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Wearable eye-tracking of visuomotor strategies in table tennis players of diverse expertise and cognitive function in a naturalistic environment

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A B S T R A C T

Understanding how gaze behaviour and visuomotor control vary across populations is crucial for optimizing performance and training in fast-paced sports. However, studies involving athletes with cognitive disabilities remain limited, particularly in naturalistic environments. This study employed wearable eye-tracking technology to examine gaze behaviour and oculomotor control in table tennis players of differing skill levels and cognitive profiles. Forty-six participants were grouped as Professional athletes, Amateur players, individuals with Down syndrome (DS), or intellectual disabilities (ID). All completed table tennis-specific tasks in naturalistic environment training conditions while wearing a head-mounted eye-tracker. Oculomotor metrics, including fixation frequency and duration, saccade frequency and velocity, and pupil diameter, were analysed. Fixation duration did not differ across groups (≈272–301 ms; $p = 0.984$, $\eta^2 = -0.032$), whereas fixation frequency varied: ID participants (80.67 ± 6.81 %) and Amateurs (78.98 ± 5.22 %) showed higher and more consistent rates, DS participants were lower and more variable (74.56 ± 17.37 %), and Professionals maintained moderately lower but strategically balanced frequency (77.78 ± 12.64 %). Although saccade metrics were not statistically significant, trends suggested more controlled patterns in Professionals (right eye (RE) length: 1414.63 ± 720.47 mm; longitudinal velocity: 13,888.52 ± 4242.25 mm/s) and higher variability in DS participants (RE length: 2254.03 ± 3215.55 mm; longitudinal velocity: 16,274.78 ± 6,837.21 mm/s). Pupil diameter was significantly larger in Professionals (RE: 5.26 ± 0.79 mm; left eye (LE): 5.40 ± 0.81 mm; $p < 0.001$), indicating higher visual engagement and cognitive arousal. Binocular vergence metrics remained stable across groups, and gaze heat maps revealed more focused visual strategies in Professionals, while participants with DS and ID exhibited dispersed, less task-relevant fixations. These findings indicate that the accuracy of eye movements, rather than their duration, serves as a sensitive indicator of visuomotor expertise. In conclusion, wearable eye-tracking in naturalistic sport environment offers valuable insights into visual strategies across diverse populations and supports the development of tailored visual training programs, particularly for athletes with cognitive disabilities.

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1. Introduction

Table tennis is one of the fastest ball sports in the world, requiring far more than basic visual ability to excel (Hassan, 2014; Kondrič, Zagatto, & Sekulić, 2013). As a dynamic interaction process (Fuchs et al., 2018), it demands the integration of vision and movement, where visual input, responsible for up to 80 % of sensory information (Hassan, 2014), plays a central role in motor coordination (Asar, Ezabadi, Baghini, & Maleksabet, 2022). In this context, specific visual skills such as convergence, divergence, speed assessment, trajectory prediction, smooth pursuit and saccadic eye movements, speed assessment, accommodation, hand-eye coordination, and stereoscopic vision are critical for high-level performance (Basiri, Farsi, Abdoli, & Kavyani, 2020; Paul, Biswas, & Sandhu, 2011; Rodrigues, Vickers, & Williams, 2002).

Research has shown that athletes generally possess superior visual abilities compared to non-athletes, likely due to sport-specific demands and training adaptations (Basiri et al., 2020). In contrast, individuals with intellectual disabilities (ID), including those with Down syndrome (DS), who compete in Class 11 para-table tennis, typically demonstrate lower visual-motor proficiency and technical performance (Kong & Ma, 2024). These athletes often show reduced return accuracy, stroke quality, and hand-eye coordination. While simple reaction time has been identified as a strong predictor of performance, cognitive ability does not appear to be related. Although various visual assessment tools, ranging from video-based analysis to emerging AI systems, have been employed, a lack of standardized and validated protocols persists.

The execution and adjustment of motor actions in table tennis depend on the quality and quantity of visual information received, which is shaped by both visual processing and ocular motor control systems (Nakazato, Aoyama, Komiyama, Himo, & Shimegi, 2024). Eye movements are more influential than head movements when tracking the ball, and these patterns vary with skill level (Higuchi, Nagami, Nakata, & Kanosue, 2018; Shinkai, Ando, Nonaka, Kizuka, & Ono, 2022). Gaze behaviour primarily involves smooth pursuit and saccades; when target speed exceeds 60–70°/s, gaze shifts rely on anticipatory saccades to maintain tracking (Nakazato et al., 2024). The spatial accuracy of these saccades directly influences visual information quality and, consequently, performance outcomes.

One well-established visual strategy linked to expertise is the Quiet Eye (QE), defined as the final steady fixation on a target for at least 100 ms within a 3° visual angle. In table tennis, QE has been shown to support fine motor control and decision-making (Hüttermann, Noël, & Memmert, 2018; Vincze, Iliescu, & Jurchiş, 2023). Another key visual factor is dynamic visual acuity (DVA), the ability to resolve details of a moving object, which plays a central role in this fast-paced sport. DVA is closely tied to oculomotor function and typically declines at higher object speeds due to the limits of pursuit accuracy and corrective saccades (Quevedo, Antonio Aznar-Casanova, & Da Silva, 2018). DVA is closely linked to eye movement strategies, with superior DVA performance largely attributable to enhanced oculomotor control and tracking abilities rather than purely image processing (Uchida et al., 2012, 2013). This relationship suggests that differences in gaze behaviour may directly influence perceptual performance and highlight the importance of considering oculomotor efficiency when investigating visual strategies across athletes with varying levels of experience and cognitive profiles.

Moreover, when attention must be distributed across multiple locations, peripheral vision (PV) becomes more effective than saccades, especially during dual-task scenarios such as motion-change detection (Klostermann, Vater, Kredel, & Hossner, 2020). PV is essential in sports with multiple stimuli and fixation points, yet it has limitations, such as difficulty processing unexpected changes or tracking distant targets, often necessitating gaze shifts that can interrupt focus (Klostermann et al., 2020; Schumacher, Schmidt, Reer, & Braumann, 2019; Zwierko, 2008). Elite athletes exhibit refined use of both central and peripheral vision to anticipate opponents' actions and navigate complex environments (Asar et al., 2022).

Several studies have explored visual training to enhance oculomotor control and visual perception in athletes. Such interventions have demonstrated improvements in hand-eye coordination, reaction time, DVA, accommodation, and saccadic precision in table tennis players (Altuncu & Aras Bayram, 2024; Basiri et al., 2020; Hassan, 2014; Paul et al., 2011). However, few studies have directly compared eye movement behaviour and visual efficiency across athletes with varying levels of experience and cognitive functioning.

Based on previous research on gaze behaviour in ball sports, we hypothesized that (1) Professional athletes would demonstrate superior oculomotor performance and more efficient gaze strategies than the other groups, reflecting the effects of extensive training and competitive experience; (2) Amateur athletes would show slightly better outcomes than participants with ID, given their higher exposure to sport-specific practice; (3) accumulated practice and systematic training would be associated with improved gaze metrics across groups, supporting the role of targeted visual training in enhancing both oculomotor and sporting performance.

This study aims to investigate differences in oculomotor behaviour and visual efficiency during table tennis-specific tasks across groups with varying skill levels and cognitive profiles; to better understand how visual-motor function relates to expertise and disability.

2. Methods

2.1. Participants

A total of 52 individuals aged between 9 and 70 years were initially recruited through convenience sampling from three distinct organizations: the A.D. School Zaragoza Tenis de Mesa, a specialized table tennis club founded in 1989; the Aragonese Guardianship Association for Intellectual Disability (ATADES), a non-profit organization established in 1962; and the Special Olympics Aragón, a non-profit sports association promoting athletic participation for individuals with ID since 1988. All participants from these diverse backgrounds trained together in an inclusive and collaborative environment at the Tenerías Municipal Sports Pavilion (Zaragoza, Spain), which also served as the consistent setting for all measurements.

All participant best-corrected distance comprehensive optometric assessment and were required to meet the following inclusion criteria: having continuous previous experience in table tennis practice, a distance best-corrected visual acuity (BCVA) of 0.8 or better in each eye (equivalent to 20/25 Snellen/0.1 LogMAR or better), absence of strabismus or binocular vision anomalies, and no ocular or systemic conditions or medications that could affect visual function. All participants attended the examination with their habitual optical correction (spectacles or contact lenses, if applicable) used during sports practice. A comprehensive optometric assessment was conducted, which included evaluation of refractive status, binocular vision, accommodative function, and oculomotor performance. Exclusion criteria comprised the presence of manifest strabismus, visual suppression, significant binocular vision anomalies, or any values outside normative optometric ranges for their age in binocular vision, accommodation, and ocular motility parameters that could interfere with task performance.

