VisionCoach: Design and Effectiveness Study on VR Vision Training for Basketball Passing

Pin-Xuan Liu, Tse-Yu Pan, Hsin-Shih Lin, Hung-Kuo Chu, and Min-Chun Hu

***Abstract*—Vision Training is important for basketball players to effectively search for teammates who has wide-open opportunities to shoot, observe the defenders around the wide-open teammates and quickly choose a proper way to pass the ball to the most suitable one. We develop an immersive virtual reality (VR) system called VisionCoach to simulate the player's viewing perspective and generate three designed systematic vision training tasks to benefit the cultivating procedure. By recording the player's eye gazing and dribbling video sequence, the proposed system can analyze the vision-related behavior to understand the training effectiveness. To demonstrate the proposed VR training system can facilitate the cultivation of vision ability, we recruited 14 experienced players to participate in a 6-week between-subject study, and conducted a study by comparing the most frequently used 2D vision training method called Vision Performance Enhancement (VPE) program with the proposed system. Qualitative experiences and quantitative training results are reported to show that the proposed immersive VR training system can effectively improve player's vision ability in terms of gaze behavior and dribbling stability. Furthermore, training in the VR-VisionCoach Condition can transfer the learned abilities to real scenario more easily than training in the 2D-VPE Condition.**

***Index Terms*—Sports VR, vision training, basketball VR, computer-aided training.**

I. Introduction

In recent years, multimedia technologies have been widely employed in sports training to improve the skills, cognition, and mindset of athletes. One notable technology is immersive virtual reality (VR), which offers the advantage of creating controllable and cost-effective training scenarios. Using VR, sports scientists can customize precise training scenarios to comprehensively explore and cultivate an individual athlete's abilities.

Basketball is a fast-paced team sport, wherein players' physical as well as mental abilities must be refined [11]. Physical ability training focuses on running faster and jumping higher, while mental ability training focuses on playing offense and defense more strategically. VR has been proven to be effective for improving basketball mental abilities such as tactical execution [35].

It has been highlighted by coaches that even professional players can benefit from improving their vision ability and require effective methods for vision training. In this study, we focus on training the ball handler's vision ability to search for a wide-open teammate that has the opportunity to shoot. In addition, the ball handler has to observe the defenders around the wide-open teammate and quickly choose the best way to pass the ball without turnover. Furthermore, the ball handler has to dribble stably while looking for and observing the wide-open opportunity, which substantially increases the difficulty of the offense. Superior sports vision ability for searching and observing wide-open opportunities on the court is usually developed after years of practice and training on the court. Through the use of VR technology, players can be trained under well-controlled conditions that mimic real-world scenarios repeatedly, enabling the trainee to develop vision ability more effectively.

In this work, we interviewed three basketball coaches to explore how they train the vision ability of players. We concluded from the interviews that three aspects need to be considered simultaneously in designing basketball vision training tasks: reaction time, cognitive processing, and dribbling. We follow the feedback from the coaches as well as the principle of optimized gaze behavior proposed by Klostermann et al. [19] to design three kinds of vision training tasks in VR. We propose VisionCoach, an immersive VR vision training system for basketball players, that simulates not only the player's viewing perspective on the court but also renders the designed vision training tasks. VisionCoach can help players train their vision ability with regard to searching for and observing wide-open opportunities. Furthermore, instead of using controllers, VisionCoach enables the player to intuitively interact with the system by using hand gestures and speech, which better fits real-world game situations because players in real games do not handle anything but the ball. In this way, the player can hold or dribble the ball while simultaneously experiencing the proposed immersive vision training system.

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Pin-Xuan Liu, Hung-Kuo Chu, and Min-Chun Hu are with the Department of Computer Science, National Tsing Hua University, Hsinchu 30013, Taiwan (e-mail: s110062534@m110.nthu.edu.tw; hkchu@cs.nthu.edu.tw; anitahu@cs.nthu.edu.tw).

Tse-Yu Pan is with the Graduate Institute of A.I. Cross-Disciplinary Tech, National Taiwan University of Science and Technology, Taipei 10607, Taiwan (e-mail: typan@mail.ntust.edu.tw).

Hsin-Shih Lin is with Physical Education Office, National Cheng Kung University, Tainan 70101, Taiwan (e-mail: sevenfour@mail.ncku.edu.tw).

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To explore the effectiveness of the proposed system, we conducted a 4 week-long between-subject study using the conventional 2D vision training method and the proposed immersive VR training system. The conventional 2D vision training method proposed by Schwab et al. [31] is called Vision Performance Enhancement (VPE) program. VPE is a well-known tool used in vision training for various sports, in which a 2D screen shows a specific sign appearing in diverse patterns and users need to answer the vision training tasks quickly. We divided the participants into two groups (one used the 2D-VPE and the other used the proposed VR-VisionCoach to train the players' vision ability) and compared the reaction time and cognitive processing correctness of the two groups. We also collected the player's gaze data acquired from the head-mounted display (HMD) as well as the video sequences of player's dribbling captured by an additional camera. The player's gaze orientation and dribbling trajectory are visualized to measure the vision training effectiveness. Furthermore, to explore whether the skills gained during VR training can be transferred to the real world or not, we design a real-world test on an actual court. We also assess several subjective feedback by using questionnaires related to system usability, sports imagery ability, presence, and simulator sickness.

II. Related Work

A. Extended Reality (XR) in Sports Training

With the rapid development of multimedia technology, VR has been used as a training medium for various sports, such as football, rugby, and basketball. Existing VR sports training systems offer comprehensive training, including training of physical motor skills, mental skills, and team tactics. For example, Stinson et al. [33] proposed a virtual soccer goalie system to explore the feasibility and practicality of sports psychology training in a VR environment. In addition, companies such as StriVR Labs [21] and Eon Sports [32] built training scenarios similar to natural sports fields of baseball and hockey based on pre-recorded 360-degree videos and use VR headsets to train athletes. Tsai et al. [35] proposed a basketball tactical training system that allows users to familiarize themselves with tactics from a first-person perspective in a 3D space. On the other hand, some research has proposed immersive systems targeted at tactical visual analytics. Chu et al. [7] proposed TIVEE, a badminton tactics system designed to assist users in exploring and explaining badminton tactics across multiple levels. Additionally, Ye et al. [43] developed a system called ShuttleSpace, which enables a badminton coach to analyze trajectory data from the player's perspective.

As an alternative, in recent years, augmented reality (AR) solutions have been proposed to achieve guidance training. For example, Lin et al. [24] proposed a HoloLens-based basketball free throw assist system, which allows users to correct their shot angle according to the instant visualization of the shot trajectory. A recent product, PuttView Outdoor [28], also visualized the ball's trajectory in HoloLens to help golfers make swing decisions.

Although a variety of novel XR sports training systems have been proposed, very few studies has been conducted on the visual abilities of athletes. In this work, we focus on designing a VR vision training system for basketball players. The field of view (FoV) of the existing AR HMDs is very small (e.g., the horizontal FoV of HoloLens is 54 degrees), which makes them inappropriate for vision training because the horizontal FoV of human eyes is approximately 200-220 degrees. In contrast, the FoVs of most VR HMDs are larger (e.g., horizontal FoV of Oculus and HTC VIVE are approximately 100-110 degrees) but are still insufficient. In this work, we choose to use a StarVR HMD [10], which has 210-degree horizontal FoV and 130-degree vertical FoV, to display the training content in a manner similar to the FoV of human eyes [41].

In summary, we propose a novel VR system with three vision training tasks to improve basketball players' vision ability and conduct experiments to validate the training effectiveness of the proposed system.

