Iterative User Centered Design of Robot-Mediated Paired Activities for Older Adults with Mild Cognitive Impairment (MCI)

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Abstract. This paper describes the design and implementation of a human-computer interaction (HCI) and human-robot interaction (HRI) based activity designed to foster human-human interaction (HHI) in older adults with cognitive impairment who reside in long term care (LTC) facilities. Apathy is a major condition among this population; apathy is associated with social isolation, cognitive decline, and a reduced quality of life. Few options exist in the treatment of apathy; multi-modal activities addressing cognitive, physical, and social domains hold the most promise but are the most resource intensive. Given the shortage of caregivers, use of technology such as social robots and virtual reality may be useful to complement activity programs. In this paper, we present the iterative design process of a virtual dog training activity using Unity game engine, the humanoid robot Nao, and the puppy robot Aibo. We solicited inputs from expert stakeholders (physicians, nurses, activity directors, and occupational therapists) and residents living in LTC facilities during each step of the design process. We describe their feedback and corresponding changes to the activity. Initial participant testing data in a LTC community, participants' final thoughts, and approval rating of the various components of the system are also presented. The participants rated the system on six categories on a scale of one to five; the mean rating per category increased by 0.58 after the second session.

Keywords: User centered design · Human-Computer interaction · Human-Robot interaction · Human-Human interaction · Social robots · Virtual reality · Mixed reality · Older adults · Cognitive impairment · Dementia

1 Introduction

Approximately 6.2 million Americans ages 65 and older live with Alzheimer's disease and related dementia (ADRD). By 2060, this number is expected to rise to 13.9 million, representing 3.3% of the U.S. population [1, 2]. Official death certificates recorded 121,499 deaths from ADRD in 2019, making ADRD the sixth leading cause of death in the United States and the fifth leading cause for those 65 and older [3]. Many individuals

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with ADRD experience difficulties with memory retention, problem solving, communication, and other everyday activities. One of the main symptoms exhibited by people with dementia is apathy; it leads to indifference, lack of initiative, aversion towards social interaction, lack of interest in daily life activities, and reduced quality of life. Apathy results in loneliness, social isolation, and further decline in mental and physical health [4].

Apathy is difficult to address and very few pharmacologic options are available. Common interventions include guided physical exercise sessions, group activities, cognitive games [5, 6], music, art, and reminiscence therapy [7, 8]. Multimodal intervention techniques that combine physical and cognitive stimulus and encourage social interaction are most effective [7]. Physical activities slow the decline in voluntary motor skills and cognitive activities and social interactions boost attention, mood, and overall cognitive function [9, 10].

These multi-modal activities are resource intensive. Unfortunately, nurses and activity personnel who provide activities to older adult residents in long term care settings are in short supply [11]. To address manpower issues in long term care, various technological interventions using Virtual Reality (VR) and Socially Assistive Robots (SAR) have been explored [12–14]. A brief background on existing VR and SAR intervention techniques for older adults in long term care (LTC) settings are presented in the next section.

2 Background

Investigators have explored robotic fitness coaches to lead group physical activities or provide feedback and encouragement [15–17]. Brian 2.1, a humanoid robot, was designed to encourage older adults to eat meals [18]. Nao, a widely used SAR, has been used to perform memory training activities with older adults [19]. These systems were designed to be used by only one user at a time and provided only a single mode of stimulation. They were also open loop systems, hence could not adapt to the participants' individual capabilities and performance.

Paro, a therapeutic baby seal robot, has been one of the most widely used SARs in LTCs, primarily to improve mood and initiate social interaction [20, 21]. Paro has been used at the individual level where the older adult held and petted it, and at the group level where it was passed around among a group of older adults to initiate conversation. While Paro can engage multiple users at the same time and initiate social interaction, it is limited in nature and dependent on the care givers and their expertise in motivating the older adults to participate in the activity.

Several LTC SAR systems used the Wizard of Oz (WoZ) paradigm [22, 23]. In WoZ-based systems, a human operator controls the system remotely but is not visible to the participants, who are under the impression that they are interacting with an autonomous agent. This enables the system to be adaptive to individual performance but requires a trained operator to manually control the system.

