Further, many studies opt for an entirely narrative-driven approach through structured interviews [45]. With the unique needs of each individual senior, a user-centered design process is crucial for both introducing the technology and familiarizing the senior with modern technology and the complicated language surrounding it.

2.3 Digital Games for Combating Social Isolation

The COVID-19 pandemic prompted researchers to take a closer look at the impacts and solutions to social isolation in the general population. Although technology in general is found to have differing affects on social isolation depending on the type, technologies like social media and digital gaming were found to mitigate the effects of social isolation in younger groups who are most studied and most influenced by modern technology [57]. Research on older adults’ engagement with digital gaming remains limited; a relatively small number of studies span a wide range of platforms, technologies, and contexts. Some older adults are already gamers who engage with complex hardware set-ups, while others have challenges accessing technology, let alone using it for play [56, 1]. Two examples of familiar games that were demonstrated through digital games are Bingo [54] and Wii Bowling [8, 26]. The games themselves were found to generate interaction among players and increase the quality of the social connection during the game. Although only a small number of seniors engage with more complex setups, some already use digital games like World of Warcraft to stay connected with their friends and family [56]. Social benefit from digital gaming is not limited to the game play itself, as studies also found that seniors could connect with friends and family over conversations of their playful experiences

[26, 56].

Some seniors may be motivated to play games through their desire to be healthy, connect with others, or just for fun. Some seniors play games as a way to reminisce about past experiences and hobbies that are no longer accessible due to age [8]. Smaller scale studies of non-gaming older adults demonstrate a clear preference for digital games with casual characteristics compared to competitive or fast-paced action games [11]. Accessibility, simplicity, and flexibility are core features that contribute to seniors preferences [11, 32]. While video games facilitating social connection are increasingly being studied as a way to combat social isolation in older adults, not all games are suitable for this purpose. Bingo and bowling are two examples of successful technology-facilitated games [54, 26] that both rely on a single simple physical interaction to interact with an engaging digital game; however, both of these examples were also co-located (i.e., players were in the same physical location). A different study on older adults playing a casual competitive digital game on a computer found that a significant positive effect was only experienced in a co-located gameplay scenario when compared to scenarios of competitive play where the senior was alone [18]. Notably, remote games with facilitated communication were not studied, and it remains a question whether a socially-facilitated remote digital game can have the same affect. One of the biggest enhancements technology provides to the gaming space is the ability to play games remotely and connect with others across the digital game space.

Despite the studied positive effects of digital games, the low prevalence of social gaming may be due to the older population's hesitancy to engage with new technologies. A study that examined older adults using computer systems – which often enable digital gaming – found a large variation in the continued use of computer systems after adoption [58]. No individual factor predicted continued use but a combination

of factors did; ease of use, interest, and technology anxiety all fluctuate throughout age, particularly in older adults [58]. Difficulties with the technology itself can, therefore, become a major barrier to adopting software intended to support seniors, who have individual needs at different times and as they age. Given the cyclical relationship between cognitive health and aging, the added cognitive load introduced by digital systems can be overwhelming [51]. The majority of modern interactive systems contain complex user interfaces and interactions that can pose a significant barrier [51]. While mobile gaming can provide a partial solution by omitting an overly complex setup, mobile apps are not inherently tailored for older adult's continued use either [55]. Complex mobile gaming interfaces and accessing the internet to use these devices can still pose a challenge [51].

2.4 Mixed Reality for Social Wellbeing

Mixed reality provides more flexibility and a new range of interactions in contrast to traditional technology. In a framework proposed by Milgram, the term Mixed Reality (MR) encompasses any combination of virtual and real world objects in a system. It includes a range of interfaces and technologies including head mounted displays (HMDs), projector displays, and simple monitors [36]. Wearable head devices enable fully immersive virtual worlds [14] and digital content immersed into the real world [42]. Screen-based displays enable divergence from traditional computer setups into tabletop games [20], exercise routines [22], and outdoor experiences [43]. Each context cites a different affordance enabled by the MR system, from it's mobility and portability to be used outdoors on a walk over a distance [43] to its ability to involve real-world objects like chess pieces as an interaction mechanism [42]. For our senior demographic, MR affords intuitive physical interactions, which provide more accessibility to otherwise complex technology [30].

With its wide range of uses and contexts, it is unsurprising that younger adults – who are the primary market for these devices – are using these technologies to support their own well being [14]. Mixed reality enables immersion into virtual worlds like VRChat to connect people to a social virtual world [14]. Existing research on social technologies for younger adults can inform the design of such technologies for older adults. For example, a mixed reality "Garden Within" experience notes the importance of natural interactions for effective therapeutic results [21]. In another study, an Augmented Reality Tabletop Chess system (ART-Chess) uses real chess pieces to improve a digital game experience [42]. These studies highlight the importance of familiar real-world interactions to enhance MR experiences. MR technologies for seniors, such as eldergames, also employ real-world physical objects like pens to replicate a physical interaction [20]. MR physical interfaces for general audiences are cited as enhancing immersion and experience [42, 14, 21]; the focus on physical interfaces for seniors lies in making the interaction accessible and intuitive [20].

MR applications for older adults are most prevalent in the physical and cognitive quality-of-life domains, with comparatively fewer uses in psychological and social domains [3]. Careful design considerations need to be taken to adapt VR and AR technologies to meet the needs of older adults [30, 19]. A study on a VR-based music therapy for seniors found promising results for VR-aided well being, but note that it is crucial to adapt the system to the audience to create an optimal experience [19]. Similarly, an AR solution aimed at easing seniors mobile phone usage highlights the importance of tangible AR solutions compared to traditional AR interactions like mid-air gestures [30]. Head Mounted Display VR is generally positively received among seniors [19, 3]. However, age was found to be negatively associated with its enjoyment [37]. Over half of the studied systems to support seniors well being were digital games [3]. Since congitive, physical, and social health are so closely linked in older adults, digital games can help reduce the risk of the cognitive and

physical decline that contributes to social isolation [3]. Games can also prompt competitiveness, another motivator for continued use of technology [3]. Another factor in increasing acceptance of VR technologies is social motivation. Since VR and AR technologies are inherently complex and require displays, audio, cameras, and other equipment to enhance the immersion, seniors may not seek out and engage with these on their own.

2.5 Tangible Interfaces For Seniors

A tangible user interface is an interface that uses physical objects to interact with a digital system. Research in technology for seniors highlights the opportunity to use tangible interfaces and components to increase acceptability [2]. Games with tangible interactions like Wii bowling [26] and the Eldergames mixed reality tabletop system [20] have found success using intuitive tangible interactions (like rolling a ball with a controller, or holding a pen) to engage with a more complicated software system. Other tangible interfaces like the one demonstrated by 360 AR Cyclotourism [40] afford the ability to reconnect older adults with familiar activities at home that may be harder to participate in due to aging. Tangible interfaces allow for an engaging virtual interaction in users' own homes; bringing familiar activities like bowling and cycling into a comfortable and accessible space.

Augmented reality is one way to facilitate tangible interactions for seniors' technology; for example, digitally augmenting tabletop game scenarios [20]. Technology with tangible interfaces for seniors primarily focus on making the users' interactions simpler, using familiar objects as input rather than screen-based interactions. Technologies like camera recognition or AR markers can network between real world objects and spaces to communicate information between the system and user. The

Eldergames project incorporates a table display fit with an overhead camera to track AR markers on a physical pen to capture the users' interactions and transmit it online [20]. AR Tangible Chess uses a camera under the table to track AR codes on the bottom of real chess pieces and augments the opponent's pieces onto the board [42]. In scenarios where the virtual and physical content closely align, like chess, there is an intuitive interaction that closely mimics real world play. On the other hand, interfaces like the pen and table used in Eldergames provide no guidance or instruction on how to use the tangible pieces to complete digital tasks. Alternative training or instruction is needed to ensure that the user knows how to use the devices to complete the tasks on the display table [20]. These systems can still struggle with acceptance due to the technology interfaces themselves and the cognitive processing and learning required of the user [20].

A variety of tools exist to enable tangible interactions in technology. There is no agreed upon approach to designing tangible interfaces. A proposal by Döring et al. suggests designing tangible interfaces by decoupling the central system and the tangible interface to allow variability in the tangible pieces [15]. Tangible interfaces themselves may introduce complexity; multiple components, moveable pieces, and constraints on tracked objects mean that the systems might require different ways to interact than their real world analogs. For example, the requirement for particular input movements with physical objects (turning, pressing, moving) with a tangible object can introduce complexity. End-users often have unique preferences for the layout of interfaces and the manipulation of objects for performing actions [15]. Considering the senior demographic has a higher prevalence of chronic conditions affecting fine motor skills – like arthritis, or complications from stroke – the flexibility of tangible interfaces can provide an accessible starting point. Tangible interfaces have been implemented using materials as simple as paper and tape to give a tactile and affordable interface [59]. Tangible interfaces have also been implemented with

more complicated hardware like 3D-printed pieces and sensors for a more accurate tactile object[28]. Research into the design of tangible user interfaces specifically for seniors is a developing area, and few studies employ a user-centered design processes [6]. There is also little acknowledgment of the closely connected relationship between social well-being and other health outcomes in the design of these technologies [6]. Tangible hardware offers more flexible interactions with digital systems and can alleviate some of the challenges seniors face with traditional technology by introducing new capabilities into the system. A variety of games using tangible interfaces have been proposed to promote cognitive health in elderly [20, 10] and physical well being [22]. Technology with tangible interfaces can be seen as new and exciting and can contribute as a motivator to help seniors adopt these systems [10] [40].

Chapter 3

Methodology

To better understand how tangible interfaces can impact the acceptability of social technologies, we worked closely with seniors to iteratively design a tangible online card game system. The card game system allows participants to play the game Crazy Eights [52] at a distance through data communications with a server. However, throughout our iterative development process the game was played in a co-located fashion with the experimenter acting as the play partner. This facilitated evaluation of the system and features by facilitating participant guidance and in administering questionnaires and interviews. The designs of each system prioritized accessibility, ease of use, and enjoyability to provide insight into whether tangible interfaces can be an acceptable design for social technologies.

Crazy Eights was selected as the game because of its simplicity and because it only has one shared card between players, which facilitates the game's technical design. To play a game of Crazy Eights, players take turns matching the rank or suit of the shared card and playing their card to replace it or drawing when no match is available. Eights are special cards that lets the player choose the suit of the deck [52]. Both players can "play" and overwrite the shared discard card.

The process consisted of three main design and development iterations. Before each iteration began we developed a version of our experimental system that was designed to use the best available technological approach to address the identified challenges experienced by older adults (as informed by our literature review). During the evaluation phase of each iteration we asked older adults to use our system to play a game of cards with it. We had them contrast their experience with a game of cards on a tablet-only interface (that we refer to as the baseline condition). After each evaluation phase, we analyzed the feedback and used it to inform the next development iteration.

