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Superiority and characteristics of visual motion discriminability in collegiate table tennis players

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Table tennis (TT) players, through repetitive exposure to visual motion, may develop enhanced visual motion discriminability due to perceptual learning. This study compared visual motion direction discrimination (MDD) abilities among TT, soccer (SC) players, and track and field (TF) athletes using random dot kinematogram tests. Participants discriminated the direction of coherently moving dots with and without surrounding dots randomly moving (background noise). TT and SC players significantly outperformed TF athletes in MDD tasks at specific visual field eccentricities. TT players showed superior discriminability in near-peripheral vision, likely due to the frequent need to track a ball in this area during play. In contrast, SC players excelled in far-peripheral vision, reflecting their experience monitoring a broader visual field. This advantage was pronounced in conditions with background noise, emphasizing the importance of figure-ground segregation for extracting the motion specific to the athlete's behavioral decision from various surrounding motions. We conclude that the sport-specific visual experiences of TT and SC players, particularly their repeated exposure to unique visual motion environments, lead to enhanced motion discriminability that is finely tuned to their respective sport's demands. This improvement supports superior visuomotor performance and underscores perceptual learning's adaptability to the distinct challenges in different sports.

Table tennis (TT) players rely on visual motion information from fast-moving balls to make split-second decisions, highlighting the critical importance of accuracy and speed in the brain's processing of visual motion[1,2]. This visual motion information is processed through the dorsal visual pathway, where the human MT (hMT+) area plays a crucial role in motion perception[3,4]. The characteristics and functional capabilities of the hMT + have been evaluated using random dot kinematogram (RDK) stimulation[5–9]. However, since motion vision assessment has not been widely applied to athletes, it remains unclear whether and to what extent TT players possess superior motion vision abilities compared to athletes in other ball sports and non-ball sports.

Motion coherence sensitivity, which describes the ability to discriminate coherent motion, has been shown to improve through repeated exposure to visual stimuli[10,11]. This enhancement is part of a process known as perceptual learning[12–14], whereby the visual system becomes increasingly attuned to significant and frequently encountered stimuli through continuous adaptation[10–12]. Watanabe et al.[10,11], indicates that an improvement in motion coherence sensitivity occurs in a retinotopically dependent manner, meaning it is localized to specific areas of the retina that experience focused visual exposure[14]. Therefore, ball sports players who regularly encounter complex visual motion during practices and games may experience similar enhancements in motion coherence sensitivity due to their repeated exposure to relevant visual stimuli in specific regions of the visual field. For instance, TT players, who must often track a ball[15–17], may develop heightened sensitivity around regions nearer to central vision, while soccer (SC) players, who require awareness of a broader visual field[18], may show increased sensitivity in peripheral areas[19]. This retinotopically specific adaptation in motion coherence sensitivity may contribute to a visuomotor performance suited to the visual demands of the respective sport[20]. However, any sport-specific improvements in retinotopic motion coherence sensitivity have not been conclusively confirmed.

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Ball sports players must distinguish not only the motion of the ball but also the movements of opponents and other players[21]. This requires them to separate the relevant motion of the ball from other surrounding movements[22], a process known as figure-ground segregation[23,24]. Athletes who regularly engage in such motion-based figure-ground segregation may, as a result of their training, develop superior abilities to isolate the ball's motion from background movements and accurately detect and discriminate its direction. However, this potential enhancement remains to be fully understood.

Therefore, using RDK stimuli, we conducted a motion direction discrimination (MDD) task to quantify motion coherence thresholds. In this comparative observational cross-sectional study, we focused on three different eccentricities of the stimulus location to examine differences among university-level TT players, SC players, and track and field (TF) athletes, with particular attention to retinotopy. Additionally, we investigated the impact of background noise on motion coherence thresholds.

TT players and SC players exhibited significantly lower motion coherence thresholds in the near-peripheral and peripheral visual fields, respectively, compared to TF athletes. Notably, this superiority of ball sports players was evident only in the presence of background noise. These findings suggest that ball sports players develop enhanced motion vision abilities through intense and repetitive exposure to visual motion, particularly in environments with complex background motion, such as opponent- and self-induced movements.

Results

An MDD task using RDK stimuli was employed to quantify and compare motion coherence thresholds (the motion coherence value at the correct answer rate of 50%)among TT players, SC players, and TF athletes. Comparisons were made at three stimulus eccentricities to investigate retinotopic specificity and the effect of background noise motion on target coherent motion by analyzing conditions with and without background random dot motion noise.

