Study on the Effects of Eye-Tracking-Based Visual-Motor Training in Table Tennis

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Abstract

[Objective] To develop a visual-motor training method for table tennis based on eye-tracking technology. [Methods] A visual tracking training software was developed using C# language and video technology. Experimental and control groups were established, and university students in the experimental group underwent 15 weeks of in-class 10-minute specialized visual-motor periodic training using the training software. [Results] The experimental group demonstrated an average tracking count 2.03 higher than the control group, with a 13% higher tracking accuracy rate; fixation count was 40.25 times fewer, and fixation duration was 15.03s (seconds) shorter; behavioral reaction time was 3.46ms (milliseconds) shorter, and movement accuracy was 22% higher. [Limitations] Due to limitations in the sophistication of eye-tracking equipment, eye movement data of participants in actual table tennis scenarios could not be obtained. [Conclusion] The results indicate that the experimental group exhibited faster information processing speed, higher visual search efficiency, and superior motor performance. The eye-tracking-based visual training software proved more direct and effective than conventional training methods.

Full Text

Abstract

[**Objective**] This study develops a visual movement training method for table tennis based on eye tracking technology. [**Methods**] Using C# language and video technology, we developed visual tracking training software and established experimental and control groups. The experimental group of college students underwent 15 weeks of specialized visual-motor periodic training for 10 minutes per class using the training software. [**Results**] The experimental group achieved an average of 2.03 more tracking targets than the control group, with 13% higher tracking accuracy. They exhibited 40.25 fewer fixations and 15.03 seconds shorter fixation duration. Their behavioral response time was 3.46 ms shorter, and their movement accuracy was 22% higher. [**Limitations**] Constrained by the advanced nature of the eye-tracking equipment, we were unable to obtain eye movement data from subjects in actual table tennis game scenarios. [**Conclusions**] The results indicate that the experimental group demonstrated faster information processing speed, higher visual search efficiency, and superior sports performance. The eye-tracking-based visual training software proves more direct and effective than conventional training methods.

Keywords: Eye tracking; Visual training; Table tennis; Sports performance

Eye tracking refers to the cognitive activity of analyzing eye movement trajectories and characteristics to reflect attention allocation, information processing patterns, and cognitive strategies during visual fixation. Eye movement metrics obtained through eye tracking technology (such as fixation points, fixation duration, saccades, and movement trajectories) can be used to analyze human viewing behavior, which represents subjective attention allocation and can, to some extent, reflect brain activity. As eye-tracking equipment becomes increasingly sophisticated and portable, eye tracking technology finds expanding applications in human-computer interaction, military, transportation, architecture, medical, education, psychology, sports, and product design, with deepening interdisciplinary integration.

Since the 1960s, scholars worldwide have applied eye tracking technology to sports science, analyzing eye movement characteristics of athletes at different skill levels and investigating how different types of stimuli affect athletes' eye movement metrics. Research has covered multiple sports scenarios including table tennis, badminton, tennis, soccer, cricket, basketball, and volleyball. Helsen et al. employed an "expert-novice" paradigm to study soccer players' eye movement characteristics, finding no significant difference in fixation duration between groups but clear differences in reaction time, fixation count, and fixation location. Expert athletes demonstrated stronger sport-specific cognitive abilities, capturing key information more quickly and processing effective information rapidly to execute motor responses. They also exhibited fewer unnecessary fixations in sports scenarios, indicating superior ability to capture critical information. Overall, expert athletes showed more effective fixation locations, fewer fixations, and shorter reaction times, reflecting stronger visual search capabilities. Ripoll et al. studied boxers' eye movement patterns, revealing that experts spent more time and made more fixations on key movement areas, using a repeated fixation pattern on several locations, whereas novices followed a sequential fixation pattern. Michael et al. investigated cricket batsmen's eye movements, finding that expert batsmen could more accurately predict ball landing location and time with shorter durations, indicating different visual search strategies between groups. Sun Guoxiao et al. found that visual motion tracking plays a crucial role in motor skill learning and movement control, and that studying athletes' visual tracking can help them quickly and accurately obtain key information in complex situations, thereby improving sports performance. Xie Tao et al. studied the superior visual tracking characteristics of table tennis athletes in real-world rally situations, finding that experts possess efficient visual tracking abilities and flexible eye movement strategies, demonstrating superior visual tracking performance. Li Anmin et al., through research on visual search in sports scenarios among table tennis athletes and ordinary college students, found that athletes had clear advantages in reaction time and accuracy, with temporal and spatial advantages in visual search ability.

