An Iterative Participatory Design Approach to Develop Collaborative Augmented Reality Activities for Older Adults in Long-Term Care Facilities

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ABSTRACT

Over four million older adults living in long-term care (LTC) communities experience loneliness, adversely impacting their health. Increased contact with friends and family is an evidence-based intervention to reduce loneliness, but in-person visits are not always possible. Augmented Reality (AR)-based telepresence activities can offer viable alternatives with increased immersion and presence compared to video calls. However, its feasibility as an interaction technology for older adults is not known. In this paper, we detail the design of two dyadic collaborative AR activities that accommodate diminished physical and cognitive abilities of older adults. The findings include a general design framework based on an iterative participatory design focusing on preferred activities, modes of interaction, and overall AR experience of eight older adults, two family members, and five LTC staff. Results demonstrate the potential of collaborative AR as an effective means of interaction for older adults with their family, if designed to cater to their needs.

CCS CONCEPTS

• **Human-centered computing** → **Empirical studies in interaction design**; **Mixed / augmented reality**; **Collaborative interaction**.

KEYWORDS

collaborative augmented reality, long term care settings, iterative participatory design, older adults, accessibility

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1 INTRODUCTION

The older adult population is steadily increasing and projected to comprise 21% of the population of the United States by 2030 [110]. As people are living longer, there is a growing need for care during the later years of one's life, with a substantial portion of this care expected to occur in long-term care (LTC) settings[111]. As of 2018, the United States had over 28,000 LTC communities, housing 5.7 million older adult residents and the demand for LTC communities is expected to surge [60]. Despite the evident need for these care settings, individuals in LTCs confront a myriad of challenges, chief among them being the issue of loneliness [27, 97]. Separation from friends and family, compounded by factors such as the socially restrictive COVID-19 safety protocols, has further exacerbated this concern [30, 39, 48, 53]. Loneliness among older adults increases healthcare utilization and premature death, as it precipitates a multitude of adverse health effects, including cardiovascular diseases, depression, suicide, and cognitive as well as physical decline [2]. In 2023, the US Surgeon General's Advisory called attention to this urgent public health issue with recommendations for addressing loneliness through multiple avenues, one of which is use of technology to strengthen social connections [16]. Social connection, defined as the structure, function, and quality of our relationships with others, is a fundamental human need and critical determinant of health [16, 55]

Improving the quality and function of social connections can alleviate loneliness and improve well being [84, 87, 89]. In non-LTC communities, such as independent living communities or living with family, social connectedness is often established through face-to-face communication and physical interactions [38, 102]. Unfortunately, older adults in LTCs are not always afforded the luxury of physical interactions with the important people in their lives, leading to a lack of quality relationships in social connections.

Recent technological advancements have prompted the examination of interactive communication technologies (ICTs) as potential strategies to enhance social connection among LTC residents. However, current ICTs, such as internet-based platforms and 2D audio-video applications, have demonstrated mixed results in their effectiveness [1, 2, 64, 71, 73]. Notably, these technologies often lack integral elements of in-person interactions, falling particularly short in promoting social presence, a key component of social connectedness. Social presence theory refers to the perception, behavior, or attitudes that reflect the physical presence of others within the ICT environment [65]. The effectiveness of an ICT for social connectedness is largely dependent on its social presence [26, 65, 82] which is significantly enhanced by communication of nonverbal behavior [24, 82] and shared activities [29, 31, 42, 46]. As social presence increases, so does social connectedness. Consequently, the need for innovative, more effective ICTs is clear, and our work aims to help address this gap.

1.1 The Potential of Augmented Reality ICTs

Building on the need for improved social presence within ICTs, we propose collaborative Augmented Reality (AR) between two individuals to enhance social connection. AR is an innovative technology that overlays digital information, such as visuals and spatially driven sound onto the user's real-world environment. This overlay can be accomplished through various types of AR, including mobile devices, projections, and head-mounted displays (HMDs) [36, 68, 81]. For the purposes of this study, we focused on HMDs due to their immersive characteristics, which increase the potential to create an enhanced sense of social presence. Current HMD devices are becoming increasingly accessible with a range of options available on the market. Moreover, the contemporary software development frameworks provided by the makers of HMDs enable the relatively simple creation of custom applications, further bolstering the feasibility of HMD-based AR (HMD-AR) interventions.

HMD-AR facilitates high quality verbal and nonverbal communication, as well as meaningful and purposeful activities– factors shown to significantly impact social presence [55, 109]. One method through which HMD-AR enhances social presence is by generating 3D, life-sized, photorealistic avatars, capable of displaying a wealth of nonverbal behaviors [82] (Fig. 1). In addition, HMD-AR allows for the placement of 3D objects within a user's own environment, which when combined with networking capabilities, enables the partaking of shared activities between two individuals that strongly enhances social presence within ICTs [26, 28, 31, 33, 42]. This shared interaction can mimic the dynamics of in-person interactions [33], adding another layer to the quality of social connectedness.

As compared to other forms of ICT connections, such as 2D audio-video applications, we postulate that collaborative HMD-AR can better simulate elements of an actual visit for the older adult. However, it is worth noting that HMD-AR use has been vastly understudied in the context of older adults who reside in LTC settings– a population with significant physical and cognitive impairments. Therefore, to evaluate the potential of this technology, it is crucial to systematically develop collaborative HMD-AR activities with these end users in mind.

1.2 Research Questions and Approach

Currently, there is a dearth of information regarding HMD-AR interactions specifically designed for LTC older adults. For HMD-AR technology to be successfully implemented in LTCs, it must be adapted to the needs of the older adults with ease of interaction. To our knowledge, there is no existing literature addressing either potential issues that may arise during implementation or exploring older adults' perceptions and acceptance of HMD-AR activities. Thus, as part of a larger study to utilize collaborative HMD-AR to reduce loneliness and improve well-being among LTC older adults, our initial step was to **a) establish collaborative HMD-AR activities acceptable to older adults residing at LTCs** and **b) identify challenges in the use of HMD-AR with this population**. Given the range of physical and cognitive impairments in this population, involving older adults from LTCs in the development of collaborative HMD-AR activities is necessary to enhance the functionality, usability, and likelihood in promoting the intended health outcome [88]. It is also essential to involve other major stakeholders in this development, i.e., the family members and LTC staff. Hence, we utilized an Iterative Participatory Design (IPD) methodology. Participatory Design (PD) is a collaborative approach that actively involves stakeholders in the design process of an intervention [67]. It has been increasingly recognized as an effective solution to developing novel interventions [96, 100]. IPD builds upon the principles of PD, acknowledging that not all issues are known beforehand and are gradually discovered through stakeholder participation via observed performance and interviews [99]. The stakeholders involved often have valuable insights drawn from their experiences, which can aid in identifying and resolving issues [41, 69, 91, 114]. **By implementing multiple design-implement-feedback cycles, IPD provides an iterative approach that allows for the uncovering of major challenges and convergence on an effective design. This methodology offers promise for the development of AR interventions that cater specifically to the needs of older adults in LTCs.** To address gaps in knowledge and facilitate future work with this vulnerable population, we present our experiences, along with those of key stakeholders, in developing HMD-AR collaborative activities through an IPD approach. We characterize the challenges encountered in developing the HMD-AR system and collaborative activities and provide strategies for overcoming these challenges.

1.3 Contributions

This paper provides the following contributions to the development of HMD-AR ICTs for older adults:

- Iterative participatory design that incorporates feedback from older adults with varying cognitive and physical abilities, their family members, and LTC staff to address acceptability, usability, and feasibility.

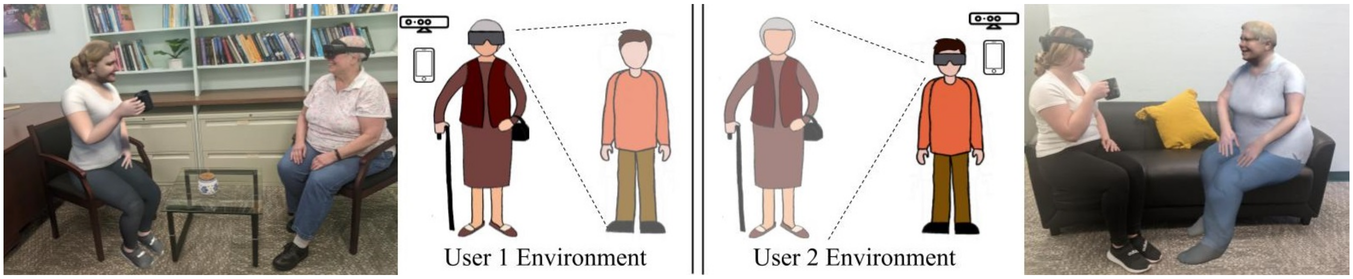


Figure 1: Collaborative AR enables users in different environments to interact with one another. Users' body gestures and facial expressions can be captured using color depth cameras and then relayed onto their remote avatars (middle). An example is illustrated, where an older adult, seated on a chair can view her granddaughter's photorealistic avatar in her environment through her HMD (left), and vice versa (right). In this study, the researchers played the role of User 2 to understand the issues that older adults and family members face when interacting with collaborative AR. Possible solutions to the encountered issues are presented, considering the inputs of all stakeholders: older adults, family members, and LTC staff. All photos are used with permission.

- Valuable insight into the classes of collaborative AR activities that older adults, particularly those residing in LTCs, can enjoy and partake in.
- Identification of the types of HMD-AR interactions that are most usable for older adults.
- Design considerations for the user interface of AR applications.
- Identification of other barriers while implementing HMD-AR interventions for older adults in LTCs.

