Universal Access in the Information Society
https://doi.org/10.1007/s10209-017-0597-x

LONG PAPER

Using an augmented reality-based training system to promote spatial visualization ability for the elderly

Zheng-Yu Hoe[1] · I-Jui Lee[2] · Chien-Hsu Chen[2] · Kuo-Ping Chang[2]

Abstract
The physical condition and cognitive ability of older adults tends to decline. This study focused on the development of an augmented reality (AR)-based rehabilitation training system to improve the spatial visualization and mental rotation abilities of elderly people. Using one's imagination to manipulate objects is common in everyday life. However, training tasks for the elderly are still presented in two-dimension, which research indicates generates a cognitive load that reduces the participants' interest and diminishes the effects of training. AR can effectively reduce cognitive load, improve one's sense of spatial direction, and increase participants' interest in training. Therefore, this study used AR technology, combined with a tangible user interface as a manual controller, to allow participants to directly manipulate a virtual three-dimensional model that used a cube to conduct mental rotation tasks (MRT) for the elderly to improve their mental rotation ability. After 6 weeks of intervention, we used an ABA (reversal) design and paired-sample *t* tests in SPSS to compare the learning effects on the experimental group's pre- and posttests. The participants' error rates significantly declined and their reaction times significantly improved during the MRT test.

Keywords Augmented reality · Spatial visualization · Elderly · Mental rotation task · Tangible user interface

1 Introduction

Spatial mental rotation, a visuospatial skill [42], refers to the ability to manipulate representations of visual objects mentally. This ability is used to rotate two-dimensional (2D) and three-dimensional (3D) objects in an imaginative space [49]. Neurobiological research associates it with the human ability to navigate and other spatially related functions [3, 5, 41, 45, 54]. Moreover, mental rotation ability greatly affects a person's life. For instance, wayfinding and map learning are associated with mental rotation ability [26, 40]. A decline in mental rotation ability leads to spatial cognition problems for older adults [10, 25, 30]. For instance, clinical evidence indicates that older adults with Alzheimer's disease have difficulty with mental rotation, which negatively affects their real-world wayfinding [7]. When people grow older, their mental rotation ability declines [18, 26, 40].

Mental rotation requires maintenance and mental manipulation of visual stimuli, similar in nature to map reading, which requires maintaining and mentally inspecting a visual configuration [39]. Reading a map requires cognitive alignment that creates a correspondence between the forward perceptual views of the world to a location on a map; mental rotation is seen as a central cognitive operation in this alignment [1]. Arthur and Passini [2] explained wayfinding and map reading as a spatial problem-solving activity. They defined cognitive mapping as part of environmental perception, where cognition is basically a source of information for making and executing a decision. Hence, perception is defined as the process of obtaining information through the

✉ I-Jui Lee
iammimosa@gmail.com

Zheng-Yu Hoe
jhoe@vghks.gov.tw

Chien-Hsu Chen
chenhsu@mail.ncku.edu.tw

Kuo-Ping Chang
m54pikachu@gmail.com

1 Physical Medicine and Rehabilitation Department of Kaohsiung Veterans General Hospital, Department of Biomedical Engineering, National Cheng Kung University, Tainan, Taiwan

2 Ergonomics and Interaction Design Lab, Department of Industrial Design, National Cheng Kung University, No.1 University Rd, East District, Tainan, Taiwan

Published online: 14 November 2017

senses; cognition is defined as understanding and being able to manipulate information. Therefore, obtaining information is not enough to be able to find one's way; understanding and manipulating the information is also an essential part of the wayfinding process [2]. In addition, practicing MRT should be beneficial for learning spatial navigational skills and how to read a map [38]. Therefore, if the degradation of mental rotation ability can be postponed by practicing MRT, it will positively affect older adults and improve their quality of life. Hence, this study attempts to enhance and maintain the cognitive functioning of older adults through the design of a spatial visualization training system for the elderly to promote their mental rotation ability.

2 Related works

Research on spatial mental rotation abilities focuses on whether spatial abilities can be trained and whether the decline in the elderly's mental rotation ability can be postponed. Previous studies have shown that the degradation of mental rotation ability can be postponed with MRT training [21, 31, 36]. This also applies for younger people; for example, the performance of orienteering tasks improved for college students who underwent the MRT test, indicating that mental rotation skills are significantly correlated with wayfinding and other spatial skills [33]. Previous research has been done on the effect of age on mental rotation ability. For instance, older adults tend to have lower scores than those of younger people on the MRT test and in map reading [10]. One reason is that MRT may be too difficult for older people to comprehend [25, 32].

2.1 Current training methods for mental rotation ability

Mental rotation ability can be trained through practice. It has been found that response times increase for degraded stimuli and can decrease when participants are allowed to practice mentally rotating imagery often [51]. Standard 2D forms of MRT are typically used for mental rotation training or mental state evaluation for elderly people [49]. In the MRT test, participants need to judge whether two stimuli are the same or mirrored and write down their answers on paper. Sometimes the stimuli are 3D objects presented in 2D, e.g., images of 3D houses or cars, which are not suitable for presentation in 2D form. If MRT stimuli are shown using 2D images, obvious depth cues, such as shadows or light effects, need to be provided [35, 60] to help older adults encode the stimuli [52].

Some training strategies allow the participants to handle a tangible manual controller in the test; for example, participants can be allowed to use a manual controller to rotate the stimuli [15, 56, 61] or to simulate the rotation process [8, 16, 22]. Gardony [15] had participants rotate virtual 3D figures with a handheld sensor to conduct Shepard's mental rotation test [49]; the results revealed that physical rotation improved mental rotation. The training approach also adopted magnetic motion controllers to allow learners to manipulate and interact with 3D objects; the results showed that women who used the manual controller had a significant improvement in the posttest [61] and reported a greater level of interest in the manual training. A manual controller thus plays an important role in a training system from training effect aspects [61]. Similarly, Weidenbauer [56] adopted a manual controller for MRT to determine whether manual training was beneficial for training mental rotation in children. In the study, virtual objects were displayed in a Virtual Reality (VR) environment, and children were able to control the virtual objects by manipulating a joystick. Children with manual training were found to have improved MRT performance [56]. These studies thus confirm that manual manipulation can facilitate mental rotation [23, 55, 59] and support the connection between mental rotation and manual training [14, 58].

2.2 Primary problem with current mental rotation training

The primary problem with current mental rotation training is that tasks use 2D materials, e.g., printed tests, letters, or images, or are presented on a 2D liquid–crystal display (LCD) monitor. When participants need to figure out spatial information using a 2D format, a heavy cognitive load is generated during training [6, 51] because people need to indirectly imagine the 3D patterns shown on the 2D display, which requires a great deal of energy. Hence, recent research has adopted VR for mental rotation training [44, 50, 62]. VR technology is a potential tool for the assessment and rehabilitation of human cognitive and functional processes [37]. It can bring considerable benefits to persons with cognitive and functional impairments caused by brain injury, neurological disorders, and learning disabilities. However, despite the availability of VR and holographic technologies, users need to wear a head-mounted display (HMD), which is not suitable for the elderly, who do not like wear additional devices on their head. Importantly, VR stimuli do not give real spatial information for users as a reference although it can help people judge the shapes of stimuli that they manipulate or see, helps an individual maintain good posture, and aids pattern perception during a task [29]. Augmented reality (AR) technology can provide spatial visualization information for mental rotation [27]. An AR strategy combined with a tangible manual controller that integrates virtual 3D spatial information can provide spatial information for the elderly as a reference, enhancing their spatial awareness [34].

2.3 Benefits of AR

AR is a mix of real and virtual environments, where the virtual elements are computer-generated. AR can potentially offer testing and training options that are unavailable with the use of conventional neuropsychological methods. Computer-generated interactive simulated environments can be used to assess and rehabilitate cognitive abilities such as mental rotation ability. In the present study, we use AR to present a complete 3D animation with real spatial information of the background environment, allowing the user to see the virtual 3D model rotate corresponding to a tangible manual controller (cube) rotating in their hand. The user has real motor perception and visual feedback from the 3D spatial visualization display. Related studies have shown that this type of manipulation can help mental rotation [23, 55, 59]. Furthermore, AR technology can present full 3D holograms and does not require the user to translate a 2D image into a 3D model. AR can reduce learners' cognitive load and increase their interest in training [19, 28, 47]. AR interfaces can directly provide real-time 3D visual support with surrounding information and promote spatial visualization, which is related to mental rotation ability [27, 34]. Although VR shares some of these advantages, AR has some distinguishing features, as described below (Table 1).

