System Architecture and User Interface Design for a Human-Machine Interaction System for Dementia Intervention

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Abstract. A growing number of older adults in America face dementia and its associated behaviors. One of the most prevalent behaviors is apathy, which leads to social isolation, reduced quality of life, cognitive decline, increased mortality and caregiver burden. Current interventions are costly and require intensive personnel resources. Given the shortage of qualified care givers, technology may be an effective and complementary approach. Research has shown that multimodal interventions that include social, physical, and cognitive activities have the best outcomes. We propose a novel system combining social robotics and virtual reality to engage older adults in tasks that target all three areas. In this paper, we describe the system architecture, which includes the Virtual system Musical Task, the social robot, the state machine, and the wand that is used as an input device. Five participants tested the system. The virtual reality and robot functioned as expected with no errors. The wand had errors below 10%. The average usability score was 89.5. Overall, this study demonstrated that the system performs as expected per the functional system requirements. Further studies are necessary to explore the functionality and usability of the system with older adults.

Keywords: Interface for disabled and senior people · Mixed reality and environments

1 Introduction

An estimated 14% of adults age 70 and older in the United States have a dementia diagnosis. As the population of older adults (65+) is projected to rise by 32 million over the next 30 years, the number of older adults with dementia is also expected to rise. Dementia results in difficulties with memory, problem-solving, language, everyday activities and often accompanied by behavioral and psychological symptoms [1]. Apathy, a syndrome with cognitive, affective and behavioral dimensions, is one of the most prevalent neuropsychiatric symptoms associated with Alzheimer's and related dementias; individuals with apathy exhibit indifference, lack of interest in activities, lack of initiative

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and poor goal-setting. Apathy leads to social isolation, further cognitive and physical decline, reduced quality of life, increased mortality and caregiver burden and frustration [2]. Apathy is difficult to treat and few pharmacologic treatments are available. Current treatments and interventions include physical activity, social engagement, and cognitive activities [3, 4], as well as music and art therapy [5, 6]. It is believed that multimodal strategies that are individualized and include physical, cognitive, and social engagement together are most successful [6]. Physical activity is known to improve voluntary motor control while cognitive activities and social engagement improve attention, visuospatial abilities and overall cognitive function [7, 8]. However, these nonpharmacologic interventions require personnel resources. There is a shortage of both formal (paid) and informal caregivers for older adults [9].

In order to address this problem, various technological intervention techniques, particularly the use of socially assistive robots (SAR) have been explored. The therapeutic baby seal robot PARO has been used to improve mood and foster social engagement [10, 11], but such intervention is passive in nature and dependent on initiative taken by the older adults and requires a trained therapist to be effective. Various SARs have been used as a fitness coach to demonstrate exercises to the older adults and provide feedback on their performance [12–14]. The socially assistive robot Brian 2.1 has been used to assist older adults in a meal eating activity [15]. Though promising, many of these SARs are built and programmed for very specific applications and hence can be limited in terms of type and variety of tasks they can perform. The use of virtual reality to administer guided exercise has also been proposed [16]. But research shows that participants are likely to respond better to instructions from physically present robots than from a virtual avatar on a computer [17, 18].

Keeping all these considerations in mind, we propose a novel system that combines social robotics with non-immersive virtual reality (VR) to create activities that encourage cognitive, physical and social engagement that can be adapted to the abilities of the individual participants. A musical task that focuses on playing a drum is presented in this paper, but the system can be adapted for a variety of multi-domain activities.

2 System Design

2.1 Architecture

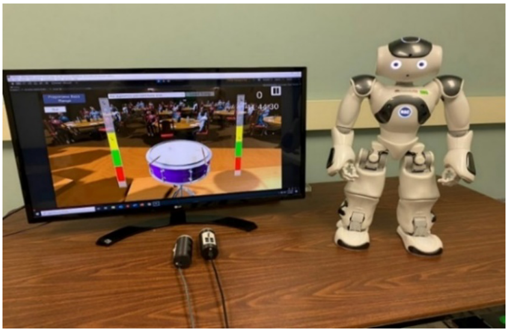


Fig. 1. System setup with VR, Wand, and NAO

The system architecture consists of four broad components: (1) a VR system presented through a computer monitor, (2) a humanoid robot as the partner and/or coach, (3) a wand that acts as an input device to interact with the VR system and as a sensor to collect data, and (4) an infrared (IR) marker used as reference for cursor position (only required for tasks that need position data). Figure 1 shows the VR environment with the humanoid robot NAO and two wands. The VR system consists of the interaction layer that interprets the data coming from the wand in the context of the current task, the communications layer that manages communication with the robot, and the state machine that controls the task, the difficulty level, score, and robot messages, encouragement/reward. The system architecture is displayed in Fig. 2.

