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Comparing Ultrasonic and Force Feedback to Foster Older Adults' Engagement in Cognitive Activities Facilitated by a Social Robot

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Abstract. Engaging in cognitive activities early and regularly has been shown to improve cognitive performance and delay the natural progression of cognitive decline for older adults. Many factors can make it difficult to achieve this, such as lack of engagement, highlighting the potential for technology to enhance engagement with cognitive activities. This paper investigates the unique combination of haptic feedback and a Socially Assistive Robot (SAR) during categorization-based activities. In this experiment, passive and active kinesthetic force feedback led to improvements in factors such as usability and affective state compared to non-contact cutaneous (ultrasonic) feedback. The robot facilitation positively impacted older adults' performance and their perception of usability and interactivity compared to using a laptop. Some design considerations emerged including the themes of control and informativeness of haptic feedback and the proxemics of the robot. This work supports the combination of haptic feedback, specifically force feedback, along with a SAR to foster engagement with cognitive activities for older adults.

Keywords: Haptic feedback · Kinesthetic force feedback · Ultrasonic feedback · Socially assistive robots · Cognitive activities · Older adults

1 Introduction

Cognitive decline is a natural part of aging, but steps can be taken to slow its progression such as engaging in cognitive activities early and often [24]. Formalized treatments such as cognitive training (CT) have been shown to improve cognition [3], the benefits of which can persist over an extended period of time [24]. However, many factors can impede access and adherence to treatment including logistical considerations, depression, and lack of motivation [6]. Engaging in cognitively stimulating leisure tasks (such as Sudoku) has also been associated with

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higher levels of cognitive performance [8], suggesting that a formalized approach is not necessary to achieve a similar benefit.

Technology that can increase engagement with cognitive activities has the potential to greatly assist older adults in slowing the rate of cognitive decline. Current CT activities and most leisure-based activities rely on auditory and visual feedback to provide information to the user [14], highlighting the unique opportunity to introduce haptic feedback. Delivering feedback through different modalities can also provide more flexibility in engaging with cognitive activities whereas sensory perception declines with age [15]. Haptic feedback, both on its own, and in combination with other forms of sensory feedback has resulted in improvements in engagement and performance in cognitive activities [12].

In this paper, we investigate non-contact cutaneous ultrasonic feedback, and kinesthetic force feedback whereas both have been shown to have a positive impact on user experience. Limerick *et al.* found ultrasonic feedback elicited similar levels of engagement to gamification in the context of interactive digital signage [13]. Force feedback has been previously investigated in the context of virtual reality, where it was more effective in terms of precision of movement, mental workload, and spatial orientation compared to vibrotactile and visual feedback [23]. To our knowledge, neither ultrasonic feedback nor force feedback have been previously investigated in the context of engaging older adults in cognitive activities.

This work also integrates socially assistive robots (SARs), which have the added benefit over current technology-based cognitive activities of being able to provide social engagement [1]. Physically embodied SARs have further demonstrated improvements in engagement and performance compared to virtual agents [21]. With respect to pen and paper CT (e.g., [14]) or screen-based tasks, previous research has shown physically embodied SARs allow for improved levels of engagement and cognitive function over the short- and long-term [1].

Haptic feedback has previously bee integrated into SARs for older adults, such as providing affective touch in companionship robots [20]. However, there is limited previous work investigating the combination of sensory feedback and SARs aimed at improving older adults' engagement in cognitive activities. Namely, in a robot-facilitated memory activity across both young [16] and older adults [17], unimodal auditory feedback was preferred and resulted in the most consistent improvements in performance compared to unimodal and multimodal vibrotactile feedback. Whereas auditory feedback is processed separately neurologically from visual and spatial information [22], and as such the combination of modalities should not be too taxing, the authors speculated this unimodal preference was due to the nature of the activity, which also required visual and spatial cognitive resources. This paper expands upon this work by comparing different types of haptic feedback on a different type of task. To assess this novel combination of SARs and haptic feedback in this context, we investigate the following research questions:

RQ1: Does force feedback or ultrasonic feedback better support older adults' engagement in cognitive activities?

RQ2: Does having a SAR facilitate cognitive activities improve the interaction with older adults compared to using a laptop alone?