2.4 Types of VR training systems

There are various types of VR training systems. VR is an immersive multimedia or computer-simulated reality. Most VR systems give no extra spatial information as a reference. A VR environment is thus a type of closed system in which the user is completely immersed. Thus, a user cannot obtain additional spatial information from their surrounding environment. Most VR applications lack motor perception corresponding to the visual feedback from the spatial visualization display. In contrast, AR supports this spatial reference information, which can help people judge the spatial information regarding the shapes that they manipulate or see [43]. AR provides spatial information to enhance performance in navigation tasks. It does not require the user to wear any equipment, which increases convenience and authenticity, especially for elderly people, who usually do not like to wear any device on their head. Moreover, some studies [53] have reported that using multimedia techniques can increase training efficiency and positively stimulates interest for both older and younger people [46]. Therefore, we adopted an AR platform combined with a tangible manual controller to allow users to rotate a virtual 3D model to provide mental perceptual feedback of 3D spatial visualization. This kind of training can enhance mental rotation ability due to its multisensory (3D visualization and spatial augmented information) feedback and physical object interaction. AR with a tangible manual controller provides a connection between motor perceptual skills and visual cognition to enhance the elderly's perception awareness during spatial visualization.

3 Methods

3.1 Participants

Thirty-five elderly adults initially participated in the study. They were recruited from senior citizen centers in Tainan, Taiwan, and Kaohsiung Veterans General Hospital in Kaohsiung, Taiwan. After an assessment using our inclusion and exclusion criteria (see below), 22 participants (mean age = 68.27 years; 14 female; 3 left-handed) were included in the study (Table 2).

Before the experiment began, a physiatrist (a medical doctor who specializes in physical and rehabilitation medicine) administered Guo's revised Chinese version [17] of the Mini-Mental State Examination (MMSE) [13] to all participants to ensure that their cognitive abilities were within the normal range. The MMSE focuses on five cognitive aspects: orientation, registration, attention and calculation, recall, and language. We additionally recruited 4 participants in our pilot study who scored > 24 on the MMSE to collect fundamental data of the mental strategies they used to handle the tasks. The inclusion criteria were: (1) 65 years of age and above, (2) an MMSE score of at least 24 (out of 30), which indicated cognitive soundness, (3) no other

Table 1 Comparison of AR and VR

AR	VR
1. User can see a mix of real and virtual environments	1. User is completely immersed in the virtual environment
2. Gives extra real spatial information as a reference	2. User cannot obtain additional spatial information from their surrounding environment
3. User has real motor perception and visual feedback from the 3D spatial visualization display	3. No real motor perception; all motor and visual feedback is computer- or machine-generated
4. User is not required to wear any equipment	4. User is required to wear equipment such as HMD
5. Affected by external light sources	5. Rarely affected by external light

Table 2 Information on subjects in the control and experimental groups

Group	Experimental	Control
Age (years)	68 (SD = 1.79)	68.54 (SD = 1.81)
Sex	7F/4M	7F/4M
MMSE score	27.82 (SD = 1.17)	27.36 (SD = 0.92)
L/R handedness	2L/9R	1L/10R
Training Method	ARSVT	2D MRT

M male, *F* female, AR-based spatial visualization training (ARSVT)

specific disabilities such as dementia or Alzheimer's disease, (4) not taking medications for physician- or self-diagnosed illnesses, (5) no physician-diagnosed comorbidities, (6) not undergoing any other therapies at the time of testing, and (7) vision and hearing within the normal range for their age. All testing was done by the same team (physiatrist and therapists).

The participants were all fluent in Mandarin Chinese or Taiwanese, and attended senior citizen centers for exercise at least two times a week. The physiatrist evaluated whether their physical health would allow them to participate in the study. We recruited only healthy participants because using participants who were already seriously aging or who had already developed Alzheimer's disease would have biased our experiments and their results, especially our training for manipulating 3D virtual reality objects, and it would have been difficult for them to pay visual attention to transform and rotate virtual 3D models. The hospital's Institutional Review Board (IRB No: B-BR-104-160-2) approved the study. All participants signed an informed consent form.

3.2 Design of manual controller

3.2.1 Gesture analysis

At the most basic level, spatial thinking requires the ability to encode, remember, transform and match spatial stimuli. Before developing the AR-based spatial visualization training (ARSVT) system, we established a manual control standard gesture pattern for the system. We observed and recorded the mental rotation behavior of elderly people without Alzheimer's disease using mental rotation skills to control objects in real situations. We did an MRT trial in the pilot study to determine the gestures used by the elderly during an MRT. We additionally recruited 4 participants (who did not take part in our main experiments) who scored > 24 on the MMSE based on the Shepard and Metzler [49] definition. The think-aloud method was adopted to collect the mental strategies that they used to handle the MRT. Next, we analyzed the manipulation gestures and created a morphological matrix (Fig. 1) to figure out how to design the manual controller with consideration of intuition and usability.

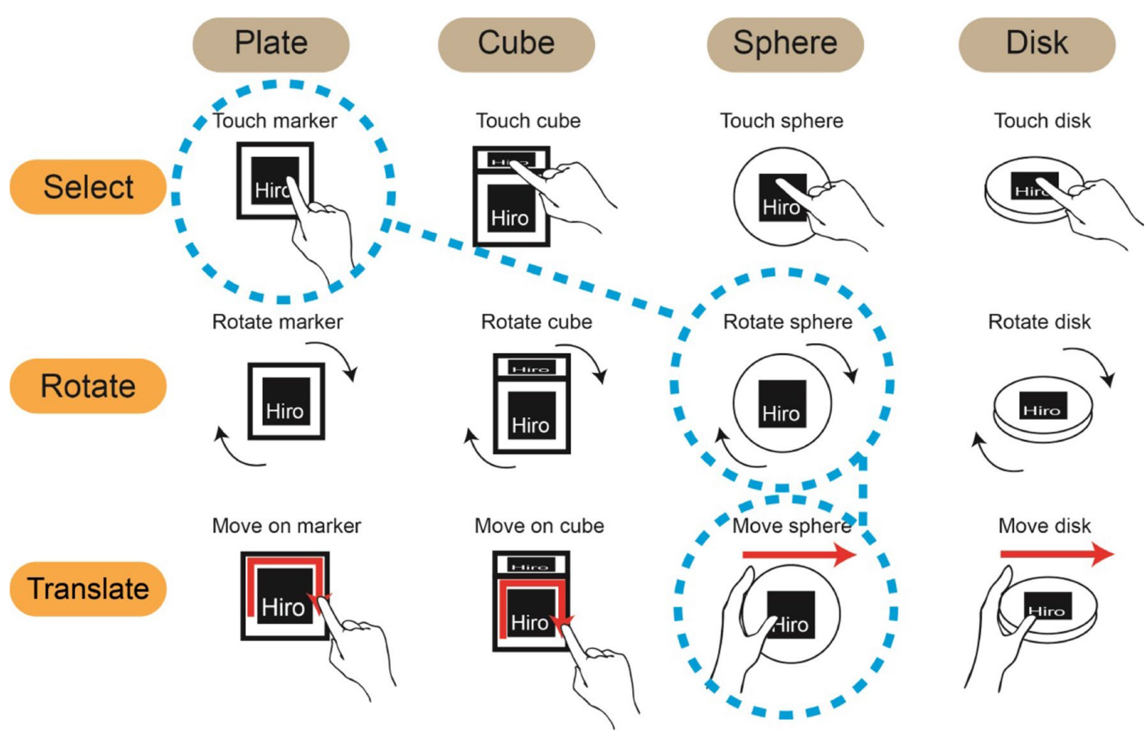

Fig. 1 Manipulation gestures and morphological matrix

3.2.2 Manual controller design

After we established and defined the manual controller's function for the ARSVT system, we started to design the controller's form and construct its AR environment. We created a manual device that looked like a cube with two plates (Fig. 2). We placed six markers (one on each side of the cube) for camera image recognition. Sometimes, some markers were obscured by participants' hands, though our system can detect the cube's *x*, *y*, and *z* center orientation in 3D space based on just one marker. With the six faces, a camera can easily recognize the manual controller. Moreover, we used a 3D printer to print the base of the dock, and fitted a button within the dock. The entire controller has three parts: (1) cube-shaped manual controller area, (2) virtual block model presentation area, and (3) tangible button area (Fig. 2). The cube-shaped manual controller controls the 3D virtual block's rotation and the red button is used to make the virtual model fall into the hole. When the model falls into the hole, the next trial begins.