2 RELATED WORKS

In this section, we present the literature on the use of collaborative AR for promoting social connectedness in different demographics, evidence of the potential of using HMD-AR technology with older adults, and its viability in replacing existing ICTs to promote social connectedness and mitigate loneliness in older adults. Lastly, this section will review the importance of co-creation and participatory design for putting together a collaborative AR system that can foster social connectedness.

2.1 AR for Social Connectedness

Several studies have been conducted with different demographics to test the effectiveness of AR-based applications to foster social connectedness. Mittmann et al. [78] developed a smartphone-based AR application that allowed adolescents to work together on a mystery in a classroom environment. Their application showed an increase in the sense of belonging and peer connectedness amongst students. Knoll et al. [62] developed a co-located escape room in an AR environment and tested it with four pairs of young adults. From a qualitative analysis of semi-structured interviews, they showed that the participants felt socially connected to their partners through the experience. However, both the aforementioned works were limited to participants who were physically present in the same room.

Modern AR technology has given rise to the exploration of AR-based applications to promote social connectedness in older adults – a group that is particularly susceptible to loneliness. Tsao et al. [104] developed a system that combined mobile AR with HMD-VR for reminiscence therapy – a prominent intervention to reduce loneliness in older adults [32]. The mobile-AR application allowed participants to select a reminiscence scenario that they wanted to see through the VR-headset. Although the system was tested with older adults, insufficient data was presented by the authors to arrive at any conclusive results. Saracchini et al. [93] developed a web-based application that connected older adults with their caregivers by allowing a remote caregiver to upload media onto an AR-mobile device or an AR-headset. This media included videos, photos, schedules, and messages. The purpose was to allow older adults in the LTC to stay connected with their caregivers through AR even if they had little technological expertise. Their validation study showed that the system was well accepted by older adults and their caregivers to stay connected with each other. However, the application was unable to foster live face-to-face interaction between older adults and their family members—something that can allow for increased social presence.

2.2 Collaborative AR

While attempts to use AR for social facilitation have shown promise, AR technology still has potential to further improve remote interaction. This is because of the high immersion and social presence that HMD-AR can offer. HMD-AR can register virtual elements, such as a photorealistic avatar of a remote family member and virtual objects for games or activities. Studies have shown that interacting with a virtual avatar of another person through AR provides a more emotionally rich experience than a video call with a mobile device [68]. Microsoft developed a *Holoportation* system that allowed such an interaction between two users and validated its feasibility as a mode of communication [83]. However, *Holoportation* was limited to viewing and verbally interacting with the remote avatar and lacked shared interaction with a synchronized virtual environment between the participants. Piumsomboon et al. [90] developed an adaptive avatar that represented a user's eye gaze direction and body gestures and could be registered in a remote environment where both the avatar and the remote user could interact with a shared virtual environment. The study conducted with the adaptive avatar showed an increase in social presence and an improvement in the overall experience of collaborating through Mixed Reality. However, these avatars were solely designed for collaboration and lacked features that are essential for social connectedness, i.e., the avatars were not photorealistic and lacked facial expressions. To our knowledge, no AR-based telepresence system exists to foster social connectedness between older adults residing in LTCs and their family members.

Since the realism and immersion of AR-based telepresence systems rely on the local user's perception of the remote user's avatar, it is crucial that older adults accept the photorealistic avatars. Cyarto et al. [40] conducted a study with older adults in which they were required to view virtual avatars of their peers and an instructor during a virtual exercise class. The body and facial movement of the peers were mapped to their respective avatars. The qualitative analysis of the study showed older adults' acceptance of the avatars. Since the avatars represented strangers and were not photorealistic, the degree of social connectedness of the participants with the avatars is not known. Hence, there is a gap in addressing older adults' perception of photorealistic avatars of someone they have seen in person.

2.3 HMD-AR's Acceptability, Feasibility, and Adaptability for Older Adults

Older adults may be hesitant to accept new technology, such as AR, if it is too complex or unable to accommodate their physical and cognitive disabilities [37, 113]. Most of the AR-based systems tested with older adults limited participation to those without cognitive impairments or mild cognitive impairments, excluding a large group of older adults who reside in LTCs [101]. Thus, the adaptability and acceptance of an AR system to the needs of older adults with cognitive and physical disabilities is yet to be explored.

Another important factor affecting the acceptance of AR technology is its level of engagement and how well it aligns with the interests of the users. Because older adults prefer connection with family members, the latter should also be included in the co-design of interactive AR systems [31, 54, 112]. Participatory design is an effective technique for garnering feedback from key stakeholders in developing new products [37, 94]. However, few AR technologies developed for older adults have included the older adults in the design phase. For example, Tsao et al. [104], Sarrachini et al. [93], and Cyarto et al. [40] evaluated their design system through qualitative analysis and discussed feedback and suggestions from the older adults for future work, the AR design itself did not include the target participants. One study [45] used an iterative participatory design approach in the development of a virtual reality based exergame for older adults. Based on the feedback from iterative rounds of testing, they designed a VR-based application that was accepted and enjoyed by the older adults. They were also able to identify design recommendations for building HMD-VR based games for those older with mild cognitive impairment.

In summary, there is a limited amount of research involving older adults with modern collaborative HMD-AR. Moreover, there is a dearth of knowledge for how to properly design AR technologies for older adults and factors impacting older adults' acceptance. Thus, there is a critical need to further explore the acceptability, adaptability, and feasibility of AR environments and activities for older adult users. The work and conclusions presented in the following sections provide design guidelines and considerations that will aid in the creation of future AR applications and research studies targeting this demographic population.

3 METHODS

We implemented a multi-step, iterative participatory design (IPD) process over a period of six months to design and evaluate collaborative HMD-AR activities that accommodate the physical and cognitive capabilities of older adults living in LTCs. Older adult users, their family members, and LTC staff participated in this IPD process. Several factors pertaining to HMD-AR interaction were considered: (1) older adults' ability to tolerate HMD-AR for up to 30 minutes without experiencing adverse effects, such as dizziness or headaches; (2) preferences for HMD-AR activities, and (3) older adults' ability to navigate the HMD-AR environment and manipulate AR objects.

3.1 Participant Eligibility and Recruitment

All IPD activities took place at a not-for-profit LTC community that provides rehabilitation and long-term care to residents. Eligibility criteria for older adults included those who were residing at the LTC for at least three months. Exclusion criteria encompassed older adults who were unable to provide consent, were unable to understand or speak English, or had an acute illness/were terminally ill. Any family members who were 18 years or older and willing to participate in the activities were considered eligible. For staff members, the eligibility criteria included those who had experience in planning or providing activities to the older adults at an LTC. Approval for this study was obtained from the Institutional Review Board of the research team. The procedures used in this study adhere to the tenets of the Declaration of Helsinki [51] and regulations of the Institutional Review Board. Participants were recruited largely through flyers and word of mouth at the LTC. Written informed consent, including media release permission was obtained from all participants prior to the study. To protect older adult participants' autonomy, we first determined decisional capacity for consent using the University of San Diego Brief Protection of Human Subjects Capacity to Consent [23]. If an individual scored 14.5 or less on the University of San Diego Brief Protection of Human Subjects Capacity to Consent Test, surrogate (family member) consent as well as participant assent was acquired. A basic script, written at a 6-grade level describing the purpose of the study, was read twice to older participants in the presence of the legal surrogate (family member) and all questions they had were addressed. Reading the script allowed for assent and objection; the principle of assent and objection recognizes that an individual without capacity may understand the elements of a research study and they can verbally or behaviorally decline participation [58, 76, 85].

Baseline data was collected on demographic characteristics, cognitive function, and physical function. The Self-Administered Gerocognitive Exam (SAGE) was used to assess cognition [95]. The SAGE has a maximum score of 22, with a score above 17 indicating no cognitive impairment, scores between 15-16 indicating mild