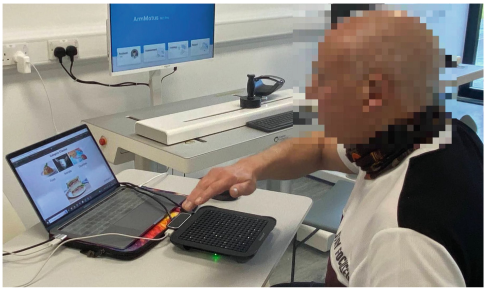
2 Methodology

This was a 2(haptic feedback) x 2(experiment facilitation) within-subjects experiment. It compared two types of haptic feedback: ultrasonic feedback (Category Checker activity) and force feedback (Clever Mind activity). The experiment was facilitated by either the SAR or video and audio delivered over a laptop. The only intervention made by an operator during each phase of the study was triggering pre-programmed technical scripts to execute the robot's behaviour and activities on each haptic device. See the experimental setup in Fig. 1.

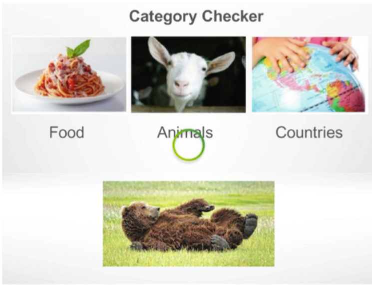
Fig. 1. Experimental Setup

2.1 Participants

This experiment received ethical approval by Heriot-Watt University. We recruited 27 independently living older adults aged 65 and older. They each received a £10 voucher as a thank you for their participation. Data was omitted for 2 participants due to technical issues, resulting in 25 participants (M = 73 years, 13 female, 12 male). No participants indicated having a tactile impairment. The 17 participants who indicated a visual impairment wore a corrective device. To account for any hearing impairments, the volume of the SAR and the laptop were adjusted to each individual's preference. No participants previously interacted with the force feedback device, 7 previously interacted with the ultrasonic feedback device, and 11 previously interacted with SARs through other academic experiments.

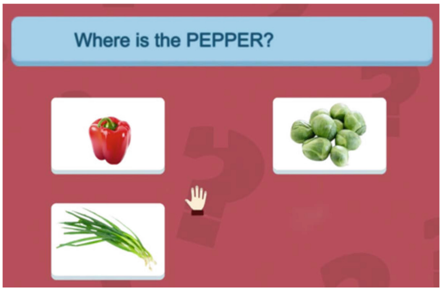


(a) Ultrasonic Feedback Device



(b) Category Checker Activity

(c) Force Feedback Device



(d) Clever Mind Activity

Fig. 2. Haptic Devices and their respective activities.

2.2 Haptic Feedback

Ultrasonic Feedback Device. Participants engaged with the **Category Checker** activity (Fig. 2b), which we developed on the STRATOS Explore device from Ultraleap (Fig. 2a). The activity originated from an exercise by the same name in the pen and paper CT resource Brainwave-R [14]. The Category Checker required the participant to categorize the image at the bottom of the screen by selecting one of the three categories: food, animals, or countries (Fig. 2b). The green circular cursor was controlled by the participant hovering their hand over the ultrasonic feedback device (Fig. 2a), and an item was selected by holding the cursor over a category for one second. While moving the cursor, the participant received ultrasonic feedback on their palm. During the one second while a category is being selected, the sensation changed from a singular point of feedback on their palm to a circular motion, similar to a loading cursor, and the center of the cursor turned orange.

Kinesthetic Force Feedback Device. Participants engaged with the **Clever Mind** activity (Fig. 2d) through the ArmMotus^{TM} M2 Pro from Fourier Intelligence (Fig. 2c). Clever Mind was already integrated into the force feedback device, and it asks the participant to select the image that fits the described category. The hand cursor was controlled using the joystick on the force feedback device requiring the participant to move their arm on the horizontal plane. When the participant moved the joystick, the device provided continuous passive force feedback of 17.5 N in the opposite direction of movement. The participant held the cursor over an item for one second to select their answer. During this one-second selection, a blue circular progress bar loads around the cursor. The force feedback also pulled them back to the center after each round, ensuring they were starting from the same place before answering the next question (active force feedback). Due to the nature of interacting with the joystick, it took longer to execute one round with the force feedback device compared to the ultrasonic feedback device.