3.3 Development of the ARSVT system

The ARSVT system was implemented on a laptop computer (Fig. 3). The system was composed of a set of manual controllers (hexahedral cube design). We designed two kinds of markers, namely cube markers and plate markers. The cube has six face markers to represent different directions (for

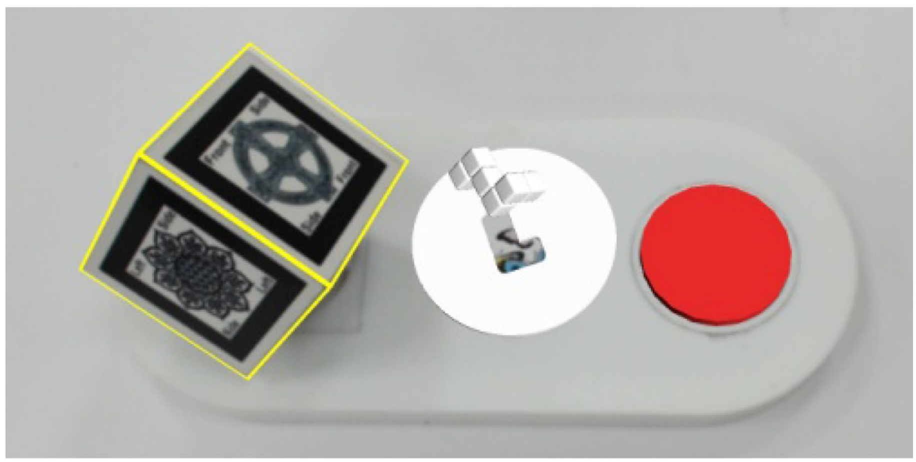

Fig. 2 Shape of manual device: 3D object (middle) and button are in AR

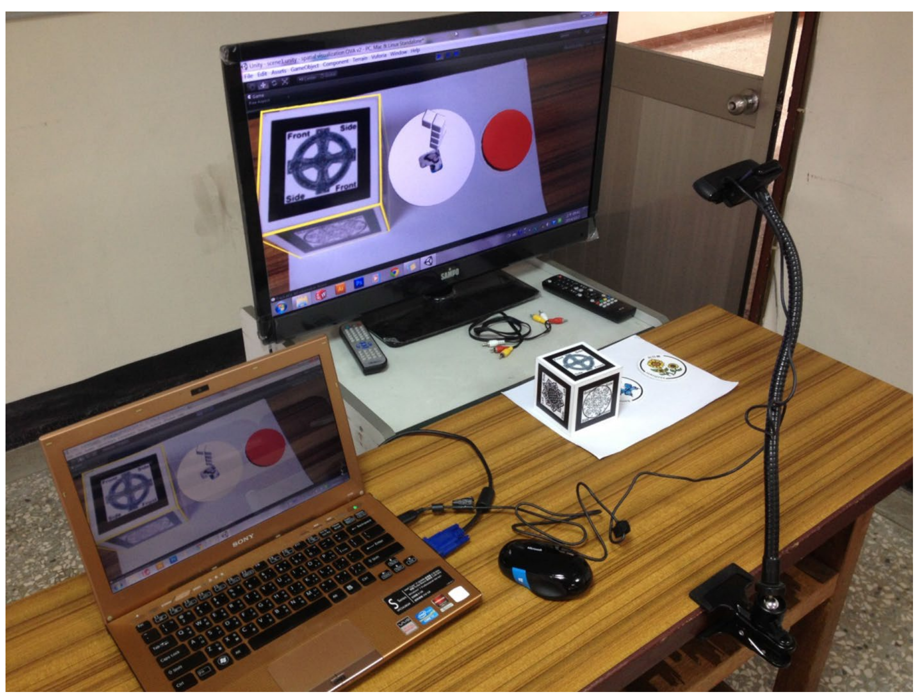

Fig. 3 AR spatial visualization training system setup

calculating the center of the cube's x, y, and z directions). Two plate markers on the right side next to the cube show the augmented 3D virtual block and the selection button. The markers are all attached to the tangible object (cube and two plates). When the camera detects them, the AR elements are overlaid on the real object. This system requires an additional camera (Logitech C920) and a monitor (32-inch LCD) for display (Fig. 3). When the markers appear, the corresponding virtual 3D objects are displayed on the monitor. Participants were able to rotate the tangible cube with attached markers to control the rotation angle of the virtual block, and pressed the second marker (button), which was on a virtual red disk, to make the virtual 3D block fall through the hole of the virtual floor. If the shape of the block did not match that of the hole, the block would be stuck until the trainers rotated the block to the right angle.

3.4 Design of testing instruments

The ARSVT system used game-based tasks for mental rotation training. We designed the game after researching many standard MRT trials. Occupational therapists and rehabilitation experts agreed that the game was suitable for training mental rotation ability. The subjects can rotate 3D objects and then make them fall through a hole on the virtual floor. This design uses hand control of a tangible cube that corresponds to rotating a 3D virtual block. This design lets the user use a real physical controller to control the virtual model's rotation, and use their hand to directly manipulate the virtual model. We designed the manual controller of the ARSVT system based on the results of gesture analysis. It is essential to determine what spatial training factors can be used in MRT test design. These factors are the fundamental units that therapists use to train people to solve spatial-related problems. After the factors were determined, we combined some of them into a prototype design and then added a scenario or interesting elements to construct an integrated MRT. Rotating the 3D object (virtual block) and making it fall through a hole on the virtual floor gives visual feedback for hand control (Fig. 4).

3.5 System development

SolidWorks® software (Dassault Systèmes SolidWorks Corp., Waltham, MA, USA) was used to construct the 3D forms and the hole. Next, these forms were exported to 3D modeling, animation, and rendering software (3ds Max®; Autodesk, San Rafael, CA, USA) to attach textures and transform them into FBX animation sequences (https://udn.epicgames.com/Three/FBXAnimationPipeline.html) so that they could be exported into Unity3D® (Unity Technologies, San Francisco, CA, USA), which was the main development engine used to create the training game. Qualcomm AR (QCAR), which has a free AR SDK, was adopted as the AR environment in the training system. The training system was constructed in Unity3D with the Vuforia platform. Unity3D is a game development engine that is widely used to visualize scenes and make games and animations. With Vuforia attached in Unity3D, QCAR can be implemented. The system implementation was carried out by coding Target Controller scripts in C#. One Multi-Target Controller (for the cube marker) and two Image-Target Controllers (for the plate markers) were used. With the Target Controller scripts hooked up to the corresponding items, users are able to perform tasks by manipulating AR markers. The tasks were coded in JavaScript and based on the box collider in Unity3D (Fig. 5).

3.6 Setting

All experimental sessions were conducted in a 3×5 m room inside a senior citizen center in Tainan, Taiwan. The room contained a table and chairs, an Intel Core i7 laptop computer, and a 32-inch LCD display (set up in front of the participants). The therapist sat on the left of the participant and guided the training process, operated the computer, and assisted the participants (Fig. 6). To begin the intervention test, the therapist showed the test sample to the participants, taught them how to use the ARSVT system, and ensured that they felt comfortable using AR technology. The participants started controlling each step of the test after the first trial task was presented. During the test, they used their hands to control the manual controller to directly manipulate the virtual block model and make it fall through the hole on the virtual floor. When they succeeded, the next task trial was presented (we arranged 30 MRT trials that were different though similar). The system ran the AR application in the background and showed the image on the LCD screen. Participants were able to practice gesture control with their hands so that they felt comfortable doing this experiment.

3.7 Phases, sessions, and experimental conditions

All participants ($n = 22$) were randomly divided into a control group ($n = 11$) and an experimental group ($n = 11$) to compare the learning effect after the intervention phase. Only the experimental group was trained using the ARSVT system (focused on 3D MRT training) during the intervention phase. The control group had 2D MRT training with extra instruction. The experiment for both groups consisted of three phases: (1) pretest, lasting for 4 weeks, in which baseline information on the participants was collected; (2) intervention, lasting for 1.5 months, in which two kinds of training type (ARSVT system vs. 2D MRT) were used to train their mental rotation ability; and (3) posttest, lasting for