For the first iteration, the system began with an initial tablet-based interaction with a simple camera-based mixed reality interaction using paper-based playing cards. In the second iteration, based on feedback, the system progressed to a more refined AR-based tangible system. In the third and final iteration, the system evolved into an NFC-enabled e-ink card system (adapted from the PROTEUS e-ink tag system, developed at the University of Waterloo [44]) where a tangible e-ink tag can be tapped on the NFC reader to perform an action, similar to tap-to-pay banking cards.

Below, additional details are provided for the design of each version of the experimental system, the procedures used during participant evaluations, and the data collection and analysis methods employed.

3.1 Iterative Design Process

This project began as an exploration into how mixed reality and tangible play could be best designed to support older adult's social connections. We adopted a user-centred design process in which we iteratively designed and developed new versions of the system as we encountered usability, acceptability, and technical issues. The

design and development of the experimental system began with an exploration of the existing literature and a requirement analysis. From there, each iteration evaluated the baseline digital condition against its respective tangible alternative with older adult participants. Following each game session participants completed an open-ended interview, and their feedback – along with researcher observations of participant interactions – was collected through notes. Some sessions were audio recorded when available and with the approval of the participant. The notes were then organized and analyzed via affinity diagramming – a technique commonly used in the qualitative evaluation of interactive prototypes [34]. For each iteration, notes were grouped to identify common challenges in the basic system interactions and to identify common system usability and acceptability issues. The findings of each round of analysis informed subsequent system design and development decisions.

3.1.1 Overview of the Three Iterations

To begin, in the first iteration, we developed an online card system for a mixed reality prototype with tangible AR-enabled interactions. The mixed reality approach presented numerous challenges for participants, revealing significant usability issues related to camera alignment, tracking stability, and the physical demands of framing AR markers as a primary interaction mechanism. None of the experimental sessions with the first prototype actually resulted in a full game being completed with participants due to technical and usability challenges, but the feedback, suggestions, and challenges informed the design and select enhancements for an improved AR condition.

In the second iteration we refined the AR-based tangible system with improvements to interaction flow, instruction, and usability. Participants from the first study were invited to participate for this iteration, and two of the former participants

returned alongside two new participants. Inviting both former and new participants allowed us to identify which challenges persisted in the refined system, and what challenges may be consistent in mixed reality interactions. Although the updated instruction, visual aid, and game cue improved certain aspects of the interaction, the core challenges of the camera-based tracking approach remained in the results and overall participant sentiments. This iteration also uncovered challenges in collecting narrative responses from the participants. These results informed a redesign of the data collection surveys to capture more open-ended responses, and the next iteration design of the system towards more friendly tangible interactions.

Based on the finding that tracking and camera framing of cards were a major challenge, we adapted our system and explored alternate ways to enable a tangible interaction without a camera tracking based system. Within context of our baseline and remote system, we adopted and integrated PROTEUS: a tangible NFC-enabled e-ink card system developed at the University of Waterloo [44]. For this final iteration of the system we adapted their e-ink price tag labels (which used NFC for data communication) to work with our online architecture and to remove the AR interactions that had resulted in confusion and usability issues in the first two iterations. We evaluated this tangible interface against the baseline condition to further evaluate tangibility as a suitable feature for social technology.

Across all three iterations of our design, participants completed think-aloud play sessions and open-ended interviews to evaluate the systems. The researcher's observations and participant feedback were collected as notes and analyzed via affinity diagramming between each iteration. The results allowed us to identify recurring usability challenges and opportunities for more accessible design.

3.1.2 Iterative Study Procedure Details

Below, we now outline the participant study details within each of the three design iterations. We briefly mention our findings below to describe how we adapted our prototype and evaluation with participants as we progressed towards a final version. Our study protocol was approved by the University of New Bruswick's Research Ethics Board, and is on file as UNB REB-#2024-143.

Each study session began with the experimenter welcoming the participant, explaining the goals of the study, and administering the informed consent form. An initial technology comfortability questionnaire was given orally, followed by a general introduction to Crazy Eights. If the participant had not previously played Crazy Eights, then a game was played with a physical card deck to teach the game to participants (if required). Next the baseline game was played or the experimental game was played (condition presentation was balanced across participants). Following the first game and questionnaires[1], the other version of the game was played. Again, the same questionnaires were administered, followed by an open-ended interview comparing the experiences of each condition. Throughout the experiment, the experimenter took notes on observations, and recorded responses to the questionnaires and interviews on paper. Each experimental session required no more than two hours to complete.

3.2 Participants

11 unique participants evaluated the system for one or more iterations. Participants were either recruited with the help of our research partner Loch Lomond Villa or

[1]In the first two iterations, the seniors system usability survey [27] and player experience inventory [25] were administered after each game. These were incorporated into an open ended questionnaire for the third iteration.

recruited independently through referrals. All participants were introduced to the system and an experiment was explained by a researcher. For the first two iterations – the original and updated MR systems – each person participated individually and signed a consent form prior to participating. The final iteration of the e-ink system had 3 pairs of participants and two individual participants. For participant pairs, the system was evaluated while the two participants played a game together and the researcher documented.

To better encapsulate the experiences of this broad demographic, we prioritized recruiting people from different living situations, from independent to community based living settings. We included seniors living to varying degrees of independence to get an overall view of the potential of mixed reality technology for this broad demographic. Table 3.1 details the varied living situations and technology familiarity of each participant in our study.

3.2.1 Participants outside of the study scope

During recruitment, one individual fell outside of the scope of the recruitment criteria due to not meeting the age requirement but expressed interest in the technology for their social well-being. This individual identified similar risk factors like living in community living and requiring daily assistance, or having difficulty maintaining social connections due to physical disability. This project relied on existing work on social isolation in adults 65 and older and retirement living populations where younger adults living in similar settings were not accounted for. However, these participant's lived experiences deserve to be studied and included as results, as they face the same challenges as many older adults and may get excluded from similar studies.

Table 3.1: Participant Profiles

P	Sex	Age	Living Situation	Technology Use	Iteration Participation
1	F	90+	Independent living community	Infrequent computer use Frequent mobile use	1
2	F	30-40	Independent living community	Daily computer use (gaming) Weekly phone calls	1, 3
3	F	70-80	Independent living (private residence)	Daily mobile use No computer use	1, 2, 3
4	F	80-90	Independent living community	Weekly phone calls Infrequent mobile use	1
5	F	70-80	Independent living community	Daily phone calls No mobile use	1, 2
6	M	70-80	Independent living (private residence)	Weekly computer use Daily mobile use	2, 3
7	F	70-80	Independent living (private residence)	Weekly phone calls Weekly mobile use	2, 3
8	F	80-90	Assisted living community	Daily phone calls No mobile use	3
9	F	80-90	Assisted living community	Weekly phone calls Infrequent mobile use	3
10	F	70-80	Independent Living (private residence)	Monthly computer use Daily mobile use	3
11	F	70-80	Independent living community	Weekly phone calls Weekly mobile use	3

3.3 Data Collection

Data collected for this study comes from three primary sources: semi-structured interviews, standardized questionnaires, and researcher observations during system use. Critical incidents were recorded as data notes whenever participants provided feedback, shared relevant insights or experiences, or expressed emotional sentiments verbally or through nonverbal cues. Data collected from these sources worked to-

gether to provide a deep understanding of how the older adult participants experienced each system condition, how they interpreted the interactions of the game, and how those interactions supported or hindered their social and usability needs. When available, the game sessions and interviews were recorded and reviewed to verify completeness and accuracy of critical incidents.

The collected data was separated into notes for each recorded data event and compiled to be analyzed with affinity diagramming [34]. Affinity diagramming is often used in prototype evaluation to organize data from multiple sources and in multiple formats [34]. This technique allowed us to capture and organize data outside of the interview responses, including observances, minor utterances, motivation, or frustration. These notes were combined with critical data notes from the interviews and questionnaires to be included in the analysis. Data notes from each iteration were reviewed independently and grouped by commonality. The groups are mapped to improvements and features needed for the next iteration of the system. The different sources of data that were collected and aggregated into notes are listed below. The questionnaires are also provided in Appendix A.

3.3.1 Technology Familiarity Questionnaire

Along with standard demographics (age, gender, etc), an initial technology familiarity questionnaire was used to introduce the experiment and help contextualize participants existing experience and comfortability with digital technology. This questionnaire included both Likert-style scaled responses and open-ended clarifying questions. The questionnaire covered experiences including existing technology use, frequency of technology use, and how technology is used for social connections. Participants were also asked about their prior experience with VR technologies. None of the respondents reported prior experience using Virtual Reality or Mixed Reality

technologies, although there was a varying degree of familiarity with those types of technologies through friends and family members as uncovered by the open-ended questions.

3.3.2 Experimental Observations

Each session included open-ended interviews conducted before and after the gameplay, and the researcher recorded written notes capturing participants' verbal responses to the questions, as well as gestures, hesitations, and other nonverbal cues relevant to their experience using the system. To facilitate collection and analysis, these observations were limited to capture critical moments in the game session, when participants verbally commented during the game session, or when the game progression stalled due to user errors or technical challenges. These observations provided insight into participants' expectations, strategies, and reactions as they interacted with each system. The data also included sentiments captured from deeper conversations that were prompted by some questions, which revealed more insight into participants' motivations and frustrations related to technology. Observational notes were recorded consistently across sessions and later integrated into the qualitative interview data for affinity diagramming and dynamic development. When available, the game sessions were recorded and reviewed to collect observational notes.

3.3.3 Interview Guide and Questionnaires

The open-ended interview guide incorporated questions adapted from the Player Experience Inventory (PXI), simplified System Usability Survey (SUS) for seniors [27], and other general questions to assess comfort with social technology. These tools were selected with the primary goals of this study in mind: understanding how

seniors currently use social technologies, identifying the challenges they encounter, and evaluating tangible interfaces as a viable interface to meet those challenges. Items adapted from the PXI and SUS were rephrased into open-ended questions to garner richer qualitative responses and better contextualize seniors' experience of the social technology through the game interface.

Holden's simplified System Usability Survey – adapted from the traditional SUS to tailor questions to be less confusing for older adults with cognitive impairments – includes 10 questions and a five-response Likert scale [27]. Since cognitive impairment information was not collected from the participants but is a known association with aging, the changes from the adapted questionnaire were relevant to all our older participants. The seniors system usability modifies the wording of the original system usability survey; for example, replacing the vague terms like "system" with the identity of the system being evaluated, and replacing the question on inconsistency with one on confusion which were previously found to be correlated [27]. The first iteration of the study employed the modified SUS directly, and following hesitations and confusion around the scaled responses during the interview, was adapted into open-ended interview questions to fit the context of the game sessions. The design of the interview was guided by R. Holden's adaptation of the Simplified System Usability Survey to simplify the wording of the questions, and capture the experience relating to each questionnaire item [27]. For example, items like question 6, "The AR Card game system was confusing for me", were further adapted to meet the context of the experiment with "Did you understand what to do to play this game like you would a normal card game?"