Though the above studies are promising, the range of activities provided solely by SARs is limited. To expand SAR capabilities, virtual reality systems and other game environments have been used in conjunction with SARs. A guided exercise program [24] used the Oculus rift head mounted display and touch controllers. The robot Tangy was used to facilitate a Bingo game with seven residents at a LTC facility [25].

These studies demonstrate the potential of SARs paired with VR or other game environments to engage older adults. However, the majority of these studies provided only a single mode of stimulation with open loop control or required operators to deliver the intervention. Research shows that multimodal interventions that involve physical, cognitive, and social stimuli are more effective than single mode intervention techniques [26, 27]. Research also shows that participants are likely to respond better to instructions from physically embodied robots than from a virtual environment on a computer [28, 29]. Last, the system should be able to adapt to each individual's capabilities with minimal input from the operator.

To combine the benefits of all of the above methods and address the limitations, we designed a virtual dog training activity using the Unity game engine (www.unity.com), the humanoid robot Nao (SoftBank robotics) as instructor, the puppy robot Aibo (Sony) (Fig. 1) and a custom-built human computer interaction (HCI) device, as described in [13]. We followed the principles of user centered design [30] to ensure the acceptability and usability of the activity by our target population.

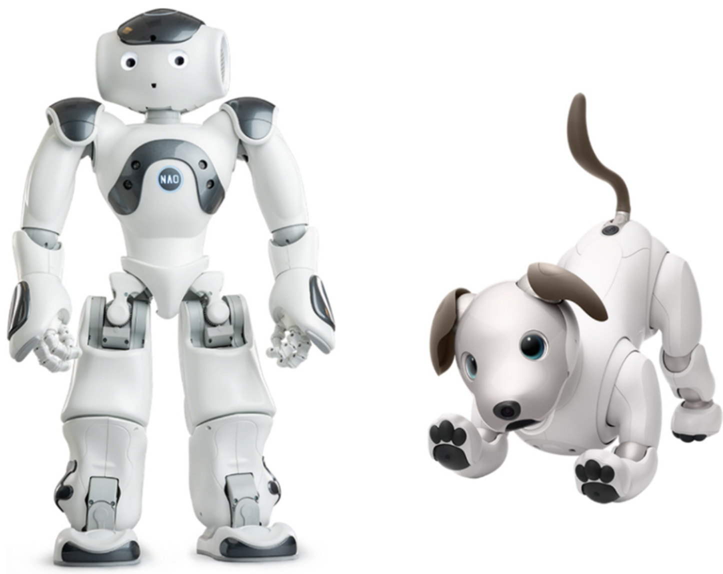

Fig. 1. NAO humanoid robot (left), Aibo puppy robot (right)

3 Robot-Mediated Activity Design

3.1 Activity Objectives

The objectives of the activity are to provide physical and cognitive challenges to older adults and to promote human-human interaction (HHI). To fulfill these objectives the activity needs to have components that require physical movement, cognitive components that require the participant to recognize, memorize, synchronize, sort, or compute, and social stimuli that require multiple participants to cooperate or coordinate to achieve a common goal. The activity should also have metrics to measure progress of each participant and provide rewards or positive re-enforcement to encourage greater effort and increase engagement. The participant should also be able to perform the activity alone for practice. To accommodate participants of different abilities, the activities should provide different levels of physical and cognitive challenges. Most importantly, the activity should be engaging and fun for the older adults. After a series of discussions with long term care (LTC) activity directors about activities that residents of their facilities enjoy the most, and consulting with geriatric researchers and occupational therapists specializing in dementia intervention, a virtual dog training activity was selected.

3.2 Robot Acceptance by Target Population

To determine if older adults would find the two robots fun and engaging, we first met with two residents of a long-term care facility via teleconferencing (due to COVID protocols) and showed them videos of the two robots. Nao was programmed to introduce itself and do a dance, Aibo was programmed to walk around and perform some tricks. Both residents responded positively to the robots and indicated they would like to interact with the robots.