Inter-group differences in MDD ability

Figure 1 presents the C50 values for each group across different stimulus eccentricities. The top row shows the C50 values under the Non-BG condition, while the bottom row displays the values under the BG condition (see Methods for an explanation of the conditions). First, we examined C50 values under the Non-BG condition. There was a significant main effect of the group in the middle eccentricity (χ^2 = 7.175, $p = 0.028$), but no significant effects were observed in the near and far eccentricities (Fig. 1A;χ^2 = 4.403, $p = 0.111$; Fig. 1C; χ^2 = 1.064, $p = 0.587$, respectively). At middle eccentricity, no statistically significant difference was observed among the groups, including comparisons between TT players and TF athletes ($p = 0.074$, $r = 0.476$), TT and SC players ($p = 0.132$, $r = 0.393$), and SC players and TF athletes ($p = 0.132$, $r = 0.313$) (Fig. 1B).

Next, the C50 values for each group across different eccentricities under the BG condition were analyzed. A significant main effect of group was observed in the middle and far eccentricities (Fig. 1D; near, χ^2 = 4.703,

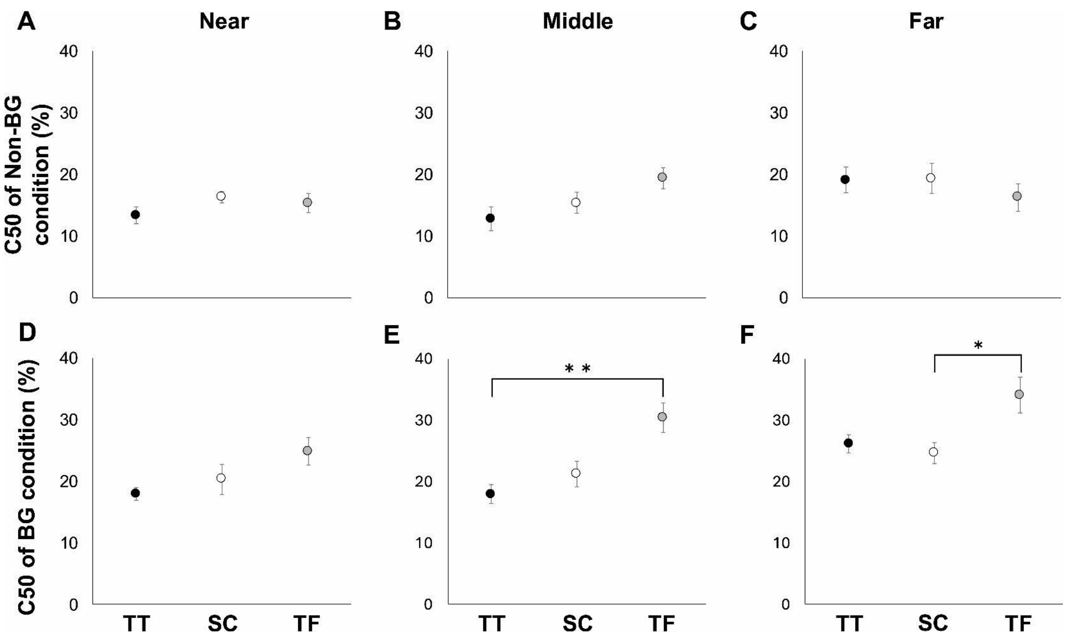

Fig. 1. Inter-group comparison of motion direction detectability (C50) in the MDD task under the Non-BG and BG conditions (black circles: table tennis (TT) players; white circles: soccer (SC) players; gray circles: track & field (TF) athletes). There were no significant differences between any type of sport when the participants performed the MDD task with no background noise. However, TT and SC players had a significantly lower motion coherence threshold than TF athletes in the MDD task with background noise. Error bars = SEM. * $p < 0.05$, ** $p < 0.01$.

$p = 0.095$; Fig. 1E; middle, $\chi^2 = 11.16$, $p = 0.004$; Fig. 1F; far, $\chi^2 = 7.395$, $p = 0.025$). TT players had significantly lower C50 values than TF athletes at the middle eccentricity (Fig. 1E; $p = 0.005$, $r = 0.704$), while no significant differences were observed among the groups at near or far eccentricities (Fig. 1D; $p = 0.063$, $r = 0.450$; Fig. 1F; $p = 0.067$, $r = 0.449$). SC players showed significantly lower C50 values than TF athletes at the far eccentricity (Fig. 1F; far, $p = 0.045$, $r = 0.519$). No significant differences in C50 were found between TT and SC players across any eccentricity (near, $p = 0.793$, $r = 0.055$; middle, $p = 0.293$, $r = 0.221$; far, $p = 0.793$, $r = 0.055$). These results suggest that athletes' motion sensitivity varies according to the type of sport in an eccentricity-specific manner, with the differences becoming more pronounced under conditions where motion detection is challenged by background noise.