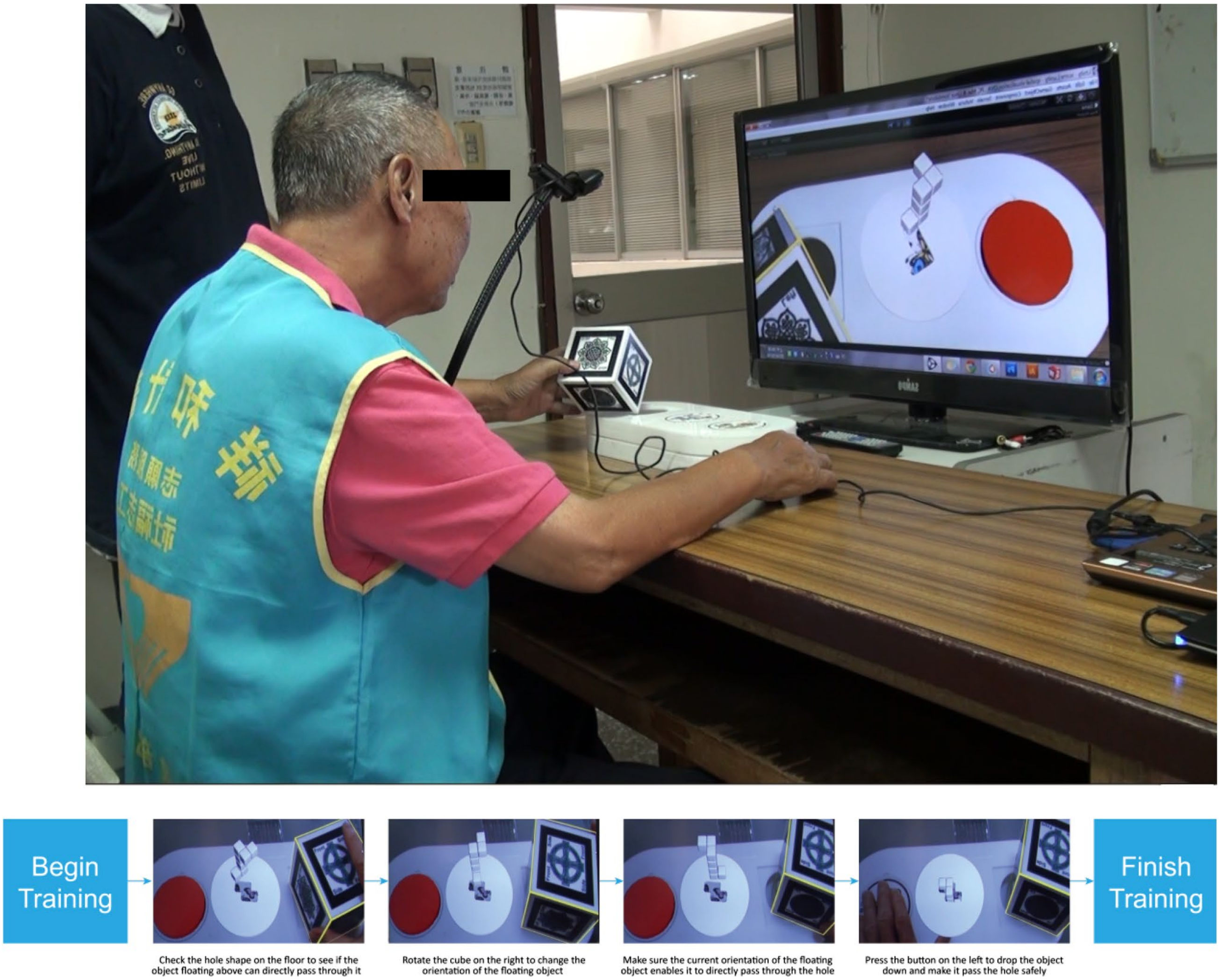

Fig. 4 Game-based tasks for spatial visualization training (rotating a 3D object and making it fall through hole on virtual floor)

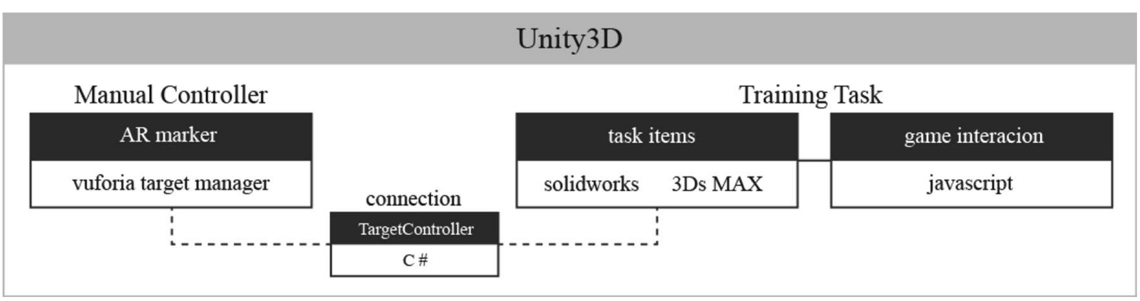

Fig. 5 Integration of AR spatial visualization training system

4 weeks. There was an 8-week hiatus after the intervention was completed to reduce recall interference (Fig. 7).

One certified occupational physiatrist with more than 15 years of experience working in the Physical Medicine and Rehabilitation Department at Kaohsiung Veterans General Hospital was responsible for the health and rehabilitation exercises of the participants. He and the occupational therapists conducted all sessions and taught all the participants how to use the ARSVT system. The occupational physiatrist supervised the experiments and

Fig. 6 Experimental scenario of spatial visualization training

each of the three therapists formed a team with one or two research assistants. We trained both groups at suitable times and in suitable places (the same three treatment rooms), especially for the pre- and posttests, and needed only to guide the participants to answer the standard 2D MRT tests printed on paper. Thus, we needed to spend a lot of time and manpower only during the intervention phase. Half of the participants (only the experimental group) needed to learn how to control the ARSVT system; hence, we also asked four senior social workers to help us with the experiments.

We adopted the standard MRT test for evaluating the mental rotation ability of both groups. The MRT test is the most commonly used test in evidence-based practice. It was defined by Shepard and Metzler [49]. Clinical medical experiments widely adopt this test to determine mental rotation ability decline. Therefore, we applied the standard MRT test for the control and experimental groups in the pre- and posttests according to the ABA design to record their fundamental data. During the MRT test, we asked both groups to conduct the trials without any extra instruction.

3.7.1 Control group

In the intervention phase, the control group underwent training using the standard MRT method twice a week for 1.5 months; however, we asked the therapists to assist them during the MRT test (e.g., give them some extra instruction). For example, during the test, therapists prepared some pen and paper to allow the patients to draw shapes with therapist help to highlight some parts of the shape (e.g., the edges of a line drawing), which would help the patients more easily imagine the objects.

3.7.2 Experimental group

The experimental group used the ARSVT system twice a week for 1.5 months (focused on 3D mental rotation training) during the intervention phase. AR technology can provide animation for people to directly visualize and manipulate real-time 3D virtual models to improve their mental rotation skills in ways that the traditional standard MRT cannot achieve using only 2D materials. Furthermore, the ARSVT system provides a tangible user interface (manual controller) for manipulation, which connects motor perception with spatial visualization feedback. Willems et al. [57] defined gestures as a kind of covert simulation of mental rotation. Using gestures reduces working memory load [16] and improves the internal computation of spatial transformations in visualization tasks such as mental rotation [8].

In addition, before the intervention, the experimental and control groups both did the same standard trials of the MRT test defined by Shepard and Metzler [49] at the pre- and posttests according to ABA design. The process definition was based on standard and evidence-based evaluation methods, and each task's questions were all different although at consistently similar levels of difficulty to reduce the test–retest effect. The pretest (as baseline) and posttest (as follow up) scores were used to compare the training effect after the intervention.

3.7.3 Procedure

Pretest phase (4 weeks) The pretest phases for each participant lasted for approximately 30–45 min. Participants were tested one at a time, and each pretest activity was done twice a week. This phase lasted for 4 weeks, during which average scores of the error rate and reaction times (RTs) for each test were recorded. Before they took the tests, the