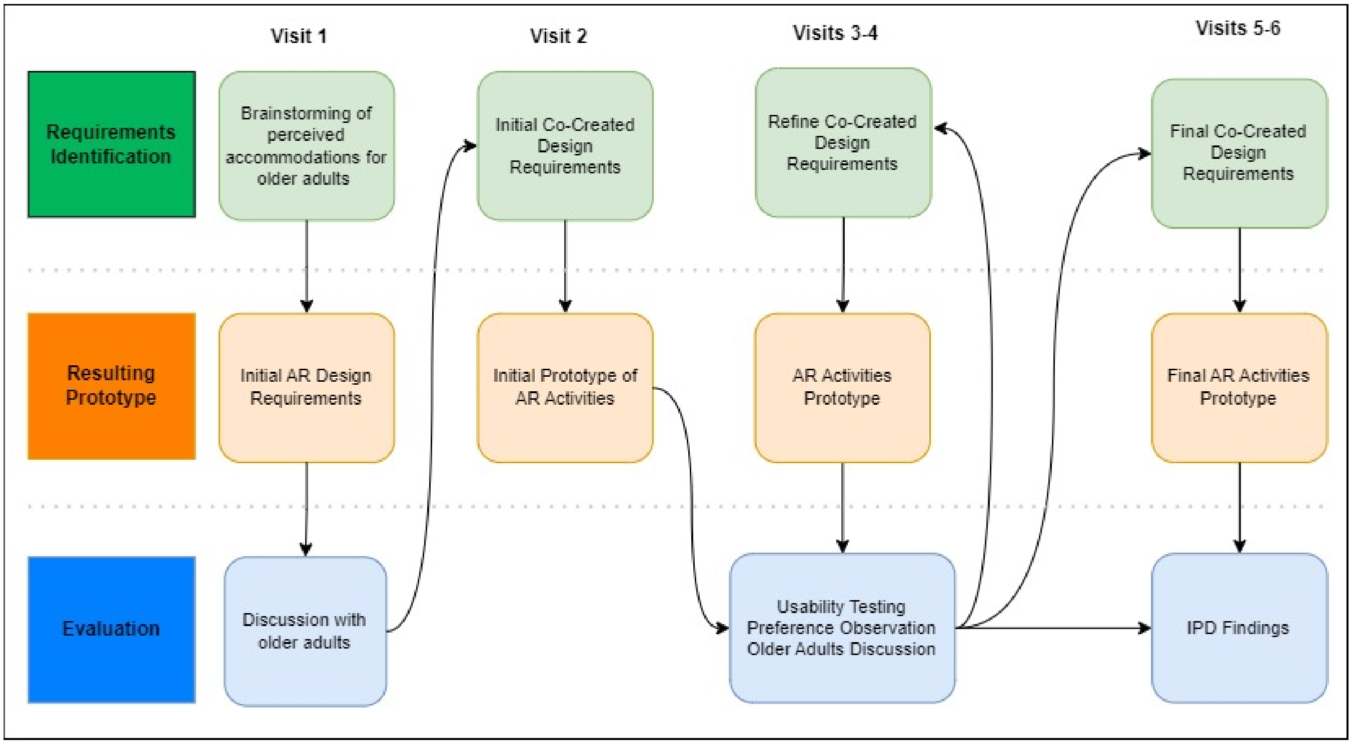


Figure 2: The figure depicts a flowchart of the iterative participatory design (IPD) process followed in the study. Visit 1 entailed exposing older adults to collaborative AR and soliciting input on activity preferences using the technology. Visits 2-4 involved prototyping the suggested activities and iteratively identifying issues, and incorporating stakeholder inputs to devise solutions. Visits 5-6 involved testing the proposed solutions with the older adults and gathering their feedback.

memory and thinking impairments and scores below 15 indicating more significant memory and thinking impairments. Physical capabilities were identified using a checklist adapted from the Occupational Therapy Practice Framework[21]. All participants received a compensation of $25 per visit.

3.2 IPD Study Design

We conducted the IPD in sequential visits (Fig. 2). The initial visit solicited participants' preferred activities and began discussion on AR usability and acceptance. Visits 2-6 focused on iterative prototype development of select collaborative HMD-AR activities chosen from ideas generated during the first visit. At each visit, participants interacted with the HMD-AR activities and feedback was garnered through observations and interviews to continue to refine the AR specific modes of interaction, game/activity logic, and user interface elements.

3.2.1 Determination of preferred HMD-AR activities from stakeholders. Our interdisciplinary team was comprised of experts from multiple disciplines: engineers specializing in AR and human computer interaction (HCI); doctorally prepared nurses in gerontological nursing; a physician neurologist specializing in dementia; and a doctorally prepared occupational therapist specializing in geriatrics. Our collective expertise and existing literature served as the starting point for identifying potential collaborative HMD-AR activities to introduce to participants at the first brainstorming visit.

During the brainstorming session (Fig. 3 (a)), participants were introduced to HMD-AR technology, specifically the Microsoft HoloLens 2 (HL2) device [8], and the potential collaborative activities that could be undertaken with it. Each participant was given the opportunity to experience the AR environment through it. First, they viewed a sample hologram of a virtual flying bird that could follow their hands (Fig. 3 (b) and (c)). Next, we presented a sample AR activity involving an avatar created using a mobile volumetric scanning application, In3D [12] (Fig. 3 (d)). The research personnel, via this avatar sitting across the participant, engaged in a conversation with them and guided them through the visual aspects of the augmented environment. After the demonstration, the older adults were asked to imagine their friends or family members sitting across from them, represented by avatars, and inquired about the types of collaborative activities they would like to perform. Family members and LTC staff were also shown the same AR scenario and asked about the activities that older adults and their family members might enjoy.

3.2.2 HMD-AR system. We decided to use HL2 because it is a state-of-the-art standalone HMD with built-in hand tracking that allows

(a) (b) (c) (d)

Figure 3: Snippets of the initial visit to the long term care (LTC) community. (a) Introductory brainstorming sessions with the research personnel and the participants. (b) A staff participant wearing the HMD and interacting with a virtual bird through her hand using the HoloLens 2. (c) First person view of the bird interaction. The collaborative AR setup (d) consisting of the research personnel's avatar seated, with facial and body gestures mapped, shown to participants to elicit ideas of activities they would like to engage in with their family members.

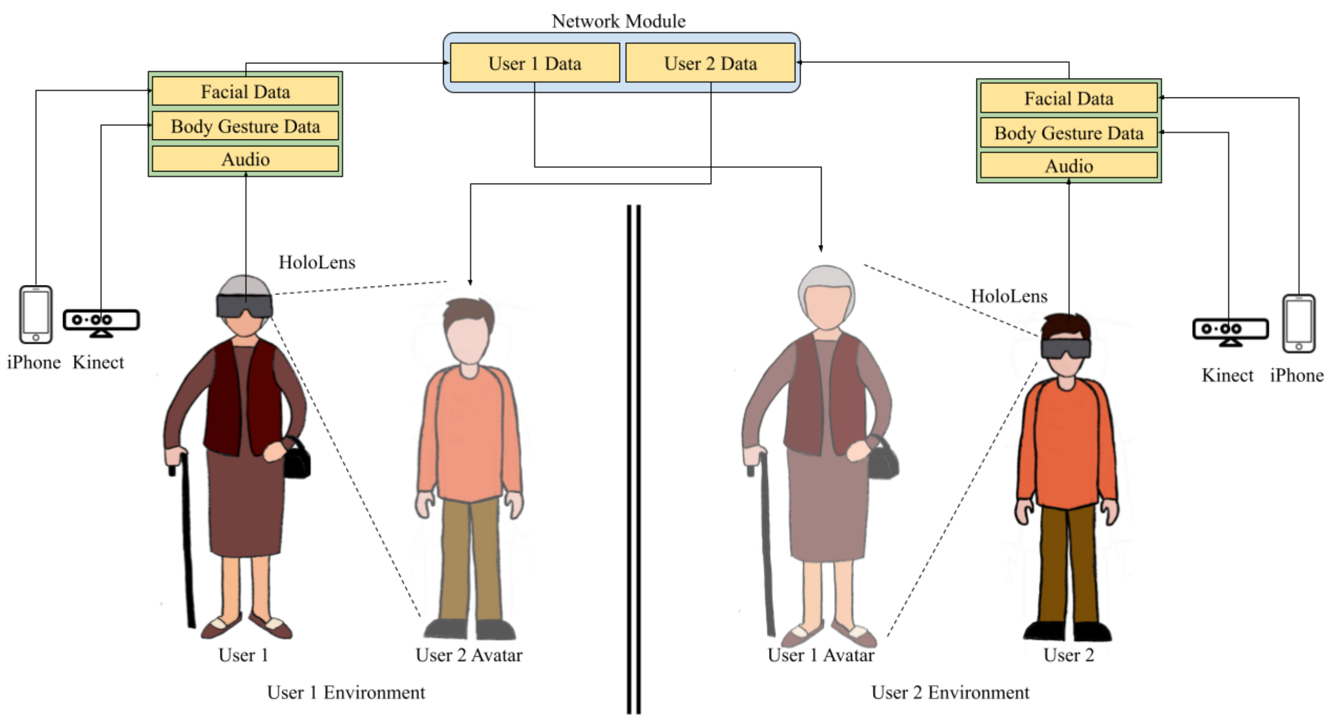


Figure 4: Architecture of the collaborative AR system used in the study. Each user viewed the remote user's avatar and interacted with the AR environment using Hololens 2. A Kinect color depth camera and an IPhone tracked each user's body gestures and facial expressions respectively and relayed them across the network to their respective avatars.

users to use their hands for interaction within an augmented environment. We created an AR scenario simulating two users in geographically separate locations both viewing and interacting in a common augmented environment as shown in Fig. 4. Using this scenario, research personnel played the role of a remote visitor interacting with the participant. The setup involved the research personnel wearing the HMD, with their facial expressions and gestures captured by an Azure Kinect [4] and the front camera of an iPhone 13 [13], respectively. The obtained facial and body gestures were mapped onto a photorealistic avatar, which the participants could observe through their own HMD. On the participants' side, a similar setup was used to record their gestures and facial expressions. The research personnel could observe the participants' gestures and facial expressions through a standard, non-custom avatar. Bidirectional audio communication was available using the microphone and speaker of the HL2.

(a) (b)

Figure 5: Standard near interactions associated with the HoloLens 2 (HL2). The interactions are performed using various hand gestures. (a) Tap interaction, where the user uses their index finger to tap on menu items to select them. (b) Pinch interaction involves the user using their index and thumb to perform a pinch movement to manipulate nearby objects.

3.2.3 Early Prototype Design. In HMD-AR, i) the graphical interface and ii) the manipulation of virtual objects are the two main elements of interaction. The manipulation of objects can be further divided into a) near object manipulation and b) far object manipulation.

For the graphical interface, the initial design was based on established principles for user interfaces for older adults [59]. This included menu items that were uniformly well spaced and at the center of the field of view (FOV) of the HMD [52]. For interacting with the menus in HMD-AR, we chose a standard tap interaction as shown in Fig. 5 (a), as most older adults are familiar with this commonly used mode of interaction for tablets and smartphones. There are no precedents or established guidelines for the use of free hand interaction for older adults using HMD-AR. Therefore, for this first design, we followed the standard methods of interaction established by Microsoft [11], which have been tested and optimized for the comfort of the general population. For near interaction, this included a pinch gesture to grab an object (see Fig. 5 (b)), while far object interaction involved first pointing at an object and then performing the pinching gesture as shown in Fig. 6.