Eccentricity dependence of MDD ability

Visual motion direction discriminability varied across sports types at specific eccentricities, suggesting that experience in each sport enhances this ability in an eccentricity-specific manner. Consequently, the relationship between eccentricity and visual motion direction discriminability may differ depending on the sport. Therefore, we examined the eccentricity dependence of MDD ability in each group (Fig. 2). A significant main effect of eccentricity was observed in TT players under both Non-BG and BG conditions (Non-BG, $p = 0.012$, $\chi^2 = 8.909$; BG, $p = 0.012$, $\chi^2 = 8.909$; Friedman test). In the Non-BG condition, TT players exhibited significantly lower C50 values at the near eccentricity compared to the far eccentricity (Fig. 2A; near vs. far, $p = 0.043$; middle vs. far, $p = 0.059$; near vs. middle, $p = 0.450$; Holm's multiple comparison test). Similarly, in the BG condition, both the near and middle eccentricities had significantly lower C50 values than the far eccentricity (Fig. 2D; near vs. far, $p = 0.026$; middle vs. far, $p = 0.026$; near vs. middle, $p = 0.895$; Holm's multiple comparison test).

A significant main effect of eccentricity was also observed in TF athletes under the BG condition (Fig. 2F; $p = 0.006$, $\chi^2 = 10.17$, Friedman test) but not under the Non-BG condition (Fig. 2C; $p = 0.339$, $\chi^2 = 2.167$, Friedman test). In the BG condition, TF athletes had higher C50 values at the middle and far eccentricities compared to the near eccentricity (Fig. 2F; near vs. middle, $p = 0.016$; near vs. far, $p = 0.027$; middle vs. far, $p = 0.255$).

In contrast, unlike TT players and TF athletes, SC players did not show any eccentricity dependence (Fig. 2B; Non-BG, $p = 0.234$, $\chi^2 = 2.909$; Fig. 2E; BG, $p = 0.529$, $\chi^2 = 1.273$, Friedman test), suggesting that the eccentricity dependence of motion detection ability varies according to the type of sport.

Inter-group differences in reaction time during MDD

Finally, we examined the reaction time of successful trials near C50. As a result, a one-way analysis of variance showed no significant group differences in any condition (Fig. 3A, $F = 0.06$, $p = 0.9429$; 3B, $F = 1.75$, $p = 0.1907$; 3 C, $F = 0.77$, $p = 0.4734$; 3D, $F = 1.31$, $p = 0.2857$; 3E, $F = 1.22$, $p = 0.3084$; 3 F, $F = 0.37$, $p = 0.6959$).

Discussion

This study investigated the potential superiority and unique characteristics of visual motion discriminability in TT players, comparing them with SC players from other ball sports, and TF athletes from non-ball sports. Both groups of ball sports players were shown to have advantages at particular eccentricities. Under the BG condition,

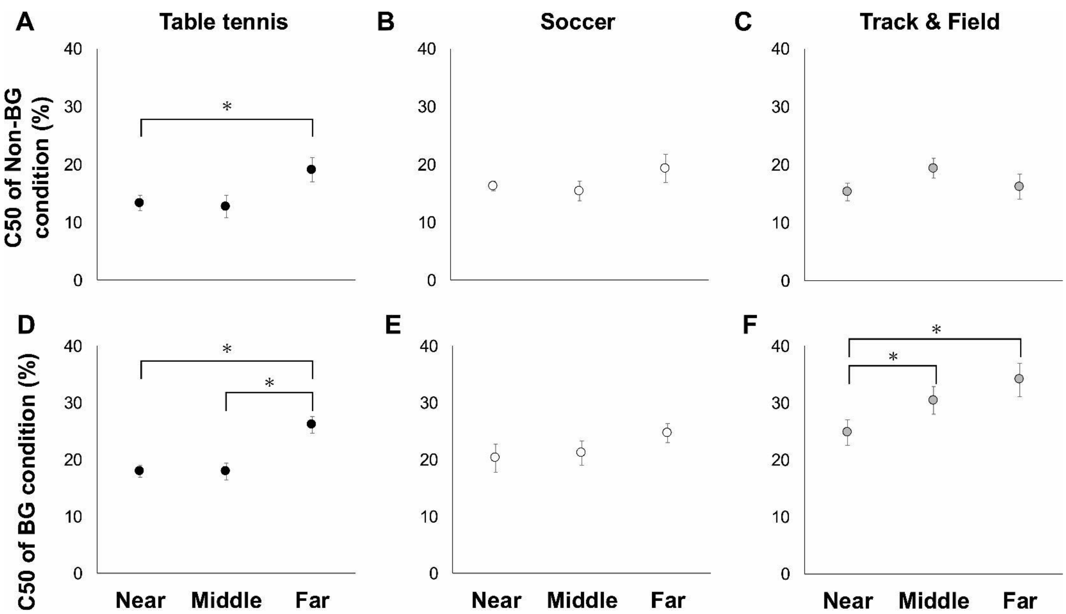

Fig. 2. The eccentricity dependence of motion direction detectability under the Non-BG and BG conditions. TT players showed a significant increase in C50 with increasing eccentricity under both conditions. TF athletes also showed an increased C50 under the BG condition only. SC players showed no significant change in C50 in either condition. Error bars = SEM. * $p < 0.05$.