B. Vision Training in Sports

Appelbaum et al. [1] divides the existing vision training methods into two categories, i.e., component skill training methods and naturalistic sports training methods. In the category of component skill training, vision skills are split into multiple components and training for each component is executed separately. Both the Sports Vision Pyramid proposed by Kirschen et al. [18] and the Welford Processing Model proposed by Welford [39] show the elements of component skill training, including static visual acuity, dynamic visual acuity, and motor reaction. These tasks are typically presented in simple visual acuity patterns through a 2D panel. Recently, some companies have proposed to integrate these tasks into a signle system, such as Senaptec Sensory Station [25], Sports Vision Performance Training by Vizual Edge [12], Sports Vision Performance by M&S [34], and Vision Performance Enhancement (VPE) program [31]. For naturalistic sports training methods, the trainees are not asked to answer questions during vision training. Usually, these kinds of methods ask the athletes to wear a pair of stroboscopic glasses that displays content to interfere with vision (e.g., Senaptec Strobe [26] and Visionup Strobe glasses [38]) or to use an eye-tracking sensor to observe the eye movement of athletes during the training process.

The effectiveness of the above vision training methods has been verified [2], [3], [14], [15], [20], [40]. For example, Krasih et al. [20], twenty-seven participants were invited to train with the Nike SPARQ Sensory Station for three days, and the results indicated that the participants showed significant improvement in vision ability. Appelbaum et al. [3] recruited 157 participants, and divided them into two groups, one trained with Nike Vapor Strobe glasses and the other without. Their experimental results showed that the participants trained with Nike Vapor Strobe glasses were more sensitive to movements.

At present, component skill training methods are more common than the naturalistic sports training methods because they can provide more systematic training. The VPE program proposed by Schwab et al. [31] is the most widely used component skill training method. It is a special vision training software for athletes that trains various visual skills like central and peripheral awareness, saccadic fixation, reaction time, scanning, tracking, and stereopsis. Most athletes use the VPE program to train for 6 weeks, 3 days a week, 7 minutes each day.

For basketball, vision training involves more aspects rather than just training the ability of finding visual information such as possible wide-open teammates. The ability of cognitive processing [17], [22], [23], [30] after receiving visual information, i.e., the process of making decisions based on the observed information, is also critical. Unfortunately, existing systematic vision training methods are based on 2D monitors and have limitations in immersively displaying the training content, resulting in a gap between the training and the real-world practice. Furthermore, the existing systematic vision training methods only focus on reducing the trainee's reflection time but lack the training of cognitive processing. Therefore, in this work we design a novel vision training VR system for basketball players, which has the following advantages:

i) Three tasks highly related to the scenarios of real basketball playing are designed and integrated to systematically train the "Foveal Spot", "Gaze Anchor", and "Visual Spot" of the trainee.
ii) By simulating scenarios of real basketball playing in the player's first-person perspective, the training process is more immersive, and the gap between the training and real playing can be reduced.
iii) The proposed system also considers cognitive processing ability and dribbling stability during training, which are important for the vision training of basketball players.

III. Basketball Vision Training

A. Background

Basketball is a five-on-five team ball game where each team tries to score as many points as possible in a limited time to win the game. In each basketball play, the player possessing the ball needs to have a good vision ability to efficiently identify wide-open teammates and quickly pass the ball to the one who has the best chance to score depending on the defenders' movements. The vision behavior of the ball handler is different when he/she is in the stop-ball state and in the dribbling state. In the stop-ball state, the ball handler has 5 seconds to observe who is the best candidate to pass the ball. In the dribbling state, the ball handler has much shorter time to observe the situation and make the passing decision. Furthermore, the ball handler needs to dribble smoothly and not drop the ball during dribbling. To sum up, developing basketball players' passing vision includes improving the ability to search for wide-open opportunities and observe defenders around wide-open opportunities, as well as maintaining the stability of the dribble to prevent turnover.

To design a proper vision training system for basketball players, we conducted semi-structured interviews with three basketball coaches of university basketball teams to understand their needs and the way they have achieved vision training. According to these interviews, there are currently no universal player vision training methods. One of the interviewed coaches introduced two vision training scenarios he designed to train his players. In the first training scenario, four players are asked to stand in their attacking positions, and each player makes a gesture indicating a number randomly. The trainee has to calculate the sum of all gesture numbers and provide the answer quickly. The coach mentioned that this kind of training scenario aims to not only speed up the trainee's reaction time when he/she sees an opportunity but also improve the trainee's cognitive aspects of mental calculation, which enforce the trainee to process more information about the current situation. In the second training scenario, four players are asked to execute specific tactics, and one of them makes a gesture indicating a number randomly. The trainee must say that number as quickly as possible. This training scenario aims to make sure that the trainee can find wide-open opportunities quickly while all teammates are moving. Furthermore, in these two scenarios, the trainee has to dribble the ball and complete the task simultaneously. Although the coach has proposed a systematic vision training method, it is difficult to accurately replicate the training content as well as efficiently digitalize the training process, resulting in high labor and time costs for training and assessing players' vision abilities.

Based on the interviews, we conclude that three aspects should be considered in the design of a vision training system.

i) The training process should focus on the reaction time of seeing a target, which trains the player to pinpoint wide-open opportunities quickly.
ii) The training process should involve a cognitive processing task that requires more information processing, which trains the player to make passing decisions correctly.
iii) The training process should involve dribbling, ensuring the player does not lose possession of the ball while observing wide-open opportunities.

Furthermore, to fairly assess the vision ability of a trainee, the vision training system should be able to control and duplicate the training content flexibly, as well as efficiently digitalize the user's interaction or feedback in the training process.

B. Task Design and Goal

As described in Section III-A, the offensive ball handler needs to have good vision to find a wide-open teammate on the court, as well as observe the defenders around the wide-open teammate to pass the ball properly without turnover. In this work, we propose a VR training system to help basketball players systematically and efficiently train and record their vision ability.

As shown in the top image of Fig. 1, Klostermann et al. [19] divided the functions of the eyes into foveal vision which acquires detailed information, and peripheral vision which is sensitive to object changes. They proposed three optimized gaze behaviors depending on the complementarity between the two visual abilities.

a) *Foveal Spot:* Athletes process information about their current gaze position through foveal vision.
b) *Gaze Anchor:* Athletes gaze in free space and process information through peripheral vision.

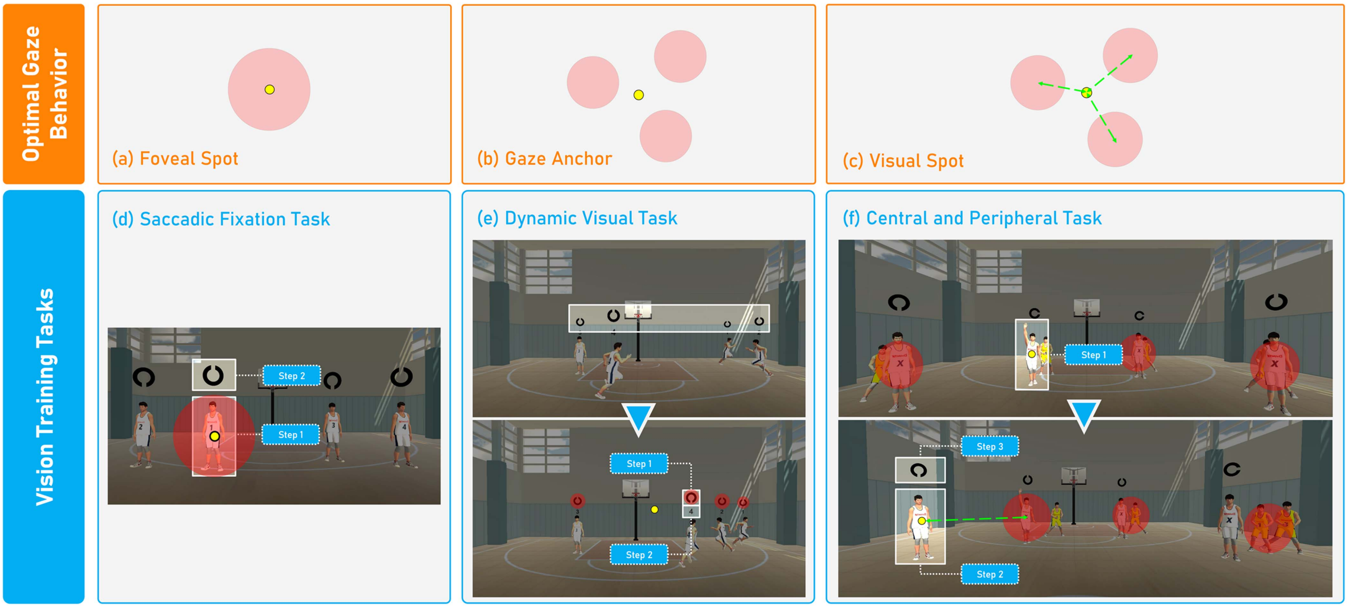


Fig. 1. Overview of the three optimal gaze behaviors and our corresponding designed vision training tasks. The yellow dots indicate the current fixation position, the red nodes indicate covert attention of the peripheral vision position, and the green arrow line indicates switching fixation positions.

c) *Visual Spot:* Athletes not only need to fixate on an object but also need to use peripheral attention to select the next gaze position to switch to.