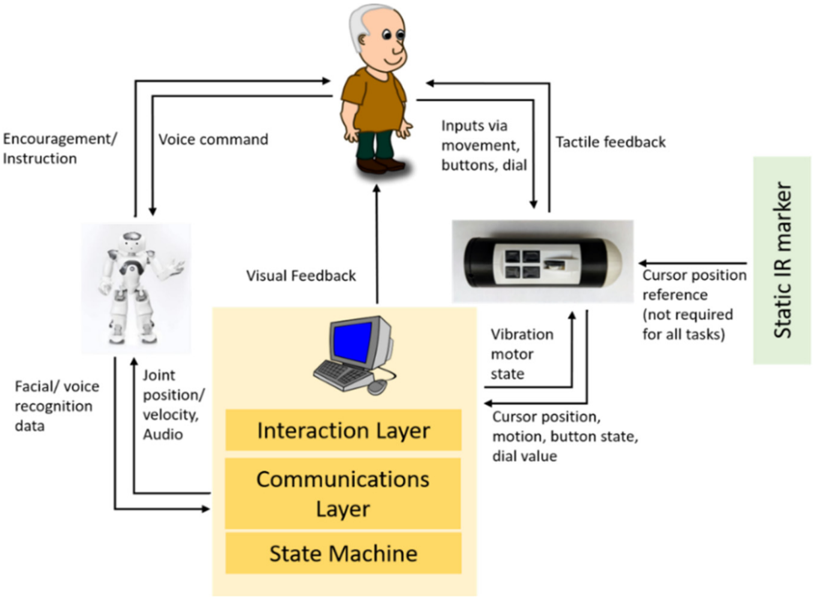


Fig. 2. System architecture with user

2.2 Task Design

The objectives of the task are to provide both physical and cognitive challenges to older adults. To fulfill these objectives the task should have components that require physical movement and cognitive effort that require the user to recognize, memorize, synchronize, sort and/or compute. The task should also have a metric to measure participant's progress and provide reward or positive reinforcement that encourages greater effort and increases focus and interaction during the task. In order to accommodate participants with different abilities, varying levels of physical and cognitive difficulty must be available. Considering the above requirements, we designed a musical task using the Unity game engine (www.unity.com).

The musical task requires the participant to play an instrument along with a song played in the virtual environment. A pre-processing step isolates the notes of a particular instrument in each song using a software-based audio spectrum analyzer. The notes are then displayed along two vertical bars, corresponding to the left and right hand, in sync with the song and NAO announces each note as it is displayed. The bars each have a yellow zone (top), a green zone (middle) and a red zone (bottom). The notes pass through each of the three zones, first entering the yellow zone at the top of the bar and exiting through the red zone at the bottom of the bar. The notes played while in the green zone corresponds to playing correctly, the yellow zone corresponds to playing too early and the red zone corresponds to playing too late. The score is increased when the participant plays in the green zone and is displayed on the upper right corner of the scene.

The participant uses two ‘wands’ for this task, each wand corresponds to a drumstick. The drumsticks are controlled by a drumming motion of the wands. The movement of the arms to play the drums provide the physical component of the task. The participant has to follow the notes and synchronize their arm motions, which provides the cognitive component. The difficulty level of each component can be varied by varying the tempo of the song and the frequency of the notes.

2.3 Wand Design

The primary means via which the user interacts with the system is through the ‘Wand’. The wand is a human interface device similar to the Nintendo Wii remote controller. Figure 3 shows the top view and side view of the wand.

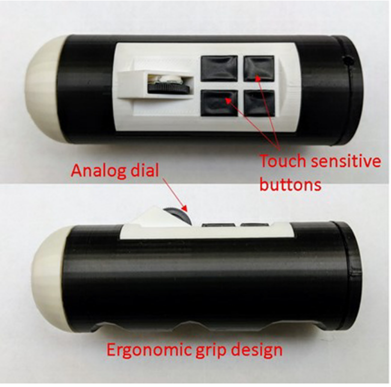


Fig. 3. Wand top and side views

The ergonomics of the wand has been designed keeping the requirements of older adults in mind and to accommodate a wide variety of palm sizes. The guidelines for hand tool designing given by the Canadian Center for Occupational Health and Safety were considered [19]. The length of the wand should be optimum; a short length will place excessive stress at the middle of the palm and if too long it will increase the weight of the device. The recommended width of handle of cylindrical-like objects is between 30 mm and 50 mm. Taking these factors into consideration, the wand has been designed with a length of 110 mm and a diameter of 40 mm. The weight of the wand is 75 g (2.65 oz). The underside of the wand includes a grip design to increase the comfort for prolonged uses and prevent slipping. The surface of the wand is a smooth hard plastic to enable easy cleaning between uses. The structure of the wand has been 3D printed to facilitate rapid prototyping and iterations based on user feedback.