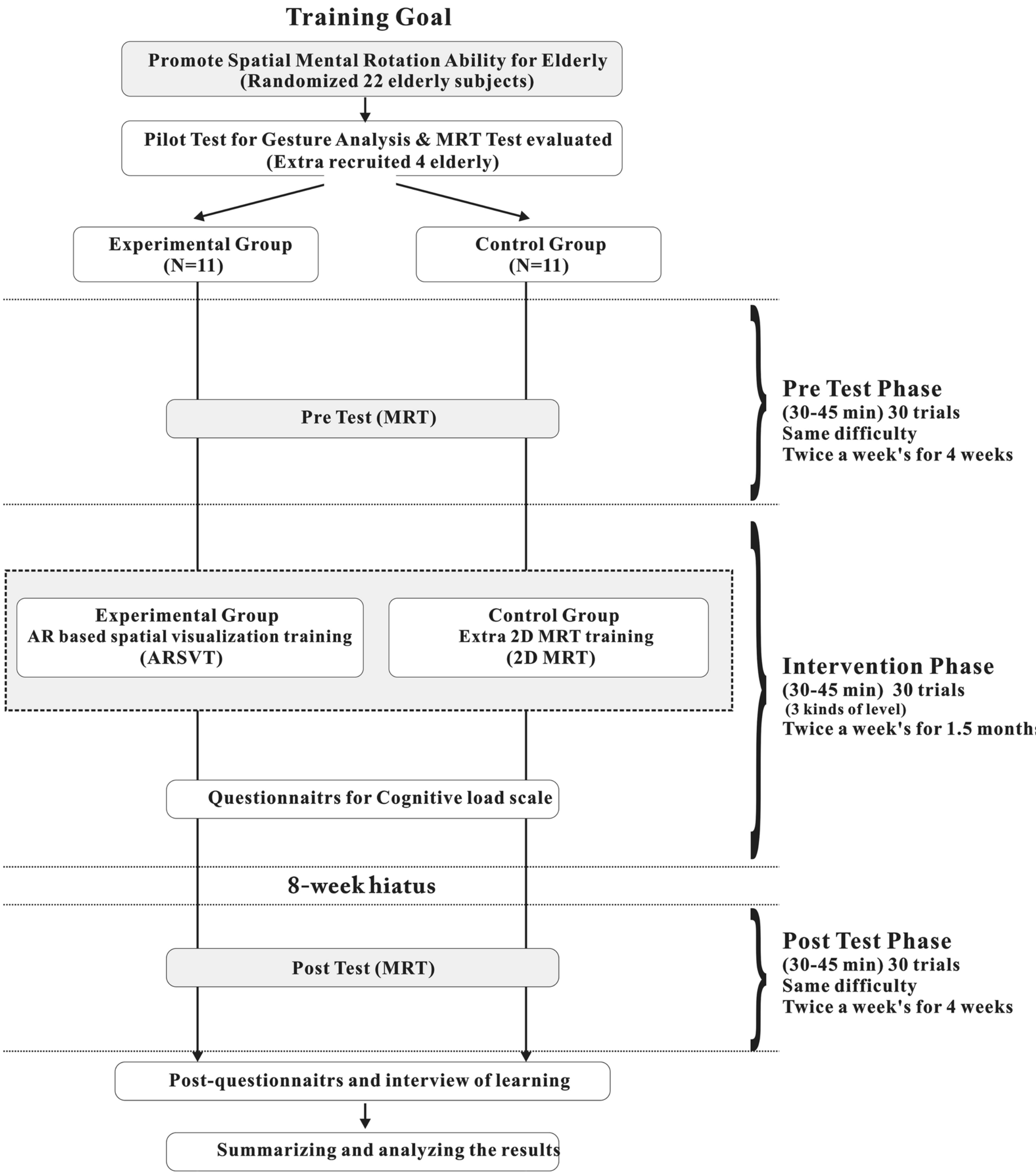

Fig. 7 Phases, sessions, and experimental conditions

participants were asked to report their personal information: name, gender, age, job, and interests. Next, the experimenter introduced the detailed procedures of taking the MRT test. The therapist gave an example of an MRT and demonstrated it to familiarize the participants with the MRT test. Afterward, each participant conducted 30 trials of the MRT test with objects printed on paper (both 2D and 3D); each question lasted 1–1.5 min; the RTs and error rate were recorded to evaluate the baseline abilities.

Intervention phase (*1.5 months*) Participants in both groups trained twice a week using different methods (2D MRT vs. ARSVT). The intervention phase lasted for 1.5 months, and the duration of each training session was 30–45 min. Participants were trained one at a time. The training game for the ARSVT system (only used for the experimental group—the control group used a different method) consisted of 30 3D MRT trials divided into three levels of complexity, defined by the number of corners of the obstacles on the object [48]. We considered the MRT test and mental rotation function to design a suitable training system. The task's scenario required participants to rotate a virtual block model and make it fall through a hole on the virtual floor. At the beginning of the game, participants saw a virtual block model displayed and a hole shown separately. They needed to determine the block model's rotation angle that would make the block match the hole. They were able to rotate their cube controller to control the angle of the block model and see the model from a different perspective. If the block fell through the hole, a green circle and a sound was triggered. The next scene of the trial was then presented. When an answer was incorrect, the system automatically showed the participant a red X. The therapist encouraged them to try again, asked them to observe the 3D object from a different perspective, and gave them extra time to practice. When they practiced, participants used their hands to manipulate the virtual 3D models many times. This type of training helped them match their motor perception with the mental rotation. During the training, participants were able to observe different views of the augmented 3D model on the 32-inch LCD display. They could simulate the 3D model rotation via the AR technology; the participants could directly use their hands to manipulate the manual controller to control the ARSVT system. We also gave the control group participants extra training. During the MRT test, our therapist pointed out which answers were incorrect and gave them a pen and paper to sketch the shape. The therapist encouraged them to try again and gave them extra time.

Posttest phase (*4 weeks*) The posttest phase, which lasted four weeks, consisted of essentially the same procedures as those in the pretest phase. The average scores and RTs on each test were recorded. The training trials were different from those in the pretest phase, which was done to reduce the test–retest effect, though the posttest task trials were consistent with the pretest task trials, as was their level of difficulty, according to experts' opinions, and they were all selected from a standard MRT testing database [48]. Each posttest activity lasted for about 30–45 min for each participant. Participants also completed a parallel set of 30 MRT trials (both 2D and 3D) with objects printed on paper as a follow up.

Test–retest reliability refers to the degree to which the obtained scores remain stable over a given time period, with no expected change in the target concept. If the pretest's MRT trials questions are the same as those in the posttest, there might be a learning effect, i.e., the posttest's score might be affected by the pretest. We cannot determine whether the pretest's affects the posttest or whether our intervention had a training effect. Therefore, in the standard experimental condition, different task trials with a similar difficulty level were prepared, and a hiatus of training of 4–6 weeks after the intervention was used to ensure that the posttest's score was not influenced by the pretest.

3.8 Measurement materials

We adopted Shepard and Metzler's [49] MRT test for testing the mental rotation training effect in the pre- and posttest design. We compared performance before and after the intervention using the paired-sample *t* test to determine whether a particular intervention method improved mental rotation ability.

3.8.1 MRT test

For mental rotation in the standard MRT test, the subject is asked to compare two 3D objects (or letters), often rotated along some axis, and state whether they are the same image or mirror images. The standard testing database of the MRT test was used for the pre- and posttest phases. There were three levels of complexity, determined by the number of corners that a stimulus had. At the first and easiest level, there were 6-8 corners; at the second (medium) level, there were 10–12 corners; at the third and most difficult level, there were 14–20 corners. Each level included four kinds of angular disparity between the two drawings: 45°, 90°, 135°, and 180°. In each of the four angular disparities, each pair of drawings was presented twice (once in a "same" trial and once in a "mirrored" trial).

Before we describe the MRT test, it should be noted that we adopted the three difficulty levels (advanced 2D MRT and ARSVT tests) in the intervention phase for both groups; however, we only used this strategy to instruct the subjects, with no data recorded.

In the pre- and posttest phases, we applied the second (medium) difficulty level for the test, and recorded the error rate and RTs in each test for comparison. We did the experimental control design this way because according to our hospital's therapists and clinical physiatrist's evaluations, our recruited participants' cognitive abilities (MMSE score > 24) were suitable to answer the second (medium) level questions. The physiatrist judged this level to be suitable for our subjects because they felt that it was neither too difficult nor easy, and early experiments found no effect of complexity on the speed of mental rotation [12]. Therefore, to avoid bias and unpredictable conditions and control the consistency of the MRT test in the pre- and posttest phases, we adopted the same difficulty level for both groups. We arranged 30 MRT trials to occur at random in our MRT test to reduce boredom and the test–retest effect.

3.8.2 Cognitive load scale

A cognitive load scale was adopted for measuring the cognitive load of individual participants [24]. It consisted of four items (see questionnaire) in a seven-point Likert scale: two items for mental load (intrinsic load) and two items for mental effort (extraneous and germane load); the total score for each aspect was 14. We report each item's average score. Mental load is related to the number of interacting information elements and the extent to which these elements interact, whereas mental effort refers to whether the instructional design was poor (extraneous cognitive load) or good enough (germane cognitive load) [51]. The cognitive load test was given to participants of both groups on the last day of the intervention stage.

3.9 Data collection, and test reliability and validity

The main researchers who examined and supervised the procedural reliability of this study were the same certified occupational therapists teams who conducted all of the tests. In addition, we held meetings with experts, carried out a pilot study to verify the test items and conducted a gesture analysis. We made a checklist for the test procedure for therapists to ensure consistency in the processes and related controls: test content, length of time, task trials, case criteria, and test environment. We also used the same hardware device to control the consistency of each 3D model presented to ensure that the same visual effects were presented, and we excluded unclear and confusing parts of the content. The reliability and validity of the tools used in this study were confirmed using a pilot study and expert judgment. The content validity was confirmed by a panel of experts to determine how well the test items reflected the range of content being measured. Moreover, we did a pilot study with an additional 4 participants with MMSE scores of > 24. Cronbach's α (> 0.89) was used to determine the internal consistency. Their answers were checked by therapists and experts who tested for normative answers after the participants had completed each test in each phase. We used questionnaires (see Appendix) combined with interviews for expert assessment and reports related to the results of tests to ensure that our results outcome is close to the real situation.

The interview process used semi-structured questions to enable the respondent (subjects, therapists, or intimate social contacts) to answer in as much detail as needed. We asked the subjects some questions after all the sessions had completed. For example, (1) "Do you feel more confident taking the MRT test after the intervention phase?" (for both groups, on a scale from 1—Strongly disagree to 7—Strongly agree); (2) "Do you feel that this training effectively promoted your awareness of spatial direction and environmental cognitive capacity?" (for both groups, on a scale from 1—deterioration to 7—great improvement); (3) "Do you feel that the ARSVT system is easy to use?" (only for the experimental group, on a scale from 1—Strongly disagree to 7—Strongly agree). In addition, we also asked our therapists and subjects' intimate social contacts some questions. For example: (1) "Do you feel that your patients or family member had sufficient ability to handle their spatial routine problem such as finding their car in the parking lot or finding their way back home after the intervention phase?" (seven-point Likert scale on a scale from 1—deterioration to 7—great improvement); (2) "Do you feel that this system was intuitive to control and could be used directly for training?" (for the therapist, on a seven-point Likert scale from 1—Strongly disagree to 7—Strongly agree). The questionnaire was given to the therapist and the subjects' intimate social contacts on the last day of the posttest stage.