2.2. Optometric examination

The optometric examination was conducted on the 52 study participants prior to the experimental eye-tracking protocol, using each subject's habitual optical correction, when necessary, to ensure the results reflected optimal visual performance under naturalistic environment sporting conditions. The assessments were carried out in a purpose-adapted room adjacent to the hall where the table tennis tables were located, maintaining stable lighting and environmental conditions throughout the testing period, which took place between 6:30 p.m. and 9:30 p.m., immediately before each group's training sessions. All measurements were performed by a single examiner to ensure consistency in data collection, evaluating multiple visual parameters including BCVA, accommodative amplitude (AA), binocular accommodative facility (AF) at distance, vergence facility (VF) at distance, and near point of convergence (NPC). Visual acuity (VA) was assessed using the standardized Early Treatment Diabetic Retinopathy Study (ETDRS) chart at 4 m (100 % contrast), with both monocular and binocular readings recorded. AA was assessed monocularly using Donders' push-up method, with expected normal values calculated using the Hofstetter's equation $AA = 18.5 - 0.3 \times age$. AF testing involved counting lens alternation cycles (0.00 D / –2.00 D) during one-minute trials, with normative values of 11 ± 5 cycles per minute (cpm) (monocular) and 8 cpm (binocular). VF was evaluated using alternating prism trials (3 Δ base-in / 12 Δ base-out), with 12 to 15 cpm successfully fusion completed considered within the normal range. NPC measurements, using a non-illuminated stimulus, showed normal break/recovery values of less than 4 cm. The presence of strabismus was ruled out through the administration of the cover test and alternating cover test. Ocular motility was quantified using the Northeastern State University College of Optometry (NSUCO) test, analysing saccades, pursuits, and compensatory head movements to verify natural oculomotor performance during sports-related tasks (Erickson, 2020; Scheiman & Wick, 2008).

Finally, 46 participants were eligible for final inclusion. These individuals were stratified into four experimental groups based on their competitive experience and cognitive profile: Professional athletes included 12 competitive table tennis players aged 9 to 58 years; Amateur athletes consisted of 19 recreational table tennis players from A.D. School Zaragoza; DS Group comprised 8 athletes affiliated with Special Olympics Aragón; and ID Group included 7 participants from ATADES without DS.

Optometric data and related clinical parameters were systematically recorded and managed using Microsoft Excel 365 (Microsoft Corporation, Redmond, WA, USA), integrating all participant information into a unified database.

2.3. Instrumentation

Oculomotor behaviour was captured using the Neon Eye Tracker (Pupil Labs, Berlin, Germany), a head-mounted, real-time gaze tracking system specifically designed for sports applications. The system consisted of several integrated components designed for precise and dynamic gaze tracking in athletic settings: binocular infrared cameras equipped with 850 nm LEDs enable high-precision eye tracking even in low-light conditions; a Neon module served as a small central sensor base mounted at the center of a lightweight spectacle frame tailored for athletes; a scene camera with a $100^\circ \times 80^\circ$ field of view was centrally positioned to capture the visual environment; an Inertial Measurement Unit (IMU) with 9 degrees of freedom (DOF) detected head orientation and movement; and a microphone allowed for optional audio capture. The device incorporated NeonNet tracking technology with both binocular and monocular recording capabilities (200 Hz sampling rate, 192×192-pixel resolution per eye), along with a front-facing RGB scene camera (1600×1200 pixels at 30 Hz) to capture the athlete's visual perspective. The system was connected to a Motorola Edge 40 Pro mobile device (XT2301–4 model, Android 14 OS; Motorola Mobility, Wuhan, China) via USB-C, enabling real-time data acquisition and processing through the Neon Companion software (v2.8.37-prod v4; Pupil Labs, Berlin, Germany). All gaze data were analysed using Pupil Cloud (Pupil Labs, Berlin, Germany), a web-based analytics and visualization platform. Recordings were automatically synchronized with the manufacturer's cloud platform (https://cloud.pupil-labs.com) for centralized storage and analysis. Key gaze metrics included binocular fixation points, saccadic movements, pupil diameter (PD), and blink rate. Calibration accuracy ranged from 1.8° (uncalibrated) to 1.3° (offset-corrected). The reliability of gaze tracking data was assured through calibration procedures repeated before each session. The Neon Eye Tracker has documented gaze accuracy of 1.3° post-calibration, and sampling rate stability was verified in real-time through Pupil Cloud logs. The adjustable headband design allowed secure fit and stability, maintaining comfort during dynamic athletic performance. Gaze data were corrected for head movements by first projecting eye-tracking measurements onto a 3D point-cloud model of the environment, which tracks the scene camera position, and then mapping the gaze onto a 2D reference image. This procedure ensures that heat maps and Area Of Interest (AOI) analyses reflect the combined contributions of eye and head movements during task performance. PD values (mean $\pm$ standard deviation (SD)) were obtained under constant luminance conditions, with SD representing within-task variability linked to transient cognitive and visuomotor demands rather than interindividual baseline differences.

2.4. Procedure

2.4.1. Pre-assessment protocol

This prospective experimental study was conducted in accordance with the tenets of the Declaration of Helsinki and received ethical approval from the Research Ethics Committee of the Community of Aragon (CEICA with reference: PI24/483). Written informed consent was obtained from all participants prior to inclusion in the study. For minors and individuals with ID, consent was additionally obtained from legal guardians. Data were anonymized using coded identifiers, and only aggregated results were reported.

The study was conducted in a realistic sport setting to enhance validity and consisted of two main phases: first, a comprehensive optometric examination was carried out to evaluate refractive status, accommodative function, vergence systems, and ocular motility; second, subjective and objective visual data were simultaneously collected using an eye-tracking system during sport-specific tasks, allowing for the recording of ocular movements in real on-track training conditions.

2.4.2. Data collection

Data acquisition took place in a naturalistic environment at the Tenerías Pavilion (Zaragoza, Spain) during evening sessions (6:30 p.m. to 9:30 p.m.) from November 2024 to March 2025 under court lighting conditions using official competition-standard table tennis tables (2.74 m × 1.525 m, 76 cm height). Each participant completed sport-specific visual-motor tasks while wearing the Neon Eye Tracker. During task execution, a dual assessment approach was applied: a subjective assessment was conducted by the same experienced examiner using standardized protocols, while an objective assessment involved real-time recording of eye movement data through the Neon system.

Participants performed visually guided tasks involving the tracking and returning of table tennis balls, designed to replicate real-game scenarios. The coach, positioned diagonally to the subject, continuously delivered balls for approximately two and a half minutes of valid eye-tracking recording. To ensure comparability across participants, the rallies followed a standardized forehand-backhand alternation pattern. The coach maintained ball placement, trajectory, and pace as consistent as possible across groups, introducing only minimal adjustments when necessary to allow less experienced players or participants with cognitive disabilities to sustain the rally. To verify the consistency of the coach's deliveries, all recorded trials were examined frame by frame using the Neon scene-camera footage. This qualitative inspection, conducted by the same examiner (AGS), confirmed that the forehand-backhand alternation pattern, ball placement, and rally tempo were maintained throughout all sessions. Although the 30 Hz frame rate of the head-mounted scene camera did not allow precise kinematic reconstruction of the ball's trajectory, the visual review revealed no systematic differences in delivery patterns across participants or groups, ensuring comparable visuomotor task demands. Representative frame sequences illustrating rally consistency are provided in Supplementary (Fig. S1). This approach ensured that all subjects performed under comparable task demands while preserving ecological validity.

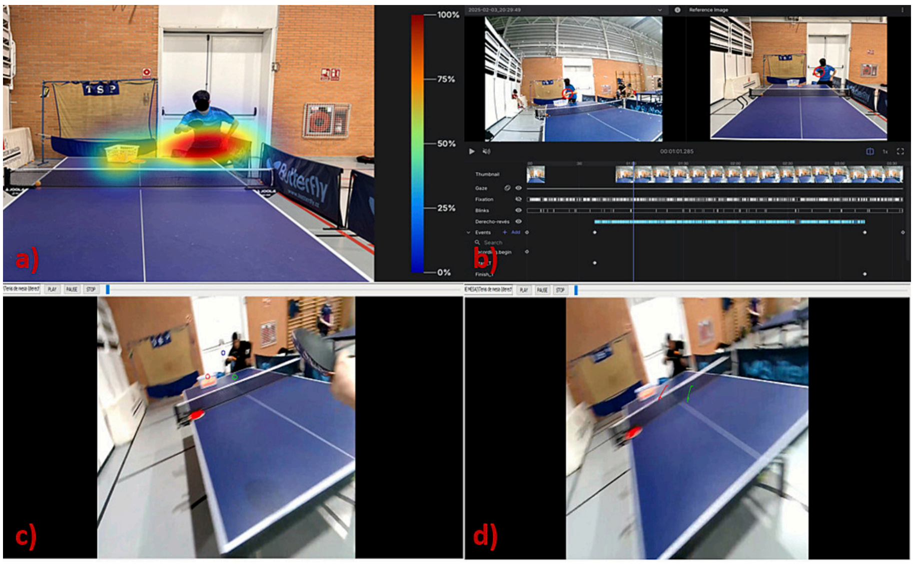

Fig. 1. a) Heat map illustrating spatial distribution of gaze points recorded during a table tennis task, highlighting areas of high visual attention intensity in warm colour. b) Screenshot of the Reference Image Mapper interface within the Pupil Cloud platform, displaying a sample environment with gaze data overlaid onto a reference scene. c) Fixation events, with each eye represented by a colored circle (red: left eye; green: right eye) and the mean fixation of both eyes in blue. d) Saccadic trajectories for each eye during task performance, illustrating the direction and amplitude of gaze shifts. All gaze events were extracted using custom-built software developed for the analysis of eye-tracking recordings. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.4.3. Data processing and event coding

The recorded videos were imported into Pupil Cloud, where each visual trial was manually segmented into discrete events based on task performance. Specifically, a timestamp labelled Start_"X" marked the initiation of the task, while a timestamp labelled Finish_"X" indicated the end of the rally, typically occurring when the participant failed to return the ball, with "X" indicating the group to which each subject belonged, to avoid confusion during post-processing. This manual event tagging and video segmentation were conducted by the same trained researcher (AGS), and events were defined as time intervals between these two markers.