At the core of the wand is an ESP32 based Node-MCU development board. The ESP32 is a dual core 240 MHz microcontroller by Espressif Systems (www.espressif.com). This microcontroller was chosen due to its relatively high processing power and built-in 12 bit analog to digital converters (ADC) and capacitive touch sensors. The wand interface includes an analog potentiometer dial connected to one of the ADC channels and four copper plated buttons connected to four capacitive touch sensors. The wand contains an Infrared (IR) positioning sensor that detects the position of up to four IR sources. The image processing and position calculation is done in hardware by the sensor itself. Using this sensor, the relative position of the wand is calculated with reference to an IR LED mounted on top of the monitor. The sensor sends the position data to the micro-controller using the i2c protocol. The wand also features an inertial measurement unit (IMU) to measure the motion and orientation of the wand. The IMU used here is the MPU9250 by InvenSense (www.invensense.tdk.com) which is a low cost, low power IMU with a three-axis accelerometer, three-axis gyroscope and three-axis magnetometer built in the same chip. The IMU connects to the microcontroller via the i2c protocol and sends raw accelerometer, gyroscope and magnetometer data at 100 Hz. The raw data are used to calculate the absolute orientation using the gradient descent method proposed by Madgwick [20].

We selected this method over other commonly used methods like complimentary filters and Kalman filters because this method is computationally inexpensive and can be computed in relatively low powered microcontrollers and, unlike complimentary filters, orientation obtained by this method remains stable over time. The orientation of the sensor frame with respect to the world frame was estimated by the numerical integration of the rate of change of orientation as measured from the gyroscope values after removal of bias. The gravity vector, known in the world frame, transformed by the orientation should be the same as the one measured by the accelerometer in the body frame. The difference between these two quantities is minimized by a gradient descent algorithm. A tunable parameter β is used as a ‘trust’ parameter that determines how much trust we will put on the gyroscope values vs the accelerometer values. The detailed mathematical equations and derivations is present in the original paper cited above.

The wand also has a vibration motor to provide tactile feedback to the user. The speed of the vibration motor can be controlled by the BJT-based motor driver using pulse width modulation (PWM). The vibration motor is turned on/off by a flag set by serial command from the computer. The wand was programmed using the Arduino IDE (www.arduino.cc). The hardware architecture of the wand can be seen in Fig. 4.

The wand communicates with the computer via USB and sends data as a string of the form (pitch, roll, yaw, position_x, position_y, button_state_1, button_state_2, button_state_3, button_state_4, potentiometer_value) and receives a single character ‘V’ to enable tactile feedback.

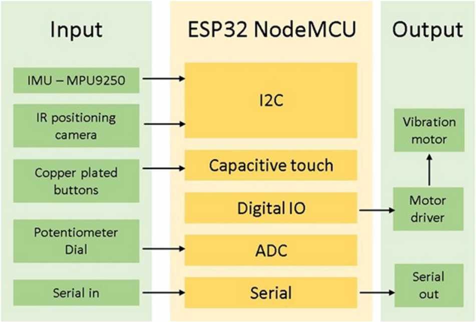


Fig. 4. Hardware architecture of the wand

2.4 State Machine

The basis of the system is interactions among the different components. We chose to use state machines to observe how each component is behaving within another component [21]. For the musical task, we use the machine to understand what errors the user has made within the game. For example, if the user is playing the game at a faster speed than directed, we change states to recognize that error. Within this error state, we can communicate appropriately with the user and the robot.