3.2.4 Iterative Testing and Evaluation. Five successive rounds of field testing were conducted at an LTC setting using the intended deployment setup to enhance discovery of potential challenges. Each field test and evaluation resulted in looping back to earlier stages of prototype development, redefining requirements, and adding improvements to the HMD-AR activity. These design iterations continued until users and researchers deemed the collaborative HMD-AR activities and derived design requirements to be satisfactory. We were also interested in the tolerability and learnability of the system to ensure that the older adults felt comfortable throughout the interaction and were able to adopt the system easily. This information was obtained during discussions with and observations of participants while undertaking the HMD-AR scenarios.

4 FINDINGS

In this section, we present participant profiles along with the findings of the IPD aimed at developing collaborative AR activities tailored for older adults in LTCs. The summary of findings for each visit is depicted in Fig. 7. The study spanned six visits over six months, during which the IPD involved gathering stakeholder perceptions on five broad topics:

4.0.1 Preferred activities using collaborative AR:. This involved identifying the collaborative AR activities preferred by older adults when engaging with their family members. Their preferences were gathered during the first visit. Two of the most favored activities, namely *Checkers* and *fireplace decoration*, were prototyped for subsequent visits, as illustrated in Fig 7.

4.0.2 Perceptions of Avatars: We gathered the perceptions of older adults regarding whether the avatar accurately represented the presence of the corresponding person. In our study, the avatar of the research assistant (RA), who was physically present among the older adults, was presented. Initially, we began with the In3D avatar generation platform [12]; however, due to issues detailed in the subsequent sections, we transitioned to the Unreal Metahuman Creator platform [15].

4.0.3 AR Interaction: We tested older adults' abilities to use interaction modalities in AR, which included two main types, i.e., near and far interaction. These were tested within the context of the prototyped activities and adaptations were made to tailor them to the needs of older adults. The adaptations were tested during visits 5 and 6.

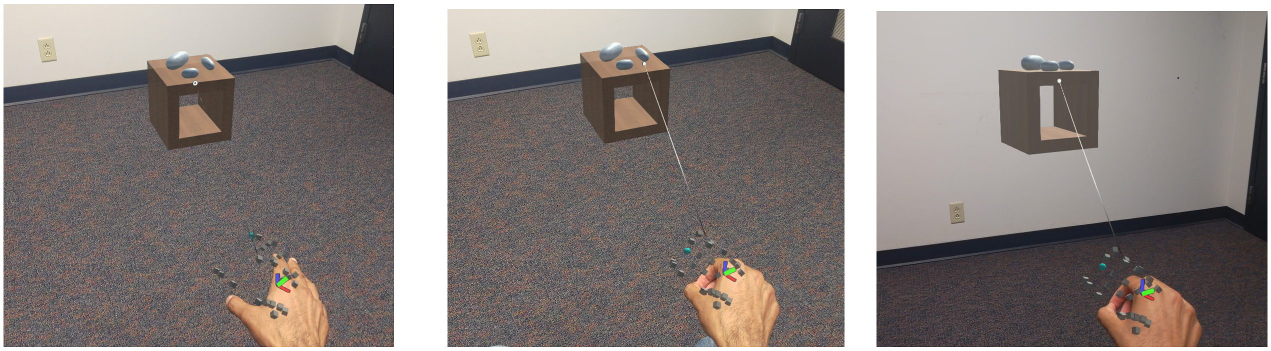
4.0.4 User-Interface (UI) elements: This included the iterative testing of the UI elements that the stakeholders, i.e., older adults, staff, and family members suggested for easier interaction.

4.0.5 HMD-AR tolerability, learnability, and remembrance of the system: We determined the assistance and guidance the older adults required for performing the activities in collaborative AR during subsequent visits and obtained strategies from staff and family members to help older adults perform these activities independently.

We first describe the participant profile for the IPD study followed by the broad topics in detail along with insights gained and possible solutions.

4.1 Participant Profiles

There were 15 participants consisting of 8 older adults (2 male, 6 female) age 56 to 87 (M = 69.7, SD = 11.7) years, 5 LTC staff, and 2 family members. None of the participants had any prior experience with HMD-AR technology. Age, gender, and cognitive profiles of the older adults are shown in Table 1 and the physical ability profile is shown in Table 2. Older adults had SAGE scores below 14, indicating



(a) (b) (c)

Figure 6: Standard far interaction method to move an object using HoloLens 2 (HL2). (a) First, one has to point their hand, such that the dotted pointer ray emanating from the palm of the hand is at the object. (b) Second, one has to pinch their fingers, using their index and thumb to grab the object. The dotted line turns solid when the object is in the user's control. (c) As the user moves their hand, the object moves accordingly.

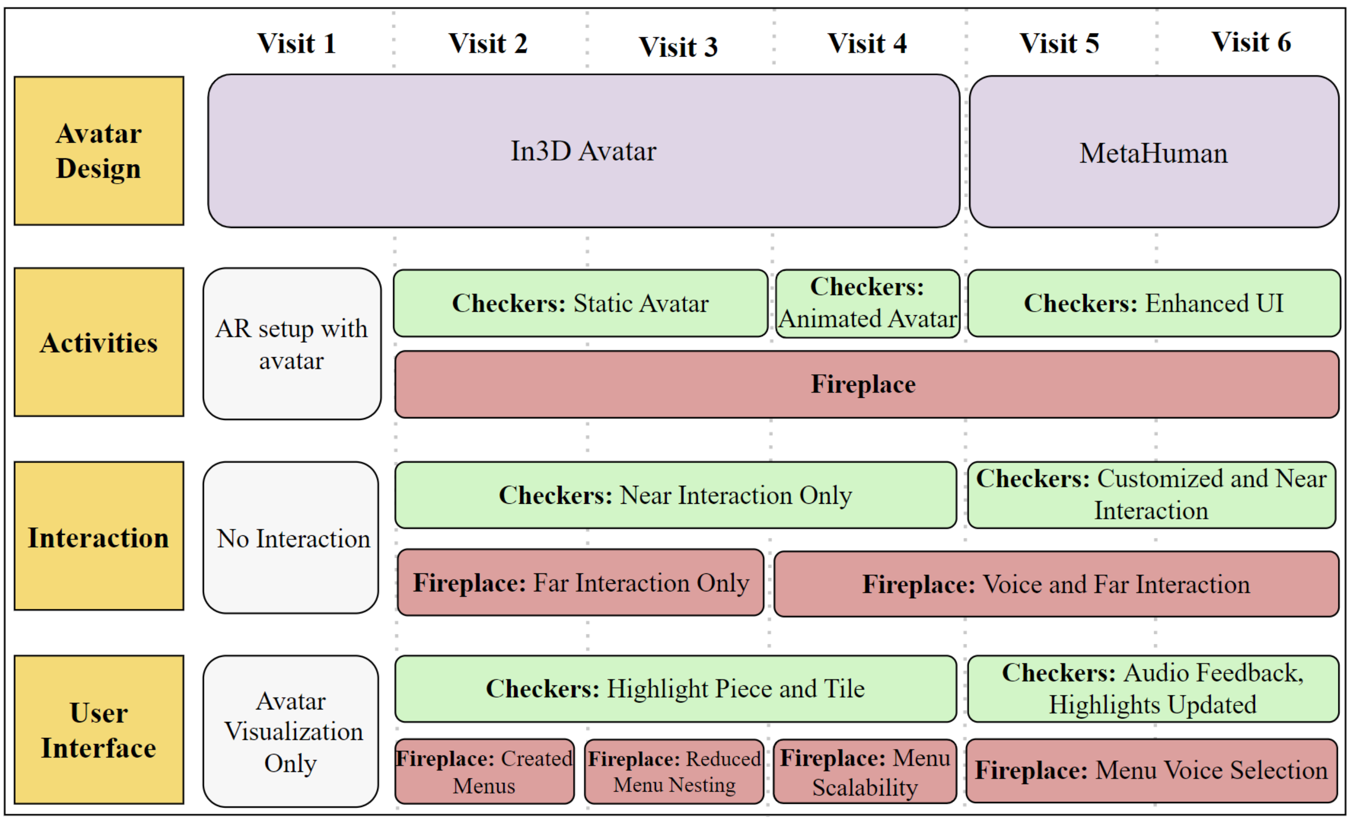


Figure 7: An overview of the major topics encountered during the iterative participatory design (IPD) study and the visit-wise changes that were implemented. There were 6 visits in total encompassing topics of avatar design, activity type, interaction modalities and user interface elements.

significant memory and thinking impairments. Seven older adults required a wheelchair for mobility. Three participants had difficulty speaking.

4.2 Preferred Activities Using Collaborative AR

The first visit was dedicated to soliciting older adults' and their family members' preferred activities in collaborative HMD-AR. To facilitate their understanding, we demonstrated an AR interaction

Table 1: Older Adults' Demographics and Cognitive Ability

Older Adult	Age	Gender	SAGE Score*
OA #1	77	F	13
OA #2	82	F	13
OA #3	72	F	5
OA #4	62	F	7
OA #5	56	M	12
OA #6	66	F	11
OA #7	87	F	9
OA #8	56	M	N/A

*SAGE = Self-Administered Gerocognitive Exam.

setting with a virtual avatar (Fig. 3 (d)). The demonstration was followed by group-based and individual interviews.

4.2.1 Observation and Guidelines. From their first experience of the AR environment, all participants showed enthusiasm and readily accepted the HMD-AR platform. They were able to visualize and describe the virtual scene and avatar.

Table 3 shows some of the activities shortlisted from the interviews. These activities were based on the mutual interest of both older adults and their family members as well as the observations of the staff members on what the older adults and their family members liked to engage in during their visits. Based on the interviews, the common features were extrapolated to understand why the participants suggested an activity.