3.3 Activity Prototype 1

The first prototype of the activity required the participants to move their "wands" in a sequence as instructed by Nao to make Aibo do a trick. The wands are a custom-built human computer interaction device as described in [13]. There were six possible motions: up, down, left, right, rotate clockwise and rotate counterclockwise. A random sequence of these movements was generated and shown on a computer screen (Fig. 2). The number of sequential movements depended on the chosen difficulty level based on the older adult's level of cognition. Nao demonstrated the movements and provided encouragement and feedback based on the participants' performance. Once the sequence was completed, Aibo performed a trick, such as sitting, dancing etc. This activity focused on gross motor movements of the arm and required comprehending instructions from Nao. We tested this activity with two pairs of nursing faculty to get their opinion on the ability of this activity to engage older adults. They were of the opinion that the randomized arm motions did not correspond to the tricks that Aibo performed and was counter intuitive. In addition, the gross arm motions may not be feasible for all members of our target population; instead, an activity that focused more on reduced arm motions and cognitive abilities would be a better strategy.

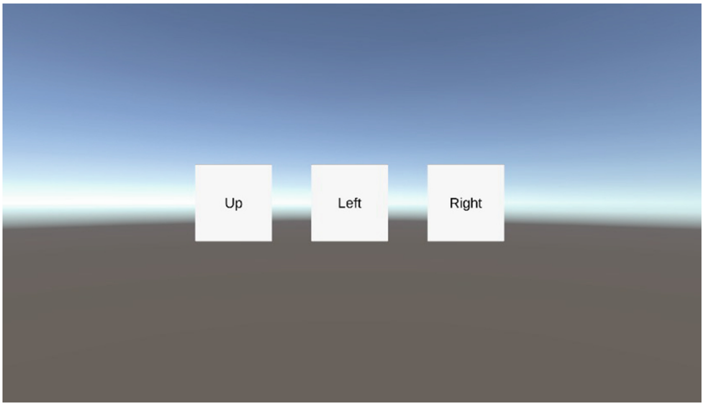

Fig. 2. Example movement sequence for Dog training activity prototype 1: The user has to move their arm up, then left and then right to complete the sequence

3.4 Activity Prototype 2

The second prototype of the activity required pairs of participants to spell out a word on the virtual environment. Figure 3 shows the user interface of this activity prototype. Each participant used a wand to interact with the system. The twenty-six randomly colored red and blue letters of the alphabet were displayed on the screen. Each participant was designated one color and could only pick letters of that color. Nao acted as the instructor for the activity. He would state a word, e.g., 'dance', and the participants had to spell the word by picking their correctly colored letters through use of the wand-controlled cursor. Once the word was completed, the puppy robot Aibo performed the corresponding trick. Nao also provided hints or encouragement as needed. The wand movements provided the physical component of the activity, memorization of the word and its spelling provided

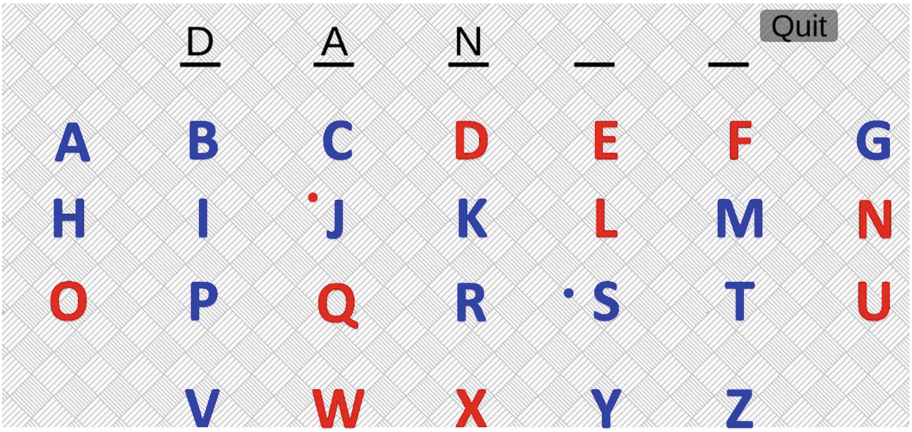

Fig. 3. Dog training activity prototype 2: The assigned word is 'DANCE', the red player has to pick the red letters and the blue player has to pick the blue letters

the cognitive stimulus. Since the participants could only choose letters of one color, they had to cooperate with each other to complete the activity, providing the social component. The activity had three difficulty levels: 1) all the letters were static; 2) letters bounced up and down from their mean position, and 3) letters changed their positions horizontally, which required the participants to track their position in order to select them. We started preliminary participant testing with this prototype.