Based on domestic and international research findings, although studies on visual search patterns of elite athletes in different sports have achieved certain results, most research has employed a single "expert-novice" paradigm to identify visual-motor characteristics and advantages of athletes at different levels, remaining at the stage of evidence accumulation and general feature description. Notably, previous studies have predominantly focused on exploring the visual-motor patterns of elite athletes, while research on training methods to improve visual-motor abilities of general athletes or novices remains scarce.

Building upon this foundation, the current study, guided by visual information processing theory, deeply integrates eye tracking technology with physical education teaching. Using modern computer technology and methods, we developed visual tracking training software and conducted periodic visual tracking training for college students in table tennis classes. Using eye trackers to analyze differences in visual-motor characteristics between experimental and control groups, we explored the impact of visual tracking training on motor decision-making and performance, and examined the effectiveness of visual tracking training software in improving the abilities of general athletes or novices, aiming to provide technological innovation for optimizing physical education and training methods.

1.1 Participants

The study involved 30 male sophomore students from a public table tennis course, with 15 randomly assigned to each of the experimental and control groups. All participants were right-handed, had normal vision without astigmatism, color blindness, or color weakness, and showed no significant difference in left and right eye vision. None had previously participated in eye movement testing. Students participated voluntarily, were informed of all experimental characteristics, and signed informed consent forms.

Table 1 Results of T test of basic information between groups

The results in Table 1 show that the experimental and control groups had the same athletic level and demonstrated consistency in age and ball-playing experience, with no significant differences ($p>0.05$).

1.2 Apparatus

The experimental equipment included one Tobii Glasses 2 eye tracker, one TaiDe Y&T V-989G table tennis serving machine, one Sony FDR-AX60 video camera, one Dell Inspiron 14R-5421 laptop for visual tracking training, one iPad 9 tablet for collecting eye movement data, ErgoLAB analysis software, and self-developed visual tracking training software (v1.0). Based on eye tracking theory and developed using C# language and video technology, the visual tracking training software abstractly simulates table tennis scenarios. Using the actual ball landing points from training, the software designs a "W" shaped flight path for the ball to move back and forth. Random numbers "1" or "2" appear on the ball for 0.5 seconds. In actual play, the ball typically takes 0.3-0.5 seconds to travel from the opponent's contact point to one's own table. Since the software primarily provides visual-motor training for novice college table tennis players, the ball flight speed is set at three difficulty levels: "easy" (1.2 seconds), "medium" (1 second), and "hard" (0.5 seconds), with each difficulty level lasting 1 minute.

Figure 1 [Figure 1: see original paper] Table tennis flight path in visual tracking training

1.3 Experimental Procedure

The independent variable was the experimental versus control group. Dependent variables included behavioral metrics (tracking quantity and accuracy), eye movement metrics (fixation count and duration), and forehand attack behavioral metrics (reaction time and accuracy) from students using the visual tracking training software.

Eye movement testing and visual tracking training were conducted in a quiet, comfortable laboratory adjacent to the table tennis classroom, where subjects were provided with comfortable, stable chairs. The visual neural pathway was used for eye movement testing. Visual scenes often contain objects unrelated to the test that attract subjects' attention and elicit eye movements toward them, reducing interest in the mental task and decreasing data homogeneity. Therefore, distracting objects unrelated to the eye movement test were eliminated before testing and training: (1) Computer screens were cleaned and hardware equipment surfaces cleared of stains; (2) Unrelated objects were removed and computer cables organized; (3) Indoor and outdoor environments were kept quiet to exclude all noise interference; (4) Proper lighting was maintained to avoid any reflective glare.

During table tennis classes, the experimental group underwent specialized visual-motor training using the self-developed "Visual Tracking Training Software." From an athlete's perspective, trainees tracked table tennis balls moving along a simulated "W" shaped trajectory on the computer screen. They were required to quickly press the corresponding number key (1 or 2) for the randomly displayed number on the ball. Correct key presses automatically displayed the next number, while the system recorded and displayed training tracking quantity and accuracy. The experimental group followed a progressive difficulty sequence: "easy" (2 times) → "medium" (2 times) → "hard" (1 time), with 1-minute intervals between sessions. Each class included 9 minutes of visual training. After 15 periodic training sessions, Tobii eye trackers and ErgoLAB software were used to collect and analyze fixation count and duration metrics and eye movement characteristics of both groups. A Sony video camera recorded subjects' forehand attack reaction times and execution accuracy for balls landing in the right longitudinal 1/3 zone of the opponent's court.