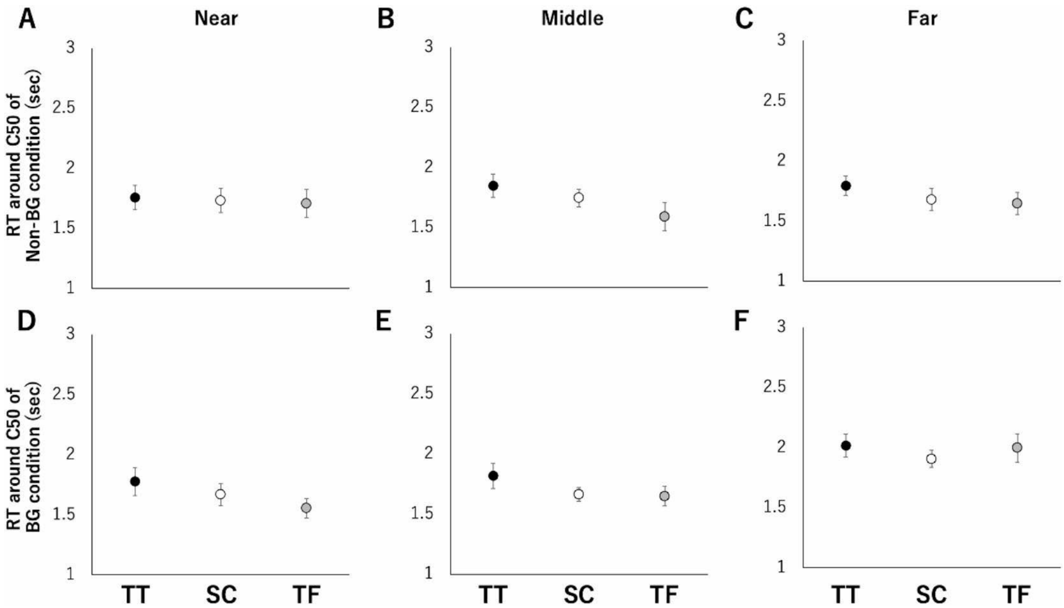

Fig. 3. Figure 3. Inter-group comparison of reaction time around C50 in the MDD task under Non-BG and BG conditions. Black circles represent TT players, white circles represent SC players, and gray circles represent TF athletes. No significant differences in reaction time were observed between the groups, regardless of the presence or absence of background noise. Error bars = SEM.

TT and SC players had significantly lower motion coherence thresholds than TF athletes at the middle and far eccentricities respectively, indicating an eccentricity-dependent superiority of visual motion discriminability. However, under the Non-BG condition, no significant difference was observed among the three athlete types at any stimulus eccentricity. Further, visual motion discriminability was significantly lower at the near and middle eccentricities compared with the far eccentricity for TT players, and TF athletes showed an increase in motion coherence threshold that was proportion to the eccentricity. On the other hand, there was no dependency on the motion coherence threshold in SC players. Thus, our results show that ball sports players exhibit a high ability to discriminate the direction of motion in visual fields specific to the sport, especially in situations where background noise is strong and it is difficult to distinguish the movement of a specific object.

Relationship between motion coherence threshold and retinal eccentricity

In this study, we found that TT players exhibit superior motion discriminability at an eccentricity of 12°, which corresponds to the near-peripheral visual field, compared to TF athletes. This finding suggests that TT players are frequently exposed to substantial visual motion in the near-peripheral visual field. During TT play, players track the fast-moving ball with saccadic eye movements[15–17], directing their gaze to the point where the ball is hit by the opponent's racket or bounces on the table to acquire detailed motion information[15]. As a result, players often perceive the ball moving across the near-peripheral visual field and away from their gaze point. This ability leads to more frequent processing of ball movement in the near-peripheral retinal region, which has higher spatial resolution and motion sensitivity. Consequently, the near-peripheral region is likely to enhance the accuracy of visual motion processing, aiding in more precise predictions of the ball's trajectory[25].

Given that players typically stand about 50 cm away from the edge of the table and the table's long axis measures 274 cm, the distance between competing players is estimated to be around 374 cm. Thus, a visual angle of 24° on each side—two times the 12° corresponding to the middle stimulus presentation position—covers a width of 160 cm, which is equivalent to the table's short axis at a distance of 374 cm. This result indicates that table tennis players primarily track the ball within a visual angle of 12°, supporting the hypothesis that visual motion discriminability improves in the frequently viewed visual field[26,27].

The SC players' superiority in motion direction discriminability in the far-peripheral visual field can be explained similarly to TT players. SC players must attend not only to the movement of the ball but also to the positions and movements of opponents and teammates within their wide visual field, making peripheral perception crucial. Notably, the motion coherence threshold in SC players is significantly lower in the far-peripheral visual field compared to TF athletes, indicating that soccer enhances the ability to process motion information in these peripheral regions. Additionally, the motion coherence threshold in SC players remained consistent from the near-peripheral to the far-peripheral visual field, reflecting the need to process motion information across a broad visual field. In fact, soccer and handball players have been reported to have significantly shorter response times to stimuli appearing in the peripheral visual field compared to non-athletes[21,28]. This observation suggests that ball sports players develop enhanced motion perception in the specific retinotopic visual field that is regularly exposed to intense visual motion experiences during practice and games[26,27].