4 Results: training effect of AR-based spatial visualization system

4.1 Reduction in error rate

In the analysis, we conducted the paired-sample t test in SPSS 19.0 to compare the experimental ($n = 11$) and control groups ($n = 11$) in terms of overall error rate on the MRT test in pre- and posttest phases. Between the two phases, we gave participants intervention (ARSVT for the experimental group; 2D MRT with extra instruction for the control group). After the intervention phase, we found that all participant of the experimental group started with a high error rate (= 52.23%) during the pretest phase, although the scores of error rate decreased significantly ($p < 0.05$) (error rate = 17.77%) in the posttest phase. These results indicate that the correct answer rates of the experimental group significantly improved ($p < 0.05$). However, the control group started with a similar error rate (= 46.33%) in the pretest; the error rate in the posttest was 31.10%. Although the control group subjects' ability also improved, the improvement was worse than that of the experimental group (Table 3). This means that after the six-week intervention stage, the experimental group's error rate was lower than that of the control group, suggesting that using ARSVT is more suitable than 2D MRT for training the mental rotation skills of older adults and the elderly.

The results show that the control group also reduced their error rate in the posttest. The therapist and expert believe that this is due to the traditional 2D MRT training and extra instruction such as drawing the spatial outline using a pen and paper with the therapist to help their mental rotation in the posttest trials. However, this training process made the participants tired, stressed, and bored during the test. In the pretest, participants in both groups complained that the MRT test is difficult. However, after receiving intervention in the training phase, we found that the two strategies (2D MRT and the ARSVT) had different effects on the improvement of mental rotation ability, and although the control group's performance was worse than that of the experimental group, both groups felt more confident in taking the MRT tests than

Table 3 Pre- and posttest scores

Group	Times test taken	Experimental ($n = 11$)		Control ($n = 11$)	
Mean error rate (%)		Pretest	Posttest	Pretest	Posttest
	1	53.33%	20.30%	47.88%	32.12%
	2	53.94%	20.61%	47.57%	32.42%
	3	51.51%	18.79%	48.79%	30.91%
	4	52.73%	18.49%	46.67%	30.61%
	5	54.24%	17.58%	46.67%	30.03%
	6	53.33%	17.88%	45.15%	32.12%
	7	50.61%	15.46%	43.64%	30.61%
	8	48.18%	13.03%	44.24%	30.00%
	Mean	52.23%	17.77%	46.33%	31.10%
Mean reaction time (s)		Pretest	Posttest	Pretest	Posttest
	1	16.56	10.68	16.93	11.21
	2	16.67	10.85	16.95	10.98
	3	16.21	11.00	17.67	11.50
	4	15.83	10.17	16.67	11.19
	5	16.45	11.01	16.56	10.96
	6	16.53	10.36	16.50	11.12
	7	16.07	10.51	17.12	11.23
	8	16.16	10.78	16.72	11.17
	Mean (SD)	16.31 (1.31)	10.67 (1.40)	16.89 (1.38)	11.17 (0.82)

they did taking the pretest. This phenomenon was especially strong in the experimental group. We calculated their data from the questionnaire of confidence agreement scale (see questionnaire). The results show that their average level of confidence agreement was good. The agreement score of the experimental group was 5.45 (SD = 0.66) and that of the control group was 4.36 (SD = 0.48) on a scale of 1–7.

4.2 Reaction time and cognitive load

The training effect was also evaluated using RTs. Based on Shepard and Metzler's definition [49], the RTs of each trial and the error rate of the MRT test were recorded. The mean RTs were recorded for correct trials only. Paired-sample t tests were used to compare the two groups' average RTs in the pre- and posttest phases. After the intervention phase (2D MRT and ARSVT), mean RTs fell in both groups. The experimental group (pretest vs. posttest) scores were 16.31 versus 10.67 s, and the control group scores were 16.89 versus 11.17 s. Both differences were significant ($p < 0.05$) between the two groups' pre- and posttest scores (Table 3). However, the control group participants stated that they did not like the extra 2D MRT trials in the intervention phase because they were bored and could not imagine mentally rotating 3D models although they were given a piece of paper and a pen to draw the outline of the spatial model. Hence, we conducted an advanced scale test of the participants' cognitive load to evaluate the mental load during training with advanced 2D MRT and ARSVT in the training phase. We ran the cognitive load scale test on the last day in the intervention phase for both groups.

A paired-sample t test was then conducted to compare the overall cognitive load of 2D MRT for the control group and ARSVT training for the experimental group. By comparing the scores of mental effort and mental load separately using a paired-sample t-test, it was found that there was a significant difference ($p < 0.05$) in terms of mental effort between 2D MRT training ($M = 7.27$, SD = 1.05) and ARSVT training ($M = 3.45$, SD = 0.5). Moreover, the mental load scores for 2D MRT training ($M = 6.73$, SD = 0.75) and ARSVT ($M = 3$, SD = 0.43) were significantly different ($p < 0.05$). The cognitive load of ARSVT training is thus significantly lower than that of 2D MRT training.

5 Discussion

Error rates and RTs in the MRT test fell significantly in the experimental group. There are three possible explanations for this. First, the visual perspective in the system was 3D; therefore, the participants might have felt as if they were actually seeing the rotation of the virtual block due to the AR providing full 3D visualization, which helped them better understand 3D mental rotation and gave visual perception feedback. In addition, AR provides spatial reference information that helps people judge the shapes of stimuli that they manipulate or see, helps an individual maintain good posture, and aids pattern perception in tasks [29]. Second, the participants used hand gestures with a tangible cube controller to control the virtual 3D object. Willems et al. [57] defined gestures as a kind of covert simulation of mental rotation. Using gestures reduces working memory load [16] and improves the internal computation of spatial transformations in visualization tasks such as mental rotation [8]. Another motor behavior that people commonly use is gestures, which can aid mental rotation. For example, people often spontaneously use gestures when they speak (co-speech gestures) to describe their solutions to spatial problems. There is a consensus in literature that co-speech gestures and speech production are tightly linked [8, 16]. A possible explanation is that participants reactivate the actions involved in solving the problems during description, and that some aspects of these reactivations are expressed as gestures [9]. We found that participants during the intervention tried to use their motor perceptual skills to simulate in their minds the real rotation to help them figure out the 3D spatial rotation status. The gestures used in the posttest were more helpful than those in the pretest. The positive results in our study are consistent with other research t indicating that gestures are beneficial for problem solving [8] and for promoting faster performance [20, 56]. Third, AR presents precise spatial data as well as spatial notions [34]. People were able to directly realize spatial concepts in AR rather than figure them out based on 2D information from flat formats such as print paper or LCD displays [11, 19, 28, 47]. When carrying out an MRT, participants might be required to construct images of the stimuli in their mind and then mentally rotate them. Perhaps they acquired or strengthened this ability during the mental rotation training with our system.

5.1 Feedback from participants

All participants in the experimental group agreed that the ARSVT system had a positive training effect (average level of agreement = 5.55; SD = 0.89; score from 1 to 7 in the experimental group). They all found that AR was entertaining since most of them had not previously seen this technology. Participants in the experimental group showed great interest in using our ARSVT system for training and showed a naturally adaptive behavior response after the intervention. The new native motor behavior learned in the intervention phase helped them imagine and infer the 3D object rotation status; they became accustomed to using the tangible manual controller to rotate the virtual 3D model, which is a synesthesia linkage between the brain and motor perception [59]. After we removed the 3D AR image, the participants still used their past multisensory experience (gesture and visual feedback) to handle the MRT task. For example, we also found that during the posttest phase, the experimental group participants unconsciously turned and rotated their hands just as if they had really been handling a 3D object. This indicated that they had established some new native motor behavior using our training process [4]. In addition, we also got some feedback on the MRT test in the pre- and posttest phases. Most participants did not like the test because it was too formal and boring and they worried about their test performance (RTs and error rate). They felt pressure, which made them frustrated. Furthermore, they could not get used to focusing on text or pictures for a long time, which is a drawback of 2D MRT. In contrast, the ARSVT test training was more like a game, which increased their interest. They also appreciated the therapist interaction and guidance, which avoided any sense of isolation, reducing their stress.

5.2 Limitations and future work

This study has some limitations. First, because this strategy is a fairly new intervention for elderly people, it was difficult to recruit participants to join the study; moreover, the participants had limited time for the tests. Accordingly, it would be advantageous to recruit and enroll more participants and extend the experiment time period to provide stronger evidence. Second, it was difficult to determine whether the mental rotation skills of our participants had actually declined because this high-level ability is not often used in everyday life by most people. Our positive findings indicate that people might change their behavior when they are aware of being observed; however, this will require a great deal of prospective observation and a long-term study. Third, we focused on the improvement of the experimental group as a whole. Future research might also take into account individual differences, e.g., gender and age, and how each individual uses the ARSVT display.