Using the Reference Image Mapper, a 3D spatial reconstruction of the visual environment was generated. This allowed mapping of gaze data onto a static reference image captured during the trial. The tool aligned scene recordings with gaze coordinates to spatially locate visual fixations within the environment (Fig. 1b). The platform's "Visualizations" module was then used to generate heat maps from aggregated gaze data, enabling the identification of visual attention zones across trials (Fig. 1a). To facilitate eye-specific analysis, a custom-built post-processing software, ETrackerParsePC 1.0 (University of Zaragoza, Spain), was employed to separate and classify data from both eyes, enabling detailed intra-subject and inter-group comparisons (Fig. 1c-1d). The software processed predefined track segments by automatically identifying participants and categorizing the segments per recording. For each eye, it extracted quantitative oculometric parameters, such as saccadic movement frequency (in percentage: %), duration (milliseconds: ms), longitudinal velocity (millimetres per second: mm/s), and length (millimetres: mm); fixation duration (ms); and pupil size (mm), exporting the results into Excel files. These datasets formed the basis for subsequent statistical analysis and graphical representation. The program's algorithm also differentiated fixation events (Fig. 1c) from saccades (Fig. 1d), ensuring a robust classification of temporal and kinematic variables across recordings.

Eye movement events were automatically detected and classified using the Pupil Labs fixation detection algorithm implemented in the Neon system. The algorithm extends the classic I-VT approach by combining optic-flow-based velocity correction with an adaptive velocity threshold that accounts for head and scene motion. In Neon, saccades are defined as rapid gaze shifts exceeding an adaptive threshold (base 750 px/s, gain 0.8), lasting at least 10 ms and with a minimum amplitude of 1.0°, while fixations are identified as periods of stabilized gaze with a minimum duration of 70 ms (Drews & Dierkes, 2024; Hessels, Niehorster, Nyström, Andersson, & Hooge, 2018). Given that wearable recordings may contain slow components or noise within events classified as rapid gaze shifts, the term 'saccades' is therefore used to refer to 'saccade-like eye movements' throughout the manuscript. The validity of these automatic classifications was verified through visual inspection of representative gaze-position and velocity traces, confirming that saccades exhibited the expected ballistic profiles, whereas fixations displayed stable low-velocity patterns (Fig. 2). These observations supported the classification of these events as true saccades, with lower peak velocities in some participants reflecting genuine

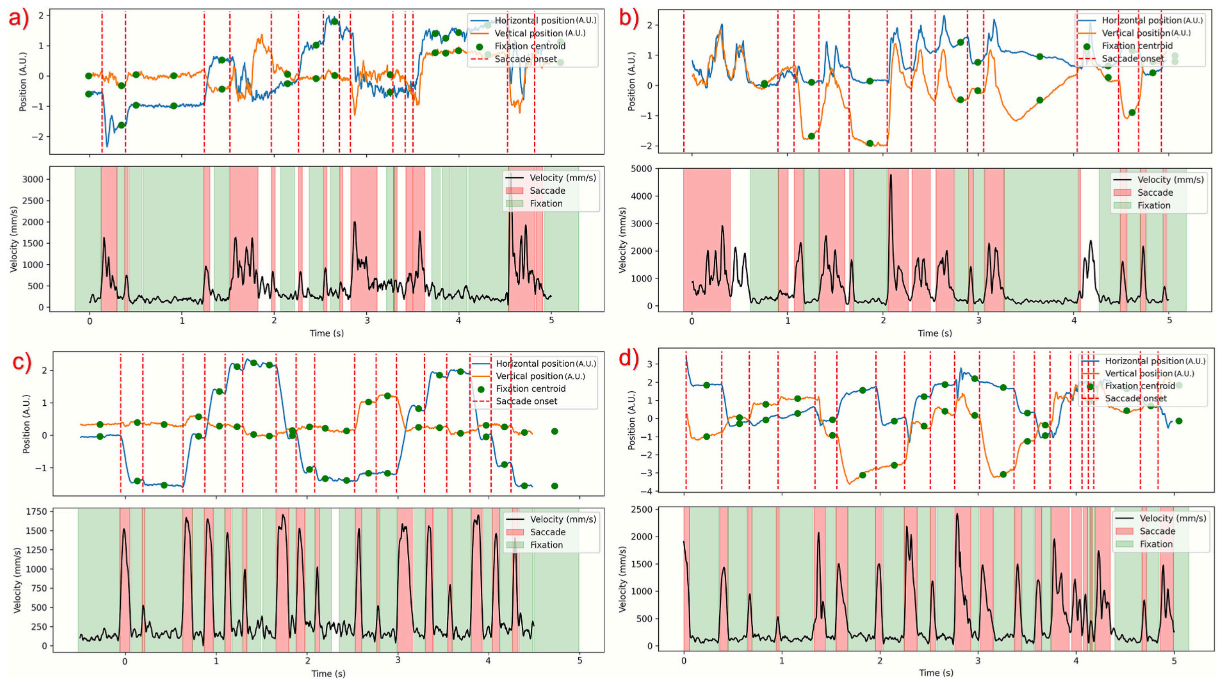

Fig. 2. Representative gaze-position and velocity traces recorded with the Pupil Labs Neon system. The upper panel shows horizontal and vertical gaze-position traces in arbitrary units (A.U.), at 200 Hz, from one participant of each group during a five second recording for a) Professional athletes' group; b) Amateur athletes' group; c) Special Olympics with Down syndrome group; and d) ATADES with other intellectual disability group. The lower panel presents the corresponding velocity profile (mm/s). Colored bands indicate events automatically classified by the NeonNet algorithm: fixations (green), and saccades (red). The ballistic peaks corresponding to saccades and the stable low-velocity segments representing fixations confirm the reliability of the automatic classification. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

interindividual oculomotor differences rather than systematic misclassification. The detected events were then processed using our custom software ETrackerParsePC 1.0 and visually validated via velocity-time graphs to ensure classification accuracy (Schweitzer & Rolfs, 2022; Stuart et al., 2019; van der Lans, Wedel, & Pieters, 2011).

2.5. Statistical analysis

Statistical analyses were conducted using custom Python scripts in Google Colab (Google LLC), based on data extracted from the sheet of the combined Excel file. After confirming non-normal distributions via Shapiro-Wilk tests, non-parametric analyses were conducted. Inter-group comparisons were conducted using Kruskal-Wallis tests, with the significance threshold adjusted to $p < 0.0083$ using Bonferroni correction to account for multiple comparisons. Categorical variables such as gender distribution were analysed using Fisher's exact test. To examine intra-subject symmetry between left and right eyes, paired *t*-tests were applied within each group for eye-specific variables, maintaining $p < 0.05$ as the significance level. Graphical exploration included bar plots with error bars (mean ± SD) and annotated *p*-values, violin plots to display the distribution of each variable by group and task type, and split violin plots for paired eye comparisons. This multimodal analysis enabled robust inter-group and intra-subject comparisons of oculomotor behaviour across training conditions.

Group size imbalances were anticipated due to the difficulty of recruiting participants from some groups. Recruitment targets were informed by prior sports vision and oculomotor studies, where samples of 8–12 per group have been sufficient to detect meaningful differences. Our final sample ($N = 46$; Amateurs $n = 19$, Professionals $n = 12$, Special Olympics $n = 8$, ATADES $n = 7$) reflects these constraints. To address unequal group sizes, we applied non-parametric tests (Kruskal–Wallis with the effect size (η^2)) and Bonferroni correction for multiple comparisons. A post-hoc power analysis based on observed means and SDs showed excellent power (>0.95) to detect large effects (e.g., saccade length, longitudinal velocity). However, power was limited for small effect sizes, such as those found in fixation duration, where >90 participants per group would be required to achieve 80 % power. Moderate effects, such as fixation and saccade frequencies, would require approximately 30–45 participants per group for adequate sensitivity. These analyses support the robustness of our findings in variables with large observed effects while highlighting the need for larger, more balanced cohorts in future studies.

3. Results

3.1. Participant characteristics

A total of 46 participants were included in the final analysis after applying exclusion criteria. The sample was composed of four groups: Professional athletes (Professionals: n = 12), Amateur athletes (Amateur: n = 19), individuals with DS (Special Olympics: n = 8), and individuals with other ID (ATADES: n = 7). Demographic and baseline optometric characteristics are summarized in Table 1.

No significant differences were observed in gender distribution across groups (Fisher's exact test, $p = 0.051$), suggesting a similar male-to-female ratio in the total sample, despite a predominance of male participants in Professionals and Special Olympics. However, statistically significant differences were found in both age and playing experience (Kruskal–Wallis, $p < 0.001$). The ATADES group included older participants with comparatively less experience, while Professionals showed the longest mean training history.