4 Experiment

4.1 Recruitment Process

Researchers contacted the administrator and medical officer at a local LTC to explain the study and gain permission to approach older adult residents. At a time specified by LTC staff, researchers presented the robots and explained the study to interested residents. Potential participants were screened for study eligibility: age 70+, residing in the LTC facility for at least three months, able to hear, speak and understand English, sit comfortably, and move both arms. During the screening process, participants were seated in front of the computer screen at a similar distance that they would be while performing the activities and asked if they could see the text on the screen. Nao was also programmed to introduce himself and state his favorite color, and the participants were asked to repeat his name and favorite color to determine if they could hear and understand Nao. Multiple voices were generated for Nao using an online AI speech synthesizer (play.ht) and the participants were asked which pitch and pace they preferred. Eligible participants provided informed consent. This study was reviewed and approved by the Vanderbilt University Institutional Review Board.

4.2 Participant Testing

Six participants were screened and consented of whom two dropped out of the study. Four participants each performed the activity twice in pairs. There was a total of five sessions, three sessions where the participants paired up with each other and two sessions where one participant paired with a researcher due to scheduling conflicts with other participants. Sessions lasted approximately 30 min. The sessions were conducted once a week and feedback from each session was used to modify the activity and the next iteration was used in the following session. All sessions were video-taped. Figure 4 shows a session in progress. After each session, the participants completed a questionnaire about their comfort level and confidence level with the various components of the system and answered several open-ended questions.

4.3 Problems Observed

Over the course of the five sessions, through our observations and participant feedback, we identified the following issues:

1. Participants had difficulty understanding the instructions of the activity and the researchers had to provide additional instructions and reminders in addition to the instructions Nao was programmed to provide.

Fig. 4. Participant testing of the dog training activity at an LTC: footage showing participants' movements (left), footage showing robot behavior (right)

2. Some participants had difficulty finding the correct letters. They mentioned that the high number of animated letters were often overwhelming.
3. We observed that occasionally the participants did not pay attention to the feedback Nao was providing and had difficulty understanding which feedback was meant for which participant.
4. We also observed that occasionally the participants were too focused on the animations on the screen and ignored Nao's feedback.

5 Activity Redesign

5.1 Architecture

The system consists of three major blocks: Human-Computer Interaction (HCI), Human-Robot Interaction (HRI), and Human-Human interaction (HHI) (Fig. 5). The VR system is run on a Windows desktop computer. It consists of the Interaction Layer that accepts input from the wands and translates it into the corresponding movements in the game environment; the Communications Layer that facilitates the communication of commands from the state machine to NAO and Aibo; and the Finite State Machine (FSM) that controls the logic of the activity, adapts the difficulty level based on participant performance, generates appropriate feedback and encouragement, and calculates the score. The participants interact with the system using the wands. A static infrared (IR) LED marker is used as a reference; the wands calculate the position of the on-screen cursor based on the relative movement with respect to this IR marker. The VR system together with the wands constitute the HCI block. The details of the wand design and communications layer can be found in [13].

HRI is controlled by the state machine described in the next section. NAO provides instructions, feedback, and encouragement, and also demonstrates the movements required for the activity. The movements and feedback messages are programmed into blocks called 'behaviors' using the 'Choregraphe' software developed by Aldebaran robotics (now SoftBank robotics). Aibo is programmed to perform tricks once each level of the task is completed. The FSM triggers the appropriate behaviors and tricks depending on the state of the task.

HHI is measured using participants' head pose data from a Kinect sensor and speech and is verified from video. Multimodal physiological data are collected using the Empatica E4 sensor (Empatica.com). The audio, video, and data from all the sensors are synchronized using time stamps.