On the other hand, in terms of cognitive processing, the participants need to shout out the corresponding pronunciation after receiving the visual information. For the visual information, we use the common visual acuity pattern in conventional training methods [8], [13], [20] to design our training task. Considering that the conventional vision training system (i.e VPE) uses the C-shaped pattern, we imitated its design to ensure that the evaluation between the two groups (i.e., 2D-VPE, VR-VisionCoach) is as fair as possible. Moreover, we conducted a pilot study to investigate which relative position is more proper to place the visual pattern. The study shows that it is better to place the pattern on the top of the teammate players because it helps to train the player's peripheral vision and prevents the patterns being frequently occluded by other virtual players.

Based on the above three optimized gaze behaviors and the common visual acuity pattern in conventional training, we designed the following three tasks related to vision training in basketball.

1) Saccadic Fixation Task: As shown in Fig. 1(d), this task requires the trainee to find the player whose jersey number is 1 and respond with the orientation of the visual acuity pattern ('C') above that player. To search for a specific player, the user needs to use the gaze behavior of the *Foveal Spot*. Furthermore, to observe the orientation of the visual acuity pattern above a specific player, the trainee needs to perform additional cognitive processing.

2) Dynamic Visual Task: All players in this task move to execute specific basketball tactics. As shown in the top image of Fig. 1(e), the task starts with all players having the same visual acuity pattern orientation. Then at a random moment, there is an orientation change in a particular player's pattern, as shown in the bottom image of Fig. 1(e). The goal of this task is for the player to report the jersey number of the player having a distinct pattern orientation. Therefore, the trainee needs to use the gaze behavior of *Gaze Anchor* to gaze into free space and use the covert attention [6] of peripheral vision to quickly determine which pattern has changed its orientation. Furthermore, to observe the jersey number of the player whose pattern orientation is changed, cognitive processing is required.

3) Central and Peripheral Task: The task begins with all teammates paired with corresponding defenders, and one of the teammates reaches out for the ball, as shown in the top image of Fig. 1(f). Note that the orientation of the visual acuity pattern is random for each teammate, and the trainee is asked to focus on the teammate who reaches out for the ball. Then, the virtual defenders move, and a random teammate will be guarded without any defender, as shown in the bottom image of Fig. 1(f). The trainee is asked to identify the teammate who is being left unguarded, i.e., without a defender and report the corresponding orientation of the visual acuity pattern above that teammate. This task requires the trainee to use covert attention of peripheral vision while focusing on the teammate who is reaching out for the ball. Then the trainee switches gaze position to the unguarded teammate, which is a *Visual Spot* gaze behavior. Finally, cognitive processing is required to observe the orientation of the visual acuity pattern.

Through these three tasks, basketball players can be trained to use the appropriate gaze behaviors to scan the court efficiently, quickly search for target players, and observe the orientation of the visual acuity pattern to answer after cognitive processing. We also asked trainees to dribble while performing these three tasks, and their dribbling stability was evaluated to investigate the interference of scanning the court and dribbling simultaneously. The proposed VR training system has the goals

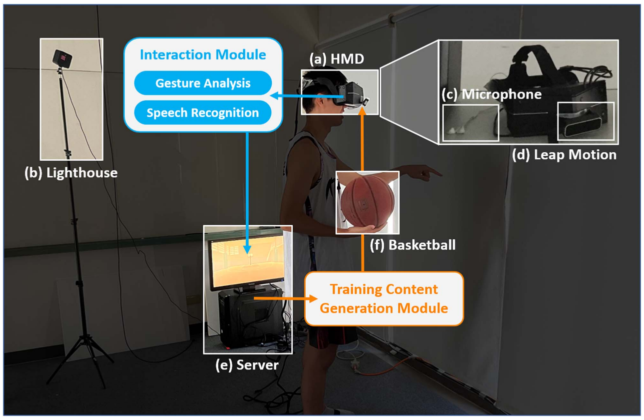


Fig. 2. System overview of our proposed system. The devices we use for training contain (a) an HMD, (b) a Lighthouse, (c) a Microphone, (d) a Leap Motion, (e) a Server, and (f) a Basketball.

of *G1 - Improving the task accuracy and reducing the reaction time*. and *G2 - Improving dribbling stability while scanning the court*.

IV. System Design

We propose an immersive vision training system for basketball players. As shown in Fig. 2, the system consists of six items of equipment and two modules of software. As for the equipment, a StarVR HMD (with 210° horizontal FoV and 130° vertical FoV) and a lighthouse are utilized to display the training content and track the trainee's head pose. A microphone and a Leap Motion sensor are attached to the HMD, so the trainee can interact with the system via voice and gestures. A server with Intel i7-12700 K CPU and GeForce RTX 3060 GPU is used to recognize the trainee's speech/gestures, generate the detailed setting of each training task, and render the virtual content. In addition, a real basketball is used for dribbling during the training. The details of the two software modules are described below.

Interaction Module: It is impractical for a trainee undergoing vision training and dribbling the ball at the same time, to use an additional controller to interact with the system. We design an interaction module based on gesture and speech, which makes interaction more intuitive and convenient during training. A Leap Motion sensor and a microphone are attached to the HMD, and the sensor signals are transmitted to the server installed with Ultraleap Gemini [36] gesture analysis software and speech recognition facility based on Microsoft Azure Cloud Cognitive Service [27]. Ultraleap Gemini tracks the trainee's hand position and detects the bones of the hand, so the user can directly use gestures to click on the UI elements to select the training tasks. The speech recognition facility recognizes the trainee's oral response to each vision training task (i.e., the orientation of a specific visual acuity pattern or the jersey number of a specific player), and the system examines whether the response is correct or not.

As shown in Fig. 3, our vision training process can be divided into two stages. In Stage 1, the trainee needs to interact with the UI panel to select the training task. To facilitate the following vision training task with dribbling, the trainee has to hold the ball with one hand and interact with the UI panel using another hand. To avoid additionally holding an irrelevant physical object while training, we allow the user to interact with the panel directly using one-hand gestures instead of a controller. In Stage 2, the trainee starts to respond to the training task. Since several users in our pilot study mentioned that leveraging the gestures to the responses of number/direction is not that intuitive compared to using speech directly, we chose to apply speech interaction in Stage 2.

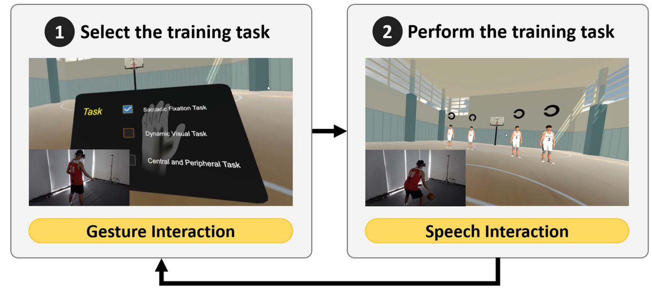


Fig. 3. User interaction flow.