Since the game aspect is a core component of the tangible system's social capabilities, the Player Experience Inventory [25] scale items were adapted and included to identify challenges as they relate to the underlying constructs of the game as a

component of the social interface. For example, items identifying meaning like "The game felt relevant to me" and "Playing this game was valuable to me" were adapted to "Do you think that you would play this game in the future?". This approach enabled a more narrative-style interview process while preserving the conceptual foundation of the original tools.

The adapted interview questionnaire provided a theoretically grounded basis for generating a qualitative assessment to explore how the system supported or hindered the usability and sociability of the technology. The full list of adapted interview questions are provided in Appendix A.

3.3.3.1 Adapting the PXI and SUS

Standardized instruments like the simplified System Usability Scale (SUS) for older adults [27] and the Player Experience Inventory (PXI) [25] were introduced early in the study; however, many participants expressed uncertainty with scaled ratings and were uncomfortable providing a numerical answer that did not adequately capture their experience. Participants often focused deeply on each question, providing rich responses, and sometimes having to be prompted further for a rating to capture their answer. Likert-style scales felt abstract or confusing to participants, and studies such as the Simplified System Usability scale for seniors attempt to alleviate some of the confusion around these questions, but still fail to fully encompass the experience of seniors during the experiment [27]. Following the pilot study, the SUS and PXI questions were adapted into an interview format. The only numerical data retained were self-reported measures of technology familiarity as part of the initial introduction to the system. The pilot responses to the system usability survey that could not provide a numerical answer but verbally expressed an experience in relation to the system were included in the affinity diagramming notes and combined with the

interview results for further analysis.

3.4 Experiment Conditions

Three tangible interfaces were tested by older adults against a digital interface baseline. Each study iteration asked participants to compare one version of the game system we developed against the baseline condition.

1. **Baseline Digital Condition** A simple android card game interface with tap and swipe interactions
2. **Augmented Reality Condition** A simple augmented reality interface using a tablet camera to track and augment paper game pieces
3. **Improved Augmented Reality Condition** An augmented reality interface enhanced with simple augmented instructions and cues
4. **Electronic Ink Condition** A python-enabled interface using an NFC reader and electronic ink cards as physical game pieces

The experimental systems are built with either Java for Android (Baseline + AR conditions) or python (E-ink condition) and are functionally equivalent but differ in the interactions required via their tangible interface. Features that would be expected of a card system and were included and adapted in all iterations of the system are:

1. Visual discard pile virtually shared between two players
2. A method to draw cards
3. A player specific 'hand' of cards

The experiment conditions share the same JavaScript server back end to track game data, enabling full cross-play between conditions if necessary.

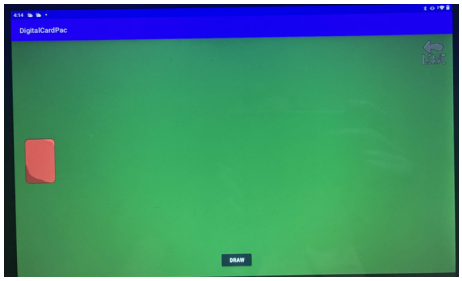
3.4.1 Baseline: A Tablet-Based, Non-Augmented Card Game

To adequately evaluate the effectiveness of a mixed reality system to support connection, we used a traditional digital interface – an Android tablet with basic touch interactions – as a baseline for comparison. The Android app baseline card game interface, as seen in Figure 3.1 was created as an Android Studio java app to enable traditional mobile device interactions. At the beginning of a game of cards, the app connects to a central Node JS server that holds the shared card deck and distributes cards to each player. For the prototype, the Node JS server and both player interfaces run on the same local network. This game interface uses generic mobile interactions like tapping, dragging cards around the screen, and digital buttons. The features and their associated interactions are as follows:

1. **Discard Pile**

   The discard pile was denoted by a blank red rectangle at the start of the game. Cards can be shared between two players by dragging the digital card across the screen into the discard rectangle. The discard pile updates immediately with the new card value and the card that was moved disappears from the user's hand. The discard pile is updated immediately to reflect the most recent card either user has placed there, and is shared between the two users. The shared discard appears larger than the other cards during the game.

   Design Note: Following iteration 1, a white glow outline effect was added to denote the discard pile



(a) Digital app before drawing cards



(b) Digital card game with drawn cards

Figure 3.1: The digital card game used as a baseline interface condition.

2. **Draw Pile** The baseline system applies the "draw pile" metaphor by using a button labelled with the word "draw" at the bottom edge of the screen. Tapping on the draw button will request a card from the shared deck on the server, and place the newly drawn card in the bottom centre of the screen to add it to the player's hand.

3. **Card Hand** The rest of the screen functions as the game board and the card player's hand. Once drawn, cards appear on the screen near the button and can be dragged and moved to a new location on the screen, as seen in Figure 3.1 (b). Following the first round, a shadow effect was included in response to feedback on the aesthetic design, and in order to replicate the dimensionality afforded by the alternative tangible system.

> *Design Note: For iteration two, cards had a shadow effect when picked up to add spatial context.*

3.4.2 AR Cards: Experimental System for Iterations 1 & 2

The AR Card Game app employs augmented reality into a traditional mobile card game. To create an immersive system with tangible interactions, this interface uses the Vuforia 1.8 SDK on top of a Java application created in Android studio. Tangible

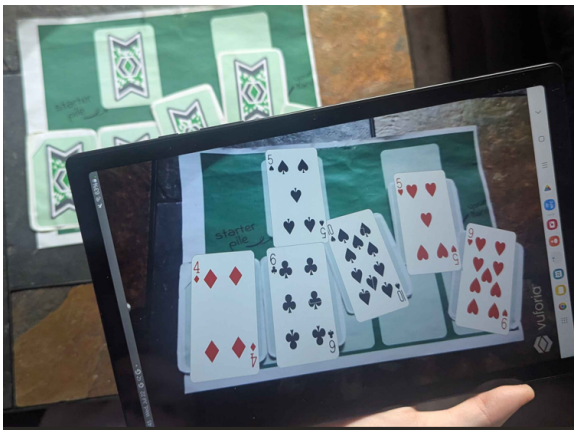


Figure 3.2: The AR cards overlaying the physical space and paper pieces

paper game 'cards' use Vuforia-enabled AR codes that are recognized by the software and assigned a card identity from the Node JS server as a graphical overlay. In this way, the game could create the illusion of shared deck of cards between players, no matter where they were located. To enable AR tracking and Vuforia code recognition, the Android device camera must be placed 1-3 meters away from the paper pieces. To facilitate this, a paper game board and a set of adjustable phone holders were provided to frame the physical game area. Figure 3.2 shows the tablet with the AR overlay with the physical board and paper cards in the play space.

1. **Discard Pile** On the game board, a labelled pile specifies the discard pile. The system recognizes when the physical cards are placed on top of the discard pile by monitoring the position of the pile and the position of each card in the game space. Cards put in this pile are virtually shared between the players and both players can view the same augmented card piece on the screen.

   Design Note: For iteration two, a white glow outline effect was added to the augmented discard pile on screen. Figure 3.3 (b) shows the added visual border on the discard pile as compared to the unimproved interface in Figure 3.3 (a)

2. **Draw Pile** By introducing mixed reality, the system enables a tangible paper card deck to be used as the draw pile and game pieces. A deck of paper cards (printed on a heavy stock paper and cut to the approximate size of a playing card) with Vuforia codes replicate the look and feel of cards. When drawn and placed in front of the screen's camera, the system assigns an undrawn playing card to the piece and the card can be used as part of the player's hand.

3. **Card Hand** The tangible pieces and the game board work together to facilitate a hand of cards. Figure 3.2 shows the augmented overlay over the physical paper board and pieces. Any unique pieces that have been recognized by the screen are assigned a playing card value, and can be moved within the physical space. A large sheet of paper was used as the "play mat", where marked spaces are provided for the player hand, discard, and draw piles. This play mat was recognized using QR codes. When a game piece code is recognized by the camera, the screen shows the augmented card face on the screen overlaying the physical game piece. Players can observe their card hand by laying their pieces on the game board (which is also recognized via QR codes on the mat) and reviewing the augmented information on the tablet.

   Design Note: For iteration two, an augmented ghost hand moving a card into the discard augmentation was included to provide timely instruction to delays in gameplay. Figure 3.3 (c) shows the ghost hand in the process of moving towards the discard pile

3.4.3 E-ink Tag Cards

Our final version of the card game system replaces our previous AR-enabled tablet interface with a windowless e-ink card game enabled via NFC and connection to



(a) Basic AR interface with no augmentation



(b) AR interface with discard border enhancement



(c) AR interface with ghost hand enhancement

Figure 3.3: Interface enhancements through discard border and ghost hand augmentation

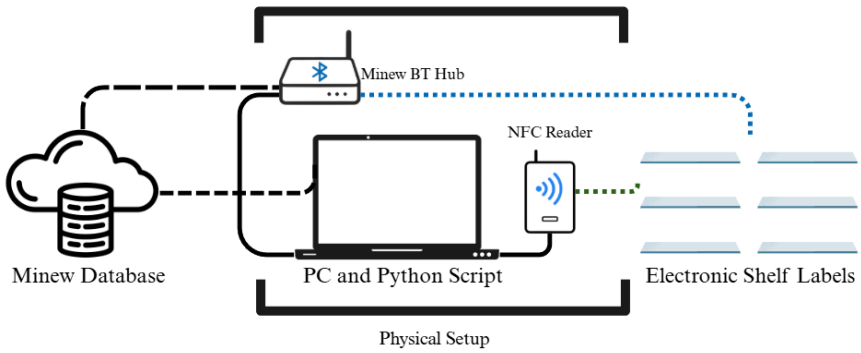


Figure 3.4: Architecture for the ESL card interface

a pc. The e-ink card interface is managed through a Python script and connects to the same Node JS server to receive and track the shared card deck. To resolve issues with the complex mobile interfaces, and introduce a more intuitive tangible functionality, this system includes a set of 10 Minew model DS305 e-ink labels with a Bluetooth hub and a cardboard game board which act as the deck of cards and play space. An ACR122U NFC reader reads the mac address of each label placed on it and requests a card identity from the Node server to assign to the label. The Minew e-ink labels connect with their proprietary cloud database to retrieve stored images available for display and interface with a Minew model G1-E bluetooth gateway to send the image data to each label. Together, the architecture (as shown in Figure 3.4) works to read an E-ink tag through NFC, distribute a card from the shared deck, and update the display through the bluetooth hub.

The interface the player interacts with is shown in Figure 3.5 next to the tablet baseline 'second player' of the card game.

1. **Discard Pile** On the game board, a labelled rectangular slot fits an NFC reader attached to the desktop system. The first tag placed in this area serves as the discard display and will continuously update to the shared value. Figure 3.5 (b) shows the full playing space with the discard label and NFC reader set



(a) Digital Interface Hand



(b) E-ink Interface Hand

Figure 3.5: Comparison of digital and e-ink condition in a shared card game

at the top. Any E-ink tags that have a card value and are placed on the labelled NFC reader are be sent to the shared discard pile; The card value transfers to the e-ink discard label assigned at the start of the game.