Boredom can have a large impact on user attention [7], and lack of attention could have had a detrimental impact on the evaluation measures (Sect. 2.4). Slightly different activities were chosen across the haptic devices to combat the potential for boredom. However, they are both categorization-based activities (i.e., requiring the participant to select the category versus selecting the image that fits within the described category - Fig. 2b and d). The activities were also analogous in terms of workload by requiring a similar level of visual processing. In both activities, the cursor was held over an item for one second to select their answer, during which a visual aid was used to indicate progress over this one-second selection period. This similarity across these activities allowed for the direct comparison of the haptic feedback addressed in this work.

2.3 Experiment Facilitation

Socially Assistive Robot Condition. In this condition, the robot acts as a facilitator to the interaction, similar to how a therapist would in a CT session (i.e., by providing detailed instructions and verbal encouragement) [6]. The ARI robot from PAL robotics (Fig. 1) was chosen based on a prior Participatory Design workshop [provisionally accepted for publication] comparing SAR embodiments in the context of this research. The SAR was positioned to facilitate the interactions with both haptic devices (Fig. 1). Besides a brief instructional video, the SAR's tablet was blank when it was verbally engaging with the participant. While facilitating the activity, the SAR offered six phrases of verbal encouragement evenly-spaced throughout the three-minute interaction (e.g., "keep going", "great work"). These were triggered by the research after correct responses, and the phrase "almost there" was initiated approximately 10 s before the end of the 3-minute interaction.

Laptop Condition. This condition exemplifies common forms of interaction with digital CT and cognitive activities through a mobile phone, tablet, or laptop/computer, which deliver visual and auditory feedback [6]. Verbal encouragement was not provided because it is not normally provided during CT or cognitive activities on these devices, which makes this condition more indicative of a typical interaction. The same voice and instructional videos were used as the SAR facilitation, but in this instance, the audio and video were played through a laptop (Fig. 1). Although the SAR was present, the emergency stop had been engaged, causing the robot's head and arms to lower, rendering it motionless and silent. This was done to keep the experimental conditions constant.

Table 1. Protocol. Conditions A-D were counterbalanced across participants.

Phase	Duration (minutes)
Condition A: Laptop Facilitation/Ultrasonic Feedback	
1.0 Category Checker Introduction	2
1.1 Category Checker Training	3
1.2 Category Checker Interaction	3
1.3 Evaluation Measures	7
Condition B: SAR Facilitation/Force Feedback	
2.0 Clever Mind Introduction	2
2.1 Clever Mind Training	3
2.2 Clever Mind Interaction	3
2.3 Evaluation Measures	7
Condition C: SAR Facilitation/Ultrasonic Feedback	
3.0 Category Checker Interaction	3
3.1 Evaluation Measures	7
Condition D: Laptop Facilitation/Force Feedback	
4.0 Clever Mind Interaction	3
4.1 Evaluation Measures	7
SAR Evaluation and Semi-Structured Interview	
5.0 The Robotics Social Attributes Scale (RoSAS)	5
5.1 Semi-Structured Interview	20
Total Duration: 1 hour 5 mins (not including two 5-minute breaks)	

2.4 Protocol

The conditions were counterbalanced across participants. Firstly, the activity instructions were provided by either the SAR or a video shown through a laptop (Table 1 Phases 1.0 and 2.0). Then the participant was asked to engage with the activity until they were comfortable with it (Table 1 Phases 1.1 and 2.1), similar to the procedure by [11]. Afterward, they interacted with the activity for 3 min (Table 1 Phases 1.2, 2.2, 3.0, and 4.0), where performance was recorded (number of correct, incorrect, and total inputs). To attain a holistic assessment of the participants engagement, they completed evaluation measures (Table 1 Phases 1.3, 2.3, 3.1, and 4.1) that assessed workload (NASA-Task Load Index (TLX) [10]), motivation (Intrinsic Motivation Inventory (IMI) [18]), usability (System Usability Scale (SUS) [4]), and affective engagement (Emotion Wheel [2]). After completion of the four experimental conditions, the participants filled out the Robotics Social Attributes Scale (RoSAS) [5] to attain their perspectives on the SAR (Table 1 Phase 5.0). The experiment concluded with a semi-structured interview (Table 1 Phase 5.1) centered around their experience with the types of experiment facilitation and haptic devices.

3 Results

This section will review the outcomes from analyzing the objective and subjective measures, followed by the qualitative analysis of the semi-structured interviews. The repeated measures ANOVA method was employed, and all reported post hoc testing used the Bonferroni technique for correcting pairwise comparisons. Descriptive statistics can be found in Table 2.

Table 2. Means and standard deviations of the significant main effects across evaluation measures and independent variables (experiment facilitation and haptic feedback administration). (*$p \leq 0.05$, **$p \leq 0.01$, ***$p \leq 0.001$)

	SAR	Laptop	Ultrasonic	Force
Correct Inputs	34.2 ± 17.9*	31.7 ± 16.9	46.5 ± 15.5***	19.4 ± 1.7
Incorrect Inputs	0.7 ± 1.3	0.7 ± 1.0	0.9 ± 1.5	0.5 ± 0.8
Total Inputs	34.8 ± 17.9*	32.4 ± 16.7	47.3 ± 15.0***	20.0 ± 1.4
NASA-TLX (out of 100)	28.5 ± 23.8	32.7 ± 26.2	38.5 ± 26.4*	22.7 ± 21.0
IMI (out of 7)	4.4 ± 1.8*	4.5 ± 1.8	4.6 ± 1.6	4.4 ± 1.9
SUS (out of 100)	77.0 ± 19.4*	73.1 ± 22.5	62.5 ± 22.0***	86.8 ± 10.9

3.1 Objective Measures

The objective data collected was the participants' performance scores, which included the correct, incorrect, and total number of inputs they achieved during each three-minute activity interaction. The data was normalized prior to the analysis to account for the difference in the amount of rounds completed between the haptic devices (it took longer to complete a round with the force feedback device than the ultrasonic feedback device).

A significant interaction was found for the number of correct inputs ($F(3,92) = 4.47$, $p = 0.005$, $\eta_p^2 = 0.13$). The subsequent post hoc analysis indicated that the SAR facilitation led to more correct inputs with the ultrasonic feedback device ($p = 0.035$, M = 0.58, SD = 0.23) than the laptop facilitation with the force feedback device (M = 0.12, SD = 0.03).

There were no significant main effects found for the number of total inputs across the haptic feedback and experimental facilitation conditions. There were also no significant main effects found for the number of incorrect inputs. This is likely due to the limited number of incorrect responses (Table 2).

3.2 Subjective Measures

The NASA-TLX resulted in a main effect for the haptic feedback (F(1,24) = 18.71, p<0.001, η_p^2 = 0.99), where the ultrasonic feedback device had higher workload compared to the force feedback device (Table 2) across all subscales: mental demand, physical demand, temporal demand, performance, effort, frustration, and overall workload. The experiment facilitation conditions did not result in any significant differences in this workload measure.

The sphericity assumption was not met for the IMI subscales, so the Greenhouse-Geisser values are reported (F(3,72) = 10.20, $p < 0.001$, $\eta_p^2 = 0.30$). Specifically, the ultrasonic feedback device resulted in higher effort/importance (p = 0.044, M = 5.7, SD = 1.0) compared to the force feedback device (M = 5.2, SD = 1.3). The ultrasonic feedback device was also rated higher in terms of pressure/tension ($p < 0.001$, M = 3.1, SD = 1.5) compared to the force feedback device (M = 2.0, SD = 1.0). There was a main effect for experiment facilitation (F(1,24) = 5.58, p = 0.027, η_p^2 = 0.19), where the laptop condition resulted in higher intrinsic motivation overall compared to the SAR condition (Table 2).

The usability assessment revealed a main effect for haptic feedback (F(1,24) = 35.30, $p < 0.001$, $\eta_p^2 = 0.60$), where the force feedback device had significantly higher usability ratings compared to the ultrasonic feedback device. There was also a significant main effect for experiment facilitation (F(1,24) = 388.09, p = 0.032, η_p^2 = 0.18), where the SAR received significantly higher usability scores compared to the laptop condition.

The results of the RoSAS measure show relatively high levels of competence (M = 5.33 out of 7), mid-level of warmth (M = 3.64 out of 7), and low levels of discomfort (M = 1.56 out of 7).

In Fig. 3, not all data points are visible because many overlap each other. Seventy-seven percent of responses were on the positive half of the scale. The SAR condition had slightly more points on the positive side of the wheel (81%) compared to the laptop condition (75%). The force feedback condition had 89% of the points on the positive side of the scale, and the ultrasonic feedback had 66% of the points on the positive side of the wheel. The force feedback/SAR condition had the most data points on the positive side of the wheel (25 out of 26). A portion of the data is in the negative/active quadrant, most of which are from the ultrasonic feedback interaction.

3.3 Qualitative Results

The semi-structured interviews were analyzed using the constant comparative method of grounded theory [9]. A researcher not engaged with this work but familiar with the methodology validated 20% of the data. This section will review the themes that arose from the resulting analysis.

Control and Cognitive Load. Participants mentioned control frequently, where the force feedback device provided more control over the interaction due to being able to physically touch it. With the ultrasonic feedback device, some

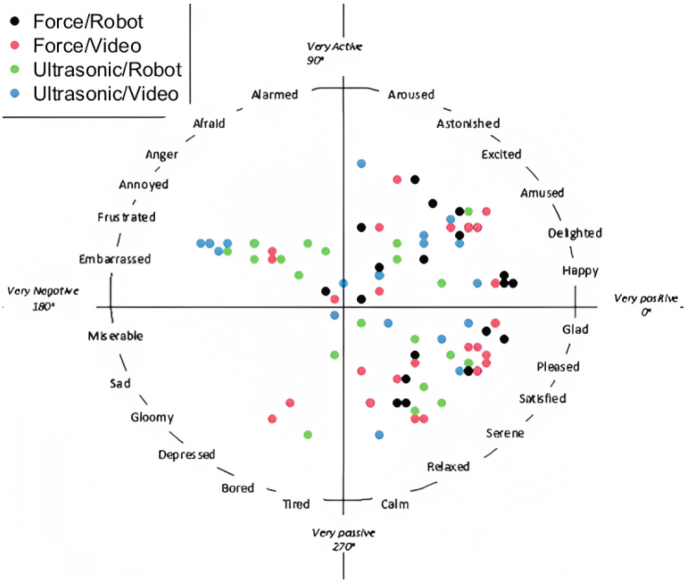


Fig. 3. Emotion Wheel

participants had difficulty keeping their hand in the correct position to maintain the cursor, which made them feel less in control. Participants' cognitive load was mainly taken up by the activities. One participant said the haptic feedback was "so much a part of what [they were] doing and so appropriate that [they weren't] 100% aware of it all the time."

Engagement and Interactivity. Many participants had reactions to the system that indicated engagement with the interaction. Words like 'fun' 'interesting,' and 'sci-fi-like' were used to describe the haptic feedback devices. Some felt the SAR's phrases of encouragement positively impacted their engagement. With respect to the interactivity of the technology, one participant said the force feedback device was "replying to me, communicating in a way." One main factor that may have impacted the interactivity of the SAR was its proxemics in relation to the haptic devices (Fig. 1). Because it was in their peripheral vision, they felt the SAR was more in the background. Even so, the presence of the SAR had a positive impact on the interaction, with one participant stating it was "like you [were] engaging with a person."

Feedback Adaptability and Informativeness. Different interaction preferences suggests the need for feedback adaptability. Some participants preferred the SAR's verbal encouragement to visual prompts on the screen. Others enjoyed having more than one modality of feedback (e.g., ultrasonic feedback and the cursor turning orange to indicate selecting a category). Participants appreciated informative feedback, like how the ultrasonic feedback indicated they had control of the cursor. The force feedback device pulling the participant back to the center let them know they were getting ready for the next round.

4 Discussion

RQ1: *Does force feedback or ultrasonic feedback better support older adults' engagement in cognitive activities?* The outcomes from this experiment indicate a preference for force feedback compared to ultrasonic feedback, including ratings of higher usability, lower workload, and 23% more positive affective ratings (Sect. 3.2). The difference in pacing between the two interactions may have also influenced their preference for the force feedback device. However, those who preferred force feedback often referred to their preference being due to feeling more in control and connected to the device. By extension, they experienced less control when interacting with the ultrasonic feedback device. Also, one participant described the force feedback device as "replying" and "communicating" with them (Sect. 3.3). This supports literature suggesting bi-directional exchange can be achieved through haptic feedback [19].

The ultrasonic feedback device also received many positive indicators; it resulted in high performance, relatively low workload (Table 2), and positive affective state for the majority of the interactions. The subset of active and negative emotions displayed in Fig. 3 could be due to reactions to losing the cursor while interacting with the device. Participants also rated the ultrasonic feedback device higher in terms of effort/importance and pressure/tension, which suggests they attributed higher internal motivation to ultrasonic feedback compared to force feedback (Sect. 3.2). Notably, the absence of the ultrasonic feedback informed participants when they lost the cursor, indicating that not just the existence, but also the absence of feedback, can be leveraged to optimize interaction.

It is important to discuss how the integration of sensory feedback (e.g., visual, auditory, haptic) is task-dependent, and the neurological literature supports this [22]. With respect to this experiment, it was vital the chosen activities were very similar to ensure the comparability of the haptic feedback. In Nault et al. [16] [17], discussed in Sect. 1, the preference for unimodal auditory feedback was attributed to the tactile nature of the activity, where adding more tactile feedback in the form of a vibrotactile device potentially overloaded that sensory channel. In contrast, the haptic feedback did not appear to result in this sensory overload in this experiment. This highlights the importance of ensuring the feedback is adaptable not only to the individual's preferences, but also to the nature of the activity. In conclusion, this experiment resulted in a preference for kinesthetic force feedback over non-contact cutaneous (ultrasonic) feedback to assist in engagement with categorization-based cognitive activities for older adults (***RQ1***). However, further research would be needed to conclude whether this result extrapolates to all types of cognitive activities.

RQ2: *Does having a SAR facilitate cognitive activities improve the interaction with older adults compared to using a laptop?* The SAR received higher usability scores and a more positive affective state compared to the laptop condition, without hindering the workload. It was also perceived to have high levels of competence, low levels of discomfort, (Sect. 3.2) and provided a social presence (Sect. 3.3). The significant interaction showed the SAR assisted the participants to perform better in the activity with the ultrasonic feedback device compared to the laptop condition with the force feedback device. This may be due to the increased workload with the ultrasonic feedback device, suggesting a SAR may be particularly helpful at improving users performance during interactions with higher workload. These improvements in performance are consistent with previous work that displayed the positive impact a SAR can have on rehabilitation performance [21]. Interestingly, the laptop condition received higher overall intrinsic motivation scores compared to the SAR condition, which could have been impacted by the novelty effect of the SAR. However, it is also possible that the SAR provided a level of external motivation that could have overshadowed their internal motivation, which would not have been captured by the IMI assessment.

In this experiment, the proxemics of the SAR was restricted by the placement of the haptic devices (Fig. 1). While not directly assessed, this placement potentially helped limit the cognitive load of the SAR, therefore freeing up cognitive resources to focus on the activity. This in turn could have allowed them to perform better (Sect. 3.1). Regarding ***RQ2***, this experiment showed the SARs facilitation of cognitive activities improved the interaction over laptop alone. This outcome supports the growing body of literature highlighting the increased benefit of physically embodied SARs over typical practices [1].

5 Conclusion

This work investigated the novel combination of two types of haptic feedback and a socially assistive robot with the aim of enhancing engagement in cognitive activities for older adults. Kinesthetic force feedback was the preferred form of haptic feedback over non-contact cutaneous (ultrasonic) feedback in the context of the categorization activities chosen for this experiment. The force feedback device had lower workload, higher usability, and 23% more positive ratings, comparatively. The introduction of a SAR to facilitate and provide encouragement to the participant resulted in improvements in the interaction (e.g., higher usability) compared to typical means of engaging with digital cognitive activities. This work further lays out some design considerations such as the feeling of control and the need for feedback adaptability in order to facilitate an engaging haptic interaction. Moving forward, a long-term assessment would be appropriate to determine whether these effects are maintainable. This paper sets a foundation for the use of haptic feedback, specifically force feedback, in combination with a SAR to foster engagement with cognitive activities for older adults.

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