Training Content Generation Module: This module generates the simulated VR content based on the vision training task type selected by the user (i.e., Saccadic Fixation task, Dynamic Visual task, or Central and Peripheral task). For the Dynamic Visual task, the virtual teammates move based on tactical trajectories randomly selected from the tactics provided in NBA2K18 [9], which is a 2017 basketball simulation video game.

V. Experiment Overview

We conducted a six-week-long controlled between-subjects study to evaluate whether the proposed system can train the vision ability of basketball players effectively. As shown in Fig. 4, the experiment consists of three sessions, i.e., the pre-test session, the training session, and the post-test session. All participants performed three separate tests (i.e., a *2D-VPE Test* using the VPE program [31], a *VR-VisionCoach Test* using the proposed VisionCoach system, and a *Real-World Test* performed on a real-world basketball court) in the pre-test session. We recorded reaction time and task accuracy for each participant, which are considered as the participant's vision ability baseline. During the training session, the participants were divided into two groups, i.e., the 2D-VPE Condition Group or the VR-VisionCoach Condition Group, based on the ranking of their vision ability baselines. Our grouping method aimed to divide the participants into two groups based on their ranking: seven participants with above-average ability and seven participants with below-average ability. Subsequently, we randomly assigned half of the above-average ability participants to the 2D-VPE Condition Group and the other half to the VR-VisionCoach Condition Group. The same group partition strategy was used for the below-average ability participants. However, due to the odd number of participants in both the

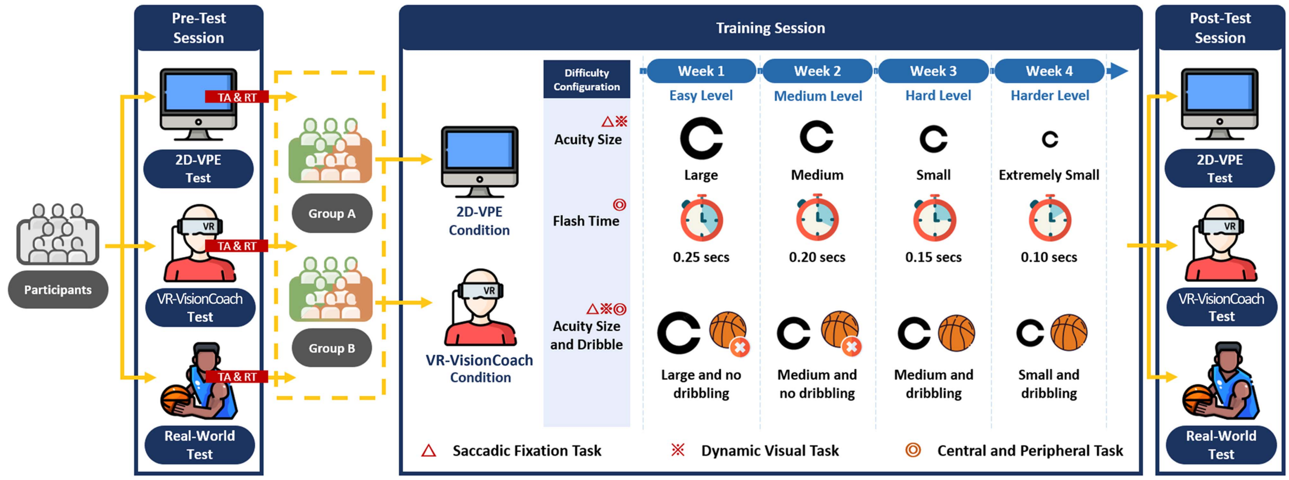


Fig. 4. Experimental procedure. The experiment consists of three sessions, i.e., the pre-test session, the training session, and the post-test session. From the pre-test session, we collected the task accuracy and reaction time of each trial of the three tests as the vision ability baseline and divided them into two groups. Among them, green represents vision ability baseline being relatively good, and red represents relatively poor.

above and below-average groups, we encountered difficulties in achieving equitable random assignment, resulting in 3 participants from the above average and 4 participants from the below average for 2D-VPE group, and 4 participants from the above average and 3 participants from the below average for VR-VisionCoach group.

The training session lasted for four weeks, and the difficulty of the tasks increased steadily every week. After the training session, the participants underwent a post-test session with the same content as the pre-test session.

A. Participants

Our system is designed for basketball players (no matter professional or non-professional) who are seeking vision training. However, we specifically targeted users from university teams or departmental teams to mitigate the potential influence of different age groups or skill levels among participants. To be more precise, we recruited fourteen students who are currently active players in their basketball teams and eager to improve their vision ability, among which nine were female, and five were male. Four participants reported having VR experience, and ten others had never experienced VR. Prior to the experiment, participants were asked to play a VR sports game (All-In-One Sports VR) to be familiar with the VR environment and reduce the potential impact of individual differences in VR adaptation.

In terms of the participants' basketball experience, two participants reported playing basketball for more than five years, six for 3-5 years, and six for 1-3 years. Six participants had experience playing as Point Guards, four as Shooting Guards, two as Small Forwards, four as Power Forwards, and four as Centers in the team. Furthermore, none of the fourteen participants reported having previous vision training experience.

B. Pre-Test Session and Post-Test Session

During the pre-test session and the post-test session, participants took the *2D-VPE Test*, the *VR-VisionCoach Test*, and the

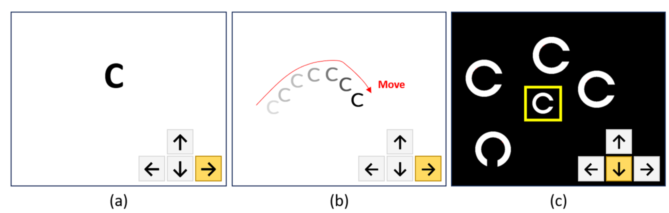


Fig. 5. Schematic representation of the content of the *2D-VPE Test* tasks. (a) Saccadic Fixation Task: Identify the visual acuity pattern direction. (b) Dynamic Visual Task: Identify the dynamic visual acuity pattern direction. (c) Central and Peripheral Task: Stare at the pattern in the yellow box and find various directions among the five patterns. The above three tasks are all answered by pressing the corresponding direction on the keyboard.

Real-World Test. In the *2D-VPE Test*, participants were asked to perform three selected tasks in VPE within a fixed period. In the *VR-VisionCoach Test*, participants were asked to perform three kinds of tasks proposed in our system (c.f. Section III-B) within a fixed period. Although we choose an HMD having the FoV close to a real human's, there is still a gap between the VR environment and the real environment. Therefore, we designed a *Real-World Test* that is similar to the VR training scenario in order to explore whether participants can transfer the learned skills in VR to the real world. It's worth noting that, unlike the VR training scenarios, we introduced a defender in front of the participants in the Real-World test. Initially, we wanted to introduce defenders in VR-VisionCoach to simulate real basketball game scenarios. Unfortunately, during the pilot study, we discovered that the defenders obstructed most of the content within the participants' field of view. Since our objective was to have participants concentrate on improving their vision abilities during training, we made the ultimate decision to exclude defenders from the system. On the other hand, in the Real-World test, we had to invite individuals to serve as teammates, and they were required to memorize the predefined movements for all assigned tasks. This proved to be a challenging endeavor for the individuals we invited, so