The influence of background noise on motion direction discriminability

The present study found that BG noise increases the C50 in the MDD task regardless of the athletic experience. This finding suggests that the presence of background noise reduces sensitivity to motion. Our results are consistent with a previous study on humans and monkeys, which found that ambient noise impairs MDD ability[29]. Compared to the Non-BG condition, participants were required to segregate a coherent motion signal from a large amount of motion noise; in other words, motion-based figure-ground segregation[22–25].

Our study demonstrated that ball sports athletes exhibit a marked superiority in the MDD task in the presence of surrounding motion noise. In the context of actual gameplay, the background noise in our study represents a visual field filled with various motions beyond the ball itself—namely, movements from the opponent, optical flow generated by the player's own movements, and the actions of spectators. The opponent's motion provides crucial cues for anticipating subsequent actions[30,31], while the optical flow aids in maintaining posture and motion control[32,33]. Amid the processing of such essential visual cues, ball players must filter out irrelevant information[34], like spectator movements, to focus on identifying the ball's trajectory and speed accurately for swift reactions. This ability requires players to skilfully distinguish the ball's motion from the surrounding dynamic background noise and analyze the motion precisely. Our findings, which indicate that TT and SC players excel in visual motion discrimination under background noise, suggest that repeated exposure to specific motion patterns in sports can enhance a motion-based perceptual figure/ground segregation ability[35,36]—a critical skill during gameplay.

Reaction time for motion direction discrimination

In the MDD task, the response thresholds of TT and SC players were lower than those of TF athletes. Based on the speed-accuracy trade-off interpretation, this could suggest an increase in reaction time for TT and SC players. However, there were no significant differences in response time across the groups. This indicates that TT and SC players enhanced their discrimination accuracy without compromising reaction time. Therefore, this study's findings do not reflect adjustments explained by the speed-accuracy trade-off but suggest an improvement of visual motion information processing in the brain.

Mechanisms leading to high visual motion discrimination ability in ball sports players

Previous studies have demonstrated that frequent exposure to visual motion stimuli even in a single day improves motion direction discriminability[37]. Notably, these improvements are specific to the visual field exposed to the stimuli[14]. This effect suggests that the daily repetitive experience of viewing a moving ball can improve visual motion discriminability in a retinotopy-specific manner. A probable neural mechanism underlying this effect is the functional enhancement of the dorsal visual pathway, which includes the hMT + area, a central region of motion vision[3,4], and the LIP area, which plays a key role in processing neural signals from the hMT + area[29, 38]. Kumano and Uka recorded neuronal responses in the MT area while monkeys performed a MDD task[29]. They found that surrounding noise increased the perceptual motion coherence threshold driven by a reduced response to a neuron's preferred motion signals and an enhanced response to non-preferred motion (noise). Moreover, human MDD performance measured by the same MDD task as this study was reported to be inhibited by the reduction of neuronal excitability with transcranial static magnetic field stimulation (tSMS) intervention in the hMT + area[4]. Therefore, our findings that ball sports players have more pronounced motion direction discriminability when motion noise is present around the target motion suggest the hMT + functions are trained in ball sports players.

Another explanation for the enhanced motion direction discriminability is the improvement of attentional function. Stimulus detection and discrimination sensitivity vary greatly depending on whether attention is directed to the target[39–42]. There is a possibility that ball sports players have a high function of directing and expanding attention to the visual field area where there is a high probability that important visual information exists[43].

During a match, ball players need to react quickly and accurately to the fast-moving ball and the movements of other players. TT and SC players need to keep track of the ball's movement while simultaneously grasping the positions and movements of surrounding players. In such situations, visual attention, the ability to quickly select and concentrate on the necessary information from multiple visual stimuli, is extremely important. Ball sports players may naturally train this ability through daily practice and matches. Further study is needed to clarify this point.

Superior visual functions in athletes

Multiple studies have supplied evidence indicating that skilled athletes exhibit augmented visual-perceptual and visual-cognitive abilities[44], as exemplified by superior visual acuity[45,46], improved contrast sensitivity[47–49], and enhanced visual tracking skills[50]. Meta-analyses of the literature indicate that athletes who attain higher levels of achievement are more proficient in discerning perceptual cues, demonstrate greater efficiency in eye movements, and possess superior attentional processing capabilities compared to their less accomplished or non-athlete counterparts[51,52]. This finding implies that the visual functions necessary for various sports have undergone improvement. The present study lends support to this notion by presenting, for the first time, evidence that ball sports players who are required to respond to the movement of visual objects exhibit superior visual motion discriminability compared to non-ball sports players. If a specific visual function required for sports is strengthened according to demand, a higher or lower function should contribute to higher or lower sports performance. In fact, our recent study[20] reported that the visual MDD performance of TT players as measured by RDK was positively associated with performance on a continuous visuomotor task simulating table tennis. It also found that these correlations could only be observed by players with a long history of playing table tennis, suggesting that training the visual functions required for visuomotor execution during play improves the visuomotor performance itself.