Figure 2 [Figure 2: see original paper] Training interface of the visual tracking training software
Figure 3 [Figure 3: see original paper] Forehand attack behavior test

2.1 Behavioral Data from Visual Tracking Training Software

Training software behavioral data refers to the behavioral data generated when subjects used the "Visual Tracking Training Software," including tracking quantity and accuracy. Tracking quantity refers to the total number of targets rapidly tracked per unit time, while tracking accuracy refers to the ratio of correct target identifications to total attempts. These two metrics primarily reflect subjects' concentration, rapid hand-eye coordination ability, and accuracy of executed actions after processing effective visual information mentally.

Table 2 Results of independent sample T-test between groups of software behavior indicators

As shown in Table 2, the experimental group's average tracking quantity was 49.92, significantly higher than the control group's 47.89, showing significance at the 0.01 level ($t=3.671$, $p=0.001$). The experimental group's tracking accuracy was 87%, significantly higher than the control group's 74%, showing significance at the 0.05 level ($t=2.393$, $p=0.023$). The experimental and control groups demonstrated significant differences in both tracking quantity and accuracy ($p<0.05$).

2.2 Eye Movement Data from Visual Tracking Training

Eye movement data from visual tracking training refers to the eye movement data generated as subjects' eyes tracked moving targets during training, primarily including fixation count and duration. Fixation count refers to the number of times subjects fixated on targets, while fixation duration refers to the length of time subjects' eyes remained fixated on targets. By tracking subjects' eye movement information to analyze eye movement trajectories and visual search characteristics, we can fully reflect subjects' subjective attention allocation, information processing patterns, and cognitive strategies during fixation.

Table 3 Results of Independent-Sample T Test of Eye Movement

As shown in Table 3, the experimental group's fixation count was 57.50, significantly lower than the control group's average of 97.75, showing significance at the 0.05 level ($t=-2.614$, $p=0.020$). The experimental group's fixation duration was 15.15 seconds, significantly shorter than the control group's 30.22 seconds, showing significance at the 0.05 level (t=-2.460, p=0.028). The experimental and control groups demonstrated significant differences in both fixation count and duration ($p<0.05$). The experimental group could obtain required visual information with fewer fixations and shorter duration, while the control group required more time for multiple searches. With shortened fixation duration, the experimental group not only improved visual search speed but also had more adequate time for information processing and searching for richer information. These results fully indicate significant differences in visual search efficiency between the two groups.

2.3 Forehand Attack Behavioral Data from Human-Machine Practice Test

After the periodic table tennis visual tracking training, a serving machine was used to test the impact of visual tracking training on subjects' table tennis forehand attack technique learning. The serving machine was set to a fixed landing point (left 1/3 zone of opponent's court), topspin rotation, and speed level 7. A video camera recorded and analyzed college students' forehand attack behavioral data after specialized visual-motor training, including reaction time and accuracy. Reaction time refers to the interval between when the serving machine's ball landed on the subject's court and when the subject's racket contacted the ball. Accuracy refers to the degree of success in returning 50 balls to the right longitudinal 1/3 zone of the opponent's court using forehand attack technique, primarily examining the impact of specialized visual tracking training on motor decision-making and performance in table tennis beginners.

Table 4 Results of independent sample T test of forehand attacking behavior index among groups

As shown in Table 4, the experimental group's forehand attack reaction time averaged 11.91 ms, significantly shorter than the control group's 15.38 ms, showing significance at the 0.01 level (t=-3.182, p=0.006). The experimental group's forehand attack accuracy was 83%, significantly higher than the control group's 61%, showing significance at the 0.01 level (t=3.826, p=0.002). The experimental and control groups demonstrated significant differences in both reaction time and accuracy ($p<0.05$).

3.1 Tracking Quantity and Accuracy

Table tennis is a complex, high-strategy net sport. With improved physical fitness, scientific training methods, and equipment innovation, balls in competition travel at speeds of 15-30 m/s, while humans require 0.3-0.5 ms to perceive and make judgments even when attention is highly concentrated in a static state. During matches, athletes continuously track the ball's movement, forming visual predictions of its flight path, speed, landing point, and spin to inform decision-making. This requires table tennis players to quickly and actively select and process effective information based on limited external information and prior experience under high-pressure, complex situations, and execute accurate motor responses. In this process, visual tracking (ball-watching) naturally becomes an important foundation for rapid and accurate action execution. Since eye trackers use corneal reflection technology to measure fixation points, researchers believe that "looking" does not equal "seeing," and "fixating" does not equal "watching." Fixation points measured solely by eye tracking technology may not represent where athletes are actually looking when thinking and making decisions. The training software's tracking accuracy setting successfully overcomes the limitations inherent in eye tracking technology previously noted by researchers. As shown in **Figure 4** [Figure 4: see original paper], the experimental group averaged 2.03 more tracking targets and 13% higher tracking accuracy than the control group, demonstrating greater concentration and focus. The significantly higher tracking accuracy in the experimental group objectively reflects faster visual search for effective information and higher accuracy in executed actions after mental processing.