2. **Draw Pile** The set of remaining e-ink tags (apart from the one denoted as the discard) serve as the dynamic deck of cards to draw from. E-ink labels without an assigned card value can be read by the NFC reader to 'draw' a card and give them an assigned value. The Bluetooth hub then updates the display of the newly drawn card to match the card identity assigned from the shared deck. The drawn card is removed from the shared deck when drawn to maintain the shared state and ensure the second player can not draw the same card.

3. **Card Hand** The set of 10 e-ink labels functions as the dynamic card hand and can be updated to display playing cards in accordance with the game state. Figure 3.6 shows the e-ink label before and after being assigned a card. The cardboard play area provides space to place the E-ink tags and organize them as one would a traditional hand of cards.



(a) Clear label



(b) Label in hand



(c) Card label

Figure 3.6: Electronic Shelf Labels repurposed as cards

3.4.4 Researcher Positionality

The primary researcher was the sole researcher present for all data collection and experiment sessions. This researcher approaches the research question and design of technologies from the perspective of a Human-Computer Interaction researcher with broad experience using a variety of digital technologies, AR systems, and emerging interaction modalities. This background provides familiarity with complex interfaces and prototypes that may differ from the lived experiences of older adults who may have limited exposure to such technologies. As a younger adult, the researcher does not share many of the social, cognitive, or physical experiences common among older adults. In particular, experiences relating to technology adoption, accessibility, and comfort may differ significantly from those of the older adults evaluating the system.

Understanding the positional difference, study design and data collection were adapted to support participant comfort and reduce the potential imbalance of technology experience. Early Likert-style questionnaires were adapted to support friendly wording and narrative responses to better understand the experiences of older adults after participants expressed uncertainty with numerically scaled responses. This methodological adaptation aims to prioritize participants' communication preferences and comfortability in sharing experiences while using the technology being

studied. Throughout the study, the researcher employed affinity diagramming as a qualitative analysis to allow participant experiences to guide theme development rather than imposing predefined categories or assumptions. This approach is intended to prioritize participants' perspectives and mitigate the influence of the researcher's technological expertise and generational standpoint on the interpretation of findings.

Chapter 4

Results

The results of the qualitative analysis are presented below with one section for each iteration. Since the results of each iteration inform the next, a brief discussion accompanies each iteration results section.

4.1 Results from the first iteration

In the first iteration of our study, five participants were recruited who were identified as being vulnerable to social isolation due to aging or living in a community care setting. None of the five participants completed a full game with the AR system due to frustrations or usability challenges with the overall system design. Three distinct coding themes emerged during the analysis of this iteration. Notes containing an experience with a particular system feature or interaction were coded into "**AR Tracking**" and "**AR Discarding**", which were two of the primary interaction mechanisms for the game. The remainder of the notes that did not fit into a feature code were structured and organized into "**Pre-existing sentiments**", encompassing both hesitation and motivation for using technology to connect with family and

friends. The full set of notes were also independently coded to capture negative, positive, and neutral experiences with the system.

4.1.1 Theme 1: AR Tracking

All of the participants in the pilot trial experienced some degree of frustration with tracking the AR cards on the tablet screen. Table 4.1 outlines a selection of notes relating to the tracking system. Two participants (P1, P4) had significant challenges tracking a single paper code through the tablet's camera and interface, which impacted their ability to start playing. Three of the four participants who did attempt to complete a game (P3, P4, P5) all shared the criticism that it was difficult to track an entire hand of cards and the discard pile on the screen at the same time (because of the space constraints due to the camera position and size of the cards).

The learning process to track individual cards led to frustration for multiple participants. Participants rationalized their challenges with using AR tracking differently. For the two participants who had challenges tracking a single card, more time was spent learning the interaction than playing a game. P4 was observed holding the paper card outside the camera frame to maintain direct sight of the physical card rather than viewing the digital overlay on the tablet screen. Even after properly tracking it, P4 would remove the card from the camera rather than placing it in the playing space with the game board, which caused confusion when the card no longer appeared on the tablet. P1 held the card directly in-front of (i.e., touching) the camera, which obscured the readability of the paper code. P1 sighed loudly and exclaimed "This is beyond me" and gave up on playing a game following the learning session, and P4 opted to not finish a full game saying "It's just not for me". Even after a significant learning period and continued correction some participants struggled to adapt to viewing and holding tangible augmented objects. P1 noted that the

main challenge was with the tablet (and camera framing) part of the interaction and not the paper cards.

The remaining three participants (P2, P3, P5) who successfully learned how to perform the AR tracking interaction for a single card revealed challenges with tracking multiple cards on the screen at once. P2 was able to track a card and get a viewable hand of cards in the playing space, but lost the tracking stability due to the device and physical setup moving. Attempting to realign the play space and camera caused technical challenges when the system tried to recognize all codes at once without a stable setup, causing the game to crash and stall. P3 and P5 noted challenges organizing the cards and playing space to adequately view all the augmented card information. Both participants suggested that smaller cards could make it easier to track a full hand. P3 also added that it was "difficult to get the cards on screen at arms length", noting the challenges keeping consistent tracking of their hand of cards. All three of these participants shared the common challenge of tracking the codes for an entire hand of cards behind the tablet's camera. The cognitive work needed to organize the physical space and verify visibility through the tablet screen may have introduced an unanticipated challenge to participants. The additional step of viewing the screen to see the cards rather than in their hand directly differed from a traditional game of cards. Whether it was challenges tracking a single card or an entire hand of cards, all four participants experienced AR tracking challenges that detracted from the usability and enjoyability of the system.

4.1.2 Theme 2: Discarding Cards in AR

The second theme revealed challenges relating to discarding cards with AR tracking. The discard interaction required moving a physical card to the augmented discard pile (located on the play mat). Two of the 5 participants who did not complete a

Table 4.1: Participant comments related to card tracking in the AR system

Participant	Comment
P5	"I can't get them all to show up on the screen" Participant struggled to organize and track cards after five had already been placed on the screen
P5	"I wish these cards were smaller" Participant had trouble framing a full hand of cards within a comfortable length
P3	"It would have been easier if the cards were smaller" Participant lined cards up but could not fit the entire card hand into the frame
P3	"It's difficult to get the cards on the screen at arms length" Participant had to readjust cards repeatedly behind the camera screen to keep track
P4	"I can't hold my arms up for a long time" Participant tried holding card behind camera frame instead of placing it within view
P1	"It was hard to follow the cards on the tablet" Participant had difficulty remembering which physical cards were which virtually augmented ones

game also did not progress far enough to perform a discard action due to unstable usability and frustration present in AR framing and tracking. Of the three participants who performed a discard interaction while experimenting with the system, two experienced errors executing the discard interaction in AR, but not in the baseline (tablet) version. By comparison, there were no comments or errors performing the discard action in the baseline condition.

Two of the three participants who performed the tangible discard action had confusion or errors when executing the discard interaction. The tangible discard interaction is designed to mimic the physical transition of a card to a shared central discard pile of a traditional card game.

An important limitation of our AR solution is the limitation of physical space to augment. The positioning of the screen must simultaneously allow physically reaching the cards, framing the play space in the tablets (dictated by the distance from play space), and the reachability of the objects in the play space. The AR setup as

shown in Figure 3.2 requires all cards – including the discard pile – to be in close physical proximity. Despite the discard pile being visually denoted in the physical space with a playing card and a labelled discard spot on the game board, P4 had trouble remembering which card was on top of the discard pile when multiple cards were displayed on the screen. P4 became confused and commented, "Where do I put this?", when attempting to discard a card over another card in their hand. This resulted in a pause in gameplay as the experimenter assisted the participant in understanding the error and interaction.

P3 had a similar spatial issue where the physical discard pile was not stationary and moved locations by a few inches. The augmented card was correctly overlayed over the physical discard but neither the physical or augmented card were in the labelled 'Discard' spot on the board. This caused P3 to lose track of which augmented card was the appropriate shared discard card. Each confusion resulted in the game stalling and not progressing as smoothly as a traditional game of cards. The stalls in the game and confusion caused by this interaction impacted participants' enjoyment of the game. P3 was discouraged and commented "I didn't really get to play" and P4 scoffed and became frustrated saying "It was consistently trouble".

4.1.3 Theme 3: Pre-Existing Sentiments, Motivation and Hesitance

The third theme groups remaining notes not related to any particular feature or interaction with the system, but were instead related to the context of our study. During the interviews and game sessions participants shared their experiences with technology and noted some of the challenges they typically face or expect to face when using it.

Positive comments revealed participants' motivations to use technology or play a digital game. For example, P2 mentioned that technology was important for them to stay connected while living in a community home. Since they often rely on others to visit, they mentioned "... there's certain times of the day people don't visit..." and "... a game fills a lull in the day.".

Many challenges and negative sentiments pertaining to technology were also accompanied by a hesitance to use and uptake technology. Participants had a diverse level of experience; three participants own and use mobile devices daily to communicate with others (P2, P3, P4), while the remaining two reported not owning (P1) or not often using a mobile device (P5).

Both conditions (i.e., the baseline and the experimental) rely on a tablet interface for the core engine of the system, which requires interaction with a traditional tablet interface at least once during the experiment. Many participants approached the game interface with the expectation of having challenges, or lacking the confidence to use the system independently.

All participants commented on least one challenge using traditional mobile interfaces, which was sometimes revealed while playing a game with the digital interface. For instance, while P2 began to play a game with the digital interface, they commented, "some phone games are frustrating because buttons are hard to hit". Two other participants shared the same sentiment around mobile technology prior to beginning an experiment, citing difficulty "... hitting the right spot copying and pasting..." (P4) and needing assistance with tasks like editing on a mobile interface (P3). In the baseline condition, P1 noted "I will probably hit the wrong button and be lost" and felt that they would not have the confidence to use the system independently following the experiment. P1 stated that they had no challenges with the tangibility of the system or design of the cards, but the tablet interface in both conditions was

the primary source of frustration. Participants sharing their challenges with using mobile devices revealed that technology hesitance seemed more prevalent among the older adults in our sample than has previously been suggested [1].

Despite the reported challenges using traditional mobile interfaces, none of the participants made any significant errors or reported particular challenges with the baseline game interface. P5 noted the system "... would be complex to begin with..." but also gained confidence after using the system, commenting "I could figure it out quickly" after having successfully performed some of the game actions. P3 similarly commented: "Once I knew which button it was easy".