Technical limitations

This study demonstrated that athletes from different sports exhibit varying visual motion discrimination abilities across different visual fields. However, several technical limitations must be addressed to enhance the robustness and generalizability of the findings presented in this paper.

First, the statistical power for comparing the three groups may have been insufficient to detect moderate effect sizes, which could explain the non-significant results observed in some comparisons[53]. To address this limitation, increasing the sample size would be essential to improve statistical power and ensure more reliable conclusions.

Second, the difference in years of sports experience between the groups needs to be taken into account in our results. The SC group has almost twice as much sports experience as the other groups. The relationship between years of sports experience and motion vision ability is unclear at this time, but this is an issue that needs to be investigated in the future.

Third, this study lacks baseline data on participants' visual motion abilities prior to engaging in sports, making it challenging to establish a causal relationship between specific sports experiences and improvements in visual motion abilities. It is possible that participants initially explored multiple sports before settling on one that aligned with their pre-existing visual abilities (e.g., peripheral vision, visual motion perception). Collecting baseline data and employing a more controlled experimental design would help clarify these relationships.

Fourth, while our statistical approach was appropriate for the data distribution, it may not fully account for within-subject correlations. Incorporating Mixed-Effects Models could offer improved sensitivity and precision in addressing this issue.

Fifth, the underlying neural mechanisms remain unclear. These differences may be related to enhancements in attentional functions or neural circuits involved in processing visual motion information. Future research should clarify this possibility by employing experimental designs that can distinguish between the roles of attention and visual information processing.

Conclusion

We showed that ball sports players had better visual motion discrimination ability than non-ball-players and that the function of different visual fields was improved depending on the sport. These findings indicate that the processing of visual motion information and the utilized visual field area differs between ball sports and that visual function is a bottleneck leading to improved performance.

Methods

Participants

University TT players (11 males; age (mean ± SD): 19.5 ± 0.9; table tennis experience: 8.0 ± 1.3 years), SC players (11 males; age: 19.0 ± 0.5; football experience: 14.4 ± 1.3years), and TF athletes (12 males; age: 19.5 ± 1.3; track and field experience: 7.0 ± 1.8years) took part in this study. TT players competed in the 2nd Division of the Kansai University League, reflecting a mid-level university performance. SC players achieved second place in the Kansai University League and reached the final eight in the All Japan University Championship, showing high-level university performance. Some TF athletes qualified for the All Japan University Championships, placing them at a mid-to-high level in university sports. All participants had normal or corrected-to-normal visual acuity. Among them, six out of eleven table tennis players wore corrective lenses (three used glasses and three used contact lenses), none of the eleven soccer players required corrective lenses, and two out of twelve track and field athletes wore contact lenses. No participants had anisometropia. All provided written informed consent regarding the purpose of the procedures of this study. This study was approved by the ethics committee of the Graduate School of Medicine, Osaka University (Permit Number: 16207), and Biwako Seikei Sport College (Permit Number: BSSC32) in accordance with the Declaration of Helsinki.

Apparatus

Visual stimuli were generated using compatible computers and displayed on a liquid crystal (LC) display (Iiyama, Tokyo, Japan; resolution, 1920 × 1080 pixels; refresh rate, 100 Hz; mean background luminance, 30 cd/m^2; screen size, 60° × 34° at a viewing distance of 57 cm). We used a chin-rest (TKD-UK1, Namoto Trading Co., Ltd., Chiba, Japan) to keep the head position fixed during the MDD task. To respond to a visual stimulus, we adopted a joystick (JC-AS01BK, Elecom, Osaka, Japan). Participants' eye positions were measured by a charge-coupled device USB camera (Grasshopper3, Point Gray, Japan) using an infrared pupil-position monitoring system (iRecHS2 ; https://staff.aist.go.jp/k.matsuda/iRecHS2/). Gaze direction was measured during the task, and most were within 0.5 degrees of visual angle from the fixation point, with no trials in which the gaze direction was more than 1 degree.

Visual stimuli

The stimulus included a fixation point (FP) and a moving dot which served as both the target stimulus and background noise. The moving dots' size, lifetime, and density were 0.1° in diameter, 180 ms (18 frames), and 1.5 dots/deg, respectively. The target stimuli were dots presented in a circular area of 8° diameter, like the RDK stimuli. They were a mixture of dots moving in specific and random directions, and the motion coherence, as their ratio, was changed every trial. The background noise was presented on the whole LC display. Each dot in the noise stimuli randomly moved in various directions (motion coherence = 0).