3.2 Fixation Count and Duration

Humans primarily perceive the world through vision. Only when attention is concentrated on specific scene or object features can we combine these features into precise perception. Fixation count and duration are important eye movement metrics reflecting subjects' visual search temporal characteristics. Fixation duration refers to the time the visual axis center position remains unchanged during fixation. More frequent fixations often indicate confusion and uncertainty in organizing elements necessary for task completion. Fixation count relates to the number of elements represented in the visual scene rather than processing depth, with a larger number of fixations indicating greater cognitive processing difficulty. Longer total fixation time within a region of interest suggests more complex or difficult information in that area, requiring more time to capture target information or greater difficulty in matching searched information with internal representations. Longer fixation duration indicates slower processing speed and lower efficiency. Table tennis players' shorter fixation duration compared to college students indicates faster and more efficient information processing speed when viewing the same experimental materials, demonstrating superior information processing efficiency and quality. As shown in **Figure 5** [Figure 5: see original paper], after visual tracking training, the experimental group made 40.25 fewer fixations than the control group, a significant difference, indicating easier cognitive processing of targets within the visual region. The experimental group's fixation duration was 15.03 seconds shorter than the control group's, enabling faster acquisition of effective information in the visual region and rapid information processing, with higher information processing efficiency. These differences indicate that novice college students' visual search is characterized by large search volume, long duration, and consequently low efficiency, while the experimental group showed small, precise searches with short duration. The experimental group's visual search temporal characteristics were superior, with more efficient visual search. The experimental group's efficient visual search characteristics were mutually verified by training behavioral data, directly reflecting faster reaction times, more tracked targets, and higher behavioral accuracy. Additionally, the experiment showed that the experimental group's eye movement data for fixation count and duration were more average and concentrated, while the control group's eye movement data showed high dispersion and greater individual differences.

3.3 Reaction Time and Accuracy

Visual perception is a crucial component of many activities, including sports. Athletes rely heavily on their vision to judge and track moving objects, make rapid decisions, and execute complex motor actions. Athletes require good visual-motor abilities including rapid localization, target tracking, visual memory, and spatial awareness. After 15 weeks of specialized visual training, the experimental group showed significantly higher concentration, visual tracking ability, and speed and quality of effective information processing within the visual region than the control group. As shown in **Figure 6** [Figure 6: see original paper], with improved visual-motor ability, the experimental group's forehand attack technique level was significantly higher than the control group's. The experimental group's forehand attack reaction time was 3.46 ms faster and movement accuracy 22% higher than the control group's. The experimental group not only had faster forehand attack reaction time but also higher accuracy. On-site human-machine practice tests and subsequent video analysis showed that the experimental group demonstrated more compact and coherent forehand attack movements, higher ball-return stability, superior technical level, and overall better sports performance than the control group.

Using the self-developed "Visual Tracking Training Software V1.0" to conduct visual tracking training for college students in public table tennis classes, we analyzed and compared eye movement characteristics and sports performance of 15 college students each from the experimental and control groups after specialized periodic visual training, reaching the following conclusions:

(1) The experimental group averaged 2.03 more tracking targets and 13% higher tracking accuracy than the control group, indicating that visual tracking training can effectively improve college students' concentration and rapid hand-eye coordination, enhancing reaction time, accuracy, and stability of visual tracking in complex sports scenarios for table tennis beginners.

(2) The experimental group made 40.25 fewer fixations on targets and had 15.03 seconds shorter fixation duration than the control group, with faster information processing speed and higher efficiency, demonstrating that visual tracking training can help trainees improve visual search ability and enhance information processing levels.

(3) The experimental group's table tennis forehand attack reaction time was 3.46 ms shorter and movement accuracy 22% higher than the control group's, with more compact and coherent hitting rhythm and higher stability, showing superior sports performance. This demonstrates that the "Visual Tracking Training Software" is a more direct and effective training method for improving table tennis motor skills and decision-making ability than conventional training means.

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Note: Figure translations are in progress. See original paper for figures.