4.1.4 First Iteration Discussion

Frustration and difficulty understanding the AR tracking needed to perform the interactions appeared to be the primary discouragement with the tangible system. However, all critical incidents resulted in confusion or frustration and a stall in the game, which distracted participants from being able to smoothly play a full game with the typical afforded social interactions. Interactions in the first iteration mostly focused on learning the system and clarifications around how the cards track properly on the screen. The demographics survey revealed that none of the participants had used VR or AR systems in the past, but some participants were also not comfortable using modern laptop, mobile, and tablet technology. The lack of previous experience with mobile technology was overlooked in the initial development as prior surveys noted high technology usage among seniors [1]. The lack of familiarity with mobile technology introduced issues for some of the participants when learning the tracking of the system. Framing the paper cards in front of a camera at the proper distance and angle for augmentation is not necessarily an intuitive interaction and is made more difficult without previous experience.

Three participants also shared the criticism that it was difficult to track all of the cards in their hand and the discard pile on the screen at the same time. Even after successfully tracking a single AR paper card, continued success was inconsistent and proved a significant source of frustration. The tangibility of the tangible interactions made possible by the physical playing cards in the experimental condition was appreciated, but using the cards in combination with the mobile technology proved to be a significant challenge.

All participants reported the baseline as their preferred interface due to the usability challenges with the tangible interaction. Even with all participants preferring the baseline condition, most did not report enjoying the game and expressed no interest in further use. Confidence in using technology was rarely observed or recorded prior to the learning phase in both conditions, like P1 who noted not wanting to use any mobile technology at all. After using the technology and observing confidence in the learning phase, participants still demonstrated hesitance for the use of mobile technology in both conditions.

While the primary limitation is caused by the physical space afforded by the system, the first iteration of the AR interface may have lacked some basic interface features that could mitigate this. Simple augmentations like a visual border around the shared discard to mimic the physical appearance of a "full pile" of cards could make the augmented interactions more intuitive and more analogous of what seniors would expect of a physical card game. The issues did not arise in the control because the discard pile was stationary on the tablet screen and could not be moved. This suggests a need to better design cues that capture the important features of physical card games.

4.1.4.1 Design Requirements from Iteration 1

The results from the first iteration revealed insight into challenges older adults face using mobile technology. While participants appreciated the idea of a tangible remote social game, the usability challenges with the AR interface prevented enjoyment of the game and a complete evaluation. The baseline condition – though preferred to the tangible condition – lacked the novelty or tangibility to provide an enjoyable experience and did not meet older adults expectations of an enjoyable social technology.

We identified several ways to mitigate the challenges participants experienced with the AR system, which we implemented for the second iteration.

To resolve frustration caused by losing track of the discard pile in the game, augmented reality affords the ability to add information into the physical environment through the display to provide guidance. For the second iteration, a glowing effect was introduced for the shared discard pile in both the digital and AR versions to maintain consistency. In the baseline condition, the digital discard pile glows when moving another card to emphasize the discard pile. The baseline was also updated to have cards appear closer to the player when touched to replicate picking up a physical card. In the AR condition, the discard pile was augmented with both a glow effect and a translucent hand moving a card towards the discard pile. The ghost hand was found to be the most effective visual instruction for seniors' use of augmented reality by Williams et al. in 2021, although audio and text instruction were found to be the most preferred by this demographic [53].

To mitigate challenges with the overall AR tracking interactions in our system and assist in framing the game space, a wider range of device holders were introduced. Participants were instructed and assisted in selecting their preferred device holder before playing by framing the board in the device's camera space prior to starting

the game. Since some participants had trouble maintaining tracking of a full hand of cards, the new device holders provided a longer viewing distance and more area within the play space tracked by the camera frame. The paper game board was also made slightly larger to give the participants more physical space to frame.

4.2 Results from the second iteration

The updated interface was introduced in the second iteration to reduce challenges associated with the tracking and discard interactions with the AR system. Since no participants were able to complete a full game with the first system interface, this was developed to further test tangible AR as a usable interface for an older adult social technology. Four total participants tested this version of the system, two from the first iteration, and two new participants. After the first four experiments revealed continued limitations and confusion among participants, no further participants were collected for this iteration of the experiment.

Two distinct themes emerged from the analysis of the second iteration: "**AR Framing**" and "**Learning**". The framing theme follows the continued challenges of AR tracking and framing the physical play space from the first iteration. AR interactions related to tracking and framing paper cards resulted in continued frustration with the AR interactions in the the system across all four participants. The learning theme reveals motivations and feelings related to the learning process of using both the AR and baseline systems.

4.2.1 Theme 1: AR Framing

Every participant reported challenges with tracking the AR cards at least once during the experiment. For all participants, the reported tracking difficulties caused

frustration and stalled the progression of smooth gameplay. Two participants (P3, P6) were able to complete a game using the tangible system, but not without feeling frustration over the continued challenges. In one of these sessions, P6 frequently commented on the tracking of the screen and adjusted the tablet stand and tracking. While playing a game with the tangible system, they narrated "... the only problem is that the screen shakes when I put my arms behind it" and "You need to have the board at an angle to work" (P6). At least 3 times, P6 stood up from the chair during a game to move the game board or adjust the placement of cards, and P6 frequently moved in their chair to use the system. Another participant (P3) verbalized their confusion and challenges during the game, "It doesn't show the card up there." and "What did you put down? I don't see it." P7 had similar tracking issues occur throughout the game, asking "Did I do something wrong?" as their discarded card became obstructed by other cards on the game board. In both instances, the participants became confused when the shared discard pile moved in the physical location or the tracking became obstructed by other cards. P3 was able to realign the cards after instruction from the experimenter, but did not typically attempt to solve the issues independently or continually readjust like P6. Tracking an entire hand also proved a challenge for the P3 who commented "Oh wait, now there's nothing on that one" after placing cards and obstructing the tracking of other cards in their hand. All participants were observed to adjust their cards while playing, either to resolve minor obstruction issues from other playing cards, or readjusting the tablet after bumping it while performing a game action. Instead of continuing to adjust the placement of their cards, P3 eventually gave up and continued the gameplay with frustration, "I'm going to say I can't play because I can't see that card again". P3 noted numerous frustrations with the AR interactions "... like, when I'm putting it in front and I see my own hand, or some of the cards [are] not showing up or the pile movement".

Two of the participants (P5, P7) did not complete a game with the tangible system due to challenges with the tracking. P5 had few direct challenges using performing the AR-enabled tracking interactions, and was able to find a comfortable and consistent tracking angle for the board and their hand of cards at the start of a game. Notably, this participant used a rollator (a walking aid), and opted to use an adjustable side table where they could comfortably play. In one instance, trying to draw a new card caused the participant to bump into the table with the game board, which caused the game board and paper card pieces to fall off. The participant apologized and opted to end the game rather than setting it up again due to the amount of setup required. P7 also opted to end the game early due to issues with tracking the cards and game space. When P7 drew their tangible cards at the start of the game, they were confused on the inconsistent tracking when cards were overlayed and slightly obstructed by others, or when the tablet camera shifted and lost temporary card tracking. After the experimenter first advised the participant on how to properly align their hand of cards, P7 was observed quietly adjusting the tablet screen, stand, and playing cards often as their arm bumped into the tablet screen or game board and the system struggled to maintain consistent tracking. After a few game moves, the participant became frustrated and rationalized, "If the tablet was floating it would be better" (P7). They then paused the game session and focused on finding a solution to make tracking the cards more comfortable. P7 appreciated the tangible AR's concept and was motivated to find a solution for their challenges, rationalizing "I wonder if a music stand would work" and using objects from their home to test different physical setups. The participant was interested in continuing but could not find an appropriate setup before the experiment ran over time. All participants had some degree of frustration with the AR tracking interactions due to the tablet camera movement or the challenge of relating the physical space to the visible enhancements.

Even though P7 did not complete a full game with it, they preferred the tangible condition and thought it could benefit some of their friends. On it's ability to be set up and played anywhere, they commented "They can go and talk to their family and play a game, they have the means to do that" (P7).

4.2.2 Theme 2: Learning

The learning theme encompasses observations of participants as they learned and gained familiarity with the system. Participants often verbalized their successes and failures when performing game actions. Comments like "Oh, that's neat!" (P7) and "Oh I see how it works now." (P6) provide insight into key moments and sentiments when older adults make connections between their actions and the system outcome.

Each participant was introduced to each system condition prior to playing a game with it, but it was often the first portion of a full game with that interface where older adults gained confidence in using the system. All participants were able to perform the actions in both conditions to draw and discard cards. However, in both the tangible and baseline condition, participants often sought reassurance from the experimenter early in the game, like P5 who asked "Is it going?" referring to their discard after making a game move in the tangible condition, or P6 confirming "Okay, so I just press the button to draw 5 cards?" in the baseline condition.

During a game with the tangible condition, P5 noticed the augmented hand on the screen while organizing their card hand before making a play. The augmented hand distracted the participant from their game and they asked, "Oh, what does that mean" before showing the experimenter. They were able to continue after a quick explanation of the hand augmentation. P3 sought assistance from the experimenter to align the tracking of the player cards when they noticed the augmentation for the discard failed to appear. The bordered discard augmentation failed to track or

flickered its tracking multiple times when the cards moved, or the participant placed a card and temporarily obstructed the code. They were often confused when the discard disappeared and commented, "It doesn't show the card up there", and "Oh wait, now there's nothing on that one!". The experimenter was able to instruct the participant to realign their card and device to resolve these issues. Eventually the participant gave up on fixing tracking and adapted by playing without knowing all of their augmented card information. P6 – who was observed to move frequently in the tangible condition to arrange the screen and cards – also verbalized their tracking strategy as they moved. They commented "... You need to have the board at an angle to work" as they stood up to view the adjust the screen and align the cards. P6 believed that the tangible AR may be difficult for other older adults and commented, "... but they have to be able to see this ..." referring to the physical play space and cards behind the tablet.

4.2.3 Second Iteration Discussion

The second iteration system attempted to resolve the AR tracking and AR discarding usability issues apparent in the first iteration. Although participants were more likely to finish a game using the augmented system compared to the first iteration, all participants experienced continued frustration and challenges using the tangible AR system. The baseline condition had an added pickup card effect and a glowing border to replicate the tangible improvements. Similar to our first iteration, there was relatively low interest and low commentary on the baseline interaction interface. Two participants preferred the baseline condition due to the tracking issues continued from the first iteration. All participants reported being able to understand and use the digital condition easily, but there was low interest in continued use of the system. P5 – who reported not frequently using mobile devices – felt that the digital system

was “fine” but was not interested in further playing games using that interface.

In contrast to the first iteration, two of the participants (P5, P7) said the tangible interface was their preferred interface and appreciated the tangible interactions and being able to hold the game pieces in the context of a two player game. Both participants were interested in trying the system again if tracking stability could be improved. All participants were able to perform the actions to draw and discard a card during a game with the tangible condition. Each participant also still experienced challenges tracking that was unique to their use of the system. P5 lost view of the entire board, while P6 completed a game but had challenges maintaining tablet stability while playing in the space. P3 was able to quickly notice tracking challenges when the visibily distinct discard disappeared, but was frustrated with the frequency of the challenges. P3, P6 and P7 all had challenges maintaining tracking of the entire card hand and had differing responses to resolving those challenges.