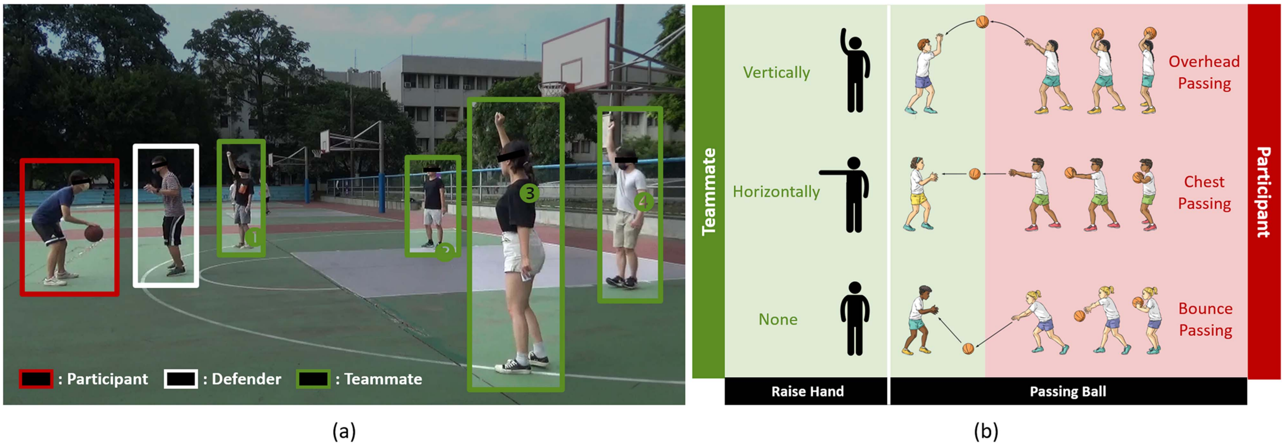


Fig. 6. Real-world test content. (a) is the real-world test scenario, with bounding boxes of different colors representing different identities, i.e., red is the participant, white is the defender, and green is the teammate. (b) is the definition of cognitive processing showing the correspondence between the types of hands raised and the types of passing we defined.

we limited both the number and complexity of the tasks for the Real-World test. Unfortunately, it consequently made the Real-World test too straightforward in the absence of defenders. Therefore, we decided to introduce defenders in the test to add interference. As shown in Fig. 6(a), the participants need to dribble the ball and observe the movements of their teammates with the interference of defenders. For each participant, the goal of the *Real-World Test* was to quickly discover which teammate had a different posture from the other three and then pass the ball to that teammate by using a specific ball-passing action (e.g., overhead passing, chest passing, or bounce passing) depending on his/her posture. The mapping of posture and passing type is illustrated in Fig. 6(b). Taking Fig. 6(a) as an example, participants need to observe that teammate No. 2's posture differs from that of the others. After the cognitive processing of the brain, the ball must be passed to teammate No. 2 by a bounce pass.

C. Training Session

The training session lasted for four weeks, with each participant training three times a week for 18 minutes a day. During the four-week training session, the task became increasingly difficult. Below, we describe the training conditions in more detail.

VR-VisionCoach Condition: Participants were asked to use our VR system containing three training tasks (i.e., Saccadic Fixation task, Dynamic Visual task, and Central and Peripheral task) introduced in Section III-A to perform vision training. The participant watched the training content via a StarVR HMD and interacted with the system through gestures and speech. As the number of training weeks increases, we increased the difficulty of the three tasks through the following rules. The size of the visual acuity pattern changed from *large* to *medium* in the second week. In the third week, the visual acuity pattern remained at *medium size*, but participants were required to dribble during vision training. In the last week, the visual acuity pattern changed to *small* size.

2D-VPE Condition: Participants were asked to interact with the VPE program using a 2D display and a keyboard. As shown in Fig. 5, corresponding to the three tasks in our VR training system, we selected three tasks with similar gaze behaviors in VPE. As training progressed over a larger number of weeks, we increased the task difficulty by reducing the size of the visual acuity patterns for the Saccadic Fixation task and the Dynamic Visual task. In addition, the flash time of stimuli was shortened for the Central and Peripheral task. On the other hand, since the 2D-VPE system requires the trainee to answer via the keyboard, participants cannot dribble simultaneously during training. In order to minimize this unfairness between VR-VisionCoach and 2D-VPE Groups, we ensured that 2D-VPE participants would receive normal dribbling training additionally.

D. Performance Metrics

As mentioned in Section III-B, the first goal of our work is *G1-improving the task accuracy and reducing the reaction time* when the trainee performs vision tasks. Therefore, in the pre-test and post-test sessions, we collected the number of questions answered by the participant (N_q), the number of questions answered correctly (N_c), and the reaction time of each question (t_q) for all the three kinds of tests (i.e., *2D-VPE Test*, *VR-VisionCoach Test*, and *Real-World Test*). Two metrics are used for quantitative evaluation: (1) *Task Accuracy* defined by $\frac{N_c}{N_q}$, and (2) *Reaction Time* defined by $\frac{\sum_{q=1}^{N_q} t_q}{N_q}$.

E. Qualitative Feedback Collection

We collected subjective responses to the proposed VR vision training system through a qualitative survey after the post-test session. The questionnaire covers the following four aspects.

a) *Usability:* This characteristic evaluates whether our proposed training system is easy to use and whether participants could clearly understand the training objectives. We used a System Usability Scale (SUS) [5] with a five-point

Likert scale to explore the score of usability, in which a higher score indicates better usability.

b) *Sports Imagery Ability:* This characteristic explores whether the participants felt the skill imagery of improving their vision ability and the strategic imagery that could demonstrate their vision ability in the real game after training. We used the sports imagery ability questionnaire proposed by Williams et al. [42], which was self-assessed by participants using a seven-point Likert scale.

c) *Presence:* We apply the Igroup Presence Questionnaire (IPQ) [37] to explore the level of immersion on a seven-point scale.

d) *Simulator Sickness:* To measure the participants' discomfort with the proposed system, we analyzed participants' self-reports on a seven-point scale for each question on the Kennedy Lane Simulator Illness Questionnaire [16].

VI. Results and Discussion

A. Quantitative Analysis

As described in Section III-B, the first goal of our work is *G1 - improving task accuracy and reducing reaction time*. We use the performance metrics defined in Section V-D to assess whether participants improved in terms of task accuracy and reaction time.

1) Performance Metrics in 2D-VPE Test *and* VR-VisionCoach Test*:* In the *2D-VPE Test*, participants trained in the 2D-VPE Condition and the VR-VisionCoach Condition can achieve skill improvement. The 2D-VPE Condition Group achieved an average improvement of 43.61% in task accuracy with a standard deviation (SD) of 22.81%, and an average improvement of 0.91 seconds in reaction time with an SD of 0.52 seconds. The VR-VisionCoach Condition Group had an average improvement of 20% in task accuracy with an SD of 23.12% and an average improvement of 0.12 seconds in reaction time with an SD of 0.36 seconds.

In *VR-VisionCoach Test*, participants trained under the 2D-VPE Condition and the VR-VisionCoach Condition also showed a trend of improvement. The 2D-VPE Condition Group showed an average improvement of 0.17% in task accuracy with an SD of 4.01% and an average improvement of 1.44 seconds in response time with an SD of 1.02 seconds. The VR-VisionCoach Condition Group achieved an average improvement of 2.26% in task accuracy with an SD of 10.2% and an improvement of 2.39 seconds in reaction time with an SD of 0.89 seconds.

On the other hand, we conducted independent samples t-tests using SPSS software. Specifically, we compared the pre-test and post-test results separately for the two groups. As shown in Table I, the analysis revealed significant differences in task accuracy and reaction time for the 2D-VPE Test within the 2D-VPE Condition group with effect size 2.36 and 1.95, respectively. However, no significant differences were found in the VR-VisionCoach Condition group. Furthermore, in the VR-VisionCoach Test, we observed significant differences in reaction time for both the VR-VisionCoach Condition group and the 2D-VPE Condition group with effect size 3.32 and 2.74, respectively. Among them, participants in the VR-VisionCoach Condition Group have more improvement. However, there were no significant differences in task accuracy for either group.