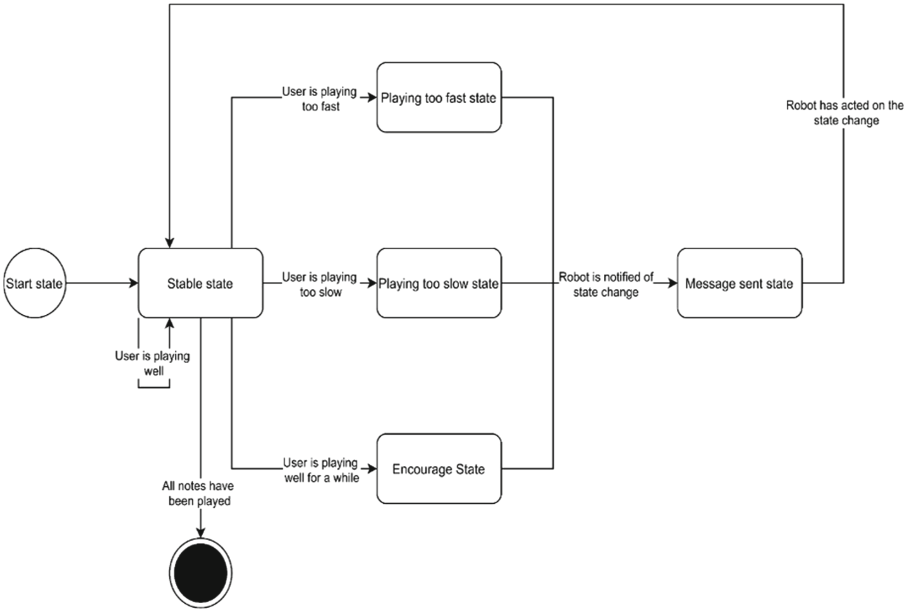


Fig. 5. State Machine for the task

For this paper, we have implemented the following states: StartState (make sure everything in the system is working as expected), StableState (the task proceeds without interruptions), PlayingTooFastState (the user hits the drum when the notes are in the yellow zone), PlayingTooSlowState (the user hits the drum when notes are in the red zone), EncourageState (the user hits the drum when the notes are in the green zone), and MessageSentState (message has been sent to the robot). These states are shown in Fig. 5.

When the system begins, the system is in StartState. In this state, preliminary tests are conducted such as whether the robot is connected, and the wands are connected. As the system is expanded with more sensors and tools, more tests can be added. Once the components are checked, the task moves into the StableState. In this state, notes are generated for the user to play and the robot is notified to alert the user to "PlayLeft" or "PlayRight". Also, the system now starts to pay attention to how the user is playing. If it notices that the user is playing too fast, it moves into the PlayingTooFastState, sends a message to the robot, moves into the MessageSentState, waits to confirm that the robot has notified the user, and then moves back into the StableState. The system moves through a similar path when it detects if the player is playing too slow or the player is playing well with states PlayingTooSlowState and EncourageState, respectively. The system moves into the final state once the song has ended.

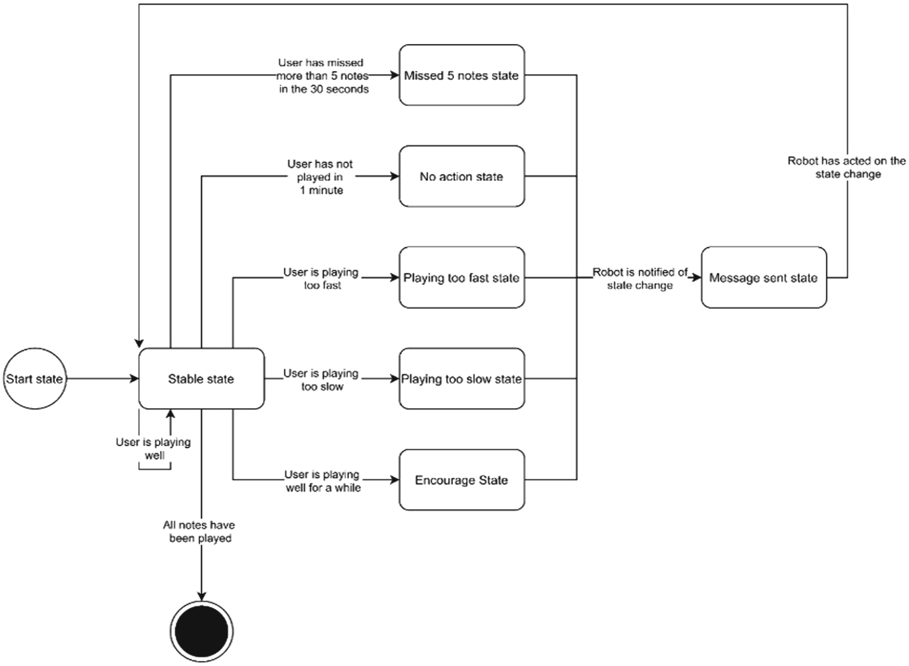


Fig. 6. Example of an expanded state machine

There are several more states that can be added to the system. As an example of how the state machine can be expanded, consider Fig. 6.