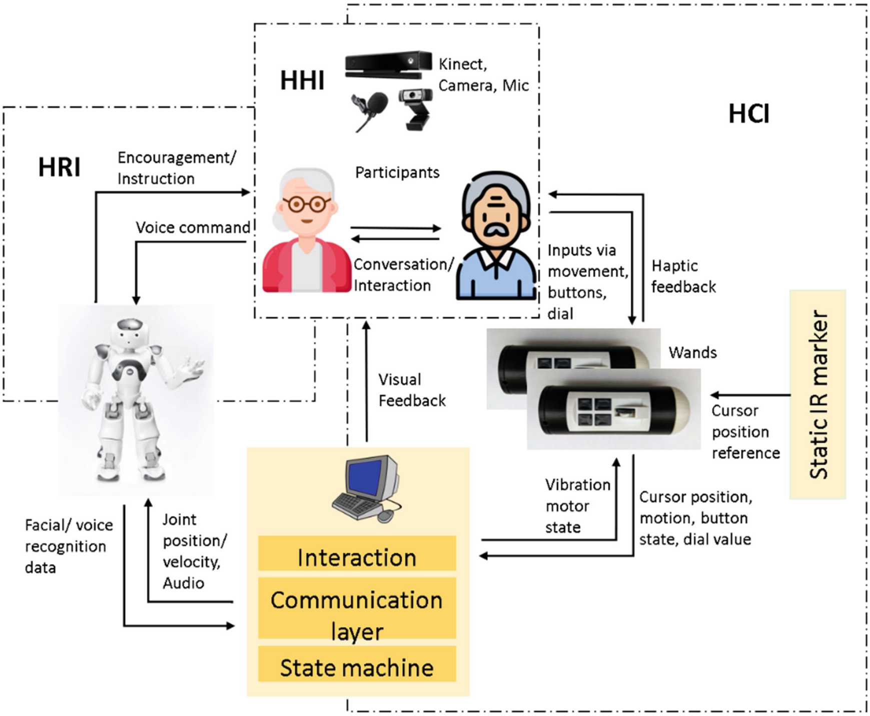

Fig. 5. Architecture of the system

5.2 State Machine

The interaction among the various components of the architecture is governed by the state machine. We designed two state machines, one for the interactive tutorial level and another for the three main levels of the activity. The tutorial level was designed to familiarize the participants with the task. Figure 6 shows the state machine that controls the tutorial level and Fig. 7 shows the state machine for the main levels. Both perform a system check on start to verify all components are connected and properly functioning before proceeding to the activity in the stable state. For the tutorial level, there is an introduction state before the stable state where Nao introduces himself and states the rules of the activity followed by a demonstration. Nao also points out the reference IR LED towards which the participants have to point their wands. He then assigns a color to each of the two participants and encourages them to pick the letter corresponding to their color. The state machine then transitions to the stable state where it monitors the performance of the participants. The system is capable of detecting if the participant is not pointing the wand towards the reference IR LED, if the participant is taking too long to pick their letter, or if they are trying to pick the letter designated to their partner. If any of the above situations arise, the state machine transitions to the corresponding state where Nao addresses the particular player by name and provides individualized feedback, then the system returns to the stable state. The state machine for the main levels also has an encouragement state where Nao provides encouragement each time a participant selects a correct letter. Once the entire word has been completed, the state machine transitions to the celebration state where Aibo performs the corresponding trick and Nao performs a celebration motion as a reward.

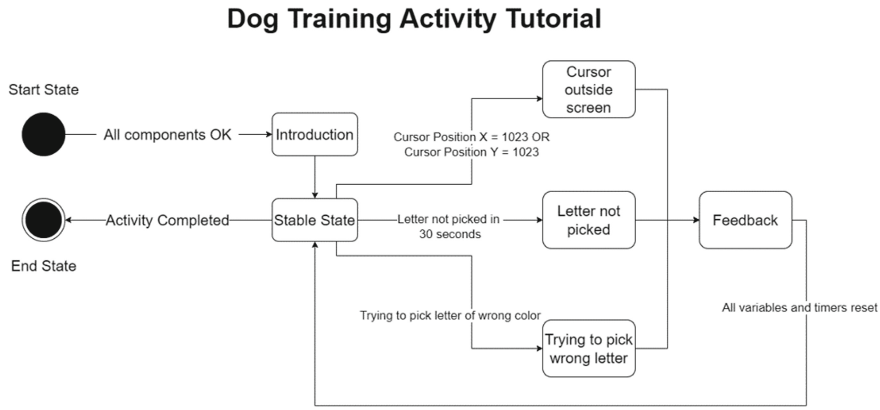

Fig. 6. State machine for the tutorial level

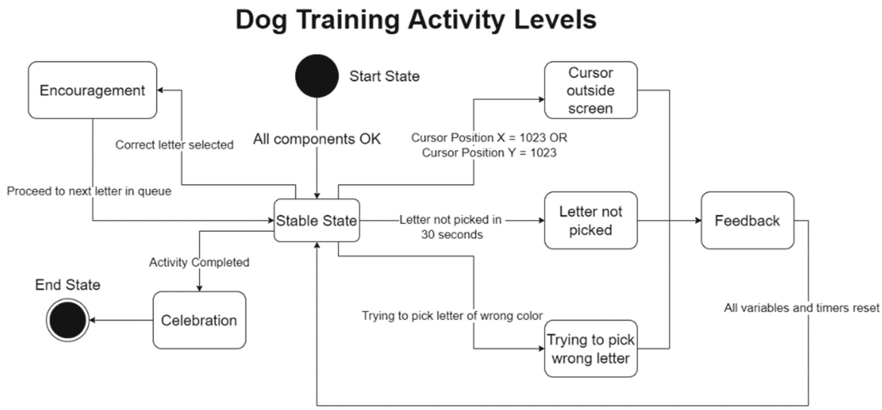

Fig. 7. State machine for the main levels

5.3 Changes to Address the Observed Problems

The following changes were made to address the issues noted in Sect. 4.3.

1. An interactive tutorial level was created where Nao provided step by step instructions and waited for the participants to complete each step. Every step had instructions and reminders after a set interval of time. A flowchart of the control logic of the tutorial is shown in Fig. 6.
2. A slider was created in the graphical user interface to control the number of extra letters that are presented on the activity screen. This was done to reduce excessive visual stimuli that led to participants being unable to find the correct letters. The slider allows the difficulty level to be determined for each pair of participants based on their cognitive function level.
3. Nao was programmed to address participants by name before giving them individualized feedback to draw their attention and avoid confusion.
4. The animations of the activity were suspended when Nao delivered instructions or feedback to reduce the number of simultaneous stimuli.

6 User Centered Design Principles

We solicited inputs from expert stakeholders (physicians, nurses, activity directors, and occupational therapists) and residents living in long term care facilities during each step of the design process. Research shows that involving target users from an early design stage results in products that are better suited to the needs of the stakeholders and better received [30–33]. The following principles of user centered design were followed:

1. Prototyping: We began the design process by creating prototypes and consulting with experts in the field as well as target users to get opinions on the concept.
2. Contextual validity: Once a prototype was selected for further development, all testing was done 'in the wild'. We conducted our testing sessions in a long-term care facility, using a similar setup that will be used for the final product, to enhance the discovery of potential obstacles.
3. Active user participation: We involved the end user from the very early stages of development starting with activity selection and prototyping to ensure the final product is acceptable and enjoyable.
4. Iterative design: After each testing session, we noted the feedback and the issues faced and addressed them in subsequent iterations.
5. Multidisciplinary design team: Our research team is comprised of engineers of various disciplines, nurses specializing in geriatrics and advised by physicians, nurses, occupational therapists, and activity directors who are all experienced in working with older adults with cognitive impairment.
6. Research flexibility: Since the testing took place outside of the laboratory, we designed the system to be modular and flexible to accommodate the many unexpected variables in the real world.

7 Data Collection

7.1 Kinect Data

We collected head pose data using the Kinect sensor to detect non-verbal communication between the participants. We assumed that if the yaw angle of the head exceeded 45° towards their partner's sitting direction, then the participant was looking at their partner. We logged the head rotation about the X, Y, and Z axis with timestamps and then isolated the instances with head yaw angle more than 45° for the left participant and less than −45° for the right participant. We verified the accuracy of the head pose detection manually from time stamped video. We also recorded audio from the sessions to detect verbal communication. This data will be later used to automatically detect participant interaction.

7.2 Physiological Data

We collected physiological data using the Empatica E4 wrist mounted sensors. E4 contains a Photoplethysmography (PPG) sensor to measure Blood Volume Pulse (BVP) from which heart rate variability can be derived, an Electrodermal Activity (EDA) sensor that measures the fluctuating electrical properties of the skin, an infrared thermopile to measure skin temperature, and a three-axis accelerometer to measure motion. We also used a similar sensor, Emotibit (emotibit.com), on one of the participants to compare its data with the E4 data to validate Emotibit as a potential alternative. The physiological data will be later used to detect stress and engagement and inform the state machine to further adapt the activity for the individual.

7.3 Activity Approval

After each session, participants completed a questionnaire and rated their comfort and confidence levels with the wand, the robot, and the VR system on a scale of 1 (least) to 5 (greatest). Each participant had performed the activity twice; their responses after the first and second sessions are summarized in the Tables 1 and 2. While the ratings are subjective and dependent on the participants' mood and well-being on that particular day, we can see an increase in the total individual scores after the second session for three out of four participants. The individual total score increased by an average of 3.5. The mean category-wise ratings also increased for five out of the six categories after the second session, with the mean increase being 0.58. After their second session, participant A1005 mentioned that while they liked the robot addressing them by name, the amount of feedback was overwhelming. They also mentioned that they had difficulty seeing the screen on that day. To address these issues, we are adjusting the feedback timing and considering other colors to improve the visibility and contrast on the screen.

Table 1. Participant ratings after first session

Participant	Wand		Robot		VR system		Total
	Comfort	Confidence	Comfort	Confidence	Comfort	Confidence	
A1001	4	4	4	4	3	4	**23**
A1002	3	2	2	3	5	5	**20**
A1004	3	2	2	3	4	5	**19**
A1005	2	2	3	4	1	3	**15**
Total	12	10	11	14	13	17	
Mean	**3**	**2.5**	**2.75**	**3.5**	**3.25**	**4.25**	

Table 2. Participant ratings after second session

Participant	Wand		Robot		VR system		Total
	Comfort	Confidence	Comfort	Confidence	Comfort	Confidence	
A1001	4	4	5	5	5	4	**27**
A1002	4	3	5	5	5	4	**26**
A1004	4	4	5	4	4	4	**25**
A1005	3	2	2	2	2	2	**13**
Total	15	13	17	16	16	14	
Mean	**3.75**	**3.25**	**4.25**	**4**	**4**	**3.5**	

8 Participant Final Thoughts

After each session, the participants were asked open-ended question: what they liked about the task, if they would like to do the task again, what changes, if any, they would like to see, and if the difficulty level of the activity was appropriate. All the participants mentioned that they liked the dog training activity and enjoyed seeing Aibo perform the tricks that they spelled out by picking the letters. Some of them wanted to play with Aibo and pet him after the session. They mentioned that they liked the moving letters and finding the correct ones. When asked if the instructions they received from Nao were clear and adequate, they said some instructions required further clarification. We made the necessary changes to Nao's instructions and when asked the same question again after their second session, they said that they were satisfied with the instructions. After their first session, one of the participants commented that having too many letters on the screen was overwhelming and they faced difficulty finding the correct ones. We implemented a slider that can regulate the number of excess letters visible on the screen. After the second session, the participants mentioned that they liked the task with reduced number of letters and did not feel overwhelmed. All of them indicated that they would like to do this activity again in the future.

9 Discussion and Conclusion

We designed this activity to keep the older adults engaged, provide physical and cognitive stimulation, and initiate social interaction. We followed the principles of participant centered design and involved the stakeholders in every step of the design process. We consulted with our panel of experts consisting of physicians, nurses, activity directors, and occupational therapists to brainstorm ideas for appropriate activities and gain an insight into the unique challenges faced by our target population. We tested our prototype activity design with two pairs of nursing faculty and incorporated the suggested changes. We consulted with older adults residing in long term care facilities to see if they would enjoy interacting with the robots and ensured that the voice of the robot and the pace of instructions was acceptable. The activity was designed to be easily modifiable and with a variety of difficulty levels to accommodate the abilities of a wide range of individuals.

A participant study involving four older adults residing in a long-term care facility showed that the activity is well received by our target population. They liked the task and the robots, especially the puppy robot Aibo. We made changes iteratively to address the problems that they faced, and the approval rating increased after their second sessions.

A limitation of this study is the small sample size. The initial aim was to conduct the study with twelve participants but due to difficulty in recruitment due to COVID-19, the number of participants had to be reduced to four. A larger sample size will enable us to test the activity on subjects with a wider range of physical and cognitive abilities and make the activity design more robust and better adapted for our target population.

Future work includes testing the system on a larger sample size, include more ways of customizing the task to make it more accommodating to a wider range of population, and using the physiological data for online stress detection to enable the system to adapt dynamically to the individual participant's abilities. We are also working on incorporating natural language processing to better identify and classify participant interaction.

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