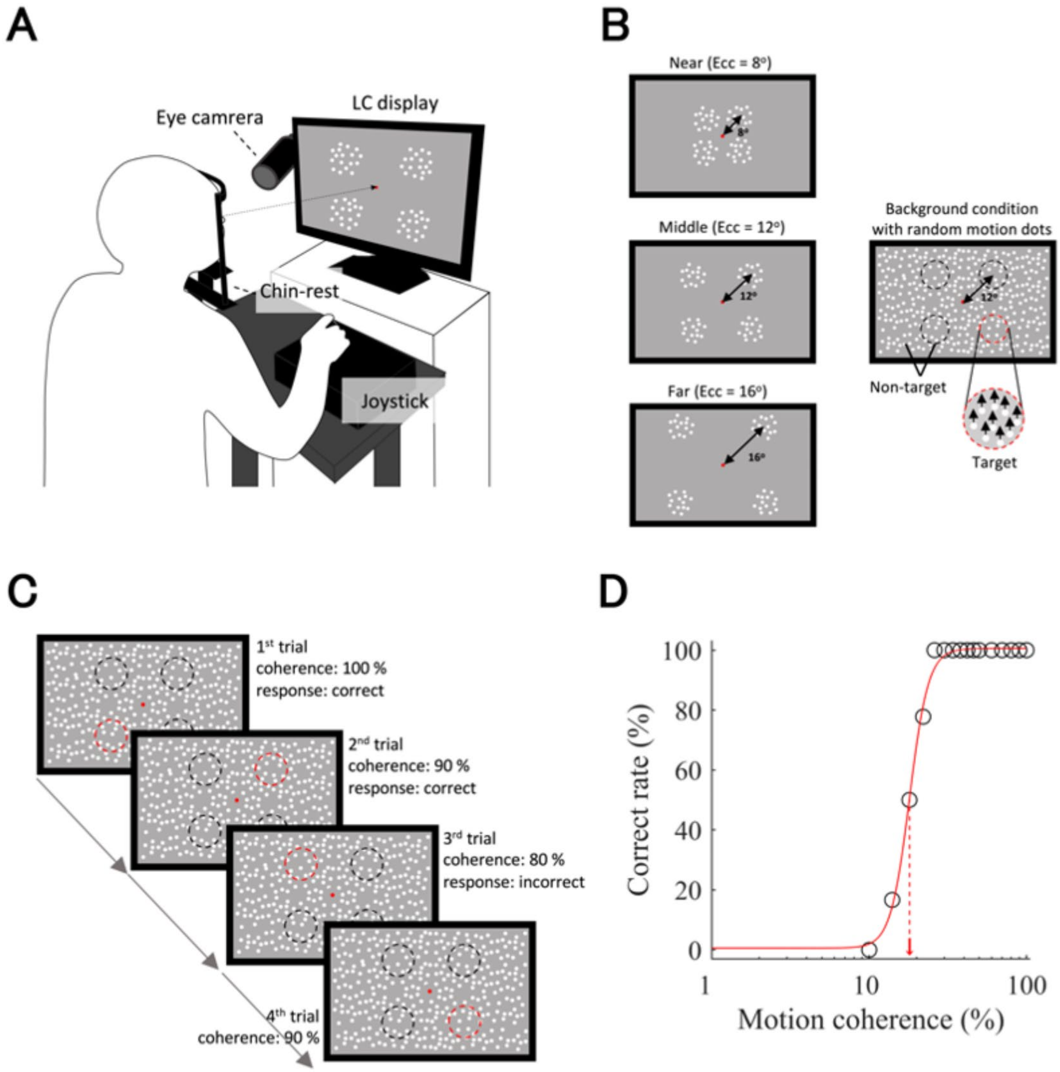

Fig. 4. Schema of the MDD task. (**A**) The experimental setup. A participant placed his/her head on a chin rest 57 cm in front of the LC display and responded to the direction of movement of the target using a joystick. Left eye movements during the task were recorded using a USB camera. (**B**) Conditions of the MDD task and stimulation composition. Participants performed the MDD task under three eccentricities (Ecc) with or without background noise. The target area was a circle (dotted line) and presented at four locations centered 8°, 12°, or 16° away from the red fixation point (FP) for each condition. The motion direction of the target stimulus was either up, down, left, or right (shown as upward in the figure). (**C**) Behavioral paradigm of the MDD task with the staircase method. The subjects were asked to gaze at the FP and detect the motion direction of the target dots using a joystick. When a subject made a correct response (1st and 2nd trials), a euphony sound was given, and the target dots' coherence was decreased in the next trial. In the case of an incorrect response (3rd trial), a cacophony sound was given, and the target dots' coherence was increased in the next trial. (**D**) Typical results of the MDD task. The correct rate was fitted to a sigmoid curve (red curve). The difference between the maximum correct rate and minimum correct rate was set to 100% (Rmax), and motion coherence values with 50% Rmax were calculated (shown as dotted arrow).