The state machine was built with the ability to be easily expanded. In technical terms, the only changes needed in order to add extra states are creating the state and its actions and a transition to the additional state. All other details are handled by the design of the state machine.

2.5 Communication Layer

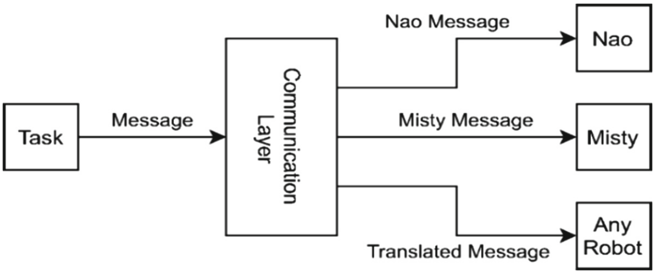


Fig. 7. Communication Layout

While building the system, we kept the expandability of robots (adding more robots in the future) in minds. Within the states, we send messages to the robot; thus, we built an intermediate layer to handle communication for different robots. The intermediate layer allows us to translate the ambiguous message such as "PlayLeft" into robot-specific messages. This design also allows us to add as many different robots as we need with changes only on the robot side and the communication layer without having to modify the task. This design can be seen in Fig. 7.

If the robot connected to the system is NAO, the steps in the communication layer are: translate the ambiguous English message to a code for NAO, send the translated message to a server, and send the message from the server to NAO. With this flow, we only need to modify a minimal amount of code to add additional robots.

3 Testing

System and usability testing was completed by five participants in order to evaluate the performance of the VR system component, the robot component, and the wand component according to their functional requirement specifications (FRS), both subjectively as a user and objectively with comparison to system logs. System usability was measured using the System Usability Scale [21] that has excellent psychometric properties of reliability and validity [22]. Participants rated comfort and confidence with each component using a questionnaire after the interaction. This study was reviewed by the Vanderbilt University Institutional Review Board and was designated as exempt research. COVID-19 precautions, such as face coverings, disinfecting between users, and social distancing, were used in order to keep the researchers and participants safe.

Participants began by completing a demographic and technology use questionnaire. Of the five participants, 2 were female and 3 were male. All of the participants had completed or were enrolled in an engineering based Bachelor's program and rated their technology skills high (above 7/10). After completing the pre-questionnaire, the participant played one song lasting approximately 3 min and 30 s using the wands in the virtual

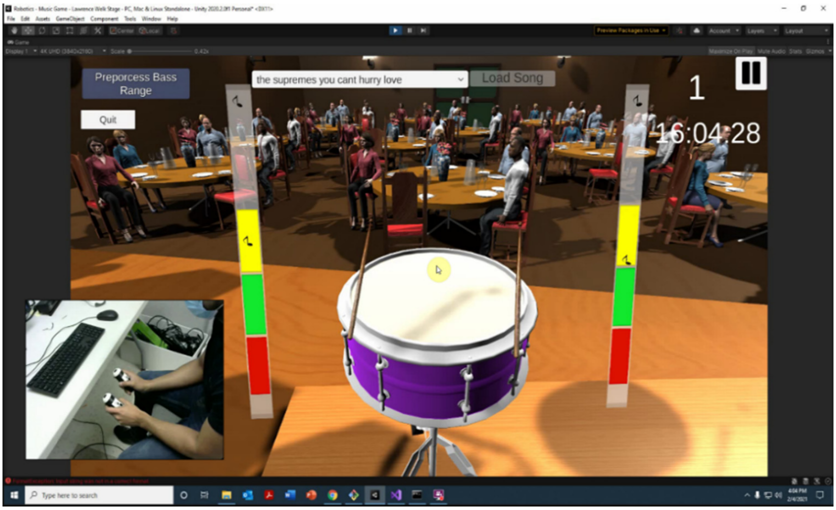
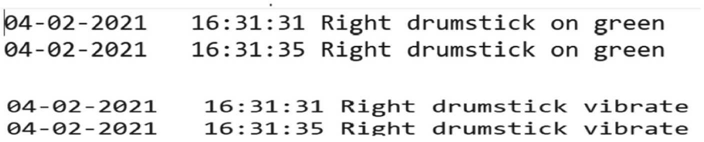


Fig. 8. Video Recording and View of Testing Setup

task. Participants were asked to purposefully play in the yellow and red zone for a few notes in order to test the state transitions and logging in each section. After the task, they completed the SUS and a post questionnaire about their confidence and comfort level with the system components.