Fourth, many systems used for mental rotation training lack real-time 3D presentation. With the ARSVT system, more interesting and useful types of MRT that are similar to real-life tasks can be implemented for training; for example, we could integrate other material into this platform to train the elderly using the ARSVT system, and make the training content close to tasks encountered by the elderly in their daily routine, such as folding clothes or locking and unlocking a door. We want to make the training system more comprehensive and diverse. The system can use any 3D content. Future training system design should consider the actual needs of the elderly and train tasks that are close to those the elderly require in real-life settings.

6 Conclusions

This study proposed the ARSVT system for training mental rotation skills of older adults. The 3D training content is generally easier for older adults to comprehend, reducing cognitive load. The paired t test results of error rates and RTs indicate that the proposed training system is efficacious. All of our experimental group participants expressed a positive attitude toward the system and its effect on their motivation to learn. The proposed system may thus replace current 2D presentation forms.

The ARSVT system was effective in helping the participants select and maintain their focus on the 3D model and better perform in the MRT trials. It encouraged them to observe and imagine spatial signals, and improved their mental rotation skills. We also interviewed some therapists and participants' family members and intimate friends, all of whom stated that, after the intervention, the participants responded more fluently in their daily routine.

A problem that some older adults often experience is wearing clothes inside out. One man reported that it was hard for him to distinguish the inside and outside of clothes so he often wore his clothes inside out, which was embarrassing. Now he is more careful checking the details and the different sides of clothes before putting them on. Also, he can recognize the right button position on his shirts and button up correctly. A woman said that clothing that comes in pairs (e.g., socks and shoes) confused her since she often mismatched them. The two items look similar and are symmetrical, which is hard for older adults to differentiate. After mental rotation training, she became more skilled at recognizing the correct items in a pair. An old man said that he no longer made any mistakes when turning the key to open his front door after mental rotation training. Before, he often failed to target the key into the keyhole and forgot the right direction of rotation. Now, he can insert the key and turn it successfully. Being able to properly adjust screws is also a benefit of mental rotation training. Another man mentioned that he had more focus when using screws and bolts. He can also figure out the correct turning direction more easily.

Although the participants could not clearly indicate what specific skills benefitted from our training, their friends and family all expressed positive opinions about their increased understanding of the spatial environment around them. Future studies need to include more elderly participants and participants with other types of mental decline, e.g., early Alzheimer's disease. We hope that this training tool might be used clinically to treat elderly patients with declining mental rotation skills. Finally, we hope that our findings will encourage new research projects on how to use visual media as useful adjuncts to other types of therapy for age-induced mental decline. In addition, training material for older adults should be more complete and more reflective of real life.

Appendix: Questionnaire

Dear participant, this questionnaire is designed to determine your subjective feelings of the use of the training system. It consists of three parts. Part I concerns your learning interest of the training system. Part II concerns the cognitive load you perceived during the use of the training system. Part III concerns your general attitude toward the ARSVT system (only for the experimental group). The responses to questions in each part use seven-point Likert-type scales, ranging from 1 (strongly disagree) to 7 (strongly agree). There is no right or wrong answer, and all of your answers will be handled anonymously.

PART I. Learning Interest (Five items)

	Strongly disagree		Strongly agree
1. During the training activities, I was engaged in the training tasks.	1	□ □ □ □ □ □ □	7
2. The training is interesting.	1	□ □ □ □ □ □ □	7
3. I like the training activities.	1	□ □ □ □ □ □ □	7
4. I would like to use this training system in the future.	1	□ □ □ □ □ □ □	7
5. I would recommend this training system to my friends.	1	□ □ □ □ □ □ □	7

PART II. Cognitive Load (Four items)

(It consists of four items: two items for mental load and two items for mental effort.)

	Strongly disagree		Strongly agree
1. It is mentally demanding to use this system to perform mental rotation training.	1	□ □ □ □ □ □ □	7
2. It is mentally demanding to learn mental rotation skills.	1	□ □ □ □ □ □ □	7
3. The use of this training system makes me distracted.	1	□ □ □ □ □ □ □	7
4. The use of this training system is stressful.	1	□ □ □ □ □ □ □	7

PART III. Attitude (Seven items)

(Only for the Experimental group)

	Strongly disagree		Strongly agree
1. I feel more confidence to take the MRT test after the intervention phase.	1	□ □ □ □ □ □ □	7
2. I feel that this training effectively promotes my awareness of spatial directions and my environmental cognitive capacity.	1	□ □ □ □ □ □ □	7
3. I feel that the ARSVT system is easy to use.	1	□ □ □ □ □ □ □	7
4. I feel ARSVT system was entertaining	1	□ □ □ □ □ □ □	7
5. I feel that your patients / family have sufficient ability to handle their spatial routine problem such as find the car in the parking lot or way finding to back home after intervention phase (from therapists and some family members' perspective).	1	□ □ □ □ □ □ □	7
6. I feel that this system is intuitive to control and could be used directly for training (from therapists' perspective).	1	□ □ □ □ □ □ □	7
7. I feel motivated to use the ARSVT system in the future.	1	□ □ □ □ □ □ □	7

References

1. Aretz, A.J., Wickens, C.D.: The mental rotation of map displays. Hum. Perform. **5**(4), 303–328 (1992)
2. Arthur, P., Passini, R.: Wayfinding: People, Signs, and Architecture. Reissued as a collector's edition in 2002 by Focus Strategic Communications, Inc. (2002)
3. Banich, M.T., Heller, W.: Evolving perspectives on lateralization of function. Curr. Dir. Psychol. Sci. **7**(1), 1–2 (1998)
4. Blakemore, S.J., Bristow, D., Bird, G., Frith, C., Ward, J.: Somatosensory activations during the observation of touch and a case of vision–touch synesthesia. Brain **128**(7), 1571–1583 (2005)
5. Buckner, R.: Memory and executive function in aging and AD: multiple factors that cause decline and reserve factors that compensate. Neuron **44**(1), 195–208 (2004)
6. Chandler, P., Sweller, J.: Cognitive load theory and the format of instruction. Cogn. Instr. **8**(4), 293–332 (1991)
7. Chen, K.C.: Mental rotation ability and topographical disorientation in patients with mild Alzheimer's disease. Institute of Behavioral Medicine, NCKU Dissertation, 1–56 (2011)
8. Chu, M., Kita, S.: The nature of gestures' beneficial role in spatial problem solving. J. Exp. Psychol. Gen. **140**(1), 102–116 (2011)
9. Cook, S.W., Tanenhaus, M.K.: Embodied communication: speakers? ─ gestures affect listeners? ─actions. Cognition **113**(1), 98–104 (2009)
10. De Beni, R., Pazzaglia, F., Gardini, S.: The role of mental rotation and age in spatial perspective-taking tasks: when age does not impair perspective-taking performance. Appl. Cogn. Psychol. **20**(6), 807–821 (2006)
11. Dunser, A., Walker, L., Horner, H., Bentall, D.: Creating interactive physics education books with augmented reality. In: Paper presented at the Proceedings of the 24th Australian Computer-Human Interaction Conference (2012)
12. Folk, M.D., Luce, R.D.: Effects of stimulus complexity on mental rotation rate of polygons. J. Exp. Psychol. Hum. Percept. Perform. **13**(3), 395 (1987)
13. Folstein, M.F., Folstein, S.E., McHugh, P.R.: Mini-mental state: a practical method for grading the cognitive state of patients for the clinician. J. Psychiatr. Res. **12**(3), 189–198 (1975)
14. Frick, A., Daum, M.M., Walser, S., Mast, F.W.: Developmental changes in the interference of motor processes with mental rotation. In: Paper Presented at the Proceedings of the 27th Annual Meeting of the Cognitive Science Society. (2005)
15. Gardony, A.L., Taylor, H.A., Brunye, T.T.: What does physical rotation reveal about mental rotation? Psychol. Sci. **25**(2), 605–612 (2014)
16. Goldin-Meadow, S., Beilock, S.L.: Action's influence on thought: the case of gesture. Perspect. Psychol. Sci. **5**(6), 664–674 (2010)
17. Guo, N.W., Liu, X.Z., Wang, P.F., Liao, Q.C., Zhen, R.X., Lin, K.P., et al.: Brief intelligence assessment of Chinese measurement and established scheme. J. Taiwan. Rehabil. Med. Mag. **16**, 52–59 (1988)
18. Hedden, T., Gabrieli, J.D.: Insights into the ageing mind: a view from cognitive neuroscience. Nat. Rev. Neurosci. **5**(2), 87–96 (2004)
19. Hedley, N.R.: Empirical evidence for advanced geographic visualization interface use. In: Paper Presented at the 2003 International Cartographic Association's International Cartographic Congress (ICC 2003), Los Alamitos, CA. (2003)
20. Hegarty, M., Mayer, S., Kriz, S., Keehner, M.: The role of gestures in mental animation. Spat. Cogn. Comput. **5**, 333–356 (2005)
21. Hertzog, C., Kramer, A.F., Wilson, R.S., Lindenberger, U.: Enrichment effects on adult cognitive development: can the functional capacity of older adults be preserved and enhanced? Psychol. Sci. Public Interest **9**(1), 1–65 (2008)
22. Hostetter, A.B., Alibali, M.W., Bartholomew, A.E.: Gesture during mental rotation. In: Paper Presented at the Proceedings of the 33rd Annual Conference of Cognitive Science Society. Cogsci. Austin. TX, USA. (2011)
23. Hoyek, N., Champely, S., Collet, C., Fargier, P., Guillot, A.: Is mental rotation ability a predictor of success for motor performance? J. Cogn. Dev. **15**(3), 495–505 (2014)