Motion direction discrimination (MDD) task

Visual stimuli were generated using a custom-made program on Python and displayed on an LC display. An FP was presented at the center of the LC display. Stimulus presentation sites were set in four quadrants of coordinates with the FP as the origin, and RDK stimuli were displayed in circular areas (diameter 8° in visual angle) within each quadrant (Fig. 4A). One of the RDK stimuli was a target stimulus, consisting of dots moving coherently in one direction and dots moving randomly. In contrast, the remaining three sites presented non-target stimuli in which all dots moved randomly. The target location was randomly changed to one of four positions for each trial. The target's coherent motion was presented in one of four motion directions: upward, downward, leftward, or rightward. To examine the effect of eccentricity on motion discrimination ability, the stimulus areas were set at three eccentricities: 8° (near), 12° (middle), and 16° (far) (Fig. 4B **left**). To examine the effect of background noise on visual motion discrimination ability, the MDD task was performed in the two conditions with or without background noise (BG and Non-BG conditions, respectively; Fig. 4B). The background noise was dots moving in random directions at 0% motion coherence, which was the same as non-target stimuli, and presented on the whole LC display outside the four stimulus presentation areas.

Figure 4C shows a schematic illustration of the experiment. Before the initiation of the MDD task, participants sat about 57 cm in front of the LC display and fixed their heads on the chin-rest to restrict their head movement. Participants were asked to gaze at the FP and to discriminate the direction of the coherent motion in the target, pushing down the joystick toward the discriminated direction. The target and non-targets were presented for 8 s. When participants made a correct answer, a feedback sound was given, and the motion coherence decreased from the current level in the next trial. Upon an incorrect response, a different feedback sound was given, and the coherence was increased in the next trial. When participants missed the target or made no joystick response within the 8 s, the next trial started after a short blank without any auditory feedback. Psychophysical functions were estimated from all the data obtained by stimuli with different motion coherence levels (100, 90, 80, 70, 60, 50, 46, 42, 38, 34, 30, 26, 22, 18, 14, 10, 9, 8, 7, 6, 5%), and C50, which gives a 50% correct answer rate, was calculated (Fig. 4D).

Experimental protocol

Participants performed five sessions of the MDD task in the BG and Non-BG conditions a few days before the experiment to familiarize themselves with the task. Each block was done in the two conditions using the same eccentricity, and individual conditions (Non-BG × Near, Middle, and Far; BG × Near, Middle, and Far) were tested three times in a block. Only one eccentricity was tested in a given block, and the order of the eccentricities tested was randomly changed for each participant. Experiments were conducted in a room illuminated at a photopic level by overhead fluorescent lights. Before the experiments, the participants had their eyes adapted to this luminance level for 5 min. The participants were able to take short breaks for any reason, including eye fatigue, whenever they wanted.

Data analysis

To quantify the motion coherence sensitivity of each participant, we fitted the psychometric curves to our data for each experimental condition using the Naka-Rushton contrast response model[54–56] with an ordinary least square criterion as follows:

$$\mathrm{response} = \mathrm{Rmax} \times \mathrm{Cn} \,/\, (\mathrm{Cn} + \mathrm{C50n})$$

Here, response represents the proportion of correct answers, C is the intensity level of the motion signal of the target stimulus (motion coherence), and C50 is the stimulus intensity at which the response is half-maximal. n (>0) is the exponent parameter that represents the slope of the function, Rmax is the asymptote of the response function (maximal response), and M is the response at the lowest stimulus intensity. Rmax, n, and C are free parameters.

To compare reaction times for correct answer trials among the three groups, measurement ranges of motion coherence were taken at equal intervals on both sides of each participant's C50. The average reaction time was calculated for data where the motion coherence was between 40% and 60%.

Statistical analysis

First, the Shapiro-Wilk test was conducted to evaluate whether the raw data followed a normal distribution. The results of C50 values revealed a significant deviation from normality ($p<0.05$), indicating that the data were non-normally distributed. As a result, the Kruskal-Wallis test was used for group comparisons of C50 values, while the Friedman test was employed for comparisons across retinal eccentricities (R version 3.4.4, R Development Core Team). Multiple comparisons with Holm correction were performed when the significance level was less than 0.05.

On the other hand, the reaction time data satisfied the assumption of normality (Shapiro-Wilk test, $p>0.05$). Therefore, a one-way analysis of variance (ANOVA) was conducted (Matlab 2024a, Mathworks).

Data availability

The research data supporting the findings of this study are available upon request. Interested researchers can contact the corresponding author to obtain access to the data.

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R.G and S.S. designed the research. R.G. and S.S. developed the motion direction discrimination task. R.G. C.A. and T.K. collected the data. R.G. and C.A. analyzed the results. R.G. and S.S. wrote the manuscript, which was edited by all authors.

Declarations

Competing interests
The authors declare no competing interests.

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