The task was set up and recorded by Flashback Express (www.flashbackrecorder.com) so that the virtual environment and video footage were recorded simultaneously as shown in Fig. 8. A timestamp was also displayed for comparison of video footage to the generated logs. The first set of logs included timestamps and in which colored area the system documented the note was played for both left and right wand. The second set of logs included time stamps when each wand relayed haptic feedback to the user. An example of both log outputs can be seen in Fig. 9. A haptic feedback is expected in the wand when the corresponding drumstick comes in contact with the surface of the drum in the virtual environment. The researchers independently compared the logs to the video recordings to evaluate the accuracy and fulfillment of the FRS.



```
04-02-2021   16:31:31 Right drumstick on green
04-02-2021   16:31:35 Right drumstick on green

04-02-2021   16:31:31 Right drumstick vibrate
04-02-2021   16:31:35 Right drumstick vibrate
```

Fig. 9. Example of log output

The main FRS of the VR system includes the note generation, tracking the user's score, logging colored area when the note was hit, and generating the drum sound at the correct time. The notes should be spawned in such a way that it keeps the user engaged and follow the rhythm of the song. The score tracking and note logging are used to inform the state machine and should be accurate, defined as less than 10% error rate. The drum noise generation should also be in sync with the note playing in order to not distract the user.

The robot is expected to maintain connection with the system at all times, without failure. The accuracy of the robot providing direction was evaluated by comparing when the robot says ‘left’ and ‘right’ to which side the note had appeared. For state transition, the robot is expected to say “You are doing great!” after five consecutive hits in the green zone; “You are playing too fast” after five consecutive hits in the yellow zone; or “You are playing too slow” after five consecutive hits in the red zone. The logs and video were used to confirm that the robot changes states correctly.

The wand should provide haptic feedback when the user makes contact with the drum in the virtual world. Logs of vibration were compared to the videos to measure that the haptic feedback occurred when a note was played. There should be no perceptible delay between the user making the drumming motion and the drum being played in the virtual environment. Finally, unintended hits of the drum when the user is not moving or missed hits when the user does move but it is not captured by the system were evaluated with an a priori error rate of 10% considered acceptable.

4 Results and Discussion

4.1 System Testing Results

For testing our system, we focused on the role of the three main components; (1) the VR system; (2) the robot component; and (3) the wand component. For the task, we tested to ensure that the notes were generated correctly, the score was kept accurately, and the task reacted in real time to wand input. The video recordings from the five participants were analyzed and used as ground truth to compare against logs generated by the system to measure the accuracy of all the components of the system.

The VR system was able to generate the notes, track the user’s score and accurately log the colored areas in which the note was played. The notes were spawned randomly while still matching the music, which kept the participants engaged and on task. The drumming sound was in sync with the wand. Overall, the functional system requirements of the VR system were met with no adjustments needed.

The robot component was tested based on whether the robot provides correct direction to the user on how to play the notes (either play the left or right note), remain connected to the system and communicate appropriately, and observe the state transitions. This component of the system also behaved with 100% accuracy. The robot was able to provide time and performance appropriate feedback. We would like to highlight that the state transitions were accurately interpreted by the robot without delay or loss of information.

The final component we tested was the wand with the criteria of whether the haptic feedback occurred correctly, the drum was hit without the intention of the user, the user intended to hit the drum but it did not occur, or the drum hit was registered twice instead of once. The haptic feedback did not have any errors; however, we did find errors for the other criteria. With our testing, we know that the drum was hit 362 times with all

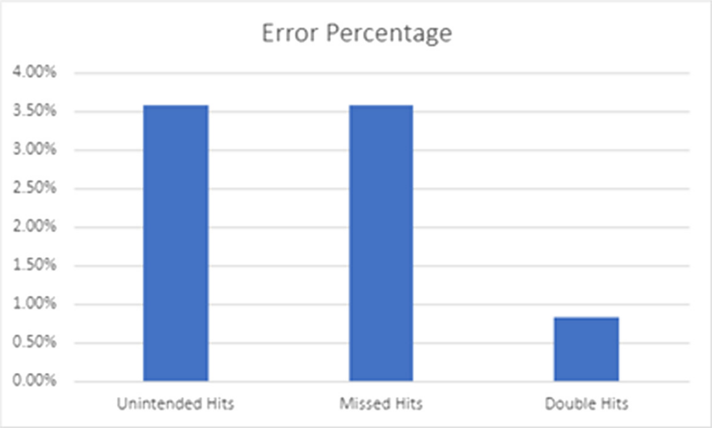


Fig. 10. Overall error percentages for hits on the drum

participants combined. Out of these hits, a total of 13 hits were unintended, 13 were missed, and 3 registered as double. The error percentage is shown in Fig. 10. While there was some error, it was well below our 10% acceptance margin. It should also be noted that no participant had a total wand error percentage above 10%, as can be seen in the Fig. 11 below. While the error level is low, it should be addressed in order to improve overall performance and user experience.