All of the participants had to learn the AR tracking tracking system, and adapt to any challenges by adjusting their tablet screen, device holder, and game pieces during the game. As noted in the AR Tracking theme, this caused frustration for all participants during the game. P6 adapted to tracking inconsistencies by physically moving and standing to interact with the system, while P4 and P6 quietly adjusted their screen and game pieces from their seats. The new device holders enabled a larger frame of playing space, but may have made it more difficult for the participants to physically interact with the system. Participants had to adjust the framing of the playing cards any time they bumped into the neck of the stand or the tablet itself when playing the game. The participants also had to adjust their space after placing new cards to ensure that they were all visible, sometimes resulting in them bumping into the tablet stand and compounding the tracking challenges. Each participant also still experienced challenges tracking that was unique to their use of the system. P5 lost

view of the entire board, while P6 completed a game but had challenges maintaining tablet stability while playing in the space.

With the added context of the first iteration, the interactions of the tangible system introduced far more complexity than was expected of a traditional card game. Participants in both iterations encountered significant issues due to the added demands of the system. The AR tangible system requires players to put in the extra effort to ensure each of the cards are visible by the device camera on top of being accessible and easy to reach for the player. The tablet interface often got in the way of performing interactions, and required extra effort from each participant to maintain alignment and tracking. The physical space also has to be closely set up behind the tablet to maintain camera sight, making it difficult to navigate an obstructed space. None of these requirements are present in the baseline system or a traditional game of cards. If a single piece of the AR interaction is confusing, frustrating, or difficult to perform then the participant is unable to progress through a game. All of the interactions in the digital baseline condition were relatively simple and easy for the older adults to perform after initially being introduced.

The results of both iterations also reveal that a traditional mobile interface also may not be usable nor enjoyable for a lot of older adults. Despite the continued challenges in learning and adapting to AR technology, some participants were still motivated by the idea of a tangible remote card game. Even though P6 preferred the digital condition, they thought the tangible system could be easier for older adults who are less familiar with mobile technology. P7 preferred the tangible condition, and thought it could be applicable to other older adults who struggle to stay socially connected.

Both iterations had lower interest in the baseline condition overall, with very few positive or negative emotional sentiments reported. Nearly all participants who re-

ported not owning or frequently using mobile devices expressed a disinterest in the mobile interface even though they identified it as more usable. A traditional mobile interface may carry negative pre-existing sentiments which impact older adults' confidence before even trying to use a system. The hesitancy about its use or continued use outside of the direction of the experimenter reveals an underlying uncomfortability with technology. Older adults gain experience and comfortability with technology by using it, but pre-existing hesitance can be a barrier to its' initial adoption [46]. Older adults often require external help when first learning new technology [51], but their continued use is influenced by technology anxiety and ease of use [58], neither of which was significantly improved by the AR system.

4.2.3.1 Design Requirements from Iteration 2

Both iterations with the AR tangible card system revealed frustration and confusion relating to AR interactions. The existing uncomfortability with mobile technology, and the added complexity of AR-enabled interactions may make mobile AR inherently challenging for older adults. AR for older adults is understudied, and current studies reveal limited success with these interfaces. A mobile AR supermarket application found success for older adults, but didn't introduce any tangible interactions into the system [31]. A similar mobile AR application for seniors aims to aid in navigation, but has not yet been tested with older adults [5]. Eldergames succeeded in incorporating tangible interactions in AR by separating the display and camera but notably only uses a single tangible object for interaction [20]. Understanding the limitation by the added complexity in framing a camera and display to capture tangible objects in real time, we prototyped and tested AR interfaces that might mitigate the need for a camera and screen coupled display. We experimented with projection-based AR – which projected card images below a QR code – but found

substantial limitations. The display area was unable to be used as play without obstructing the tracking or display of cards from the camera and projector. For older adults – who suffer increasing risk of cognitive decline and mobility problems [50] – the challenge of framing a space without the mobile interface becoming a barrier may introduce too much complexity and cognitive load for the task of playing a card game.

Despite the challenges, both iterations reveal older adults' motivations for using technology with tangible interfaces for social play. Previous research shows that older adults are motivated to use technology to participate in activities that are harder due to aging (e.g, cycling [40] and bowling [8]). Several participants appreciated the design of the cards and the idea of tangible objects as input for a game that can be played at a distance. Tangible objects are appreciated as an input mechanism, but the primary limitation of the system lies in the application of the objects as input and the digital interface itself. If tangible objects can be implemented in a system without the tangible interactions and interface themselves becoming a barrier, the system can be more accessible to a larger portion of older adults.

4.3 Results from the Third Iteration

With the third iteration, an e-ink tag enabled tangible card system was created leveraging the previous game system. It was evaluated with 8 participants. Four of the eight participants (P2, P3, P6, P7) had evaluated the system in at least one of the first two iterations.

Four themes emerged from the analysis of the third iteration data. The first theme "**Comparison with Baseline and Traditional**" is comprised of challenges and motivations participants expressed while using the unique features of the tangible

interface. The second theme "**Adapting and developing strategies**" connects participants expressions of the game actions and how they adapted to learning the system. This theme revealed both positive and negative sentiments associated with adapting to the tangible interface and its use. The "**Features and Accessibility**" theme closely follows hows older adults adapted to the system, but relates to particular feedback or actions pertaining to the direct usability of the system by a diverse demographic of older adults. The final theme labelled "**Existing Technology Usage**" follows participants expressions and feedback on the enjoyability of the system. This theme unveiled similar data to the motivation theme from the first two iterations but coded uniquely as a result of more data being applicable to the enjoyment and fun participants had using the system.

4.3.1 Theme 1: Comparison with Baseline and Traditional Card Games

Expressions relating to the interactions in the e-ink tangible condition revealed common frustrations and confusion around the interactions and tangible system. All participants commented at least once about the delay between performing actions and visual feedback in the tangible condition. Performing an interaction in the tangible condition takes longer for the user to perform and for the server to sync the Bluetooth card labels to the game state. For most actions the system takes 5-10 seconds to display the card visual after being detected by the NFC reader, but on a poor connection the delay could take up to 30 seconds. The delay in updating the game state – which was only present in the tangible condition – caused confusion for multiple participants. Note that an audio cue was used for instant feedback on performing actions, which was demonstrated to each participant when learning a system. Only one participant found the audio to be a sufficient feedback: "... you

know it will take a bit but the sound will work (P3)". P8 handled the delays by seeking reassurance from the experimenter, asking "What is this one?" when labels were slow to update visually. In another instance, P10 became frustrated and said "It's not working, I drew a card and don't know what it is". The same participant later became confused on whether the game had ended after a longer delay in syncing their drawn card with the e-ink label. Other participants found the visual update delay after performing actions to be frustrating more than confusing. P2 exhibited frustration and had to continually prompt the second player to wait while their card visuals updated.

Some of the participants strategized by seeking reassurance from the experimenter on actions after performing them. All participants verbally relayed their action in the game at least once while using the tangible condition.

Every participant also only ever held one card at a time during the game play, leaving all cards not currently being used to perform an action in the game space. None of the participants held the e-ink tags as a regular deck of cards – they chose to organize their card hand within the play area to their own comfort for playability. Two of the participants (P3, P7) chose to stack labels on top of each other during organization, while the remainder often organized a horizontal row of labels. In the baseline condition, most participants did not organize their cards beyond a traditional horizontal line, instead taking care to reorganize their cards if a newly drawn one would overlap with an existing card.

For discarding, the tangible interface requires participants to touch the e-ink card to the nfc to 'discard' and remove the empty e-ink label from the space to be used again, unlike a traditional game where the discarded card stays in the discard pile. Six out of eight participants placed the card on the nfc reader and removed their hand until the action completed before returning the card to the side. Due to the

visual delay, P3 returned an empty card that was slow to update back to their board of cards. They fixed this quickly when the label updated to the empty image. In contrast, discarding a card in the baseline condition provided an instant visual update and required no manual reorganizing. Half of the participants preferred the tablet condition over the tangible interface, with P2 citing it was " ... because of the delays". The discrepancy between traditional card game actions and the tangible interface may have created frustration and reduced the overall enjoyability of the system.

4.3.2 Theme 2: Adapting and Developing Strategies

The learning and strategizing theme relates to how participants performed actions and adapted to using the system in both the baseline and tangible conditions. Strategizing refers to how participants developed strategies to play the game, organize their game interface to proceed, or perform the interactions needed to progress the game and. This theme includes user errors, moments when participants sought reassurance from the experimenter, or any sentiments expressed relating to the interaction of the system. Some participants also narrated their actions as they performed them. All participants were found to strategize either verbally or through non-verbal cues in both conditions. Participants exhibited different forms of strategizing for each interface. In the baseline condition, strategizing mostly took place in the form of expressions for the card game gameplay itself. Participants often narrated their actions as they played like "I'm going to play a 7 of hearts here" (P6), "There it is! 3 of hearts" (P6), and "Yep, I got your queen" (P10). In the tangible condition, more participants were found to verbally reassure themselves or narrate their actions as they pertained to performing the draw and discard interactions rather than the gameplay itself. For example, P3 narrated their gameplay slowly, "So if I want to

give her this 8..?", as they moved their card onto the NFC reader.

Before playing a game with either interface, each participant learned the actions and rules for that particular interface. Participants often still had questions or sought guidance when performing these actions shortly after beginning a game. While starting a game session with the tangible condition, P3 asked for another demonstration on drawing a card, and excitedly exclaimed "I get it now" after successfully performing two more draw actions. In the baseline interface, a similar learning curve was demonstrated with P6 who paused after drawing their starting cards and added "Just wait a moment." while they recalled the interactions for playing and discarding.

There were two instances of participants making an error using the digital tablet interface. Both P2 and P6 made errors in drawing too many cards onto their screen. With no ability to delete or "undraw" a card, the participants asked for assistance from the experimenter, who moved the card out of the visual space of the screen. For the tangible condition, participant errors and confusion over the state of the game stalled the progression of the game. Participants also formed strategies to progress the game, and all were able to complete a game with the tangible interface.

4.3.3 Theme 3: Features and Accessibility

Older adults were often not shy in sharing feedback and suggestions on general system accessibility for their demographic. Participants noted multiple times during or after a game session that a particular interaction was easy for them but that someone else in their demographic may have challenges. The audio was adjusted each session during the initial system training to verify that each participant could hear the sound cues to indicate game play. Some participants still noticed that the short audio cues may be difficult for someone hard of hearing (P3, P11) and one suggested that card labels buzzing would be more accessible than audio cues (P3).

None of the participants noted any difficulties viewing the card images, and some appreciated the visual card design with comments like "anybody could see that" (P8). P3 showed initial concern that the cards were small and other older adults might have a hard time seeing the images, but then held the card close to their face and reasoned "... if they can't see well they have to hold it like this" (P3).

Some feedback and accessibility suggestions resulted from the frustration of playing the game with a slight delay between performing actions and visual feedback. P2 and P11 suggested features to better help them remember their cards and organize their hand, like colorful stickers on the e-ink labels (P2) or LEDs flashing on the cards waiting for updates (P11). P3 suggested a tactile feedback for instant card feedback, suggesting "... what if it buzzed [while waiting to update]?" so they could avoid accidentally returning it to their board.

All participants verbally noted the tangibility of the cards as a nice feature in the e-ink label condition. The e-ink labels are thicker than traditional cards since the size is limited by the nfc chip and ink display. We prioritized tangibility but recognized that cards did not feel exactly like traditional paper cards due to the plastic casing on the cards. What we had not considered was that traditional playing cards may be more difficult for some older adults due to poor grip strength [33] and reduced dexterity [12]. The design of the e-ink playing cards revealed an unconsidered accessibility feature of the thicker card solution. For some participants, the tangible solution made the simple act of playing cards accessible again. While playing a game with the e-ink labels, P2 commented "I can't hold a regular deck of cards, they're too flimsy. I like that these are bigger and easier to hold." Another participant mentioned "I only have one working hand so these are easy" (P11). All participants were physically able to hold the tangible pieces and perform the actions.

4.3.4 Theme 4: Existing Technology Usage

Despite 7 out of 8 participants owning a cell phone, the ways in which they reported using these devices in their daily lives varied greatly. Of the 7 participants who owned cell phones, 5 of them rated their self-perceived mobile device comfortability as "Very comfortable". However, some of these participants also noted caveats with their comfortability. For instance, P7 reported being very comfortable using mobile devices, but also described situations where they were confused or did not know how to deal with errors; in these situations, they needed to ask others for help. P7 and P8 both reported using their mobile devices for phone calls similar to a landline, but rarely using it for other social purposes like texting or social media. Despite having similar reported uses of technology, P8 reported their comfortability using mobile devices as "somewhat uncomfortable". P9 who stated "I'm on my tablet all the time" also noted only using their device for news and to scroll social media rather communicating with others. The same user reported being very comfortable using it but only due to having accessibility features set in advance. P11, P3, and P6 all noted being very comfortable using mobile technology, and using it for texting and video calls. On staying connected and family at a distance, P3 noted "... if you were away you would just Facetime". P11 suggested they may be more comfortable than other older adults using mobile devices, stating "My career helped me pick things up fast". They also relayed the importance of learning social technology in their old age, saying "... once people learn to text that's what they do [to connect with others]...".

While most of the participants reported high comfortability using technology, most older adults have also adapted this use to fit their expectations of it. Before beginning the experiment, P8 commented "I'm not very tech savvy" despite later reporting using their mobile device daily to call their loved ones. In this instance, P8's comfort-

ability pertained to using mobile devices as a whole, and the participant admitted that they did not use many features beyond traditional phone calls. P7 noted similar use of their mobile device for calls only, but rated their comfortability as "very comfortable", pertaining to their specific use of the device rather than its whole set of features.

None of the participants reported any prior use of AR or VR but had varying degrees of familiarity with it through media and family. Most participants appreciated the novelty of a tangible system that interfaced with a mobile phone with comments like "it's neat" (P6) and "it's fun because it's interesting" (P7). P9 expressed curiosity for the system while playing a game with the tangible e-ink interface, asking "how do they know what card I have?" and "how does it get to the internet?". P9 was disinterested in the system overall but thought it could be enjoyable for a younger family member of theirs.

4.3.5 Discussion of Third Iteration Results

Compared to the first two iterations using the mobile AR system, the e-ink card system was found to be more usable and more enjoyable by the older adult participants. In addition, all participants were able to learn and perform the actions in the baseline condition and e-ink tangible condition to complete a game. Since the visual playing cards appear on the cards themselves and the actions are tracked by the NFC reader on the board, the e-ink tag provided more flexibility for managing and using the physical play space. Each participant had unique approaches to organizing the play space and performing the physical actions. Despite the reported increased usability, older adults still had challenges and frustrations using the tangible card system. The technology interface introduced additional steps to perform each action compared to a traditional card game and the baseline (e.g. framing a card in the

camera, or having to remove blank labels from the board). The requirements of the AR system for stable and consistent tracking proved to be a challenge, and increased the complexity of each action in the system. These challenges were reduced in the e-ink tangible condition, but the delay between actions and visual feedback introduced frustration. In a normal card game, there is no delay between performing actions and progressing the game. Technology is inherently limited by the speed of data connection, but reducing the delay in transferring data can better match the expected pace of a card game.

4.3.5.1 Design Requirements from Iteration 3

The accumulated results of the three experiment iterations provide insight into how technology with tangible interfaces might best be designed for older adults. Our results suggest that older adults are most comfortable using a technology when its behaviour is consistent with the real-world context. In our case, the tangible card system needs to meet the expectations of playing a card game in real life, including instant feedback after making a move, and quick back and forth play with another player.

For all three iterations, the added cognitive work of each interaction with the system – compared to a traditional game of playing cards – introduced challenges. The first two iterations failed to produce a usable prototype because each action (draw, discard) was complex and took multiple steps to perform. Interacting with the AR system required additional work to frame a QR code with a camera and track the cards on the tablet screen. Older adults found the actions in the e-ink condition easier to perform and less complex. Even though the e-ink condition was easier, some older adults still found it complicated because of the delay between performing an action and the interface visually updating.

Considering the limitation inherent in some technologies, like the AR system tracking and e-ink visual feedback delays, alternative designs can be introduced to mitigate such challenges. Many participants suggested their own ideas, like smaller cards or different device holders to mitigate the challenges in the AR system related to positioning the cards relative to the tablet's camera. For the e-ink visual delays, additional feedback can be introduced apart from the audio cues. Some participants suggested designs on the e-ink label hardware itself could help keep track of and organize the information on the cards. Others suggested different feedback forms, like an LED light, or haptic buzzing feedback. E-ink labels are limited in their capability since they are made for retail uses, but custom e-ink tangible pieces can be created to incorporate additional feedback.

Chapter 5

General Discussion and Conclusion

5.1 Discussion of Key Findings

5.1.1 How Older Adults Adapt and Learn Technology

The structured interviews provided a place for seniors to share their experiences with the system after having tried to play a game with it. Seniors often used this time to share their ideas on improving the system by making it more enjoyable or more usable. Many participants suggested an improvement for a feature or an interaction that they found challenging. In addition to direct comments from participants, observations of how the participants performed certain actions or strategized to play the game with the provided interface revealed how design choices aided or hindered the interaction. Interactions that took longer than expected in the tangible interfaces – like drawing a card and framing a card's AR code so that it would be correctly displayed – created frustration and confusion compared to the expectations of a traditional game of cards.

The added complexity and learning needed for each interaction in the AR conditions

detracted from the overall usability of the system. Some participants gave suggestions, like smaller cards, for making framing the cards easier. Other participants gave up and did not complete a game. The e-ink tangible condition had a comparable amount of physical movement required for each interaction, but reduced the complexity and cognitive work needed to complete those interactions. Participants adapted different strategies for organizing their space and performing the game actions. Unlike the AR condition, the game actions in the e-ink condition were simple and required little cognitive work to perform. This enabled older adults to use the interface in the way they expected; they could move the cards around easily, hold a single card comfortably, and remove their hand from the game while performing an action.

5.1.2 The Digital Literacy Debt

Although a recent survey claims 88 percent of Canadian seniors use mobile technologies [1], the extent to which they are comfortable using these devices varies significantly. Our results found that existing technology comfortability reflected how older adults personally used each device, whether for texting, video calls, scrolling social media, or only making phone calls. Following this, some people can report higher comfortability using a mobile phone but within the context of only using that cell phone for phone calls in a similar manner to a landline. Additionally, older adults may use these devices for social contexts within a limited context of how they expect socialization, like only talking over the phone instead of video calls.

Additional collected comments about each participants use of these devices reveal that high comfortability using a device does not imply high diversity in how they use that device. This can be seen clearly in the results from the AR-based system; most participants knew how to use the device to the extent of traditional interactions

like swiping, tapping, and navigating between screens. This comfortability using traditional interactions did not predict the same comfortability for mobile-enabled AR. Participants struggled to understand how to frame an AR code within the screen and maintain camera tracking of the code to fully visualize the AR effects. While participants may be comfortable making phone calls, texting, and video calls, their assessment of their own comfortability does not account for the full capabilities of each device (e.g., using the device camera or navigating unfamiliar interfaces). Across all of the evaluated systems, participants reported fascination or were surprised at how a complex system cleanly connected to a mobile format. These results indicate that many older adults had not considered this as a possibility when factoring in their comfortability. Participants, therefore, seemed to self report their comfortability with devices based on their own device usage.

These results are indicative of a digital literacy debt among older adults. Recent studies also highlight that older adults may become skilled in particular tasks while rarely interacting with or learning others [46]. Although it is known that older adults struggle to adapt to and pick up new technology like VR and personal computers [58], it also has implications for challenges and barriers in using technology that they consider themselves to be comfortable using. For this reason, mobile-based AR systems (at least with current limitations) may not be a suitable solution for social-connection technology aimed at older adults. Seniors own mobile devices, and use them for social media, video calls, and phone calls, but may not be comfortable using more advanced features that AR systems require without additional training and assistance. In our AR experiments, numerous participants could not play or complete the game due to not being able to consistently use the camera to track or frame an image, even with assistance from a board and device holder to capture the right image distance. Taking photos with a mobile device is a technology skill that younger adults may take for granted, and is not inherent in mobile technology

use, particularly for older adults. While this is clearly a limitation of the technology as it was presented to our participants, it is also indicative of digital literacy debt, requiring significant training and motivated learning from an older adult to use mobile devices in more complicated contexts (that exposes technical limitations) than they are familiar with. If technical limitations can not be completely removed from a system, additional training and instruction for using the technology (and managing the technical challenges) may be able to reduce the barrier.

5.1.3 Social Technology for Seniors

Designing technology for seniors requires careful consideration, as it is noted that many technology-adverse seniors would require an in-person introduction to a new, more-complex technology before using it for the first time. By using the experiment system in a non-remote context, despite enabling and emphasizing remote play by obscuring the information, seniors may feel more comfortable using and accepting the technology. This is not indicative of the acceptance of the technology in a remote context – although the system is not limited to a remote context. However, comments about others that would benefit from the technology – who like playing cards but have poor eyesight, or could benefit from the reduced cognitive load from the simplistic interface – indicate that seniors might value tangible technology in social contexts. These is important feedback since our systems were not evaluated in the remote and social scenarios that motivated their creation in the first place. Future work, should explore the use of technology like ours, once the technology is able to provide enough robustness and reliability that can make them sufficiently usable for use by older adults.