The main features of the preferred activities that emerged from the interviews showed that the participants, especially older adults, preferred simpler activities. Since cognitive decline is prevalent in older adults, it is important to select activities that impose lower cognitive load. Most of the activities they suggested were the ones they engaged in regularly. "*I can play poker. How about Bingo?*" OA #4 suggested. "*Checkers is a good one. Bingo is a game they love. Maybe card games would be a good one, too. They just like games in general.*" Staff #1 told us.

Nostalgia was another notable feature of the type of activities that were suggested. "*I grew up with Checkers,*" Family #1 recalled as he told us how he wants to play Checkers with his mother who now lives at the LTC.

Since AR has the potential to allow the older adults to engage in activities that many of them could not do in real life due to physical disabilities, they expressed an interest in crafts like "baking a cake" or "decorating a fireplace" like they used to do before they started using a wheelchair.

Another common feature of the suggested activities was comfort. When asked what they enjoyed doing the most with their children, OA #5 stated, "*we talk*". Similarly, Family #1 told us: "*...talking, giving her updates on the news, giving her updates on the new grandbabies.*"

Based on these discussions, we chose Checkers and fireplace decoration as our initial prototype activities since they encompassed most of the features desired by older adults and family members (see Table 3).

4.3 Perceptions of Avatars

During the first visit, we created a photorealistic avatar using the In3D volumetric scanning application [12] with the avatar shown seated across the participant (Fig. 3 (d)). All 8 older adult participants accurately identified the avatar as that of one of the research personnel's without needing prompts. However, they commented on some aspects of the avatar's physical attributes, including its hair and shoes, which they thought were "*unnatural*" and "*unusually transparent*". Before the second visit, we made the avatar's feet and hair smoother using Blender [5], a graphical software editor. During the next three visits involving Checkers, participants observed the avatar's body movements and facial expressions. They reported several irregularities in the avatar's body gestures such as they found the avatar joints to be *"fidgety"* and the smile *"exaggerated"*. The participants' reactions towards the edited hair were unchanged from Visit 1.

We determined that the unnatural smile and joint breakage was caused by improper rigging of the avatar's skeletal structure and facial mesh. This rigging was automatically made during the generation process by the In3D app. Because creating realistic hair texture and movement is a difficult problem in graphics and is impractical to fix by manual editing, we used a new avatar creation software, Metahuman Creator [15]. A Metahuman avatar with the likeness of an actual person can be achieved by importing a 3D scan of the person's face, obtained using a third-party app such as Polycam [17], onto the Metahuman body. Perceptions of participants using Metahuman and In3D were recorded during visits 5 and 6. The participants were shown a sample animation in AR of both the avatars (see supplementary video 1 and 2) and asked three questions regarding the resemblance, naturalism of movements, and preference for interaction (see Table 4). Fig. 8 shows the comparison of a volunteer, his avatar created using the In3D and Metahuman applications.

4.3.1 Observations and Guidelines. Older adults perceived the realism of the avatar as a critical point. This was also true for staff and family members, as seen from their overwhelmingly favorable responses towards the Metahuman (see Table 4). "*I like him. He has got a good smile, good hair unlike the other one which is weird, and (this one is) not overly friendly,*" OA #1 said when looking at the new Metahuman avatar. " *I like this one better (Metahuman). He is friendlier and I like the guy's smile. He seems more open to interacting with me,*" said OA #2.

Many participants justified their preference of the Metahuman by saying that it felt *"more life-like"* (Staff #1), which is an important aspect of social presence. "*This (In3D) avatar looks more like a drawing, or cartoony while the other one looks more real,*" Staff #3 told us when asked why she preferred Metahuman over the In3D avatar.

4.4 Near AR Interaction

For the Checkers activity, we used the default near interaction technique to move the Checkers pieces; participants were to pinch and hold to move the pieces. Based on Visit 2 observations and feedback, we rescaled and repositioned the checkerboard and the Checker pieces to make them easier to grasp. Those who were struggling to pick and move the pieces experienced two issues:

Table 2: Older Adults’ Physical Profile

Older Adults	OA #1	OA #2	OA #3	OA #4	OA #5	OA #6	OA#7	OA #8
Stand from seated position	Yes - I	No	No	No	No	No	No	No
Stable when standing	Yes - I	No	No	No	No	No	No	No
Able to walk	Yes - A	No - W/C	No - W/C	No - W/C	No - W/C	No - W/C	No - W/C	No - W/C
Able to reach forward	Yes - I	Yes - I	Yes - I	Yes - I	Yes - I	Yes - I	Yes - I	Yes, barely
Able to grasp with hands	Yes - I	Yes - I	Yes - I	Yes - I	Yes - I	Yes - A	Yes - I	Yes - I
Able to pinch with fingers	Yes - I	No	Yes - I	Yes - I	Yes - I	Yes, barely	Yes, barely	Yes - I
Able to open hand	Yes - I	Yes - I	Yes - I	Yes - I	Yes - I	Yes - I	Yes - I	Yes - I
Able to speak clearly	Yes	Yes	DS	Yes	DS	Yes	Yes	DS

I = Independent, W/C = Use a wheelchair, A = Assistance, DS = Difficulty Speaking

(a) (b) (c)

Figure 8: Photorealistic avatars generated of a (a) volunteer using the (b) In3D and (c) Metahuman applications. The pictures are used with permission.

Table 3: List of Shortlisted Activities and their Features

Social Activities	Features
Poker	Common; Available at the LTC
Bingo	Common; Available at the LTC ; Simple
Playing Cards	Common; Available at the LTC
Checkers	Common; Available at the LTC; Simple; Nostalgic
Fireplace Decoration	Nostalgic; Creative
Gardening	Nostalgic; Comforting
Sitting and Talking	Simple; Comforting

(1) they were unable to pinch properly to pick a piece due to low hand dexterity and/or (2) they were unable to hold the pinching position long enough to move the piece. Further revisions resulted in a custom mode of interaction of passing the index finger through a piece that would automatically latch onto the finger and only unlatch when a piece is placed back on a black Checker tile (see Fig. 9, supplementary video 3). Both techniques (pinching and tapping) for near interaction were tested and compared during Visits 5 and 6.

4.4.1 Observations and Guidelines. When participants were interacting with the AR environment for the first time, there was a learning curve associated with being able to interact with virtual

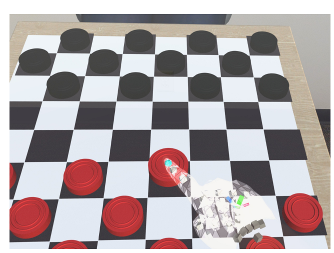


Figure 9: Custom mode of interaction for picking up a Checkers piece. A piece is picked up by passing the index finger through it. The piece is placed back whenever the user touches their desired black tile on the checkerboard.

Table 4: Participants' Avatar Preferences: Metahuman versus In3D

Participant	Which avatar looks more similar to the study personnel?	Which avatar has more naturalistic movements and expressions?	Which avatar would you prefer to interact with?
OA #1	Metahuman	Metahuman	Metahuman
OA #2	Metahuman	Metahuman	Metahuman
OA #3	Both look the same	Both look the same	Either
OA #4	Metahuman	Metahuman	Metahuman
OA #5	Metahuman	Metahuman	Metahuman
OA #6	Metahuman	Metahuman	Metahuman
OA #7	Metahuman	Metahuman	Metahuman
OA #8	Metahuman	Metahuman	Metahuman
Staff #1	Metahuman	Metahuman	Metahuman
Staff #2	Metahuman	In3D	Metahuman
Staff #3	Metahuman	Metahuman	Metahuman
Staff #4	Metahuman	In3D	Metahuman
Staff #5	Metahuman	Metahuman	Metahuman
Family #1	Metahuman	Metahuman	Metahuman
Family #2	Metahuman	Metahuman	Metahuman

pieces mid-air. All staff and family members struggled to pick a piece in the beginning, but three out of five staff members and one family member were eventually able to do so more easily by the end of their first session. When we asked Family #1 if he could easily move the pieces, he replied, "*It's a matter of getting used to seeing depth but otherwise yeah... it's just a matter of getting used to it*". "*I think it just needs practice on our part,*" Staff #5 said.

On the contrary, none of the older adults were initially able to pick up the Checkers pieces. Those who were nearly able to pick up pieces had greater mobility and ability to reach forward. One solution to this issue was to move the checkerboard closer to the participant. However, this came at a cost – the participants were unable to view the checkerboard and the complete profile of the avatar together, when it was brought closer, due to the restricted FOV of the HL2. "*I only see his upper torso; I don't see the other items*," OA #4 told us. OA #2 expressed similar concerns: "*I see only the avatar's body, but don't see the checkerboard*."

To resolve this issue, we prioritized the participant's ability to reach the pieces and repositioned the virtual environment such that they were able to reach the farthest edge of the board with ease while being able to see the complete virtual environment through minimal movement of their head. Once we asked the participants to move their head around, they were able to navigate the rest of the virtual environment. With the repositioning of the virtual environment, all the older adults were able to reach the pieces but only two out of eight were able to pick and move them easily, hence the custom mode of interaction described above was designed.

All except one older adult (OA #8) were able to move Checkers pieces with customized interaction. OA #8 had very low mobility and dexterity and was unable to reach the pieces despite moving the checkerboard close to him. Participants who were able to use the default pinching interaction to move pieces preferred it over the custom interaction because it felt more intuitive and naturalistic

Table 5: Participants' Preferences for Methods of Near Interaction

Participant	Which method do you prefer for picking a Checkers piece?
OA #1	Custom
OA #2	Custom
OA #3	Pinching
OA #4	Custom
OA #5	Custom
OA #6	Pinching
OA #7	Custom
OA #8	Could not move a piece using either
Staff #1	Pinching
Staff #2	Pinching
Staff #3	Custom
Staff #4	Pinching
Staff #5	Pinching
Family #1	Pinching
Family #2	Custom

(see Table 5). "*I liked pinching because it feels like I am doing something, tapping with my finger doesn't feel like I am doing anything*." OA #3 said. When we asked Staff #4 why she preferred pinching over custom interaction, she told us: "*It feels like you are picking something*." On the other hand, 4 out of 8 older adults preferred using the custom interaction because they were able to interact, which was not possible otherwise. "*I can use it to play. I cannot play Checkers in real life. I can actually do this. This is cool*." OA #7 said.