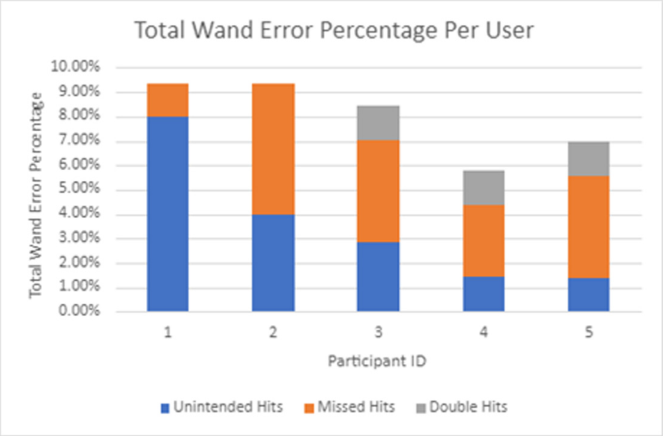
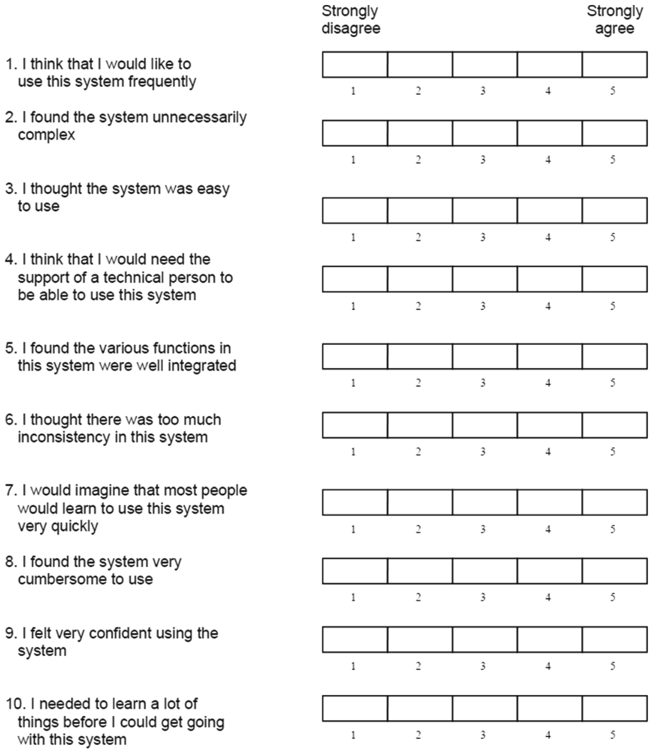


Fig. 11. Total wand error percentage for each user

4.2 Usability Results

The System Usability Scale (SUS) is used to measure the perceived usability of the system. This scale is used across a wide variety of hardware, software, websites and validated with an empirical evaluation in which a comparison of 200 studies that used the SUS as a “robust and versatile tool for usability professionals” [21, 22]. Figure 12 shows the standard version of the SUS. In order to calculate the system usability score, the scale position of even numbered items is subtracted from 5. For odd numbered items, 1 is subtracted from the scale position. This scales all of the responses to a scale of 1–4 with 4 being the most positive response for each question. The sum of the questions is multiplied by 2.5 to get an overall SUS score ranging between 0–100. This score represents the user’s perception of the usability of the system.



	Strongly disagree				Strongly agree
1. I think that I would like to use this system frequently	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
2. I found the system unnecessarily complex	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
3. I thought the system was easy to use	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
4. I think that I would need the support of a technical person to be able to use this system	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
5. I found the various functions in this system were well integrated	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
6. I thought there was too much inconsistency in this system	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
7. I would imagine that most people would learn to use this system very quickly	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
8. I found the system very cumbersome to use	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
9. I felt very confident using the system	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
10. I needed to learn a lot of things before I could get going with this system	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5

Fig. 12. Standard version of the system usability scale

Participants’ SUS scores ranged from 85 to 95 with an average SUS score of 89.5. In general, a score above 68 is considered average while an SUS score above 80.3 is considered excellent [22]. This suggests that the system is very usable compared to other systems that were tested using the SUS. The item results are shown in Fig. 13 and it can be seen that overall, the responses to the questions did not have much variability, suggesting that the system is perceived as usable and not complex. The participants were able to figure out the system with little to no input from the researchers and enjoyed the interaction. Even though they were not the target group, the participants, on average, indicated that they would like to use the system again which suggests that overall the system is engaging. However, it is important to note that the current participants all rated their technology skills as high and therefore may view the system as more easy to use than the target population of older adults. Future studies with the target population are necessary to confirm the SUS results.