5.1.4 Diversity in the Senior Demographic

Previous work highlights the diverse experiences in relation to technology use and adoption present in the older adult demographic [58]. Some seniors use smartphone technology daily to enhance their lives, while others struggle with basic digital literacy, or complex conditions that make using these interfaces difficult. Although a large majority of participants reported daily smartphone use, the degree to which they use these technologies for socialization still varies. Older adults who are less comfortable using modern technology are inherently more vulnerable to social isolation due to the physical isolation from contacts that comes with aging, and they may struggle to effectively use these technologies to reduce that gap. Those who struggle to keep up with their existing devices capabilities due to a digital literacy debt are also at risk, as they may be reported as more technologically savvy despite finding challenges in effectively using some of the capabilities that their devices allow.

Designing technology aimed at older adults necessitates keeping this diversity in mind. Older adults that are more comfortable with using technology do not want a simpler system that doesn't embody their full capacity. The results from the third iteration reveal that some of the participants who most often used mobile technology still prefer a digital system over a tangible usable system due to their existing capabilities and familiarity for these systems. For some participants, the tangible interface introduced complexity and physical movement that was inconvenient compared to a familiar digital interface that they already knew and found easy to use. Some older adults already approached a digital interface as a significant learning barrier, and preferred the tangible solution as a more hands-on technology after learning how to use it. There was no unanimous agreement on which interface was preferred. Some participants would not consider using a digital-only social card game compared to a tangible one, and others would not consider using a tangible system compared to a

more familiar digital one.

Given the digital literacy debt, each older adult has their own skills and capabilities for learning and using technology. Older adults have different physical capabilities and challenges using technologies, like reduced grip strength which could affect how technology is held or reduced dexterity making precisely touching small screens difficult [12]. 3 of 8 of the third iteration (i.e., the e-ink tag) participants commented on their challenges using a traditional mobile device. On the other hand, some participants who did not report physical decline that impacted usage, simply preferred the digital interface for its simplicity. For these participants, it was within their capability and comfort to effectively use a digital interface. Even so, most participants commented on the suitability of the tangible interface's hand-held pieces and low-digital skill requirement for others who they know may struggle to use a traditional mobile interface. To design technology aimed at this broad demographic, a single pre-determined interface may not be suitable or applicable to each person. Doering et al. proposes a design approach where tangible input interfaces can be interchanged and connected to a central system [15], and this seems to align with our results. Notably, Doering et al.'s findings are limited to tangible interfaces and does not consider interchanging tangible and non-tangible interfaces like our tangible card system. Interfaces that can be interchanged and used to each persons' preference may be the most effective way to reach this demographic (and beyond). Mobile interfaces already offer a variety of accessibility features, but the ability to interchange the traditional interface for a tangible one may be able to increase the accessibility of existing technologies.

5.2 Limitations

Many studies with older adult populations suffer from the same limitations of limited demographics and limited diversity in the participant population. To alleviate this, we set a broad participant criteria of being over 65 or younger than 65 but living in a senior community setting. Factors like chronic health conditions, social class, and private demographic information were not collected from the participants and are unknown. Similarly, all participants had to be of sound mind to sign the consent form, so no participants with significant cognitive impairment – which is more prevalent among seniors due to dementia, Alzheimer's, and other forms of cognitive decline – were included. There is also an inherent bias in recruiting research participants for technology in this demographic. Older adults who are uncomfortable or disinterested in technology may be less likely to participate in research, and their feedback and sentiments on improving social technology remains understudied. Participating in this research and responding to recruitment indicates that these older adults are already motivated to learn and understand technology. These results should serve as a preliminary scope into designing for the overall senior demographic. If technology with a tangible interface can be made more usable or enjoyable for older adults already willing to use or learn such a technology, progress can be made for reaching more diverse older adult participants.

The tangible interface was designed to enable a remote social connection, but the impact of tangible technology on the social experience of the system was not studied. While it is known that games and tangible technologies can provide a social benefit [56, 18, 40], the acceptability of our studied technology in a remote social context was not evaluated by this experiment. Additional surveys like the Social Presence in Gaming Questionnaire [13] will accompany future work to evaluate how tangible technology is experienced in a social context.

5.3 Future Work

Tangible user interfaces for seniors have found success in physical, and cognitive domains, and their prevalence for social wellbeing is slowly increasing. The complex relationship between social, cognitive and physical wellbeing in seniors provides an important-but-complicated area for designing technology to mitigate the risks of aging. Social wellbeing is associated with increased physical and cognitive health, so future work on tangible interfaces should look at the multiple facets of health outcomes when designing technology. For example, the experiment used a simple card game, Crazy Eights, but the system could work with many other card games. Our results suggest technology with the goal of supporting seniors wellbeing must be adaptable to each senior's expectations and usability needs. A centralized system with interchangeable tangible connection points [15] can be adapted to the needs of a particular senior to target their specific capabilities. Future work can look at combining work in cognitive, physical, and social tangible user interfaces to provide a multi-faceted approach to seniors' wellbeing.

The rise of social isolation in this population indicates that traditional strategies like phone or internet outreach [16] may not be a sufficient solution. Coupled with the lack of digital literacy in the demographic [51], seniors continue to struggle to adapt and uptake modern technologies. Future work should look at expanding technologies beyond a single interface and look at adaptable interfaces that can be fine-tuned, or interchanged to meet the needs and preference of diverse users.

Being playable across platforms ('cross platform') is a common feature of many video games [47], and is commonly used for younger adults to stay socially connected and for entertainment regardless of the system they use [57]. Cross platform gaming includes connecting different hardware systems and different input modalities to a common central software system [47]. Console systems and desktop systems used

for cross-play video gaming can enable flexible hardware systems with unique input capabilities. Gamers can play the same game while using a completely different input modality, from game controllers to a traditional desktop and keyboard, to customizable input methods. While older adults can be slower to uptake video games and modern gaming systems [7], the theme of adaptable interfaces and interactions offer a promising solution to designing technology for older adults.

Many older adults already unknowingly engage in a form of cross platform technology outside of video games by using their preferred devices to make phone calls and connect to social media where the other users may be using an entirely different device to connect. Accessibility features within preferred devices are already used to some extent to enable older adults to engage with technology that may otherwise be challenging due to low vision, being hard of hearing, or any other decline that may accompany aging. When a tablet device is already a challenge to use despite these features, additional interfaces to engage with the technology may be of more benefit. Smart home solutions are a common area explored with older adults due to this particular suitability [35]. Technology with tangible interfaces created for older adults should prioritize accessibility through flexible interfaces to a central system [15]. With this, older adults can select their own preferred methods that reduce barriers in accessing, using, and maintaining social connections via technology. Future research should also consider the long-term uptake and adoption of tangibly-enabled technologies to further evaluate the acceptability of tangible interfaces for social connectivity.

5.4 Conclusion

We followed a user-centred design process that included three iterations of a card game system to better understand how augmented reality and tangible interfaces could impact the acceptability of social technology. We interviewed eleven older adults and collected data as they played games with the various conditions. Our first two iterations used a mobile-enabled AR tangible interface, but found consistent challenges and limitations in deploying AR tangible interfaces. While the technological limitations of the mobile-enabled AR interface was not suitable for many participants, our third iteration explored whether removing the barrier of a mobile device could mitigate these challenges by adapting an e-ink tag card game interface. The e-ink tangible interface still differed from the expectations of a traditional card game, but was found to be dramatically more usable than the AR-enabled interface. Older adults were easily able to learn and use the tangible e-ink system, and they were motivated by the idea of a tangible social game that could be played at a distance with friends and family.

Our results demonstrate a successful adaptation of a tangible interface for older adults. Since older adults tend to require more time to learn new technologies and often rely on an in-person instruction [4, 2], the preliminary success in learning and enjoying the use of a technology with a tangible interface is a good indicator for potential continued use. Designing tangible interfaces for seniors requires making simple tangible interactions and minimizing complicated interactions with the technology itself. In addition, older adults have a diverse experience level and capabilities, and no single technological interface may be applicable to all older adults. Technology for social connections and remote play can benefit from interchangeable interfaces and adjustable feedback settings to meet a variety of skill levels, preferences, and needs.

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Appendix A

Questionnaires

A.1 Technology Familiarity Assessment

Owned Devices

Cell Phone	House Phone	Computer	Tablet	Virtual Reality

How often do you connect with loved ones using technology?

Once a day	Once every couple of days	Once a week	Occasionally	Rarely

How often do you use these devices?

Device	**Mult. times a day**	**Once a day**	**Once every couple of days**	**Once a week**	**Once a month**	**Once a year**	**Never**
Cell Phone	☐	☐	☐	☐	☐	☐	☐
House Phone	☐	☐	☐	☐	☐	☐	☐
Computer	☐	☐	☐	☐	☐	☐	☐
Tablet	☐	☐	☐	☐	☐	☐	☐
Virtual Reality	☐	☐	☐	☐	☐	☐	☐

Table A.1: Frequency of Device Use

How comfortable are you using each of these devices?

Device	**Very comfortable**	**Somewhat comfortable**	**Neither comfortable nor uncomfortable**	**Somewhat uncomfortable**	**Very uncomfortable**
Home Phone	☐	☐	☐	☐	☐
Cell Phone	☐	☐	☐	☐	☐
Computer	☐	☐	☐	☐	☐
Tablet	☐	☐	☐	☐	☐
Virtual Reality	☐	☐	☐	☐	☐

Table A.2: Technology Comfortability by Device

Listed Difficulties:

A.2 Guiding Interview Questions (Iterations 1 & 2 - AR Interface)

Q1. How do you most often keep in touch or in contact with others?

Q2. Which of the 2 games did you prefer?

Q3. How does interacting with the game feel?

Q4. What were some challenges you found during playing the games?

Q5. Was there anything that was confusing initially but that you figured out before finishing the game?

Q6. Is there anything that was confusing about the game, interaction, or system that you still are unsure about?

Q7. How does the game feel compared to a traditional game of cards?

Q8. What are some ways you would recommend improving the system?

A.3 Guiding Interview Questions (Iteration 3 - E-Ink Interface)

A.3.1 Adapted PXI and SUS fpr Player Experience

Did you like playing the game?

Do you think that you would play this game in the future?

Do you think that you are good at playing the game?

Do you feel like you could win the game?

Did you understand what to do to play this game like you would a normal card game?

Were you able to focus on the game as if you were playing a regular game?

What are the ways this game felt different than a normal card game?

Would you be interested in playing a complete card game like this with friends or family?

If yes, who do you think you would play this game with?

A.3.2 Co-design Focused Questions

Q1. How do you most often keep in touch or in contact with others?

Q2. Which of the games did you prefer?

Q3. How does interacting with the game feel?

Q4. What were some challenges you found during playing the games?

Q5. Was there anything that was confusing initially but that you figured out before finishing the game?

Q6. Is there anything that was confusing about the game, interaction, or system that you still are unsure about?

Q7. How does the game feel compared to a traditional game of cards?

Q8. What are some ways you would recommend improving the system?

Glossary

Tangible Interface: A technology interface that employs physical objects as input and/or output to interact with digital information or systems

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