Table 1

Participant demographics and visual screening summary. The table reports mean values ± standard deviation (SD) for age, years of playing experience, training time, and all optometric variables across the total sample and by group: Professional athletes, Amateur athletes, Special Olympics participants, and ATADES participants. The *p*-values correspond to Kruskal-Wallis tests comparing all four groups with Bonferroni correction, with significance set at $p < 0.0083$ and marked in bold. For gender distribution, the p-value was obtained using Fisher's exact test.*

Mean (SD)	Total sample	Amateur	ATADES	Professionals	Special Olympics	p-value
Gender nM/nF	39/7	14/5	5/2	12/0	8/0	0.051
Age (years)	20.90 (15.42)	20.36 (12.31)	47.71 (3.04)	26.23 (12.60)	27.50 (8.93)	**<0.001**
Experience (years)	5.37 (4.75)	3.76 (2.60)	2.75 (1.56)	8.91 (4.80)	2.57 (1.39)	**<0.001**
Training time (hours/week)	3.02 (1.42)	4.00	1.00	4.00	1.00	**<0.001**
Rx RE (D)	−0.21 (1.38)	−0.25 (1.25)	+0.75 (1.10)	−0.75 (1.50)	+0.25 (1.00)	0.027
Rx LE (D)	−0.18 (1.31)	−0.20 (1.20)	+0.80 (1.15)	−0.70 (1.45)	+0.30 (1.05)	0.010
BCVA RE (LogMAR)	0.00 (0.03)	−0.02 (0.10)	0.06 (0.03)	−0.02 (0.10)	0.04 (0.05)	**<0.001**
BCVA LE (LogMAR)	−0.01 (0.04)	−0.03 (0.09)	0.05 (0.03)	−0.04 (0.10)	0.05 (0.03)	**<0.001**
AA RE (D)	9.01 (2.54)	9.65 (2.32)	6.20 (2.00)	9.17 (2.08)	8.10 (2.40)	**<0.001**
AA LE (D)	9.44 (2.91)	9.80 (2.60)	6.30 (2.20)	9.97 (3.01)	8.45 (2.25)	**<0.001**
BAF (cpm)	10.75 (4.20)	11.00 (4.00)	7.00 (2.50)	11.91 (4.17)	9.20 (3.60)	0.046
VF (cpm)	7.95 (3.18)	8.10 (2.95)	6.20 (2.40)	8.58 (3.22)	7.30 (2.80)	0.692
NPC (cm)	8.65 (4.01)	8.80 (3.90)	9.50 (3.60)	7.41 (4.27)	9.00 (4.10)	0.676
PD RE (mm)	4.69 (0.70)	4.98 (0.80)	4.07 (0.62)	5.26 (0.79)	4.26 (0.66)	**0.002**
PD LE (mm)	4.80 (0.71)	5.05 (0.81)	4.06 (0.65)	5.40 (0.81)	4.33 (0.59)	**0.001**
Mistakes during rallies	5.41 (3.30)	7.68 (1.97)	4.43 (0.98)	1.08 (0.29)	7.38 (2.72)	**<0.001**

* Abbreviations: SD: standard deviation; nM: number of males; nF: number of females; Rx: refraction; BCVA: best corrected visual acuity; LogMAR: logarithm of the minimum angle of resolution; AA: accommodative amplitude; BAF: binocular accommodative facility; VF: vergence facility; NPC: near point of convergence; PD: pupil diameter; RE: right eye; LE: left eye; D: diopters; cpm: cycles per minute; cm: centimetres; mm: millimetres.

Moreover, Professionals and Amateurs reported significantly higher weekly training times, with only the Professional group engaging in official competitions.

Regarding visual function, BCVA showed statistically significant inter-group differences in both eyes ($p < 0.001$). The Special Olympics group and the ATADES group displayed slightly higher LogMAR values (i.e., lower acuity), although all participants met the inclusion criterion of $\geq$0.8 decimal acuity (LogMAR $\leq$0.1) in both eyes. These results suggest mild differences in visual capacity that remain within functional norms.

Although differences in refractive error reached *p*-values below 0.05, they did not remain significant after Bonferroni correction (adjusted $\alpha = 0.0083$), indicating no statistically significant group differences for this parameter. In contrast, AA ($p < 0.001$) and PD ($p < 0.0083$: RE: $p < 0.002$, $\eta^2 = 0.278$; LE: $p < 0.001$, $\eta^2 = 0.298$) showed robust inter-group differences, with the ATADES group presenting more hyperopic mean refractions, reduced AA, and smaller pupil sizes, likely associated with their older age profile.

PD also showed distinct variability patterns that provide insight into attentional and autonomic modulation during task execution. The SD values indicate the extent of within-task fluctuations in pupil size, with higher SDs reflecting greater cognitive and physiological responsiveness. Professional and Amateur groups exhibited larger mean PDs and moderate SDs (RE: 5.26 ± 0.79 mm; LE: 5.40 ± 0.81 mm; and RE: 4.98 ± 0.80 mm; LE: 5.05 ± 0.81 mm, respectively), suggesting sustained attentional engagement and adaptive pupillary control. Conversely, the ATADES group showed smaller means and lower SDs (RE: 4.07 ± 0.62 mm; LE: 4.06 ± 0.65 mm), indicating more stable but reduced pupillary dynamics, consistent with their older age and lower autonomic activation. The Special Olympics group presented intermediate patterns. These distributions are visually represented in Fig. 3, where overlaid histograms and kernel density curves illustrate the differences in PD variability across groups.

Differences in BAF approached significance ($p = 0.046$) but did not reach the adjusted threshold for statistical significance. In contrast, VF and NPC showed no significant differences among groups ($p > 0.0083$), suggesting that vergence function is broadly comparable across participants and appears unaffected by age differences.

Errors during rallies were defined as instances in which the ball went out of play, preventing the continuation of the trial. For each participant, the total number of errors was calculated from the recorded events. At the group level, Amateur players exhibited the highest mean number of errors (7.68 ± 1.97), followed by Special Olympics (7.38 ± 2.36). The ATADES group showed a lower mean number of errors (4.43 ± 0.98), while Professional athletes committed the fewest errors (1.08 ± 0.29). Differences were highly significant ($p < 0.001$), indicating a clear effect of competitive experience on performance accuracy during rallies. These results suggest that higher levels of expertise are associated with fewer execution errors, reflecting more precise motor control and task familiarity.

3.2. *Eye movement behaviour during task execution*

Objective gaze metrics were extracted from eye-tracking recordings using Pupil Cloud, and the key parameters included were described in detail.

3.2.1. *Fixations*

The average fixation duration was similar across all groups, ranging from 271.88 ms (Special Olympics) to 300.63 ms (ATADES), with overlapping SD and wide confidence intervals. The statistical analysis (Kruskal-Wallis test) confirmed that no significant differences were present between groups ($p = 0.984$, $\eta^2 = -0.032$), suggesting a comparable temporal stability of fixation during task execution regardless of skill level or cognitive profile (Table 2 and Fig. 4a). This consistency in fixation duration may reflect a shared basic mechanism of visual attention maintenance among all participants when performing visually guided actions in a sport-specific context. The highest fixation frequency was observed in the ATADES group (80.67 ± 6.81 %; range: 68.15–85.83 %), followed closely by Amateurs (78.98 ± 5.22 %; range: 66.24–85.98 %). Professional athletes showed slightly lower fixation frequency (77.78 ± 12.64

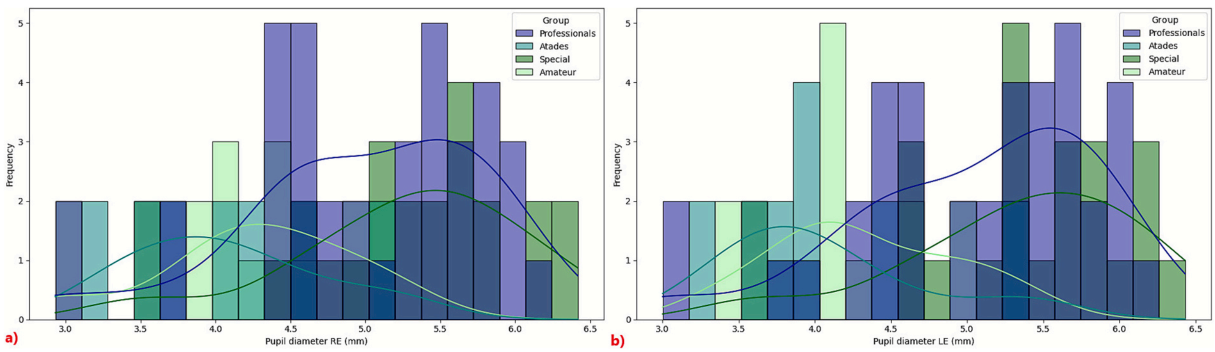

Fig. 3. Overlaid histograms showing the distribution of pupil diameter for (a) the right eye (RE) and (b) the left eye (LE) across the four experimental groups (Amateur, ATADES, Professionals, Special Olympics). Each histogram is colored according to the group it represents, with a legend indicating the colour for each group. The curves overlaid on the histograms are Kernel Density Estimates (KDEs), which provide a smoothed representation of the data distribution. These plots allow for a visual comparison of the shape, center, and spread of pupil diameter distributions between the different groups.

Table 2
Summary of fixation and saccade performance during the table tennis visual tracking task across groups. Fixation parameters include duration in milliseconds (ms), frequency (%), and displacement of the binocular vergence axis in the horizontal (DPx) and vertical (DPy) directions in prismatic diopters (Δ). Saccade parameters include duration (ms), length in millimetres (mm) for right eye (RE) and left eye (LE), and longitudinal velocity (mm/s) for both eyes. Data are presented as mean value (standard deviation) [minimum / maximum].

	Amateurs	ATADES	Professionals	Special Olympics
Fixations				
Duration (ms)	276.43 (34.04)	300.63 (58.07)	281.22 (65.85)	271.88 (68.46)
	[186.98 / 335.71]	[226.04 / 401.37]	[175.64 / 389.29]	[140.76 / 360.98]
Frequency (%)	78.98 (5.22)	80.67 (6.81)	77.78 (12.64)	74.56 (17.37)
	[66.24 / 85.98]	[68.15 / 85.83]	[47.21 / 89.28]	[32.52 / 85.05]
DPx (Δ)	−22.60 (15.64)	−18.05 (11.43)	−21.94 (17.16)	−28.44 (17.00)
	[−62.26 / -3.10]	[−41.08 / -7.73]	[−51.06 / 8.01]	[−48.34 / -1.57]
DPy (Δ)	0.74 (0.44)	0.73 (0.44)	0.79 (0.48)	0.55 (0.59)
	[−0.11 / 1.91]	[−0.01 / 1.37]	[−0.07 / 1.72]	[−0.27 / 1.54]
Saccades				
Duration (ms)	70.99 (16.95)	69.47 (22.74)	79.43 (49.33)	96.35 (81.58)
	[46.70 / 112.40]	[49.67 / 104.67]	[43.65 / 210.26]	[52.07 / 296.90]
Frequency (%)	21.02 (5.22)	19.33 (6.81)	22.22 (12.64)	25.44 (17.37)
	[14.02 / 33.76]	[14.17 / 31.85]	[10.72 / 52.79]	[14.95 / 67.48]
Length (mm) for RE	1106.56 (381.77)	1108.10 (707.09)	1414.63 (720.47)	2254.03 (3215.55)
	[556.63 / 1943.33]	[614.34 / 2581.12]	[652.47 / 3008.48]	[730.26 / 10,176.41]
Length (mm) for LE	1118.81 (386.70)	1052.14 (608.77)	1382.37 (722.74)	2284.90 (3328.71)
	[587.86 / 1988.72]	[585.17 / 2257.04]	[669.59 / 3032.69]	[720.77 / 10,489.75]
Longitudinal velocity (mm/s) for RE	12,381.01 (2163.18)	12,998.03 (4203.35)	13,888.52 (4242.25)	16,274.78 (6837.21)
	[8116.80 / 17,637.95]	[8862.58 / 21,496.16]	[9927.98 / 25,650.68]	[9820.93 / 31,908.19]
Longitudinal velocity (mm/s) for LE	12,501.75 (2246.00)	12,472.22 (3405.62)	13,658.90 (4142.71)	16,248.96 (6962.02)
	[8161.85 / 17,540.35]	[8768.10 / 18,545.03]	[9903.20 / 25,095.50]	[9638.96 / 32,311.13]

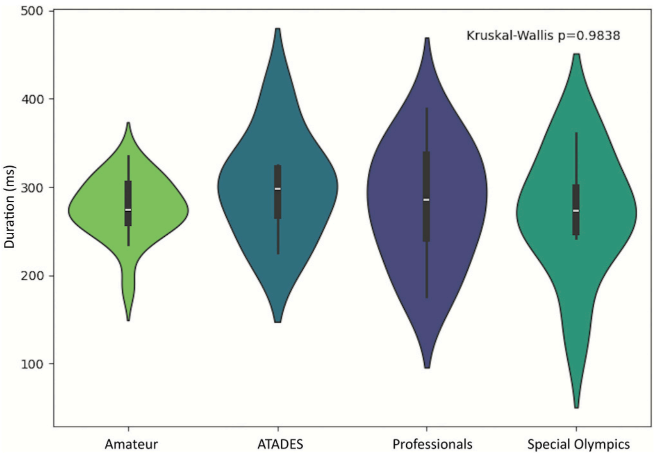

Fig. 4. Violin plots of the average fixation duration in milliseconds (ms). Within each violin, the white line indicates the median, and the black bar represents the standard deviation. Statistical significance was assessed using the Kruskal–Wallis test. The *p*-value is displayed; however, it does not reach statistical significance based on the Bonferroni-corrected threshold ($p < 0.0083$).

%; range: 47.21–89.28 %), while Special Olympics participants exhibited the lowest and most variable fixation frequency (74.56 ± 17.37 %; range: 32.52–85.05 %). This pattern suggests that ATADES participants and Amateurs maintained more stability and sustained visual attention effort, whereas the greater variability and lower fixation rates among Special Olympics participants may indicate less efficient or inconsistent visual engagement. Professional athletes, despite having slightly lower fixation frequency, likely demonstrate a more dynamic balance between fixations and saccades, reflecting efficient visual scanning strategies adapted to task demands (Table 2). These differences suggest that participants with greater sports experience or cognitive training tend to generate a higher number of briefs, task-relevant fixations, reflecting more efficient visual scanning, and information acquisition strategies.

The displacement of the binocular vergence axis was quantified in both horizontal (DPx) (Fig. 5a) and vertical (DPy) (Fig. 5b) directions, expressed in prismatic diopters (Δ). The variable DPx refers to the horizontal vergence distance; that is, the separation between the fixation points of the left and right eyes, calculated at a fixed reference distance of 2.5 m, which was determined during preliminary tests as the average fixation distance maintained by participants during gameplay. Positive DPx values indicate convergence relative to the 2.5 m baseline (i.e., the visual axes intersect in front of the reference plane), while negative values denote divergence (i.e., the visual axes intersect behind the reference plane). The variable DPy reflects the vertical displacement between the

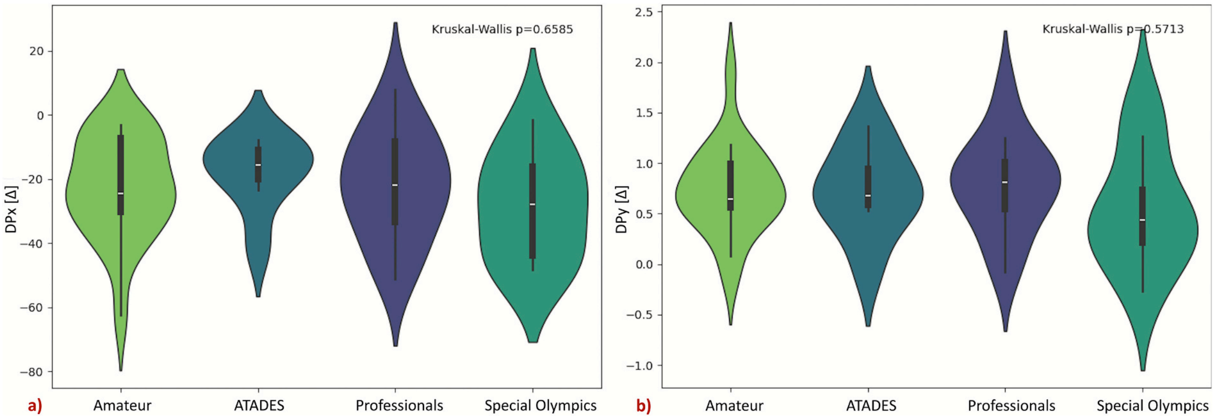

Fig. 5. Violin plots by group representing a) the displacement of the binocular vergence axis in the horizontal direction (DPx), and b) the displacement in the vertical direction (DPy), both in prismatic diopters (Δ). Within each violin, the white line indicates the median, and the black bar represents the standard deviation. Statistical significance was assessed using the Kruskal–Wallis test; *p*-values are shown in each panel, with both above the Bonferroni-corrected threshold ($p < 0.0083$), indicating no statistically significant differences between groups.

visual axes, with values representing the relative height difference between the eyes' fixation points.

The DPx showed consistently negative values across all groups, indicating a general trend toward divergence relative to the 2.5 m fixation reference. The Special Olympics group exhibited the most pronounced divergence (−28.44 Δ), followed by the Amateur (−22.60 Δ), Professional (−21.94 Δ), and ATADES (−18.05 Δ) groups. Despite these variations in magnitude, the inter-group differences were not statistically significant ($p = 0.659$, $\eta^2 = -0.033$). The wide SD and overlapping confidence intervals suggest considerable individual variability in vergence (continuous convergence-divergence) behaviour during fixation tasks (Table 2 and Fig. 5a). The DPy remained close to zero across all groups, with slightly elevated values in the Professional group (0.79 Δ) compared to ATADES and Amateur (both ≈ 0.73 Δ), and the Special Olympics group showing the lowest mean value (0.55 Δ). These small vertical displacements reflect minimal misalignment in the vertical plane, and again, no statistically significant differences were observed between groups ($p = 0.571$, $\eta^2 = -0.024$) in Table 2 and Fig. 5b. So, the absence of significant group effects in both DPx and DPy suggests a relatively stable pattern of binocular coordination in terms of vergence alignment, regardless of participants' skill level or neurodiversity status.

3.2.2. *Saccades*

Saccadic eye movements were analysed to assess oculomotor behaviour during task execution, given their importance in fast-paced sports like table tennis for redirecting gaze between relevant elements. Metrics evaluated included mean duration, frequency (%), length, and longitudinal velocity for each eye, to explore differences across the four groups (Amateur, ATADES, Professionals, and Special Olympics) in terms of gaze shift efficiency and speed (Fig. 6).

No statistically significant differences were found in saccadic duration across groups ($p = 0.984$, $\eta^2 = -0.032$; Fig. 6a), indicating similar temporal characteristics of rapid eye movements regardless of skill level or cognitive profile. Mean durations ranged from 69.47 ms (ATADES) to 96.35 ms (Special Olympics), with higher variability observed in the latter group (SD = 81.58 ms; range: 52.07–296.90 ms). These findings suggest that while saccade timing remains stable across populations, greater dispersion in neurodiverse individuals may reflect increased heterogeneity in oculomotor control.

The highest saccade frequency and dispersion were observed in Special Olympics participants (25.44 ± 17.37 %; range: 14.95–67.48 %), suggesting less accurate and less efficient gaze behaviour (i.e., accurate describes eye movements landing on or near the ball trajectory with minimal corrective movements). This was followed by Professional athletes (22.22 ± 12.64 %; range: 10.72–52.79 %), whose saccadic patterns likely reflect more purposeful and efficient visual scanning strategies. Amateurs (21.02 ± 5.22 %; range: 14.02–33.76 %) and the ATADES group (19.33 ± 6.81 %; range: 14.17–31.85 %) showed progressively lower frequency and variability, indicating more stable but potentially less dynamic visual engagement.

Although the Kruskal–Wallis test did not show statistically significant differences in saccade length across groups for either eye (RE: $p = 0.390$, $\eta^2 = 0.001$, Fig. 6b; LE: $p = 0.487$, $\eta^2 = -0.013$, Fig. 6c), high interindividual variability was particularly notable in the Special Olympics group. Their mean saccade length reached 2254.03 ± 3215.55 mm (range: 730.26–10,176.41 mm) for the RE and 2284.90 ± 3328.71 mm (range: 720.77–10,489.75 mm) for the LE. Professional athletes also showed relatively high values (RE: 1414.63 ± 720.47 mm; LE: 1382.37 ± 722.74 mm), while both ATADES and Amateur participants presented the lowest mean amplitudes, with RE values around 1100 mm. These results, though not statistically significant, suggest a possible trend toward broader visual exploration in both elite and neurodiverse groups.

To confirm that low-velocity events, notably in the Special Olympics group, corresponded to saccades rather than noise, the saccade main sequence (peak velocity vs. saccade amplitude) were plotted and representative gaze-position and velocity traces inspected (as previously described and show in Fig. 2). The main sequence retained the expected log-log linear relationship in all groups (Fig. 7). No significant group-level differences were found in longitudinal saccadic velocity for either eye (RE: $p = 0.195$, $\eta^2 = 0.041$, Fig. 6d; LE: *p*

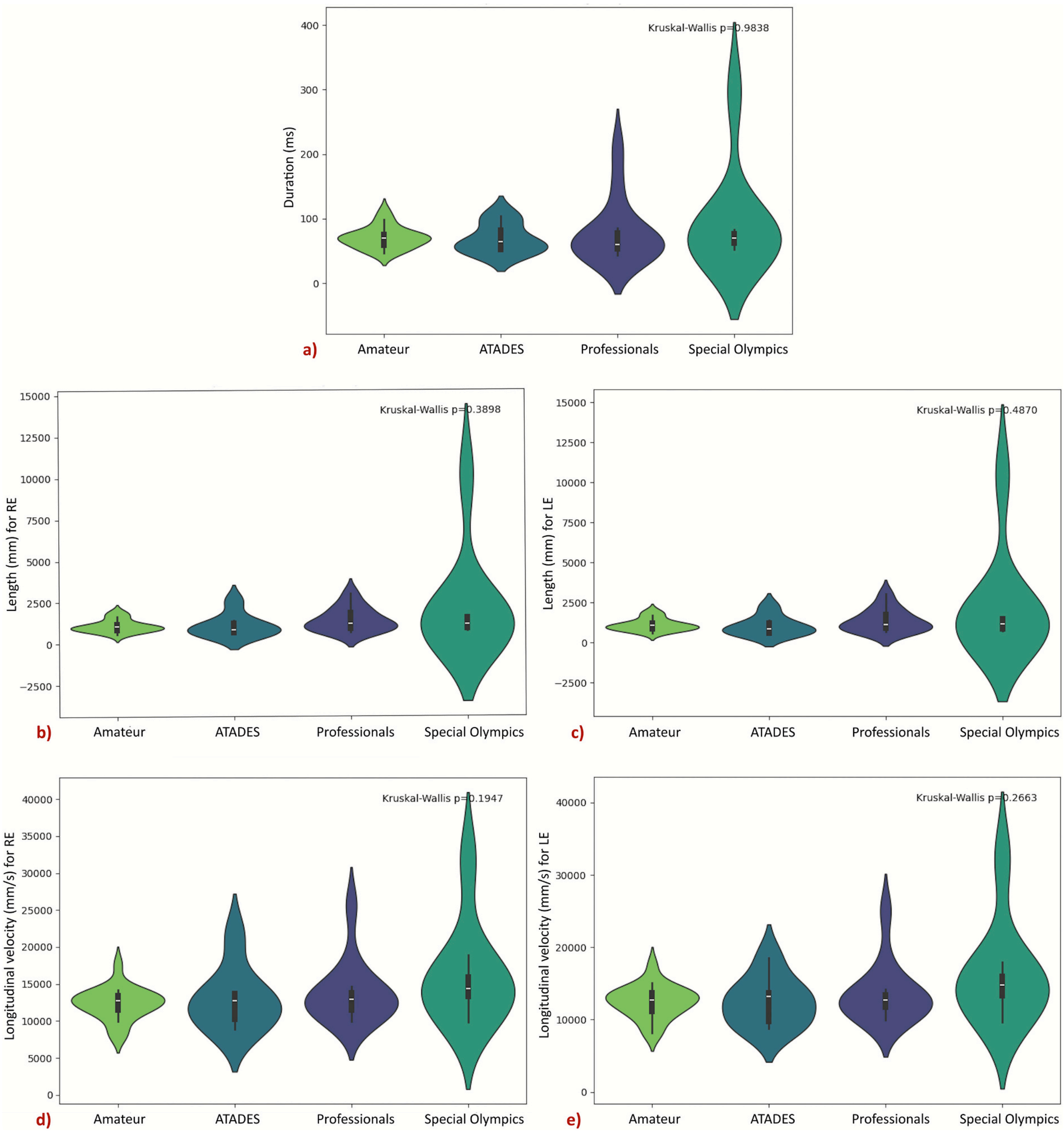

Fig. 6. Violin plots by group representing a) the average saccade duration in milliseconds (ms); b) saccade length in millimetres (mm) of the right eye (RE); c) saccade length in mm of the left eye (LE); d) longitudinal velocity in mm per second (mm/s) of the RE; and e) longitudinal velocity in mm/s of the LE across all track segments. Within each violin, the white line indicates the median value, and the black bar represents the standard deviation. Statistical significance was assessed using the Kruskal–Wallis test. The p-values are displayed; however, they do not reach statistical significance based on the Bonferroni-corrected threshold ($p < 0.0083$).

$= 0.266$, $\eta^2 = 0.023$, Fig. 6e). Nevertheless, the Special Olympics group showed the highest mean velocities (RE: 16,274.78 ± 6837.21 mm/s; LE: 16,248.96 ± 6962.02 mm/s), along with the widest spread of values. This may reflect increased, yet more variable, oculomotor activity. Amateur participants had the lowest longitudinal velocities (RE: 12,381.01 ± 2163.18 mm/s; LE: 12,501.75 ± 2246.00 mm/s), suggesting less intense gaze shifts, while Professionals showed moderately elevated values (RE: 13,888.52 ± 4242.25 mm/s; LE: 13,658.90 ± 4142.71 mm/s), possibly linked to their refined visuomotor control from training.

3.2.3. Differences between RE-LE parameters

PD, saccade length, and longitudinal velocity were analysed to compare oculomotor behaviour between eyes. Paired violin plots

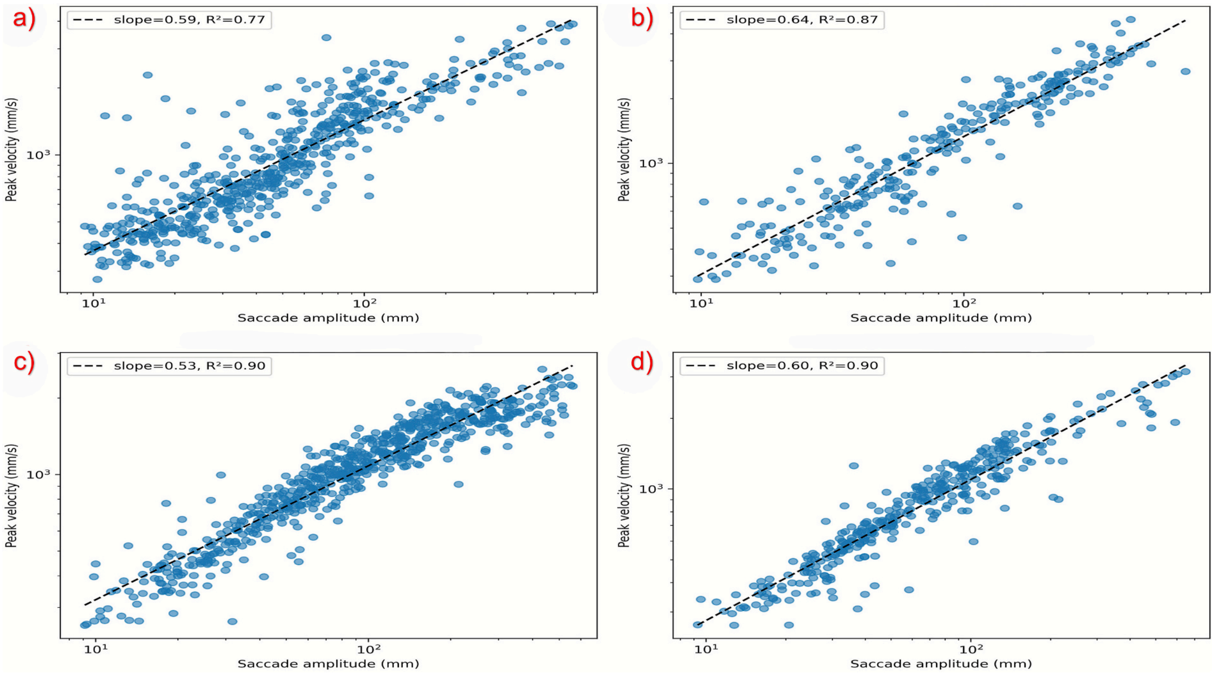

Fig. 7. Peak saccadic velocity (mm/s) versus amplitude (mm) plotted in log–log coordinates for saccades for one representative participant by group, the dashed line is the linear regression in log–log space. a) Professional athletes' group (slope = 0.59, $R^2 = 0.77$); b) Amateur players' group (slope = 0.64, $R^2 = 0.87$); c) Special Olympics with Down Syndrome group (slope = 0.53, $R^2 = 0.90$); and d) ATADES with other intellectual disability group (slope = 0.60, $R^2 = 0.90$).

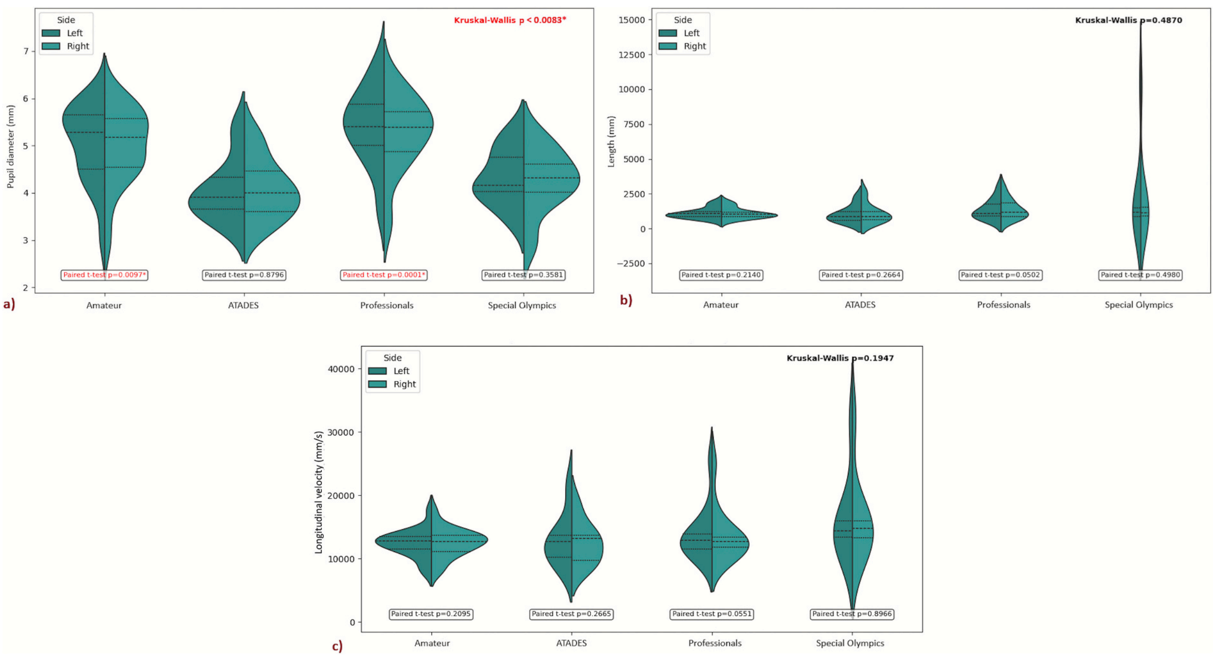

Fig. 8. Violin plots by group representing saccadic eye movement parameters separately for each eye: a) pupil diameter in millimetres (mm), b) saccade length in mm, and c) longitudinal velocity in mm per second (mm/s). Within each violin, the dashed line indicates the median, and the solid lines represent the standard deviation. Group-level differences were assessed using the Kruskal–Wallis test with Bonferroni correction ($p < 0.0083$ marked in red). Paired comparisons between left and right eyes within each group were conducted using two-related-samples tests; exact p-values are shown below each pair ($p < 0.05$ marked in red). For each eye: left eye is shown in dark green, and right eye in light green. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(Fig. 8) show the distribution and median values of these parameters across the four experimental groups: Amateur, ATADES, Professional, and Special Olympics, with comparisons conducted using two-related-samples tests.

A Kruskal–Wallis test revealed statistically significant differences in PD between groups ($p < 0.0083$; Fig. 8a), indicating group-specific modulation of pupil size during task execution. The Professional and Amateur groups exhibited larger mean PD compared to the Special Olympics and ATADES groups. This pattern may reflect higher levels of cognitive load, arousal, or attentional engagement typically associated with more intensive sports training. Significant interocular differences were observed in the Professional group (paired *t*-test, $p = 0.0001$) and the Amateur group ($p = 0.0097$), with larger PD in the LE. In contrast, no significant differences between eyes were found in the ATADES or Special Olympics groups. These findings suggest that pupil size asymmetry may be linked to lateralised visual processing or ocular dominance in populations with higher levels of visuomotor demand, while a more symmetrical pupillary response is preserved in groups with neurodevelopmental or intellectual conditions. Notably, most participants were right-handed and exhibited RE ocular dominance, which may have influenced the direction and magnitude of the observed asymmetries.

No significant differences were detected between groups in terms of saccadic length ($p = 0.487$, $\eta^2 = -0.013$; Fig. 8b). Substantial intra-group variability was evident, particularly within the Special Olympics group, as illustrated by the wider distribution in the violin plots. Importantly, no significant interocular differences in saccadic amplitude were found in any of the groups, suggesting balanced bilateral coordination of eye movements across all participants. The absence of lateralisation effects may indicate that saccadic motor control is generally symmetrical regardless of training level or neurodevelopmental status. Despite the lack of interocular asymmetry, the variability observed within groups could reflect individual differences in visuomotor strategies or adaptations.

For longitudinal saccadic velocity (Fig. 8c), no statistically significant differences were found between groups ($p = 0.195$, $\eta^2 = 0.041$). The Special Olympics group showed notable variability, with a wider distribution compared to other groups, reflecting greater heterogeneity in oculomotor performance. Importantly, no significant interocular differences were observed in most groups; however, the Professional group showed an interocular difference ($p = 0.055$), which may indicate a tendency toward subtle lateralised control of saccadic velocity in expert performers, although this did not reach statistical significance. The ATADES and Amateur groups exhibited narrower distributions and lower mean velocities, consistent with less dynamic oculomotor behaviour. Overall, the absence of significant group-level differences suggests that longitudinal saccadic velocity remains relatively stable across diverse cognitive profiles and experience levels.

Taken together, these findings indicate that Professional athletes exhibit refined oculomotor control, evidenced by larger PD and subtle interocular asymmetries in both pupil size and longitudinal saccadic velocity. In contrast, the Special Olympics group showed greater variability across oculomotor parameters, likely reflecting individual differences in cognitive-motor integration and visuomotor strategies. The absence of significant asymmetries in the Amateur and ATADES groups suggests more symmetrical oculomotor function in less trained or neurodiverse populations. Overall, these measures provide important understanding into the visual strategies underlying different levels of sports expertise and neurodiversity, highlighting the importance of tailoring visual assessments and training programs to individual profiles in both applied sports and cognitive science contexts.

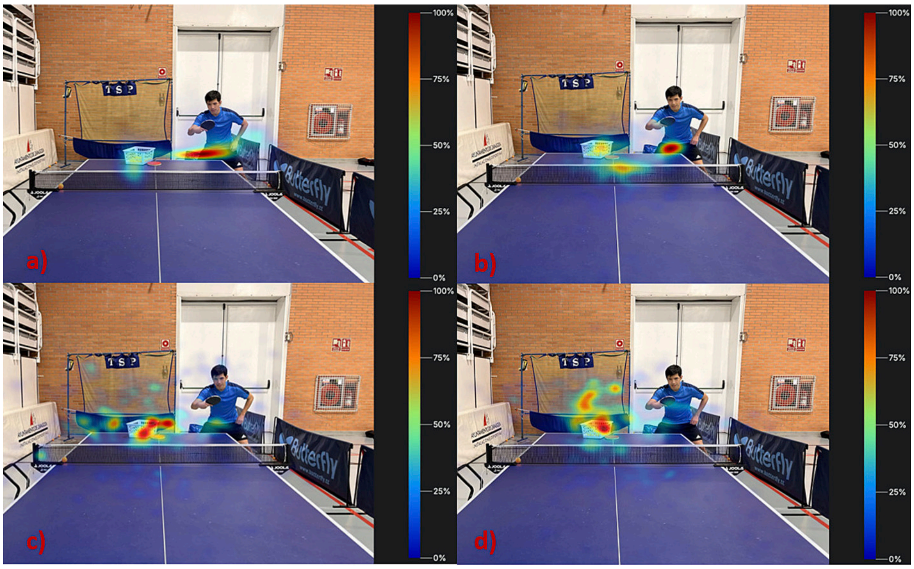

Fig. 9. Heat maps showing aggregated gaze concentration during exercise execution for a) Professional athletes' group; b) Amateur players' group; c) Special Olympics with Down Syndrome group; and d) ATADES with other intellectual disability group.

3.3. Heat map visualization and gaze distribution

Gaze heat maps were generated using the "Visualizations" module in Pupil Cloud, representing spatial fixation patterns across trials. Representative maps from each group are shown in Fig. 9.

The Professionals (Fig. 9a) displayed a tight and centralized cluster of fixations on the opponent's side, focusing not so much on the ball's trajectory but rather on the specific area where they intended to return the ball. In contrast, Amateur athletes (Fig. 9b) also showed a gaze pattern with fixations concentrated on the opponent's side of the table but with more varied and dispersed fixation points compared to Professionals. Compared to Professional and Amateur players, the Special Olympics group (Fig. 9c) and ATADES group (Fig. 9d) exhibited more dispersed and erratic gaze behaviour, frequently fixating on irrelevant environmental regions (e.g., table edges, ball basket, walls…), with the Special Olympics group showing slightly greater fixation dispersion than ATADES participants.

4. Discussion

This work provides new insights into how oculomotor behaviour and visual efficiency differ across populations with varying levels of expertise and cognitive functioning in table tennis. The observed differences in pupil size, number of fixations, and saccades highlight the role of visual-motor strategies in performance, particularly among experienced athletes. Notably, the binocular vergence analysis revealed consistent divergence patterns (negative DPx values) across all groups, with no significant differences in horizontal (DPx) or vertical (DPy) alignment. These results indicate that vergence stability during fixation tasks is maintained across populations, even when fixation patterns vary. Overall, these findings underscore the importance of tailored visual training interventions, especially for individuals with ID, to enhance perceptual-motor integration in dynamic sports environments.

It can be found previous studies consistently showing that expert table tennis players possess superior visual search strategies and decision-making abilities compared to novices (Asar et al., 2022; Chang et al., 2019; Jafarzadehpur & Yarigholi, 2004). In line with the findings of Jafarzadehpur and Yarigholi (Jafarzadehpur & Yarigholi, 2004), our results show both parallels and distinctions in visual function across groups. The AA was highest among experienced athletes (mean ≈ 9 D), whereas participants with ID demonstrated substantially reduced values (below 6 D). Similarly, BAF exceeded 12 cpm in Professionals, compared to approximately 6 cpm in the ATADES group. These trends partially replicate earlier observations, where table tennis players exhibited significantly greater BAF (14.3 ± 4.5 cpm) than non-athletes (9.7 ± 5.9 cpm). However, in our study, although BAF differences approached significance ($p =$ 0.046), they did not reach the corrected threshold for statistical significance. By contrast, NPC and VF did not differ significantly across groups, consistent with prior work. These findings suggest that accommodative function is sensitive to sport-specific demands and functional profile, while vergence mechanisms appear more resistant to modulation. As such, accommodation may represent a promising target for visual training interventions in both athletic and neurodiverse populations. Our heat map analyses corroborate these facts, revealing that experienced athletes exhibited a more concentrated focus with a smaller radius around the ball-return area. Interestingly, this focused gaze behaviour coexisted with similar binocular vergence patterns (DPx/DPy) across groups, implying that strategic visual attention may operate independently of basic vergence mechanisms during gameplay. This expertise allowed them to extract relevant information more efficiently, leading to more accurate predictions of opponent actions, ball trajectories, and overall play patterns within very short timeframes (Jafarzadehpur & Yarigholi, 2004; Piras, Lanzoni, Raffi, Persiani, & Squatrito, 2016). Importantly, such predictive advantages may be linked not only to general gaze concentration but also to the modulation of microsaccades, which have been associated with the anticipation of motor act outcomes in dynamic sport situations (Piras, Raffi, Lanzoni, Persiani, & Squatrito, 2015). Moreover, expert players demonstrated enhanced perspective-taking abilities, reflecting a refined capacity to anticipate opponents' intentions based on subtle visual cues (Chang et al., 2019). This focused visual strategy was also evident, although less pronounced in Amateur athletes, while participants with DS and ID displayed markedly more dispersed and inconsistent gaze patterns across the playing area.

The QE has previously been established as a robust indicator of expertise and superior performance in table tennis (Hüttermann et al., 2018; Vincze et al., 2023). Research in simulated competition contexts has shown that elite players exhibit longer QE durations prior to executing "winner balls" (shots that result in points) compared to those preceding forced or unforced errors, indicating that QE duration tends to increase with shot quality (Vincze et al., 2023). In table tennis, this strategy is often directed toward the intended landing zone of the ball, with skilled players typically fixating on the ball only early during rallies or serves (Rodrigues et al., 2002). Such prolonged fixations contribute to the optimal organization of the neural mechanisms involved in motor execution. In our study, although fixation duration did not significantly differ across groups, experienced players demonstrated a markedly higher number of fixations. The absence of vergence differences (DPx/DPy) alongside varied fixation performance suggests that expertise-driven visual adaptations may prioritize cortical processing (e.g., attentional allocation) over subcortical oculomotor adjustments like vergence. This suggests greater visual engagement and more active scanning of the playing environment, likely supporting better anticipation and real-time decision-making. Fixation duration was broadly comparable across groups; however, Professional players showed variability in fixation frequency, suggesting more flexible and strategic gaze deployment to track the ball, anticipate opponent actions, and update spatial orientation-hallmarks of expert visual strategies. Amateur players, on the other hand, showed the fewest fixations, indicating a more limited use of visual information during play. This difference implies that while the time spent fixating may remain similar across skill levels, the accuracy of those fixations could distinguish experienced players by reflecting superior attentional control and perceptual-cognitive integration. Additionally, experienced athletes experienced fewer interruptions during tasks (e.g., missed balls), further supporting the role of effective visual behaviour in enhancing motor performance. These results reinforce fixation behaviour as a sensitive indicator of visual-motor expertise, even when fixation duration remains consistent across groups. These findings are consistent with previous research linking DVA to oculomotor strategies. The superior DVA in baseball players is primarily attributable to enhanced tracking and eye movement control rather than image processing alone (Uchida et al., 2012, 2013). Applying this framework, the more flexible fixation frequency and accurate saccadic behaviour observed in Professional players in our study may reflect superior DVA-related tracking abilities, whereas the less stable patterns in Amateur and ATADES participants could indicate reduced oculomotor efficiency under dynamic gameplay conditions.

Previous research has shown that elite table tennis players exhibit superior saccadic control, including smoother eye velocity during rallies (Shinkai et al., 2022) and distinct patterns in both near and far saccadic movements when compared to sedentary individuals (Behdari, Zorba, Göktepe, Soslu, & Bezci, 2019). These athletes also tend to delay saccade initiation and demonstrate greater saccadic amplitudes, allowing for more efficient tracking of fast-moving targets like a table tennis ball (Basiri et al., 2020; Klostermann et al., 2020). In our study, although no significant differences were found across groups in terms of saccade duration, speed, or amplitude, experienced athletes performed a significantly higher number of accurate saccades compared to the other groups. Amateur players showed the lowest saccade performance, while participants with DS and ID presented intermediate values, likely reflecting more variable and less strategic gaze behaviours. These results suggest that the frequency of saccadic shifts, rather than their magnitude or speed, may serve as a more sensitive marker of visual expertise in fast-paced sports contexts, as it was already stated in other scenarios (Orduna-Hospital, Hernández-Aranda, & Sanchez-Cano, 2023). Notably, the stability in vergence measures (DPx/DPy) across groups implies that saccadic frequency and vergence control may represent distinct layers of oculomotor adaptation in table tennis. The lower mean saccade velocities observed in participants with ID or DS likely represent genuine neurophysiological differences in oculomotor control rather than pursuit contamination. Previous research has shown that individuals with neurodevelopmental conditions, including DS, often display reduced peak velocities and greater variability in saccadic performance (Luna, Velanova, & Geier, 2008; Weiss, Kelly, & Phillips, 2016). Consistent with this, our main-sequence analysis (Harris & Wolpert, 2006) confirmed the expected amplitude-velocity relationship, supporting the validity of these saccades.

Findings suggest that visual strategies for controlling gaze position in dynamic table tennis rallies are primarily associated with eye movements rather than head movements (Shinkai et al., 2022). While eye movements are crucial for acquiring information about the ball and the opponent, head movements appear to be more intrinsically linked to the execution of stroke movements (Shinkai et al., 2022; Shinkai, Ando, Nonaka, Kizuka, & Ono, 2024). They further demonstrated that gaze, head, and arm movements are tightly coordinated during forehand rallies, emphasizing that effective visuomotor control relies on the integration of eye, head, and limb actions (Shinkai et al., 2024). This highlights the specialized role of ocular motor control in fast-paced racket sports. Head movements could not be objectively measured between groups; however, based on the observation of the players during the tests, the group that demonstrated the greatest control of both body and head was the group of Professional athletes. The remaining groups showed more inconsistent recordings during the exercises (greater movement in the videos) and a higher number of fixations outside the table tennis area. The minimal vertical misalignment (DPy $\approx 0\ \Delta$) across groups further supports the primacy of eye movements overhead adjustments for visual tracking. Observational data suggested that experts exhibited greater head/body stability, whereas other groups showed erratic movements.

Table tennis players, especially those at higher skill levels, consistently demonstrate significantly shorter reaction times to visual stimuli compared to novices or non-athletes (Altuncu & Aras Bayram, 2024; