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Mixed Reality Shopping-task-based Intervention for Cognitive Engagement in Aging

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As global aging accelerates, the prevalence of mild cognitive impairment (MCI) continues to rise, highlighting the need for ecologically valid cognitive-motor rehabilitation technologies that can enhance users' motivation, adherence, and training intensity. In this study, we developed a mixed reality (MR) supermarket shopping system that leverages head-mounted and hand-tracking sensors to capture users' cognitive and motor performance in realistic daily activities, such as price calculation and beverage preparation. Fifteen older and twenty young adults (older adults: 54–65 years; young adults: 19–21 years) participated in 30 min MR-based shopping tasks using a Meta Quest 3 headset. System usability, workload, sense of presence, game experience, simulator sickness, and physiological responses were evaluated. Results showed that both age groups rated the system as usable and enjoyable, with no significant difference in overall usability or enjoyment score. The young participants reported higher physical workload, whereas the older adults rated the interface quality higher, suggesting age-friendly accessibility. Minor visual fatigue was reported without severe cybersickness. The older adults demonstrated lower speed but maintained over 80% task completion and perceived the system as beneficial and motivating. These findings support the feasibility of sensor-enabled MR systems across age groups, indicating strong potential for use in cognitive-motor rehabilitation and the early detection of age-related functional decline.

1. Introduction

Population aging has become a major global concern, and the prevalence of mild cognitive impairment (MCI) continues to increase with age. MCI is an intermediate stage between normal cognitive aging and dementia, and individuals with MCI often experience difficulties in executive function, working memory, and motor coordination. Therefore, early cognitive intervention is essential to delay further decline and preserve independence in daily activities.

Traditional cognitive rehabilitation methods such as paper-based exercises or two-dimensional computer programs have limited ecological validity and lack real-world

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interactivity. In recent years, virtual reality (VR) and mixed reality (MR) have been explored as potential tools to enhance rehabilitation by providing immersive and interactive environments that simulate daily-life tasks.[1–5] Studied have shown that a simulated cooking task may improve executive function in older adults.[6–8] Similarly, Thapa *et al* proposed an immersive environment that integrates physical actions with cognitive decision-making to promote engagement and motivation.[1] However, most existing systems emphasize visual immersion but neglect ergonomic and usability factors for elderly users.[9]

In this study, we developed an MR supermarket shopping system that combines cognitive and fine motor training through realistic daily-life tasks, such as price calculation and beverage preparation. The system was designed to simulate familiar activities that stimulate executive function, visuospatial awareness, and hand-eye coordination.

The MR system relies on multiple embedded sensors, including those for depth sensing, inside-out tracking, and optical hand-tracking, to detect users' gestures, spatial orientation, and object interactions in real time. In addition, the system is integrated with real-world convenience store barcode scanners, allowing participants to scan actual product barcodes that are recognized within the MR environment according to predefined conditions. These sensor-based capabilities enable the precise measurement of cognitive-motor performance and adaptive task feedback, making MR a powerful technological tool for rehabilitation and functional assessment.

Age-related differences in usability, workload, and satisfaction may affect user's task performance, engagement, and rehabilitation outcome. Therefore, in this study, we aim to evaluate the usability, workload, and sense of presence of, and satisfaction with the MR supermarket shopping training system in two age groups: older adults and young adults. The objectives are (i) to identify differences in user perception and workload between age groups, and (ii) to provide design recommendations for improving accessibility and cognitive-motor training in aging populations.

2. Data, Materials, and Methods

2.1 Participants

Participants were recruited from two age groups based on predefined eligibility criteria, and written informed consent was obtained in accordance with the protocol approved by the institutional ethics committee. Inclusion criteria were as follows: (1) participants are required to provide written informed consent prior to entering the study and (2) young adults are aged 18–25 years and older adults 54–65 years. Exclusion criteria included (1) any history of orthopedic, neurological, or neuromuscular disorders within the past three months and (2) inability or unwillingness to cooperate with the experiment owing to cognitive, behavioral, or personality-related factors, including refusal to participate in MR-based training tasks.

The recruitment and screening procedures are presented in Fig. 1. A total of 35 participants were enrolled in this study; the baseline demographic information is shown in Table 1.

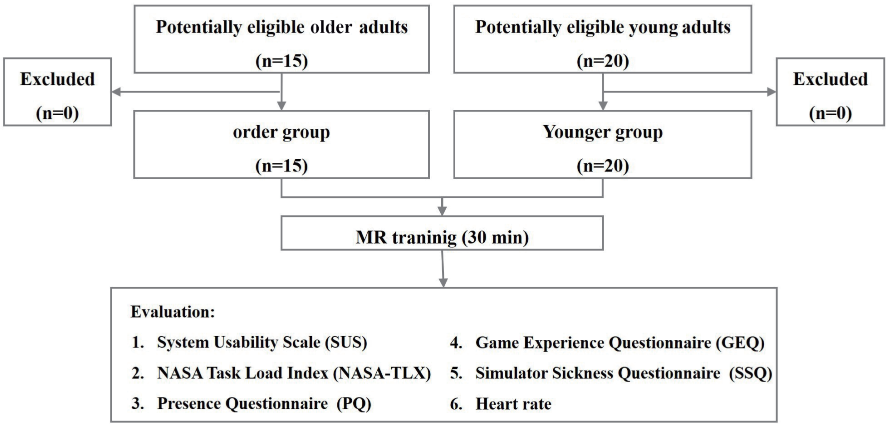


Fig. 1. Flow diagram of participant inclusion.

Table 1
Demographic characteristics of the two groups at baseline.

	Older (n = 15)	Young (n = 20)	p value
Age (years), mean (SD)	59.67 ± 3.352	20.25 ± 0.967	0.000*
Sex (female/male), n (%)	2/13 (13/87)	8/12 (40/60)	0.087
Years of education (years), mean (SD)	10.40 ± 2.230	15.05 ± 0.887	0.000*
Body mass index, mean (SD)	22.95 ± 2.445	20.37 ± 5.600	0.106

*Group differences were analyzed using independent samples in t-tests (continuous variables) and Chi-square tests (categorical variables), $p \leq 0.001$ was considered highly statistically significant.

2.2 MR supermarket shopping system

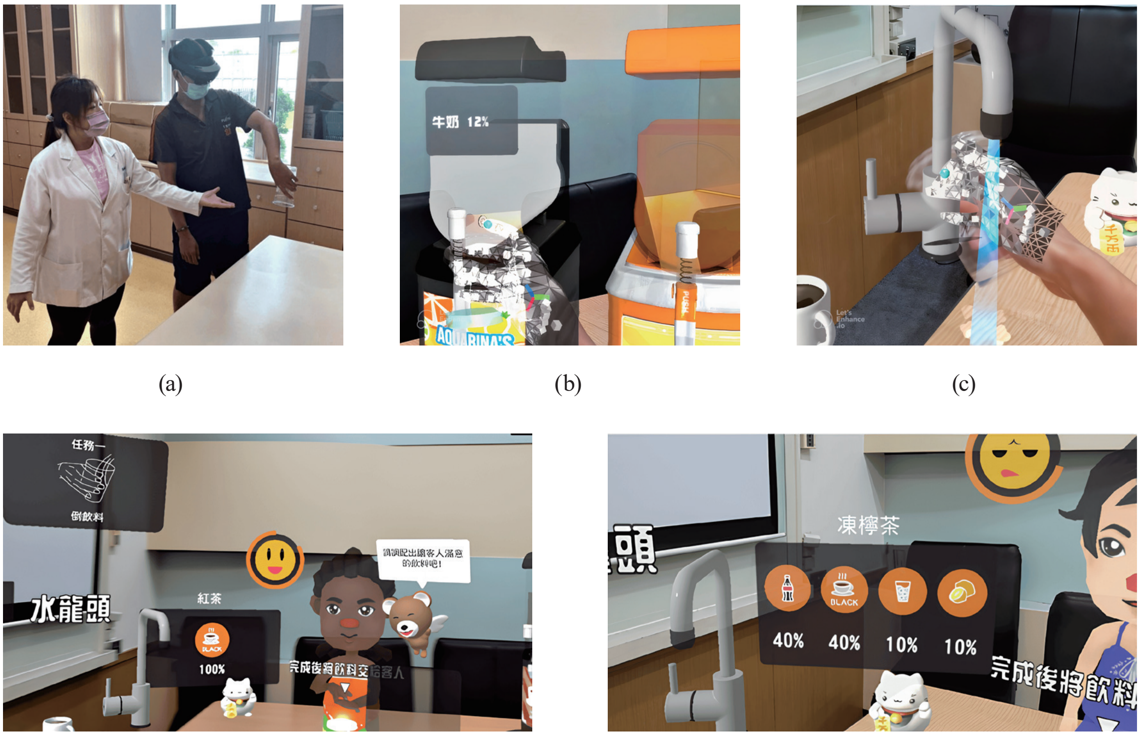
The proposed MR shopping-task-based intervention is implemented through an MR supermarket shopping system, which serves as the technical platform supporting the intervention design and task execution. The MR supermarket shopping system was developed using Unity 2022.3 LTS (Unity Technologies, San Francisco, USA), a widely adopted cross-platform game engine that provides high rendering stability, flexible asset integration, and native support for XR interaction frameworks. Unity was selected because it offers robust development tools for MR interaction, integrates seamlessly with hand-tracking and spatial-mapping application programming interfaces (APIs), and allows the efficient customization of task logic and sensor-driven feedback essential for cognitive-motor training.

The MR application was deployed on the Meta Quest 3 head-mounted display (Meta Platforms Inc., USA). The device incorporates inside-out tracking, optical hand-tracking, and depth sensing, enabling the real-time detection of upper-limb gestures, wrist rotation, reach trajectories, and object manipulation without the need for external markers. Its lightweight design, high-resolution passthrough, and standalone processing capabilities make it suitable for prolonged cognitive-motor training among both the young and older adults. The training system included two major functional modules.

2.2.1 Beverage Preparation Module [Figs. 2(a)–2(e)]

This module required participants to follow sequential prompts to prepare beverages in accordance with virtual customer orders. The task involved interacting with both a virtual soda fountain machine and a physical cup that were tracked through optical hand-tracking. Three missions were included.

1. Preparing a drink based on the displayed order, which requires ingredient selection and step-wise execution.
2. Washing the cup. This is designed to train wrist rotation through sensor-based motion tracking.



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

Fig. 2. (Color online) Overview of the MR supermarket training system integrating sensor-based interaction and real-world object recognition. (a) Participant interaction and system architecture: A participant performs the MR tasks while being guided by an instructor, demonstrating natural hand interaction with the MR environment. The system architecture integrates optical hand-tracking, depth sensing, and task logic modules for gesture-based interaction measurement. (b) MR integration in operation: Participants can pick up and manipulate a real cup, placing it in the sensing area to perform the filling and blending of virtual beverages. This process is supported by optical hand-tracking sensors that detect finger movements and object manipulation, thereby achieving the goal of MR integration. This design ensures a high degree of consistency between the task's operability and the physical perception of real-world activities. (c) Cup-washing submission of the beverage preparation module. (d) Beverage preparation module interface: The module includes a virtual guide and a virtual guest, who provide both voice and visual guidance. Task-related images and text are also displayed to guide the participant in selecting and delivering the correct drink order, thus enhancing task clarity and engagement. (e) Drink order complexity: The drink order in the beverage preparation module consists of a mixture of a minimum of one and a maximum of four virtual beverages.

(f)

(g)

Fig. 2. (Continued) (Color online) Overview of the MR supermarket training system integrating sensor-based interaction and real-world object recognition. (f) Internal view of price calculation module: Barcode-scanning detection, item-list presentation, and system feedback, all recorded through optical hand-tracking and object-recognition logic, are demonstrated. (g) External view of barcode scanning: A participant performs the real-world barcode-scanning action. The physical barcode reader communicates with the MR environment, enabling synchronized real-object sensing and in-system feedback.

3. Performing an inverted-cup placement task specifically designed to train wrist rotation and upper-limb fine motor control, supported through Quest's depth-sensing and optical tracking.

This module simultaneously targeted cognitive sequencing, fine motor abilities, and visuomotor coordination.

2.2.2 Price Calculation Module [Figs. 2(f) and 2(g)]

To simulate realistic convenience-store checkout tasks, this module required participants to retrieve physical items, scan barcodes, and verify purchasing information. To achieve this, we connected an external commercial barcode scanner to the MR system. The scanner allowed participants to scan real retail product barcodes, which were mapped to a predefined database within Unity. The software generated randomized product-retrieval missions, prompting users to locate and pick up the correct physical item before scanning it. Once the barcode was scanned, the MR interface provided immediate feedback (correct/incorrect item, subtotal updates, and task progression). This design simulated real checkout workflows and engaged executive functions such as item identification, task matching accuracy, price calculation (subtotals and final totals), decision-making, and error correction. The integration of real objects with MR feedback created a hybrid sensor-based training experience that more closely mirrors real retail operations than fully virtual simulations.

The MR supermarket shopping system provided a first-person MR experience by blending physical and virtual objects. A performance-based adaptive mechanism adjusted task difficulty automatically, and audiovisual feedback was given to enhance engagement.

2.3 Intervention

Each participant underwent a 30 min training session in a quiet indoor environment. Before the session began, a licensed occupational therapist explained the activity procedures and questionnaires that would be administered after the session. Then, each participant's baseline heart rate (HR) was measured.

In the beginning, a 3 min familiarization phase was provided for participants to practice basic MR interactions, such as hand gestures, object selection, and following on-screen prompts, to ensure comfort with the system's optical hand-tracking interface.

The formal training consisted of two sequential modules, which includes a 10 min price calculation module and a 15 min beverage preparation module. A short 2–3 min eye-closed rest period was provided between modules.

Throughout the session, participants interacted with the virtual environment using natural hand gestures and real-object manipulation as required by each task. Upon completing the 30 min MR intervention, the therapist again measured the participant's post-test HR. Participants then completed five standardized questionnaires assessing usability, workload, sense of presence, game experience, and simulator sickness.

2.4 Evaluation measures

Participants' experiences and responses were evaluated using four standardized questionnaires, one custom-developed satisfaction questionnaire, and one physiological measure; the details are listed in Table 2. The standardized questionnaires included the System Usability Scale (SUS),[10–12] NASA Task Load Index (NASA-TLX),[13,14] Presence Questionnaire (PQ),[15] Game Experience Questionnaire (GEQ),[16,17] and Simulator Sickness Questionnaire (SSQ).[18,19]

SUS is a widely recognized and statistically robust tool for comprehensively measuring users' subjective perceptions of system or interface usability. It combines positive and negative statements to mitigate response bias and acquiescence effects among respondents. The SUS score can be mapped to acceptability ranges (not acceptable, marginal, and acceptable) and a grade scale (A to F). It provides a reliable benchmark for perceived usability, where higher scores consistently indicate higher perceived system quality.

NASA-TLX is a multidimensional assessment tool designed to measure the perceived workload during a mission and is widely applied in human factors engineering research.

PQ and SSQ, originally developed for VR studies, are frequently applied to assess the sense of presence (i.e., the subjective experience of "being in" the MR environment) and potential cybersickness symptoms, respectively.

GEQ was employed to assess participants' subjective gaming experience. We utilized the GEQ core module, a widely adopted instrument in human–computer interaction and game

Table 2
Questionnaires and physical measurement for MR intervention.

	Components or contents	Scale type	Number of questions	Score
SUS	Usability Learnability	Likert five-point scale	10	0–100
NASA-TLX	Mental demand Physical demand Temporal demand Performance Effort Frustration level	0–100 continuous scale	15 + 6	0–100 x
PQ	Involvement Sensory fidelity Adaptation/immersion Interface quality.	Likert five-point scale	29	0–116
GEQ	Sensory and imaginative immersion Competence Negative affect Flow Tension Positive affect Challenge	Likert five-point scale	33	0–132
SSQ	18 uncomfortable feelings	Likert four-point scale	18	0–54
SQ	Author-designed questions	Likert five-point scale	5	0–20
HR	1 physical measurement	Continuous scale	1	About 50 to 150

research, for measuring the multidimensional player experience. It has demonstrated effectiveness in various immersive technology studies (VR and MR), including the comparison of different levels of immersion, the assessment of the impact of different game modes, and usability studies. The six components of the module are detailed in Table 2. Specifically, the ‘flow’ construct refers to a psychological state of task immersion characterized by focused attention, intrinsic motivation, and a seamless progression during activity performance.

The Satisfaction Questionnaire was developed by our research team to evaluate participants’ subjective satisfaction with this system. Its items were derived from established usability and experience-evaluation frameworks. Content validity was evaluated by two senior occupational therapists and one MR system designer to ensure relevance and clarity. Prior to the formal experiment, the questionnaire was pilot-tested with five individuals to confirm comprehension and item interpretability; minor wording adjustments were made accordingly.

HR was measured before and after the MR session as an objective physiological indicator of arousal and stress response, providing complementary data on participants’ physical reactions to the intervention.

2.5 Statistical analysis

Demographic data were compared using the chi-square test for categorical variables and independent sample t-tests for continuous variables. Independent sample t-tests were further applied to examine intergroup differences in questionnaire outcomes, including usability, workload, immersion, game experience, and symptom scores. Intragroup changes in HR before and after the activity were analyzed using paired-sample t-tests to assess physiological responses. A two-tailed significance level of $p \leq 0.05$ was considered statistically significant, and $p \leq 0.001$ was regarded as highly significant. All statistical analyses were performed using SPSS version 18.0 (IBM Corp., Chicago, NY, USA).

3. Results

3.1 Demographic comparison

As shown in Tables 1 and 7, the two groups differed significantly in age ($p = 0.000$) and years of education ($p = 0.000$), but did not differ in sex ($p = 0.087$), BMI ($p = 0.106$), or baseline HR ($p = 0.577$). These variables were considered when interpreting the results of subsequent analyses.

3.2 Usability and workload

The usability outcomes assessed by SUS revealed that both groups rated the MR supermarket shopping system within an acceptable usability range (Table 3 and Fig. 3). The older group had an overall score of 64.66 ± 18.847, while the young group scored 74.75 ± 14.910, indicating no significant group difference ($p = 0.086$). However, within the subcomponents, the learnability item showed a significant difference between groups (older group: 55.33 ± 27.332; young group: 53.13 ± 23.253, $p = 0.035$), suggesting that the older participants may have perceived the system as slightly easier to learn.

Regarding the perceived workload measured using NASA-TLX, the overall workload of the older group (38.67 ± 16.242) was significantly lower than that of the young group (47.86 ± 10.698, $p = 0.046$). Among the six subscales, a significant group difference emerged in physical demand (5.51 ± 5.074 vs 14.74 ± 5.672, $p < 0.001$), indicating that the young participants perceived greater physical exertion during the MR intervention.

Table 3
Scores of system usability scale.

Components	Older (n = 15)	Young (n = 20)	p value
System usability scale			
Usability	67.50 ± 19.508	80.16 ± 14.632	0.981
Learnability	53.33 ± 27.332	53.13 ± 23.253	0.035*
Total	64.66 ± 18.848	74.75 ± 14.910	0.086
NASA TLX			
Mental demand	6.76 ± 7.381	9.65 ± 5.592	0.160
Physical demand	5.51 ± 5.074	14.74 ± 5.672	0.000**
Temporal demand	4.27 ± 5.150	6.74 ± 3.818	0.144
Effort	7.27 ± 6.340	6.49 ± 3.820	0.659
Performance	12.42 ± 5.587	8.77 ± 5.198	0.071
Frustration	2.44 ± 5.940	1.47 ± 2.349	0.478
Total	38.67 ± 16.242	47.86 ± 10.698	0.046*

Group differences examined by independent sample t-tests were considered statistically significant at $p < 0.05$ (*) and highly significant at $p < 0.001$ (**).

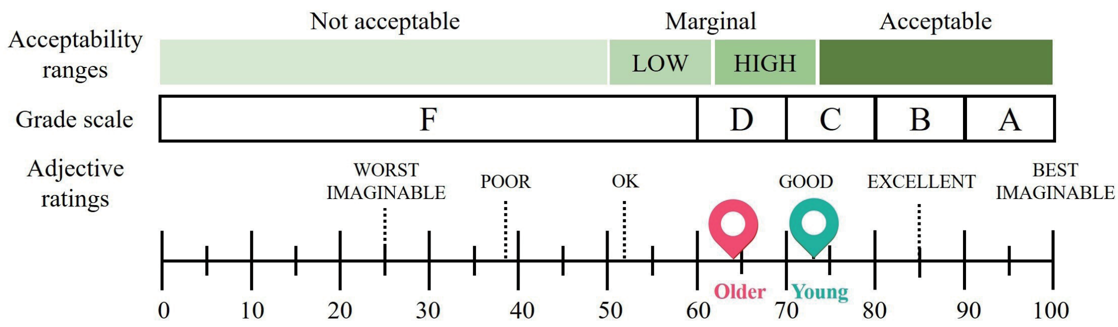


Fig. 3. (Color online) Usability ratings of the older and young participants.

3.3 Sense of presence and game experience

Table 4 shows the sense of presence and game experience results. The older participants rated interface quality significantly higher than did the young participants (older group: 7.33 ± 2.257; young group: 5.00 ± 2.938, $p = 0.015$). Other subscales showed no significant differences.

In the GEQ results, both groups reported similar overall scores (older group: 107.87 ± 14.297; young group: 105.25 ± 13.178, $p = 0.803$), suggesting that both age groups experienced comparable enjoyment and flow during the MR intervention.

3.4 Satisfaction

As shown in Table 5, satisfaction levels were generally high for both groups. The young participants gave higher ratings for information clarity (older group: 4.00 ± 0.845; young group: 4.60 ± 0.598, $p = 0.034$) and perceived rehabilitation usefulness (older group: 3.86 ± 1.125; young group: 4.65 ± 0.489, $p = 0.019$), indicating that the MR supermarket shopping system was well understood and perceived as beneficial. No other items differed significantly between groups. The internal consistency of the Satisfaction Questionnaire demonstrated acceptable reliability, with Cronbach's $\alpha = 0.745$.

3.5 Simulator sickness symptoms

As shown in Fig. 4 and Table 6, the overall simulator sickness symptoms were mild among participants. The most frequently reported symptoms were eye strain (30.56%), difficulty focusing (22.22%), increased salivation (22.22%), and blurred vision (22.22%). Symptoms related to nausea, vomiting, or vertigo were not observed.

The average SSQ score was low (older group: 2.53 ± 3.314; young group: 2.20 ± 3.365), with no significant difference between groups ($p = 0.772$). Among all symptoms, only "difficulty concentrating" showed a significant group difference, with the older group reporting a higher score than the young group (older group: 0.33 ± 0.488; young group: 0.00 ± 0.000. $p = 0.019$). No significant group differences were observed for other symptoms.

Table 4
Scores of sence of presence and game experiment questionnaires.

Components	Older (n = 15)	Young (n = 20)	p value
Presence questionnaire			
Involvement	31.87 ± 10.364	34.85 ± 5.274	0.320
Sensory fidelity	17.60 ± 4.014	19.05 ± 3.187	0.242
Adaptation/immersion	11.47 ± 3.739	13.50 ± 2.524	0.063
Interface quality	7.33 ± 2.257	5.00 ± 2.938	0.015*
Total	68.27 ± 17.023	72.40 ± 10.128	0.412
Game experiment questionnaire			
Sensory and imaginative immersion	3.37 ± 0.735	3.47 ± 0.648	0.516
Competence	3.81 ± 0.773	3.75 ± 0.756	0.932
Negative effect	1.93 ± 0.632	1.88 ± 0.853	0.146
Flow	4.21 ± 0.639	3.61 ± 0.791	0.381
Tension	1.69 ± 0.570	1.65 ± 0.921	0.123
Positive effect	3.43 ± 0.759	3.63 ± 0.741	0.990
Challenge	2.91 ± 0.705	2.34 ± 0.713	0.198
Total	107.87 ± 14.297	105.25 ± 13.178	0.803

*Group differences examined by independent sample t-tests were significant ($p \leq 0.05$).

Table 5
Scores of satisfaction questionnaire.

Contents	Older (n = 15)	Young (n = 20)	p value
1. To what degree did you feel unhappy when the experience was over?	2.47 ± 1.187	2.55 ± 1.276	0.845
2. Would you like to repeat the experience you just had?	3.87 ± 0.990	4.15 ± 0.875	0.377
3. How much would you be willing to pay to have a similar experience?	2.87 ± 1.356	3.15 ± 1.348	0.544
4. Is the information provided by the system clear?	4.00 ± 0.845	4.60 ± 0.598	0.019*
5. Do you think that this system will be helpful for your rehabilitation?	3.86 ± 1.125	4.65 ± 0.489	0.009*
Average	3.41 ± 0.798	3.82 ± 0.605	0.095

*Group differences examined by independent sample t-tests were significant ($p \leq 0.05$).

3.6 Heart rate

HR was analyzed to examine physiological responses of the two groups before and after the intervention (Fig. 5 and Table 7). For the older group, the average HR increased slightly from 74.33 ± 13.978 bpm before the activity to 76.47 ± 13.887 bpm afterward, showing no significant difference (p = 0.326). In contrast, the young group exhibited a more pronounced increase, from 77.15 ± 15.090 to 84.58 ± 15.632 bpm, which was statistically significant (p = 0.001).

The overall average HR during the task was determined to be 75.40 ± 13.33 bpm in the older group and 81.13 ± 14.56 bpm in the young group (p = 0.241). Both groups primarily remained within the aerobic metabolism zone (Fig. 5).

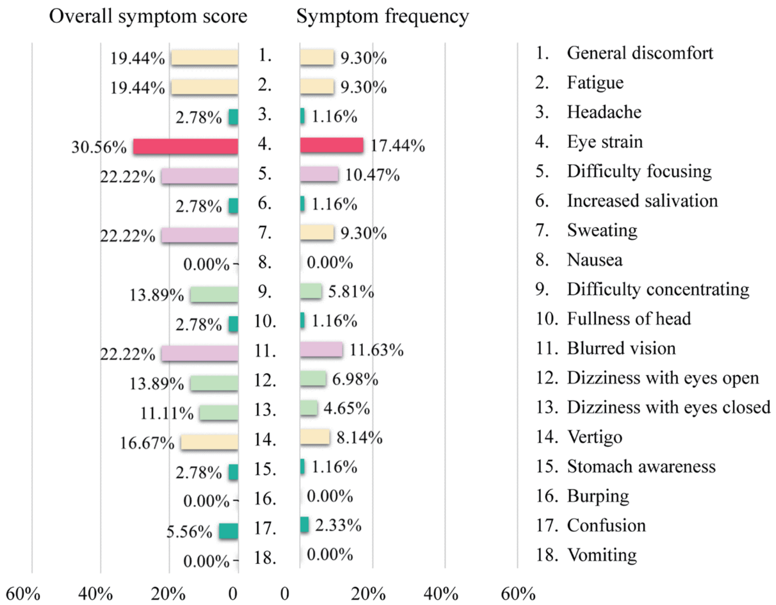


Fig. 4. (Color online) Percentage of overall score and frequency of simulator sickness symptoms among all participants.

Table 6
Scores of simulator sickness symptoms.

Components	Older (n = 15)	Young (n = 20)	p value
General discomfort	0.13 ± 0.352	0.25 ± 0.550	0.451
Fatigue	0.07 ± 0.258	0.30 ± 0.571	0.117
Headache	0.00 ± 0.000	0.05 ± 0.224	0.330
Eye strain	0.40 ± 0.632	0.40 ± 0.754	1.000
Difficulty focusing	0.27 ± 0.458	0.20 ± 0.523	0.691
Increased salivation	0.07 ± 0.258	0.00 ± 0.000	0.334
Sweating	0.33 ± 0.488	0.15 ± 0.366	0.234
Nausea	0.00 ± 0.000	0.00 ± 0.000	—
Difficulty concentrating	0.33 ± 0.488	0.00 ± 0.000	0.019*
Fullness of head	0.07 ± 0.258	0.00 ± 0.000	0.334
Blurred vision	0.40 ± 0.632	0.20 ± 0.523	0.328
Dizziness with eyes open	0.20 ± 0.561	0.15 ± 0.366	0.752
Dizziness with eyes closed	0.13 ± 0.352	0.10 ± 0.308	0.767
Vertigo	0.07 ± 0.258	0.30 ± 0.571	0.117
Stomach awareness	0.07 ± 0.258	0.00 ± 0.000	0.334
Burping	0.00 ± 0.000	0.00 ± 0.000	—
Confusion	0.00 ± 0.000	0.10 ± 0.308	0.163
Vomiting	0.00 ± 0.000	0.00 ± 0.000	—
Average	2.533 ± 3.314	1.73 ± 2.685	0.772

*Group differences examined by independent sample t-tests were significant ($p \leq 0.05$).

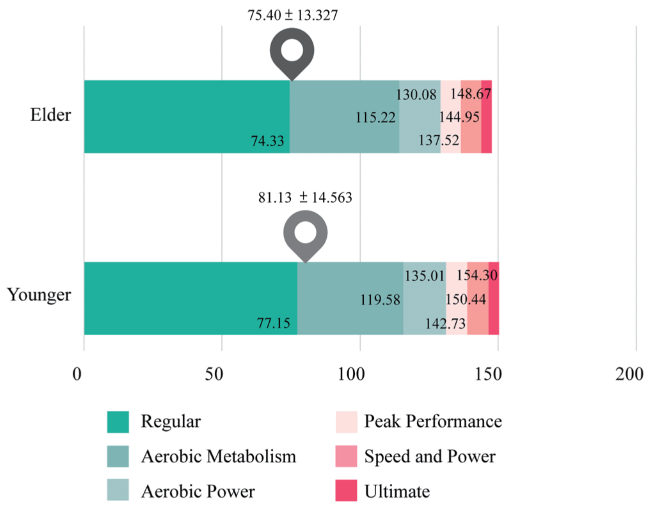


Fig. 5. (Color online) HR zones for the older and the young participants during the activity.

Table 7
HR before and after MR activity.

Group	Baseline	Post-test	p value
Older (n = 15)	74.33 ± 13.978	76.47 ± 13.887	0.326
Young (n = 20)	77.15 ± 15.090	84.58 ± 15.632	0.001**
p value	0.577	0.096	

**Differences between baseline and post-test results examined by paired sample t-tests were highly significant ($p \leq 0.001$). Group differences were examined by independent sample t-tests.

3.7 Mission

Task performance analysis revealed significant age-related differences across multiple missions(Table 8). In Mission 1 (Complete guest order), the young group achieved a higher execution count than the older group (older group: 8.79 ± 2.455; young group: 10.00 ± 0.865, p = 0.022), along with a substantially lower error rate (older group: 29.3%; young group: 1.9%, p = 0.034).

In Mission 2 (Wash the cup), although execution counts did not differ significantly between groups (p = 0.239), the older adults exhibited a markedly higher error rate (7.88%) than the young group (0%, $p < 0.001$).

In Mission 3 (Dry the cup upside down), the performance gap widened: the young group completed significantly more correct executions (older group: 5.36 ± 3.608; young group:10.05 ± 0.759, p = 0.042), with all the older participants making errors (100%) compared with 30% in the young group ($p < 0.001$).

4. Discussion

In this study, we investigated age-related differences in user experience with an MR supermarket shopping system integrating cognitive and fine motor components. The results

Table 8
Task performance of the older and young participants in three missions.

	Older (n = 15)	Young (n = 20)	p value
Mission 1: Complete guest order			
Execution count	8.79 ± 2.455	10 ± 0.865	0.022*
Error rate (95% CI)	29.3% (17.38–41.21%)	1.9% (0.18–3.65%)	0.034*
Mission 2: Wash the cup			
Execution count	8.21 ± 2.607	10.05 ± 0.759	0.239
Error rate (95% CI)	7.88% (1.33–14.43%)	0% (0.00–0.00%)	0.000**
Mission 3: Dry the cup upside down			
Execution count	5.36 ± 3.608	10.05 ± 0.759	0.042*
Error rate (95% CI)	100% (100–100%)	30% (11.02–49.23%)	0.001**

Group differences examined by independent sample t-tests were considered statistically significant at $p < 0.05$ (*) and highly significant at $p < 0.001$ (**).

demonstrated overall high usability and positive engagement across both age groups, supporting the system's feasibility for use by adults of various ages. These findings are consistent with those of prior MR-based cognitive–motor intervention studies, which similarly reported high acceptance, strong engagement, and age-dependent interaction patterns in older adults and patient groups.(20,21)

This work also has direct relevance to the fields of sensors and materials. The MR system depends on continuous real-time sensing, including hand-tracking, gesture recognition, spatial mapping, and object manipulation accuracy, made possible through optical depth sensors and inertial measurement components embedded in the head-mounted device. Observed behavioral differences between age groups therefore provide valuable insights into how sensing precision, gesture-detection thresholds, and interface material responsiveness are affected under various cognitive and motor conditions. These findings highlight key application considerations for sensor calibration, interaction material design, and adaptive MR sensing algorithms for aging populations. Compared with previous MR-based cognitive interventions, which were primarily focused on virtual cooking tasks, simplified visuomotor exercises, or fully virtual training scenes that rely on controller-based inputs or limited gesture recognition,(20–22) in this study, we introduced several technological and methodological advances. The MR supermarket shopping system integrates a physical object (real cup), optical hand-tracking, and an external sensor device (commercial barcode scanner) to create a hybrid MR environment that more accurately reflects real-world instrumental activities of daily living (IADLs). This multimodal combination enables sensor-enabled fine-motor tracking, multistep cognitive sequencing, and ecologically valid retail tasks such as drink preparation, object retrieval, and price calculation. In addition, SUS or interviews were used in previous studies to understand users' experiences,(23,24) whereas in our study, we used four standardized questionnaires plus a physiological indicator for a more comprehensive assessment. These contributions offer new insights into how age affects gesture-based interaction, interface perception, and sensor performance in mixed-reality environments—design implications that were not fully addressed in earlier MR-based rehabilitation studies.(20–22)

Usability and workload analyses revealed distinct interaction patterns between groups. While both groups rated the system within a "good" usability range, the young participants exhibited slightly higher total SUS scores, reflecting greater familiarity and comfort with digital interfaces. A significant difference in learnability was observed, with the older adults reporting lower ease of learning, suggesting potential adaptation challenges to interactive or gesture-based controls. The reduced gesture amplitude, slower response initiation, or more cautious hand motion seen in the older adults may require dynamic sensitivity adjustments in tracking sensors, reinforcing the importance of age-adaptive sensing thresholds in MR systems. These age-related differences are comparable to findings in previous MR cognitive training studies, where older adults typically demonstrated slower initial adaptation and lower interaction fluency but ultimately attained stable and meaningful performance with supportive visual cues and simplified task structures.(22)

In workload assessment, the young participants reported significantly higher physical demand and total workload, indicating greater physical engagement during the task. In contrast, the older adults showed lower physical effort and overall workload, suggesting a more conservative or efficiency-oriented interaction approach. Despite these contrasts, both groups maintained low frustration and effort levels, indicating that the system's task design was appropriately balanced and manageable.

Interestingly, the older adults rated interface quality more favorably, highlighting the suitability of the system's visual clarity, intuitive layout, and moderate pacing for age-related perceptual and motor capacities. This finding emphasizes the value of clear contrast, simplified object geometry, stable visual cues, and reduced task-switching complexity when designing MR environments for elderly users. Similar to prior MR-based rehabilitation studies, visual simplicity and task predictability were found to be critical in preventing cognitive overload among older adults and individuals with MCI.(22)

SQ demonstrated acceptable internal consistency (Cronbach's α = 0.745), supporting its reliability for assessing user satisfaction in this MR-based training context. Although SQ was developed specifically for this study, its psychometric performance indicates that it captures coherent dimensions of user experience. SQ results may also reflect generational differences in technology acceptance. According to the Technology Acceptance Model, perceived usefulness and perceived ease of use strongly shape users' attitudes toward adopting new systems. Young adults, who grew up immersed in digital technologies, likely enter MR environments with higher baseline familiarity and lower cognitive barriers, thereby perceiving greater rehabilitative value and adapting more seamlessly to gesture-based interactions. In contrast, older adults generally have less frequent exposure to digital interfaces and may initially approach emerging technologies with greater caution, which can moderate the perceived usefulness despite positive experiential outcomes. Nevertheless, the high satisfaction and willingness for repeated use observed among our older participants indicate that once the MR system provides clear guidance, intuitive interaction, and stable sensory feedback, age-related differences in technology acceptance can be substantially reduced, reinforcing the system's potential for broader rehabilitative applications.

Physiological findings further supported age-appropriate system responses. The young participants exhibited a significant post-test HR increase, suggesting higher aerobic activation and adaptive capacity to dynamic movement. Conversely, the older adults showed a mild but safe cardiovascular response that remained within the moderate intensity ranges recommended for their age. This demonstrates that the MR activity can elicit effective yet safe physiological engagement across diverse user groups. Comparable studies employing MR cognitive-motor tasks have likewise shown that immersive interactions can promote meaningful physiological activation without exceeding safety thresholds, supporting their suitability for older adults.

Regarding simulator sickness, both groups reported low symptom levels overall; however, the older group showed significantly higher scores for "difficulty concentrating." This pattern suggests that older adults may experience subtle cognitive fatigue or attentional strain rather than overt physical discomfort. Age-related declines in working memory and attentional control may contribute to this effect, particularly in visually rich or immersive environments that require constant sensory integration. Therefore, for MR applications targeting older populations, optimized visual simplicity, slower pacing, and periodic rest intervals should be considered to mitigate cognitive overload.

Task performance analysis revealed clear efficiency differences between age groups. The young participants achieved higher completion rates and lower error frequencies across all missions, reflecting superior visuomotor precision, processing speed, and task adaptation. In contrast, the older adults exhibited slower execution and higher error rates, particularly in tasks requiring complex spatial reasoning and fine motor control. These patterns likely reflect age-related declines in visuomotor coordination and reaction time. Nonetheless, the successful task completion by most of the older participants in earlier missions demonstrates the system's feasibility when task complexity is appropriately adjusted.

This study has several limitations. First, the sample size was modest and based on convenient sampling, which may constrain the statistical power and limit the generalizability of the findings. Second, the MR intervention was administered as a single-session experience; thus, learning trajectories, retention effects, and longer-term cognitive-motor benefits could not be assessed. Third, although the gender distribution differed between the groups (older: 40% female; young: 13% female), this difference did not reach statistical significance (chi-square test, $p = 0.087$), indicating that it is unlikely to have materially affected the primary outcomes. Nonetheless, future studies should include further examinations of potential gender-specific patterns in MR-based cognitive-motor engagement. In addition, age-related disparities in digital familiarity were not controlled and may have affected usability ratings and interaction performance, particularly for the older adults who typically report lower exposure to digital technologies.

Overall, these findings underscore the potential of MR-based training to enhance cognitive-motor engagement in both young and older adults. For older users, progressive task difficulty, adaptive feedback, and supportive visual design can help sustain motivation and ensure safe, effective participation. Future research should include clinical populations, such as individuals with MCI, and adopt longitudinal designs to explore the system's rehabilitative and cognitive benefits over time.

5. Conclusions

The results of this study demonstrated that the sensor-enabled MR supermarket shopping system is feasible and enjoyable for both young and older adults. The young participants exhibited greater physical workload and higher physiological activation, reflecting stronger engagement with the task, whereas older participants rated the interface quality more favorably, indicating that the system's visual clarity and pacing were well suited to their perceptual and motor capacities. Both groups expressed strong motivation and satisfaction, suggesting that the MR-based activity successfully balanced challenge and accessibility. Collectively, these findings highlight the potential of MR technology as a supportive platform for cognitive and motor rehabilitation among aging populations. Future research should be focused on optimizing adaptive interface design, tailoring task difficulty to individual ability levels, and investigating long-term intervention outcomes in clinical or rehabilitative settings.

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References

1 N. Thapa, H. J. Park, J. G. Yang, H. Son, M. Jang, J. Lee, S. W. Kang, K. W. Park, and H. Park: J. Clin. Med. **9** (2020) 1283. https://doi.org/10.3390/jcm9051283
2 R. Y. C. Kwan, J. Y. W. Liu, K. N. K. Fong, J. Qin, P. K. Leung, O. S. K. Sin, P. Y. Hon, L. W. Suen, M. K. Tse, and C. K. Lai: JMIR Serious Games **9** (2021) e28400. https://doi.org/10.2196/28400
3 P. Makmee and P. Wongupparaj: Psychosocial Intervention **31** (2022) 133. https://doi.org/10.5093/pi2022a10
4 J. Buele and G. Palacios-Navarro: Front. Aging Neurosci. **15** (2023) 1191729. https://doi.org/10.3389/fnagi.2023.1191729
5 Q. Yang, L. Zhang, F. Chang, H. Yang, B. Chen, and Z. Liu: J. Med. Internet Res. **27** (2025) e59195. https://doi.org/10.2196/59195
6 V. Manera, P. D. Petit, A. Derreumaux, I. Orvieto, M. Romagnoli, G. Lyttle, R. David, and P. H. Robert: Front. Aging Neurosci. **7** (2015) 24. https://doi.org/10.3389/fnagi.2015.00024
7 I. A. Chicchi Giglioli, C. Bermejo Vidal, and M. Alcaniz Raya: Front. Psychol. **10** (2019) 2529. https://doi.org/10.3389/fpsyg.2019.02529
8 F. Borgnis, F. Baglio, E. Pedroli, F. Rossetto, L. Uccellatore, J. A. G. Oliveira, G. Riva, and P. Cipresso: Front. Psychol. **13** (2022) 833136. https://doi.org/10.3389/fpsyg.2022.833136
9 M. Schaumburg, A. Imtiaz, R. Zhou, M. Bernard, T. Wolbers, and V. Segen: Ageing Res. Rev. **109** (2025) 102771. https://doi.org/10.1016/j.arr.2025.102771
10 J. Brooke: SUS, A 'quick and dirty'usability scale. Usability Evaluation in Industry. P. W. Jordan, B. Thomas, B. A. Weerdmeester, and A. L. McClelland, Eds. (Taylor and Francis, London, 1996) 1st ed.
11 A. Bangor, P. T. Kortum, and J. T. Miller: Intl. J. Human–Computer Interact. **24** (2008) 574.
12 A. Bangor, P. Kortum, and J. Miller: J. Usability Stud. **4** (2009) 114.
13 S. G. Hart and L. E. Staveland, Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research, in Advances in Psychology (1988, Elsevier) pp. 139–183.
14 S. G. Hart: NASA-task load index (NASA-TLX); 20 years later. in Proc. the human factors and ergonomics society annual meeting. 2006. Sage Publications Sage CA: Los Angeles, CA.
15 B. G. Witmer, C. J. Jerome, and M. J. Singer: Presence: Teleoperators & Virtual Environ. **14** (2005) 298.
16 W. IJsselsteijn, W. Van Den Hoogen, C. Klimmt, Y. De Kort, C. Lindley, K. Mathiak, K. Poels, N. Ravaja, M. Turpeinen, and P. Vorderer: Proc. Measuring Behavior (2008. Maastricht Netherlands).
17 E. L.-C. Law, F. Brühlmann, and E. D. Mekler: Proc. 2018 Annu. Symp. computer-human interaction in play (2018).
18 R. S. Kennedy, N. E. Lane, K. S. Berbaum, and M. G. Lilienthal: The Int. J. Aviation Psychol. **3** (1993) 203.
19 P. A. Howarth and P. Costello: Displays **18** (1997) 107.
20 E. Park, B. J. Yun, Y. S. Min, Y. S. Lee, S. J. Moon, J. W. Huh, H. Cha, Y. Chang, and T. D. Jung: Cogn. Behav. Neurol. **32** (2019) 172. https://doi.org/10.1097/WNN.0000000000000197
21 E. E. Medina, M. A. N. Webster, J. Huber, and A. C. Glueck: J. Clin. Med. **14** (2025) 7998. https://doi.org/10.3390/jcm14227998

22 S. Desai, R. Mutsuddi, and A. J. Astell: Front. Sports Active Living **6** (2024) 1419263. https://doi.org/10.3389/fspor.2024.1419263
23 G. Burdea, K. Polistico, A. Krishnamoorthy, G. House, D. Rethage, J. Hundal, F. Damiani, and S. Pollack: Disabil Rehabil Assistive Technol. **10** (2015) 421. https://doi.org/10.3109/17483107.2014.900575
24 S. J. Yun, M. G. Kang, D. Yang, Y. Choi, H. Kim, B. M. Oh, and H. G. Seo: JMIR Serious Games **8** (2020) e18127. https://doi.org/10.2196/18127

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