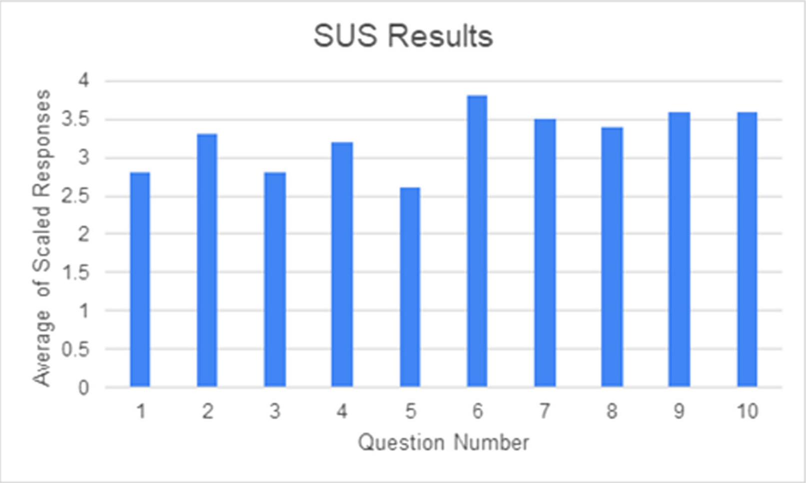


Fig. 13. Average scaled SUS responses per question

4.3 Post Questionnaire Results

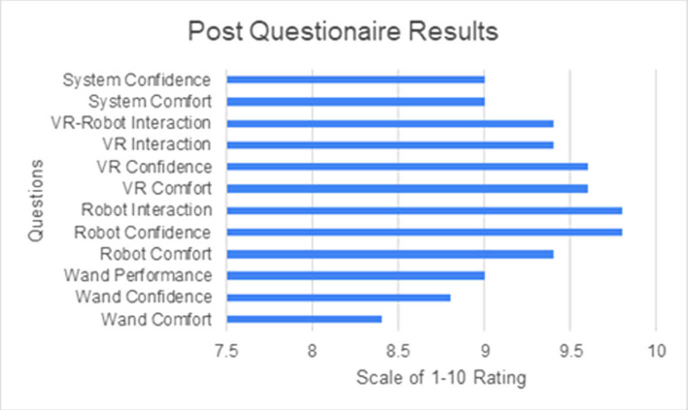


Fig. 14. Post questionnaire average results per question

In the post questionnaire, we tested the comfort and confidence the users felt with our system on a scale of 1–10. We asked the participants for their opinions on their comfort with using the components, confidence on how they felt using them, their interactions with the components, and the intracomponent interactions. The results of the questionnaire are shown in Fig. 14 as averages of the answers from the users. The wand comfort and confidence had the lowest scores, which is consistent with the error percentages as no other system component had errors. For the wand, qualitative feedback included the desire for rubber grippers on the side of the wand and decreased sensitivity to address the unintended and double hits. Missed hits were often caused by two notes spawning too close together. We will include a delay between notes to address this problem. While the overall percentage wand errors were low, it was noticed by participants and will be addressed in future works. Suggestions for improvement of the robot interaction included the addition of new feedback beyond the current states. As discussed previously, the state machine will be expanded to incorporate varied feedback. Overall participants were very positive about the system with the main feedback expressing desire for more song choices.

5 Conclusion

Based on the results of our study, the state machine, the task, the robot, and the wand work well within our margin of acceptable error. User feedback indicates that the system is easy to use, the components interact well, and overall confidence and comfort level with the system is high. There is no component of the system with major problems.

Limitations of this study include small sample size and the fact that the participants are not the target population. Further studies are necessary to explore the functionality and usability of the system with older adults. Overall, this study proved that the system performs as expected per the functional system requirements.

Future work includes further development with the addition of new states and expansion of the task. New tasks will also be added to allow for more utilization of the wand. Natural language processing for the robot, physiological data tracking of the user, and expanded sensors to inform the state machine will also be integrated. This system has opened several possible research routes to be followed.

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