To summarize, for near interaction, the restricted FOV should be navigated to allow for an easy view of the virtual environment

Table 6: Participants' Preferences for Methods of Far Interaction

Participant	Do you prefer voice commands or point and pinch for selecting items?
OA #1	Voice Commands
OA #2	Voice Commands
OA #3	Voice Commands
OA #4	Voice Commands
OA #5	Point and Pinch
OA #6	Point and Pinch
OA #7	Voice Commands
OA #8	Could not use either
Staff #1	Voice Commands
Staff #2	Voice Commands
Staff #3	Point and Pinch
Staff #4	Voice Commands
Staff #5	Voice Commands
Family #1	Point and Pinch
Family #2	Point and Pinch

while allowing the user to easily reach the interactable objects. To pick and move the pieces, naturalistic interactions that parallel real-world actions are preferred but other options should be provided to accommodate for low mobility and low hand dexterity.

4.5 Far Interaction

During Visit 2, participants evaluated the first prototype of the fireplace decoration activity that involved far interaction. Three older adults could not point and pinch because of dexterity issues and it was not intuitive for the remaining five. Staff and family members were able to move objects using the gesture, albeit after some practice. To simplify the interaction for older adults, they suggested translating only yaw rotation of one's hand while moving an object to keep it upright (see supplementary video 4) and keeping only the user's dominant hand active within the FOV as opposed to both hands. During Visit 3, one of the staff members suggested to implement voice commands to make the movement the objects easier for older adults, since they are familiar with voice-based assistants like *Siri* [18] and *Alexa* [3]. During Visit 4, the testing of the voice commands revealed that HL2's speech-to-text functionality was not robust enough for lengthy item names such as "*Vintage Victorian Painting*". A simplified approach using short, basic voice commands was devised and tested during Visit 5. This included a combination of pointing at an object and using a short voice command to select since older adults could point at objects quite easily (see supplementary video 5). During Visits 5 and 6 voice-based object selection and the additional voice commands to move, place, rotate, and scale objects were evaluated (see Table 6 for preferences and Appendix for list of voice commands).

4.5.1 Observations and Guidelines. We observed several issues with older adults navigating AR far interactions i.e., lack of insight to AR default movements, neck mobility issues to adjust their gaze for hands to be within the FOV, and variability in command preferences. "*I see the pointer and I am trying to get it, I am pinching my fingers, but it doesn't seem to be picking up the object*", OA #3 told us while pinching in the direction of a clock incorrectly. OA #4 struggled with keeping her hands in the FOV which would cause her to lose hold of the objects: "*Sometimes when picking up the objects, it suddenly stops moving. I don't understand why*".

When switching to the voice functionality for interacting with an object, five out of eight older adults preferred it over hand interaction (see Table 6). "*I prefer the voice interactions, because I feel moving the item is much smoother*", OA #3 said. Similarly, OA #1 noticed: "*I like the voice functionality because its clearer and does not shake as much (when moving the object)*".

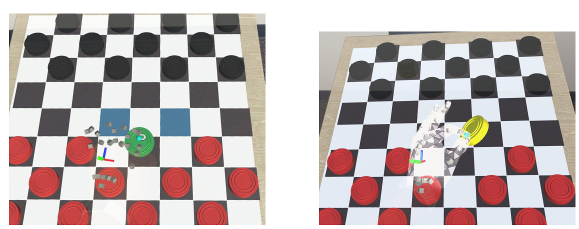
However, two out of three older adults preferred the pinching gesture over voice commands. One participant, OA #8 was unable to interact with game objects using either mode of interaction. All three participants (OA #5, OA #6, and OA #8) had speech impairment and were unable to use voice commands.

Most staff members were able to perform the point and pinch interaction although four out of five staff members preferred voice commands. Both the family members enjoyed the pinch gesture. "*Oh, I can see if I rotate my hands, the object also moves. That's so cool*", Family #1 said while trying out the point and pinch gesture for the first time.

It was noted that both family members erroneously suggested that their parents would prefer point and pinch over voice interaction. Family #1 told us: "*I think for probably this type of interaction, my mother would prefer the hand (point and pinch) interaction*". Similarly, Family # 2 said :"*I kind of like this type of interaction. I think she would also like and prefer it*".

Staff members recommended to further simplify the pinch and point interaction. The simplification of object rotation (see supplementary video 4) and use of single dominant hand in the scene are case in point.

In summary, the majority of older adults in our study preferred using voice interactions to move far objects in AR. In terms of the staff and family members preferences, it came down to their personal choice, although all of them were able to perform both modalities of interaction. This may be the case with more functional older adults and hence both modalities of interaction should be available for far interaction in AR.



(a) (b)

Figure 10: (a) Highlighting (green) a Checkers piece and possible positions it can be placed makes for easy interaction. (b) Two older adults were color blind and suggested using yellow, rather than green as the highlight color when a piece is picked up.

4.6 User Interface

During the Checkers game development, we incorporated visual feedback as visual cues can enhance the user experience when interacting with virtual objects [98]. At Visit 2, we evaluated the color of a Checker piece toggled to green every time a participant interacted with it (Fig. 10 (a)). We also highlighted the checkerboard tiles blue to indicate the possible positions that a Checkers piece could take. Before Visit 4, we added an auditory cue based on suggestions to indicate when the piece had latched onto the checkerboard. During Visits 5 and 6, we had participants evaluate all three visual and auditory feedback mechanisms (see Table 7).

For the fireplace activity, users first chose a certain type of fireplace and then chose the decorative items from a set of menus. During Visit 2, four types of fireplaces were presented: Ornate, Rustic, Modern, and Traditional (Fig. 11 (a)). Each type had individual menu items, with items further divided by size (large, medium, small). These nested menus were replaced by a simplified two-level hierarchy of selecting the fireplace type and then the decoration items and were evaluated during Visits 3 and 4. Participants were also asked about the visibility of menu items and the font size of the text on the menu to find a scaling factor that works for everyone. Visits 5 and 6 entailed testing of the implemented voice command functionality for item names, moving objects, and changing the overall size of menu UX elements (see Table 8).

4.6.1 Observations and Guidelines. For most participants, highlighting the pieces in a different color enhanced their interaction with the virtual Checkers piece (see Table 7). "*That (the highlight) would help with depth perception here when it's black pieces on black squares.*" Family #1 said.

For choosing the color for visual cues, it is important to pick colors that are easily visible. Initially, we chose green as the color for highlight to have a stark contrast between the rest of the checkerboard and the highlighted piece. However, during the testing, we realized that two of the older adults were colorblind. Based on their suggestions, the color of the highlight was changed to yellow and both the colorblind older adults were able to visualize it (Fig. 10 (b)).

Most participants showed a preference for the highlighted tiles on the checkerboard that indicated the next possible positions of a Checkers piece (see Table 7). Many staff and family members found it to be profoundly useful for older adults with short term memory. Staff #5 said: "*... with the highlighters and stuff like that, it would help with the short-term memory.*" When we asked Family # 1 what he thought of this feature, he said:"*It gives you your options. For somebody who is not sure of it. Like my mom experiences a little bit of memory loss, that would be perfect.*" Those who did not like any visual cues mentioned that they do not feel the need for them to be able to play Checkers.

For the auditory cues, participants seemed to prefer it for its realism. When we asked Staff #3 if she likes the auditory cue, she replied: "*Yes, I think it's more realistic.*" One staff member (Staff #1) who did not like the auditory cue reported that he generally does not like audio feedback due to over-stimulation.

Although both the visual and auditory cues were helpful to most, the final design of the activities should give the participants the freedom to choose between them based on their personal preferences since these cues may be distracting to some. This is also true for fireplace UI elements, especially the size of the menu items and text. All participants except OA #5 were able to clearly see the menu items. OA #5 did not know how to read, and hence relied on pictures of items to make her decisions. "*I cannot read ... I would like to have the menu's bigger so that I can see the pictures of the menu items bigger*" she told us. Three out of 8 older adults were unable to read the text and preferred a larger font size (Table 8). Hence, the size of the text and the menu items were adjusted to suit all participants. All participants except OA #3 requested to have the option to control the size of the menu elements, which was incorporated in the final design using voice commands (see supplementary video 6). "*I would want to have the option to scale more because just like on a computer, you can change the font size.*" [OA #1]

Many participants also expressed their desire to use voice commands to select menu items (see Table 8). The menus were modified to include voice commands for item selection (Fig. 11 (b)).

When evaluating the structure of the menus, older adults disliked the nesting of menus, and most were confused by having to backtrack through them if they decided to change the fireplace decoration theme. All of them approved of the simplified two-level menus. Thus, when making design choices, it is important to make sure that the functionality of an element does not come at the cost of high cognitive load that may result in frustration and confusion.

4.7 Tolerability, Learnability, and Remembrance of AR Interactions

After every session, we asked the participants to report any incidents of exhaustion, dizziness, or nausea. None reported any such incidents associated with the use of the HMD for at least 30 minutes.

We also observed the participant's ability to remember the prototype activities and the interaction modalities to inform us of the degree of instruction required at subsequent visits. We observed that the participants remembered the instructions for performing the activities for the duration of a visit. However, for the next visit, spaced between 3-4 weeks, older adults required a review but were quick to remember their experience from past visits. For instance, OA # 1 recalled: "*Oh! I remember I had trouble last time also while picking it up.*"

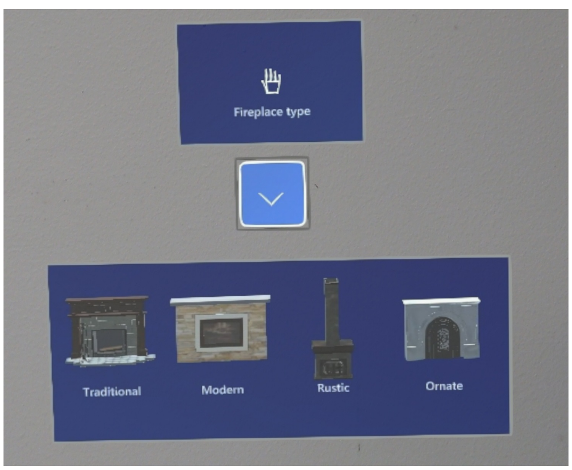
On the other hand, the staff and family members were able to perform the interactions for the subsequent visits independently. However, they all suggested that most of the older adults would require assistance in the form of a tutorial. "*Older adults may have memory deficit issues, so they might need reminders from time to time*". Staff #2 told us. Similarly, Family #2 mentioned: " *I think for my mother, it would take a couple of times of practice and then she can do the interaction.*

The staff also gave suggestions for incorporating a tutorial or a guide for these activities. For the fireplace activity, Staff #3 recommended: "*It would be great to have physical slides of how the menu items look for them during the tutorial.*" Staff #5 suggested: "*For the voice commands it would be better to have a list of the commands, in big font both as a physical copy and also on the HMD that they*

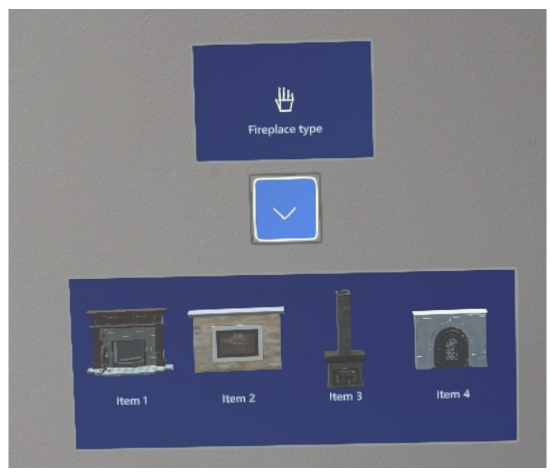
Table 7: Participant's Preferences for the UI Elements in Checkers

Participant	Do you like the sound?	Do you like when the pieces highlight?	Do you like it when the tiles highlight?
OA #1	Yes	Yes	Yes
OA #2	Yes	Yes	Yes
OA #3	Yes	Yes	No
OA #4	Yes	Yes	Yes
OA #5	Yes	Yes	Yes
OA #6	Yes	No	Yes
OA #7	Yes	Yes	Yes
OA #8	N/A	N/A	N/A
Staff #1	No	Yes	Yes
Staff #2	Yes	No	Yes
Staff #3	Yes	Yes	Yes
Staff #4	Yes	Yes	Yes
Staff #5	Yes	Yes	Yes
Family #1	Yes	Yes	Yes
Family #2	Yes	Yes	Yes

*OA #8 was unable to participate in the UI design since he was unable to move any pieces



(a)



(b)

Figure 11: The fireplace type menu consisting of 4 options: Traditional, Modern, Rustic, and Ornate. (a) represents the initial iterations where the fireplace type names are present and (b) represents the voice adapted menu where names are replaced by item numbers for the robustness of the speech to text functionality of the HoloLens 2 (HL2).

can pull up... (For Checkers), I think they will be more receptive to the video of a person (for explaining the tutorial)."

5 DISCUSSION

We used IPD as a method to develop collaborative HMD-AR activities for older adults in LTCs. Overall, older adults were enthusiastic about the technology as evidenced by their participation and suggestions for improvement. However, we found the need to tailor AR activities for these older adults who experienced a range of physical limitations, including reduced ability to locomote and impaired fine motor control (e.g., grasping; pinching) as well as cognitive limitations, such as a reduced ability to verbalize thoughts or verbally communicate, and difficulties with seeing or reading text. Modifications such as simplifying gestures, adapting interfaces, adding voice commands alongside gestures, and ensuring graphics and text readability enabled easier interaction for the older adults. Other disabilities not encountered during the study, but prevalent among older adults at LTCs, include hearing and vision impairments, as well as balance problems (vertigo, dizziness) [66]. Thus, specific adjustments must be made to accommodate these problems to facilitate the adaptation of AR activities. For example, for older adults affected by hearing impairments, the volume and pitch settings of the HL2 device can be customized according to their hearing comfort level [10]. Moreover, modifications can be made to the HL2

Table 8: Participant's Preferences for the UI Elements in Fireplace Decoration Activity

Participant	Do you prefer to use voice commands or finger tap to select menu items?	Are the menu items clearly visible?	Is the text on the menus readable?
OA #1	Hand	Yes	No
OA #2	Voice	Yes	Yes
OA #3	Voice	Yes	Yes
OA #4	Voice	Yes	Yes
OA #5	Hand	No	No
OA #6	Hand	Yes	Yes
OA #7	Voice	Yes	Yes
OA #8	N/A	Yes	No
Staff #1	Voice	Yes	Yes
Staff #2	Voice	Yes	Yes
Staff #3	Voice	Yes	Yes
Staff #4	Voice	Yes	Yes
Staff #5	Voice	Yes	Yes
Family #1	Voice	Yes	Yes
Family #2	Hand	Yes	Yes

applications to enhance hearing by directing more of the device sound to the participants unimpaired ear [80]. For those with vision impairments, the flexibility of having larger text on menus and being able to scale text to the required size is effective [25]. In addition, calibrating the HL2 for each participant's vision ensures the best viewing experience [9]. Other modifications shown to be helpful include computer vision or image processing techniques for vision enhanced imagery, such as magnification [115] and contrast/edge enhancement [116]. An exhaustive set of modifications that can be made to HMDs according to the type of visual impairment is described in [70]. For older adults with balance impairments, use activities that allow them to remain seated to minimize fall risks. In advanced telepresence activities that involve locomotion [105], reliance on the family member rather than the older adult can reduce fall risks. HMD AR has also shown to be feasible for balance training activities [79]. Perhaps such activities can be performed collaboratively with a balance coach on the remote side, rather than a family member and more suited to older adults with balance problems. Considering these limitations during the design phase will enhance AR interactions that are accessible and enjoyable and will enable older adults to fully utilize the breadth of possible AR activities.

5.1 Generalizability to Diverse Older Adult Populations

Aside from physical limitations, the background, education, and cognitive abilities of older adults must be considered. For example, we encountered one participant with weak reading skills, highlighting a potential barrier to AR engagement for older adults. Designing AR interfaces, such as voice prompts or visual cues, can ensure that AR activities remain accessible to older adults with low literacy or cognitive impairment. Also, it has to be noted that this study was conducted in a developed English speaking country with high literacy levels. To make collaborative AR viable in other countries or diverse populations, additional aspects need to be considered. First, in the US as well as other countries, English may not be the preferred language of use. The menus and UIs of the AR activities will need translation into the preferred languages. A number of software apps are available, but final text needs to be verified by a native speaker to ensure grammar differences and common idioms. HL2 voice functionality may not be robust to varied English accents of a more diverse population [56]. In these cases, alternative translation plugins, such as Google Translate [7] and Duo Lingo[6], which have been trained on larger and more diverse data sets can be used. The activities through which older adults in other countries may prefer to interact with their family members may be different than the ones obtained during our study. Checkers may not be a well-known game in other countries and fireplaces may not be common in warmer countries for the decoration activity to have much meaning. Activities that the populace finds enjoyable should be co-created to enhance the connectedness with family members when interacting through AR. Another nuanced aspect of design considerations is that most of the avatar generation software used has been developed in advanced countries, where most of their training data comes from the general population. The avatars generated may not generalize well for people of developing countries [92]. This includes skin color, texture, and facial features. The avatar may need to be manually edited using graphical software such as Blender and Maya to increase their likeness to the person [44]. Finally, the digital literacy of older adults in developing countries and their exposure to digital media may be less than that of their counterparts in developed countries, requiring more elaborate and detailed tutorials in using AR technologies. The family members and the older adults' offspring, who are often more tech savvy, can serve as an important conduit in helping older adults to adopt and use HMD-AR technology.

In our study, despite having a sample size of only two, both family members enjoyed interacting through the AR HMD and expressed enthusiasm about the potential of collaborative AR technology to enhance the lives of older adults. One of the family members, (Family #2), later confided with the RA, "*This is their entire world (LTC), and it's so great that you all are doing this because it opens them up to interact with the outside world in a creative way, and that's a very good thing*". Thus, we believe family members can play a crucial role in the successful adoption of technology at LTCs, and additional studies with larger sample sizes involving them need to be conducted. However, it is also noteworthy that both of the family members in the study initially reported that older adults would prefer hand interactions over voice commands, contrary to the findings reported from older adults themselves in our study. This observation raises the possibility that family members may overestimate the capabilities of older adults. This discrepancy highlights the importance of involving older adults themselves in the design process and obtaining their direct feedback.