24. Hwang, G.J., Chang, H.F.: A formative assessment-based mobile learning approach to improving the learning attitudes and achievements of students. Comput. Educ. **56**(4), 1023–1031 (2011)
25. Jansen, P., Heil, M.: Gender differences in mental rotation across adulthood. Exp. Aging Res. **36**(1), 94–104 (2010)
26. Jenkins, L., Myerson, J., Joerding, J.A., Hale, S.: Converging evidence that visuospatial cognition is more age-sensitive than verbal cognition. Psychol. Aging **15**(1), 157–175 (2000)
27. Kaufmann, H., Schmalstieg, D.: Mathematics and geometry education with collaborative augmented reality. Comput. Graph. **37**(3), 339–345 (2003)
28. Klatzky, R.L., Wu, B., Shelton, D., Stetten, G.: Effectiveness of augmented-reality visualization versus cognitive mediation for learning actions in near space. ACM. Trans. Appl. Percept. **5**(1), 1–23 (2008)
29. La Grow, S.J.: Blindness and brain plasticity in navigation and object perception. J. Vis. Impair. Blind. **102**(2), 107–108 (2008)
30. Lee, S., Kline, R.: Wayfinding study in virtual environments: the elderly vs. the younger-aged groups. J. Archit. Res. **5**(2), 63–76 (2011)
31. Mahncke, H.W., Bronstone, A., Merzenich, M.M.: Brain plasticity and functional losses in the aged: scientific bases for a novel intervention. Prog. Brain Res. **157**, 81–109 (2006)
32. Maitland, S.B., Intrieri, R.C., Schaie, K.W., Willis, S.L.: Gender differences in cognitive abilities: invariance of covariance and latent mean structure. Aging Neuropsychol. C **7**, 3253 (2000)
33. Malinowski, J.C.: Mental rotation and real-world wayfinding. Percept. Mot. Skills **92**, 19–30 (2001)
34. Martín-Gutiérrez, J., Saorín, J.L., Contero, M., Alcañiz, M., Pérez-López, D.C., Ortega, M.: Design and validation of an augmented book for spatial abilities development in engineering students. Comput. Graph. **34**(1), 77–91 (2010)
35. McCarthy, A.L.: Improving Older Adults' Mental Rotation Skills Through Computer Training. University of Akron, Akron (2010)
36. Mowszowski, L., Batchelor, J., Naismith, S.L.: Early intervention for cognitive decline: can cognitive training be used as a selective prevention technique? Int. Psychogeriatr. **22**(4), 537–548 (2010)
37. Park, H.: The effect of activities in virtual worlds as a communication environment to understand each other. J. Cyber. Ther. Rehabil. **3**(1), 71–82 (2010)
38. Parsons, T.D., Courtney, C.G., Dawson, M.E., Rizzo, A.A., Arizmendi, B.J.: Visuospatial processing and learning effects in virtual reality based mental rotation and navigational tasks. In: Engineering Psychology and Cognitive Ergonomics. Understanding Human Cognition. Lect. Notes. Comput. Sci. 8019, 75–83: Berlin: Springer. (http://link.springer.com/chapter/10.1007%2F978-3-642-39360-0_9). (2013)
39. Pazzaglia, F., Moe, A.: Cognitive styles and mental rotation ability in map learning. Cogn. Process. **14**(4), 391–399 (2013)
40. Peich, M.C., Husain, M., Bays, P.M.: Age-related decline of precision and binding in visual working memory. Psychol. Aging **28**(3), 729–743 (2013)
41. Podzebenko, K., Egan, G.F., Watson, J.D.: Real and imaginary rotary motion processing: functional parcellation of the human parietal lobe revealed by fMRI. J. Cogn. Neurosci. **17**(1), 24–36 (2005)
42. Rabbitt, P.: Handbook of Human Intelligence. Q. J. Exp. Psychol. Sect A Hum. **40**(1), 167–185 (1988). **Sternberg, Rj**
43. Rieser, J.J. (ed.): Blindness and Brain Plasticity in Navigation and Object Perception, vol. 14, pp. 263–264. Taylor & Francis, Abingdon (2008)
44. Rizzo, A., Buckwalter, J., Larson, P., Van Rooyen, A., Kratz, K., Neumann, U., Kesselman, C., Thiebeaux, M.: Preliminary findings on a virtual environment targeting human mental rotation/spatial abilities. In: Paper Presented at the European Conference on Disability, Virtual Real. Assoc. Technol. (1998)
45. Roberts, J.E., Bell, M.A.: Two-and three-dimensional MRT lead to different parietal laterality for men and women. Int. J. Psychophysiol. **50**(3), 235–246 (2003)
46. Shelton, B.E., Hedley, N.R.: Using augmented reality for teaching Earth-Sun relationships to undergraduate geography students. In: The First IEEE International Workshop on Augmented Reality Toolkit, Conference Paper. (2002)
47. Shelton, B.E., Hedley, N.R.: Exploring a cognitive basis for learning spatial relationships with augmented reality. TICL **1**, 323–357 (2004)
48. Shepard, R.N., Cooper, L.A.: Mental Images and Their Transformations. MIT Press, Cambridege (1986)
49. Shepard, R.N., Metzler, J.: Mental rotation of three-dimensional objects. Science **171**, 701–703 (1971)
50. Sjolie, D., Bodin, K., Elgh, E., Eriksson, J., Janlert, L.E., Nyberg, L.: Effects of interactivity and 3D-motion on mental rotation brain activity in an immersive virtual environment. In: Paper Presented at the Proceedings of the SIGCHI Conference Human Factor. Comput. Syst. (2010)
51. Sweller, J., Van Merriënboer, J.J., Paas, F.G.: Cognitive architecture and instructional design. Educ. Psychol. Rev. **10**(3), 251–296 (1998)
52. Tsai, L.S.: Insightful solution of a geometry problem with instructional cues: I Group experiments. Percept. Mot. Skills **67**(3), 699–705 (1988)
53. Van Gerven, P., Paas, F., Van Merriënboer, J., Hendriks, M., Schmidt, H.G.: The efficiency of multimedia learning into old age. Br. J. Educ. Psychol. **73**(4), 489–505 (2003)
54. Vingerhoets, G., De Lange, F.P., Vandemaele, P., Deblaere, K., Achten, E.: Motor imagery in mental rotation: an fMRI study. Neuroimage **17**(3), 1623–1633 (2002)
55. Wexler, M., Kosslyn, S.M., Berthoz, A.: Motor processes in mental rotation. Cognition **68**(1), 77–94 (1998)
56. Wiedenbauer, G., Jansen-Osmann, P.: Manual training of mental rotation in children. Learn. Instr. **18**(1), 30–41 (2008)
57. Willems, R.M., Toni, I., Hagoort, P., Casasanto, D.: Neural dissociations between action verb understanding and motor imagery. J. Cogn. Neurosci. **22**, 2387–2400 (2010)
58. Wohlschlager, A., Wohlschlager, A.: Mental and manual rotation. J. Exp. Psychol. Hum. Percept. Perform. **24**(2), 397–412 (1998)
59. Wraga, M., Thompson, W.L., Alpert, N.M., Kosslyn, S.M.: Implicit transfer of motor strategies in mental rotation. Brain Cogn. **52**(2), 135–143 (2003)
60. Wright, R., Thompson, W.L., Ganis, G., Newcombe, N.S., Kosslyn, S.M.: Training generalized spatial skills. Psychon. Bull. Rev. **15**(4), 763–771 (2008)
61. Yeh, S.C., Wang, J.L., Wang, C.Y., Lin, P.H., Chen, G.D., Rizzo, A.: Motion controllers for learners to manipulate and interact with 3D objects for mental rotation training. Br. J. Educ. Technol. **45**(4), 666–675 (2014)
62. Yurt, E., Sunbul, A.M.: Effect of Modeling-Based activities developed using virtual environments and concrete objects on spatial thinking and mental rotation skills. Educ. Sci Theory Pract. **12**(3), 1987–1992 (2012)