TABLE I
Statistical Analysis of the Performance Metrics of the Two Groups in the Pre-Test and Post-Test

	2D-VPE Test			
	Task Accuracy		**Reaction Time**	
	Pre	**Post**	**Pre**	**Post**
2D-VPE Condition	75.97	90.51*	0.98	0.68*
VR-VisCoach Condition	76.87	83.53	0.87	0.83
	VR-VisCoach Test			
	Task Accuracy		**Reaction Time**	
	Pre	**Post**	**Pre**	**Post**
2D-VPE Condition	99.08	99.14	2.39	1.91*
VR-VisCoach Condition	98.06	98.81	2.39	1.59*
	Real-World Test			
	Task Accuracy		**Reaction Time**	
	Pre	**Post**	**Pre**	**Post**
2D-VPE Condition	98.57	97.14	1.30	1.20
VR-VisCoach Condition	95.71	100.0*	1.41	1.23

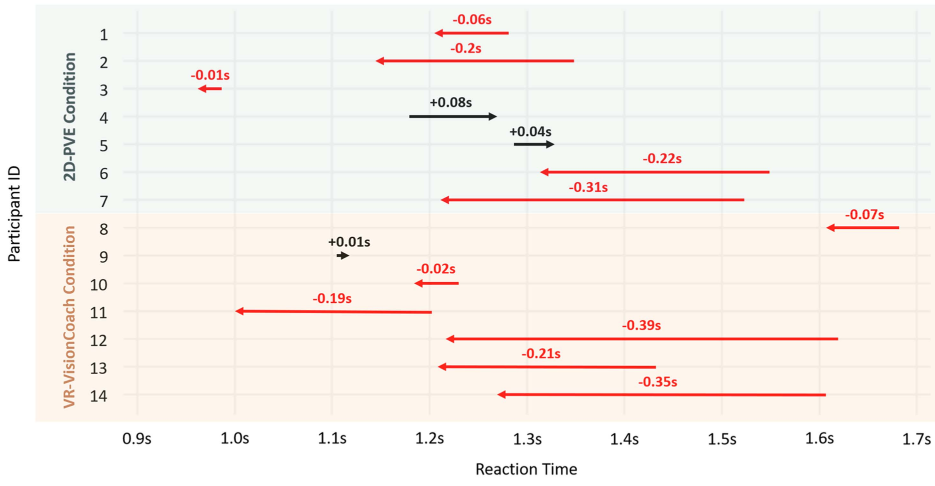
Note. *p <.05.

The above results indicate that regardless of whether the participants were trained in the 2D-VPE Condition or in the VR-VisionCoach Condition, they can show considerable improvement in task accuracy and reaction time for both the *2D-VPE Test* and the *VR-VisionCoach Test*. However, participants trained under 2D-VPE Condition had more improvement in the *2D-VPE Test* compared to those trained under VR-VisionCoach, and participants trained under VR-VisionCoach Condition had more improvement in the *VR-VisionCoach Test* compared to those trained under 2D-VPE Condition. Please refer to the supplementary section for more details of each participant's individual task accuracy and reaction time in the 2D-VPE Test and VR-VisionCoach Test.

2) Performance Metrics in Real-World Test: Given that the gap of FoV between the training using 2D-VPE/VR-VisionCoach and the training on the real court may influence the learning performance, we designed and conducted *Real-World Test* to analyze whether the skills learned during the four-week-long training can be transferred to the real world. As described in Section V-B, in the *Real-World Test*, the participants need to correctly discover which teammate adopted a different posture and identify the posture to pass the ball with a specific way through cognitive processing. As shown in Fig. 7(a), in the pre-test session, participants under both training conditions experienced cognitive mistakes, i.e., passing the ball in the wrong manner to the correct teammate. However, after four weeks of training in the VR-VisionCoach Condition, participants who had cognitive wrong in the pre-test session had improved, while the participants in the 2D-VPE Condition still experienced cognitive errors. As for the reaction time performance, Fig. 7(b) indicates that participants trained under VR-VisionCoach Condition

Condition	Participant ID	Pre-	Post-	Difference
2D-VPE Condition	1	10	10	—
	2	10	9	-1
	3	10	10	—
	4	10	10	—
	5	10	9	-1
	6	9	10	+1
	7	10	10	—
VR-VisionCoach Condition	8	9	10	+1
	9	9	10	+1
	10	9	10	+1
	11	10	10	—
	12	10	10	—
	13	10	10	—
	14	10	10	—

(a)



(b)

Fig. 7. Real-world test analysis results with quantitative evaluation. (a) is the task accuracy result. (b) is reaction time result.

improved significantly more than those trained under 2D-VPE Condition.

On the other hand, we performed independent samples t-tests utilizing the SPSS software. More specifically, we conducted separate comparisons of pre-test and post-test results for both groups. As illustrated in Table I, our analysis unveiled noteworthy disparities in task accuracy in the context of the Real-World Test with effect size 2.08, while no statistically significant differences were observed in reaction times.

From the results, it can be concluded that participants in the VR-VisionCoach Condition showed a trend toward improvement in all three tests in terms of both task accuracy and reaction time. In contrast, from the results of *Real-World Test*, we further found that the cognition of basketball vision ability obviously cannot be effectively trained through 2D-VPE Condition, which also shows that the training based on our proposed VR system is more suitable for basketball vision training.

B. Dribbling Data Analysis

As mentioned in Section III-B, the second goal of our work is *G2 - Improving dribbling stability while scanning the court*. We attempted to visualize the dribbling status to figure out whether the dribbling can be stably maintained or not. To understand the dribbling status, a ball detector trained based on YOLOv4 [4] is utilized to detect where a ball is in a video sequence. We applied a mask of Gaussian distribution to the location of the ball in each frame and fused the masks over time to form a heatmap.

In general, the ball moves back and forth between the participant's hand and the ground, forming a straight trajectory in our visualization. As the speed of the ball is usually slower near the hand and faster near the ground, a red area is formed near the hand and linked to the ground via a thin blue-green line. During stable dribbling, the red circle should be rounder and smaller, and the blue-green line should be slenderer, indicating the player can always dribble the ball consistently by returning it to the hand at a similar position with a similar trajectory. We

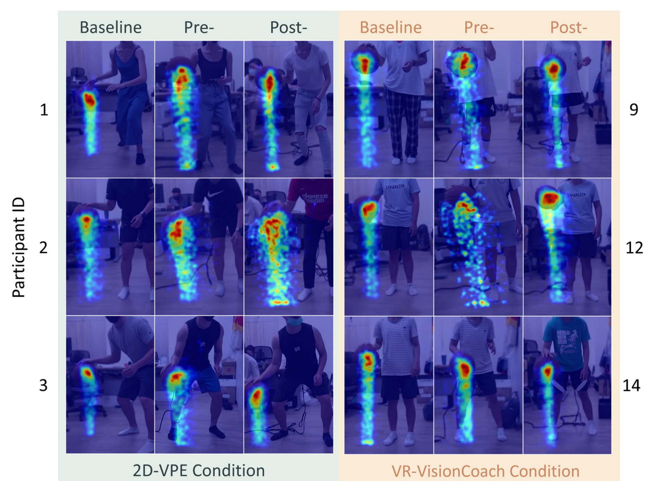


Fig. 8. Dribble visualization results. Baseline dribbling refers to the dribbling performed by the participant without the headset. Pre-dribbling and Post-dribbling are dribbling results in the participant's VR-VisionCoach Test (where he/she wore a VR HMD) for the pre-test session and post-test session, respectively.

visualize each participant's Baseline dribbling, Pre-dribbling and Post-dribbling. Baseline dribbling means the participant dribbles without the headset. Pre-dribbling and Post-dribbling are dribbling results in the participant's VR-VisionCoach Test (where he/she wore a VR HMD) for the pre-test session and post-test session, respectively.