5.2 Dealing with Frustrations

An important aspect to consider when introducing new technology to people, especially older adults in particular, is dealing with frustrations of not being able to learn and use it quickly. In these cases, it has to be made clear to them that the goals of such studies are for them to provide their critiques and suggestions for a) developing activities they enjoy and b) helping design the AR application so they could actually partake in the activities. As such, the pressure should not be on them to perform a given activity or task. In our case, the co-creation approach started at the time of informed consent to ensure participants' understanding of the goals of the research activities. Nurse experts who are part of the research team trained the engineers in a) nonverbal and verbal communication techniques and b) observing older adults for behaviors indicating anxiety and frustration. The engineer RAs used structured scripts for guidance in communicating with the older adults and quickly established rapport and trust with participants. LTC staff were always present during the study sessions in order to provide assistance or support if needed. Older adults interact with these staff members on a daily basis and felt secure with their presence. We ensured participants were comfortable with the HMD-AR prior to enrolling them. Although at the initiation of the study several older adults voiced frustration towards the initial AR modalities, they displayed strong determination to build their skills (OA #1:*"I know next time I'll conquer this task"*). All participants returned for repeat sessions to continue to provide feedback. This also includes OA #8, who had difficulties using both voice and hand interactions. The performance of the older adults showed that the learning curve was steep, but not insurmountable with appropriate guidance and assistance. All older adults enjoyed providing us with suggestions to improve the ease of using the AR technology. There were no adverse events.

In cases where older adults face challenges using both voice commands and hand gestures, such as OA #8, we noticed that they were still competent in the use of alternative control mechanisms. They were able to operate an automatic wheelchair using a small joystick. From this observation, a potentially viable option for them to interact in AR would be to have a similar virtual or physical joystick that they could use to move a pointer in the virtual environment. Another option would be involving family/ staff members in the AR experience. Family members can assume the role of operator for the AR experience, allowing older adults to engage in the activities by observing and communicating desired actions using whatever modality of communication works best for them. This approach acknowledges the importance of social connections and support systems, enabling older adults to participate in AR activities that might otherwise be inaccessible to them. It reinforces the idea that AR technology can be a bridge to strengthen relationships between older adults and those they care for and love.

5.3 Comparison with Previous Studies and Applicability to Other Population Groups

The results obtained from our study are comparable to previous experiences of introducing AR for older adults. When interacting with Hololens 1, the previous version of HL2, where the primary mode of interaction was through a hand-held controller, older adults did prefer a combination of using gaze and the controller as the most convenient form of interaction[20]. In terms of collaborative AR, when a meal eating activity[63] that represented remote users using generic avatar busts was introduced to older adults, they showed increased enthusiasm that resulted in positive mood changes. Even with other forms of AR technologies that include smartphones and tablets, older adults were able to learn to use them, debunking the commonly held misconception that older adults are averse to technology[22, 42]. Similar to our experience, these works have also shown that older adults can adequately master difficult and time-consuming technologies if it gives them great benefit, but adoption can be increased by making a system easier to use [35]. As older adults see benefits and usefulness in technology, they are more willing to spend time to learn and adopt it [35, 77].

Our study primarily focused on older adults with limited capabilities, which raises the question of whether our findings are applicable to more functional older adults, other vulnerable populations or even the general population. While our results provide valuable insights into addressing the needs of those with significant limitations, it is reasonable to assume that the design principles we have established can be extended to cater to a broader range of older adults and other vulnerable population groups. Other groups which can benefit from collaborative AR include care givers and the general population who are socially isolated [103], populations with memory issues, post traumatic stress disorder (PTSD) [47], veterans, and children with autism [19]. It is also likely that among these groups there will be people with varying cognitive and physical abilities, and an IPD approach would help identify challenges and possible solutions. Further research involving a larger and more diverse sample population is necessary to confirm this generalization.

An overarching principle that emerges from our study is the importance of balancing functionality with simplicity when designing AR activities for older adults. While it is essential to provide a rich and engaging experience, it should not come at the cost of complexity that might deter or frustrate older users. There should be maneuverability or flexibility in the design space to accommodate for personal preference and choice. Finding this balance to ensure that AR applications are both functional and user-friendly will make large strides towards achieving the broader goal of enhancing the quality of life for older adults, and will also improve the reach of collaborative AR for other population groups that can see benefits from it.

5.4 Infrastructure Requirements

Regarding the infrastructure requirements, collaborative AR does require a few extra devices in addition to the HMD itself. Two similar body and facial tracking setups would be required on both the local and remote participant sides. Each setup requires a color-depth camera for capturing body and facial expressions, a laptop for transmitting the captured expressions through the network, and a reliable internet connection. Over the six-month period of the study, we found that a speed of at least 5MB/s was required for the smooth running of the developed prototype activities. At LTCs that lack the required speeds or during high internet loads, a mobile 5G hotspot can be used, as done for the 4th visit during our IPD study. For locations and countries that have slower internet speeds, sending only the upper body joints of the users across the network reduces the networking bandwidths almost in half; this is a viable solution for activities where the older adult and the family members avatars are seated.

In terms of the computing requirements, since AR applications are developed using game engines such as Unity or Unreal, the computing devices used should have a minimum of 8 GB RAM and a dedicated graphics processor to run satisfactorily. To lighten the computing load, the nonverbal behavior pose preservation algorithm [106–108] used in our collaborative AR activities can be disabled. This can be considered a viable trade off as majority of the time, older adults are focused on the activity rather than the avatar's movements, and improvements in the avatar's nonverbal behavior from the pose preservation are noticed less frequently. Since the AR setup involves networking between remote and local devices, the firewalls at the respective LTCs should be configured to allow the devices to communicate through the necessary ports.

In regards to the HMD itself, the HL2's battery lasts about 3 hours with continuous usage and it has a full battery recharging time of about an hour. The HL2 uses 3D holographic projection technology and is relatively expensive costing around $3500 per device. HMDs such as the Quest 3 [14], which are 80% cheaper and use video see-through AR technology can be used as cost-effective alternatives. When using see-through AR technology, care must be taken to ensure that older adults do not experience balance problems or dizziness because video see-through AR can be more disorienting than holographic projections [61].

6 LIMITATIONS, FUTURE WORK AND CONCLUSION

The current IPD study has several limitations. First, by design we focused on older adults with cognitive and physical impairments, and we cannot generalize our findings to the preferences of healthier older adults. Many older adults with fewer or no such impairments may prefer active hand and gesture-based interactions in HMD-AR. As such, both voice and hand gestures should be available to cater to a wide range of older adult populations. Second, the study was conducted at only one LTC with a sample size of 8 older adults and 2 family members. While the older adult sample size is reasonable for a study of this type, a larger group of family members may uncover additional aspects that were not captured in our study. Third, the study considered older adults' perceptions of photorealistic avatars of research personnel present at the site, and not the perceptions of avatars of the older adults themselves or people familiar to them. There are significant aspects of perception to consider when considering the digital representation of oneself or known individuals [72, 86]. These include issues related to one's comfort with the digital representation of their physical attributes such as hair, skin, body proportions, and other ethical questions regarding whether these aspects should be enhanced or altered [49, 50]. Such concerns require further examination, particularly from the perspective of older adults.

While the motivation of using collaborative HMD-AR is to foster social connectedness among older adults at LTCs, this paper was focused on adapting collaborative HMD-AR activities for older adults. In the future, we will assess the impact of these adapted HMD-AR activities on developing social connectedness and mitigating loneliness among older adults residing in LTCs. This includes conducting a longitudinal randomized controlled trial (RCT) for older adults that compares the effect of HMD AR (experiment group) with audio-video applications, such as Zoom (control group) on loneliness. The study will be longitudinal in nature, where older adults will perform their choice activity of either Checkers or fireplace decoration in HMD AR, adapted according to the findings from this work.

Our research highlights the necessity of considering the ethical principles of justice, autonomy, privacy, and dignity when designing ICTs for older adults and other vulnerable populations, especially those with existing cognitive and/or physical impairments [57, 74]. Older adults are often absent or restricted in technology design phases. A recent review [75] reported that while most studies emphasized the importance of involving older adults throughout the design process, only 47% involved older adults in the actual design and prototyping phases. Exclusion of older adults may stem from negative stereotypes and ageism [57, 74, 75] or issues arising from various vulnerability among populations (e.g., inability to comprehend information, communication difficulties, undervalued social groups, etc.) [43, 74]. While our study made initial considerations towards privacy during prototype development, privacy concerns will need to be addressed in more depth as we proceed with our research, both for the older adult and the family member. Choukou et al. [34] reported that while both older and younger adults are supportive of technology to enhance their autonomy and socialization, both groups expressed high concern in trusting the protection of private information with their use. Lastly, inclusion of vulnerable older adults in the design and prototyping phase enhances their dignity by acknowledging their importance as the end users of the technology [43].

In conclusion, our research highlights the significance of iterative participatory design in creating AR activities tailored to the unique needs of older adults. By considering older adults' cognitive and physical capabilities, involving family members when necessary, and prioritizing simplicity without compromising functionality, we can unlock the potential of AR to enrich the lives of older adults. Further research in this field will contribute to a deeper understanding of the design principles that serve not only older adults, but also have the potential to enhance social interaction for other populations.

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A TABLE OF VOICE COMMANDS

Table 9: Basic Voice Commands used in the Fireplace Activity

Command Type	Command	Function
Menu Access	Open Menu	Brings the menu into the field of view
	Close Menu	Removes the menu from the field of view
Menu Scaling	Scale More	Increases menu size by 20% (custom % can be pre specified)
	Scale Less	Decreases menu size by 20% (custom % can be pre-specified)
Item Placement	Select Item	Selects pointed at item for voice commands
	Place Item	Deselects item at its current location
	Delete Item	Deletes item from current location
Item Movement	Move Left	Moves item left by a pre-specified amount
	Move Right	Moves item right by a pre-specified amount
	Move Front	Moves item forward by a pre-specified amount
	Move Back	Moves item backward by a pre-specified amount
	Move Up	Moves item up by a pre-specified amount
	Move Down	Moves down down by a pre-specified amount
	Rotate Item	Rotates item clockwise by a pre-specified amount
Assistance	Help Page	Displays a list of all the voice commands