As shown in Fig. 8, for participants in the 2D-VPE Condition Group as well as the VR-VisionCoach Condition Group, the dribbling trajectories were diverse and not very stable in the Pre-test session because they were not used to dribbling while wearing a VR HMD. After a four-week training procedure, the visualized ball trajectories for the VR-VisionCoach Condition Group became slenderer, but the visualized ball trajectories for the 2D-VPE Condition Group were still diverse. These results show that the proposed VR vision training system improved the

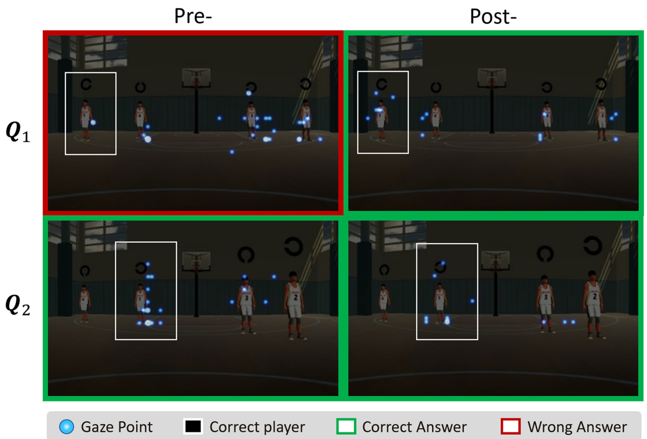


Fig. 9. Examples of gaze analysis visualization for the pre-test and the post-test.

participants' dribbling stability while they were scanning the court and making the decision.

C. Gaze Data Analysis

To further investigate the learning performance of the participants trained under the VR-VisionCoach Condition, we used the eye tracking sensor equipped in the StarVR HMD to obtain the participants' gaze orientation data and then visualized the fixation points sampled with 10 FPS. Note that the fixation points were sampled from the beginning of that question to the time the participant answered the question.

Fig. 9 shows two examples to demonstrate the visualized fixation points in two questions. The white rectangle indicates the target player in each question. The boundary of the frame is colored by green or red depending on whether the participant answered the question correctly or incorrectly, respectively. For Question #1, the target player was far from the middle of the court, so the participant looked around all players on the court in both the pre-test and post-test. In the pre-test session, the participant spent a considerable amount of time on the wrong players and still answered incorrectly in the end. In the post-test session, the participant answered Question #1 correctly. For Question #2, the participant answered it correctly in the pre-test as well as post-test sessions.

However, the number of fixation points in the post-test was considerably less than that in the pre-test, which means the participant spent lower time on cognitive processing to confirm the information. These results proved that the participants who had been trained for four weeks under the VR-VisionCoach Condition can identify the target player more accurately and efficiently.

D. Qualitative Questionnaire Analysis

As a novel training method, we conducted qualitative questionnaires to investigate four aspects of the proposed immersive vision training system, i.e., *usability*, *sport imagery ability*, *presence*, and *simulator sickness* (cf. Section V-E). All fourteen participants had used our proposed VR system in the pre-test and post-test sessions, and they were asked to fill out the questionnaires based on their impressions of using the proposed VR system after the post-test session.

TABLE II
RESULTS OF THE FOUR FACTORS IN THE SLATER-USOH-STEED PRESENCE QUESTIONNAIRE

Factor \ Group	2D-VPE		VR-VisCoach	
	Mean	SD	Mean	SD
General	6.29	0.49	6	1.15
Spatial Presence	4.71	1.5	4.86	1.77
Involvement	5	0.58	4.43	1.51
Realism	5	0.82	4.29	1.25

Usability: The result of usability in the SUS questionnaire [5] was Mean = 86.43 and SD = 7.32, which is excellent performance as defined in an earlier study [5]. The participants gave positive feedback on using the proposed immersive training system. This result indicates that the proposed immersive basketball vision training system can be successfully used to train basketball players' vision ability in the future.

Sports Imagery Ability: Sports imagery ability includes Skills Imagery and Strategy Imagery. For the Skills Imagery, the 2D-VPE Condition Group and the VR-VisionCoach Condition Group obtained an average score of 5.57 and 5.38, respectively (using the 7-Points-Likert Scale). The SD of the former was 0.81, while the SD of the latter was 1.4. The 2D-VPE Condition Group had a slightly higher average score than the VR-VisionCoach Condition Group. This might be because the tasks in the 2D-VPE Condition were simpler to achieve and the participants would have more confidence on their skill imagery. For the Strategy Imagery, the 2D-VPE Condition Group and the VR-VisionCoach Condition Group obtained an average score of 5.38 and 5.57, respectively (using 7-Points-Likert Scale). The SD of the former was 1.12, while the SD of the latter was 1.29. The VR-VisionCoach Condition Group had a slightly higher average score than the 2D-VPE Condition Group. As the training content of the VR-VisionCoach Condition simulates the real training scenario more closely than the 2D-VPE system, it helps the participants to more easily transfer the skills they learned through the VR training system to their real-world performance.

Presence: Table II presents the results of Slater-Usoh-Steed presence questionnaire [37] using a 7-Points-Likert Scale. For the characteristic of Spatial Presence, the VR-VisionCoach Condition Group had a higher average score (4.86) than the 2D-VPE Condition Group (4.71), indicating that the participants trained using the proposed VR-VisionCoach system can grasp the immersive environment more easily.

Simulator Sickness Saredakis et al. [29] reviewed papers on the use of head-mounted displays that reported average total SSQ scores, including 55 publications with a total of 3016 participants. The average total SSQ for these works was 34.26. However, our overall SSQ achieved an average total SSQ of 19.77, which shows that the level of sickness caused by our system is acceptable. In addition, as presented in Table III,

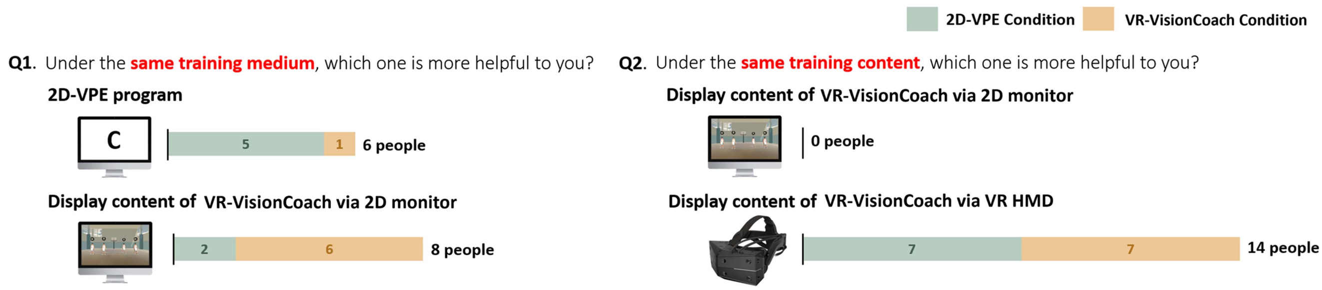


Fig. 10. Statistics results and schematic of various training contents and media.

TABLE III
RESULTS OF THREE INDIVIDUAL GROUPS OF SYMPTOMS IN THE SIMULATOR SICKNESS QUESTIONNAIRE

Symptoms	Group	Mean	SD
Nausea	2D-VPE	6.81	4.66
	VR-VisCoach	24.53	21.23
	Overall	**15.67**	**17.39**
Oculomotor	2D-VPE	14.08	11.93
	VR-VisCoach	36.82	22.07
	Overall	**25.45**	**20.73**
Disorientation	2D-VPE	11.93	14.88
	VR-VisCoach	57.67	43.6
	Overall	**34.8**	**39.28**

we report scores for three separate symptom groups, clearly seeing higher scores for function and disorientation. Among the fourteen participants, eight participants reported eyestrain, while nine had difficulty focusing and blurred vision. We believe that the design of the HMD may not fit the size of every participant's head, so it may wobble slightly when the participant is dribbling, resulting in difficulty in focusing and blurred vision. Furthermore, the HMD also emits strong lights on the screen, so participants may suffer from eyestrain when they have to concentrate on the screen for a period of time. In contrast, we found that most of the nausea symptoms came from sweating, mainly caused by the fact that participants had to dribble during the task while experiencing the proposed immersive training system. Nevertheless, the participants mentioned that when they were given breaks between each training task for about a minute, the sickness symptoms significantly reduced.

E. Comparison of Training Content and Display Medium

We also provided another training condition that uses the same training content as the VR-VisionCoach system but displays the content via a 2D monitor. Unfortunately, owing to the COVID-19 pandemic, we were not able to recruit enough participants who can dribble while wearing an HMD. Therefore, instead of separating the recruited participants into three conditions, we conducted our experiments based on only two condition groups. However, we still explored the feasibility of the training scenario that uses the designed basketball vision training contents and displays the content via a monitor. All fourteen participants were asked to experience this training scenario for 5-10 mins and then answer two questions: (Q1) Using the same display medium (i.e., a 2D monitor), which kind of training content is more helpful for you to train your basketball vision ability? (Q2) Using the same training content (i.e., the content in the proposed VisionCoach system), which kind of display medium is more helpful for you to train your basketball vision ability?

The responses of the 14 participants are shown in Fig. 10. With different training contents but the same display manner (i.e., a 2D monitor), six participants felt that the conventional 2D training content (i.e., VPE) can better facilitate vision training, while the other eight participants felt that our designed basketball training content was better. Participants who chose the former stated, *"Conventional 2D training content can improve reaction time."* (P3, 2D-VPE Condition), and *"I think conventional 2D training content requires more attention.* (P11, VR-VisionCoach Condition)". By contrast, the participants who preferred the designed basketball training content provided feedback such as, *"The conventional 2D method is more like an eyesight examination, and it is difficult to make connections with the scenario of playing basketball.* (P7, 2D-VPE Condition)", and *"The designed basketball training content can help me intuitively associate with the real court conditions.* (P13, VR-VisionCoach Condition)". The participants' comments help us conclude that the conventional 2D training content (i.e., VPE) requires the participants to focus on a single object, quickly find the change, and press the corresponding key to answer the question. However, more participants considered that in a basketball game, the player should not only focus on one of their own teammates but also glance at the defenders to decide whether there is a good opportunity to pass the ball and how to pass the ball in a safe way. Compared to the conventional 2D training content, the designed basketball training content closely resembles the real game scenario, and they can transfer the learning experience to the real world better.

For the question regarding using the same training content (i.e., the content in the proposed VisionCoach system) but displaying the content in different manners, i.e., a monitor or a VR HMD, all 14 participants chose to display basketball training content via VR HMD. Examples of participants' comments include *"Except for the weight of the HMD, the 3D stereo content can enhance the feeling of being in a basketball court and dribbling the ball simultaneously, similar to the real scenario on the court.* (P2, 2D-VPE Condition)", *"The immersive basketball training content simulates the real situation in* *the game, allowing me to apply the practiced skills to a real game more directly.* (P5, 2D-VPE Condition)", and *"Experiencing basketball training content via VR HMD is more consistent with real situations, such as head movement and gaze orientation.* (P8, VR-VisionCoach Condition)". In summary, it is clear that although the HMD causes some inconvenience (e.g., the weight of HMD or the extra localization setting of the HMD), displaying the basketball vision training content via a VR HMD can not only provide immersive vision training using the first-person FoV but also train players to maintain stable dribbling, which mimics real basketball game scenarios.

F. Discussion

To meet the training tasks recommended by the basketball coach, it is indeed challenging to ensure that the difficulty levels in VR-VisionCoach and VPE systems perfectly align in terms of content design. We can only do our best to have VR-VisionCoach simulate the training process similarly to the VPE system, gradually progressing from simple to difficult. However, due to the aforementioned limitations, there might be some potential unfairness in this study, including: (1) The difficulty level of 2D-VPE is system-dependent. Although we made our best efforts to align it with the difficulty level of VR-VisionCoach based on expert interviews and pilot studies, deviations may still exist. (2) Due to the interaction method in the VPE system, participants in the 2D-VPE condition require additional dribbling training. This might introduce bias compared to our proposed system that allows simultaneous training. On the other hand, recruiting a large number of participants for a 6-week training process presents a challenge. While significant differences in statistical analysis and improvements in visualization were observed, the smaller sample size in the between-subjects study may raise concerns. Additionally, despite efforts to ensure both groups had similar vision ability before the six-week training, some consideration of individual metrics had to be sacrificed in order to achieve an overall balance across the six reference metrics, potentially resulting in bias in the comparison.

VII. Conclusion and Future Work

In this paper, a novel VR vision training system for basketball players is proposed to simulate the player's viewing perspective on the court as well as generate the designed vision training tasks. The designed systematic training tasks can better improve the vision ability of basketball players, in terms of task accuracy, reaction time, gaze behavior, and dribbling movements. Compared to participants trained under convention 2D-VPE, participants trained under the proposed immersive training system have noticeably improved performance in terms of measurements of vision ability, proving the effectiveness of the proposed training system. Furthermore, the results also show that the skills gained from the designed training tasks in VR can be transferred to the real-world condition to observe and identify a wide-open teammate to pass the ball to, which increases the chance of scoring.

In the future, we will focus on the following aspects.

i) Although we have built a speech recognition module in our system to recognize the answer of the participants, the recognition accuracy is only around 80% owing to variations in participants' pronunciation and accent. Therefore, our user study requires additional labor to double-check the answers of the VR-VisionCoach test. We plan to improve the speech recognition model by using more collected training data.

ii) We have proposed a method to visualize the dribbling stability. In the future, we will collect more dribbling data and define more objective metrics to evaluate dribbling stability.

iii) In addition to the proposed three training tasks, we plan to design more training tasks focusing on various eye gazing behaviors. Furthermore, we will modularize the system to allow the user to change the court/player models so that athletes playing diverse kinds of sports can select suitable tasks to train their vision ability.

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Pin-Xuan Liu received the BS degree in computer science and information engineering from Fu Jen Catholic University, Taipei, Taiwan, in 2021, and the MS degree in computer science and information engineering from National Tsing Hua University, Hsinchu, Taiwan, in 2023. She is currently working toward the master's degree with the Department of Computer Science, National Tsing Hua University, Taiwan. Her research interest is virtual reality.

Tse-Yu Pan received the BS degree from the Department of Computer Science and Information Engineering, National Taiwan University of Science and Technology, Taipei, Taiwan, in 2013, and the PhD degree from the Institute of Computer Science and Information Engineering, National Cheng Kung University, Tainan, Taiwan, in 2018. He is an assistant professor with the Graduate Institute of A.I. Cross-disciplinary Tech, National Taiwan University of Science and Technology, Taipei, Taiwan. After graduation, he served as a postdoctoral fellow and adjunct assistant professor with the Department of Computer Science from 2019 to 2023. His research interests include human–computer interaction, virtual reality, computer vision, and multimedia content analysis.

Hsin-Shih Lin received the PhD degrees from the Department of Physical Education, National Taiwan Normal University. He is an adjunct assistant professor with Physical Education Office, National Cheng Kung University. His research focus on sport sciences.

Hung-Kuo Chu received the BS and PhD degrees from the Department of Computer Science and Information Engineering, National Cheng-Kung University. He is a full professor with the Department of Computer Science, National Tsing Hua University. His research interests focus on image-based modeling, neural rendering, deep image/video synthesis, texture synthesis and inpainting, digital-twins simulation, and virtual/augmented reality.

Min-Chun Hu received the PhD degree from the Graduate Institute of Networking and Multimedia, National Taiwan University, in 2011. After graduation, she served as a postdoctoral researcher with the Research Center for Information Technology Innovation in Academia Sinica and as an assistant/associate professor with the Department of Computer Science and Information Engineering, National Cheng Kung University. Currently, she holds a position as a professor with the Department of Computer Science, National Tsing Hua University. She has received several awards, including Exploration Research Award of Pan Wen Yuan Foundation (2015), Outstanding Young Researcher Award from the Computer Society of the Republic of China (2017), IEEE Tainan Section Best Young Professional Member Award (2018), Google Research exploreCSR Award (2021-2022), CES Innovation Awards (2023), and NSTC Ta-You Wu Memorial Award (2023). Her research interests encompass digital signal processing, multimedia content analysis, pattern recognition, computer vision, computer graphics, virtual reality, and augmented reality.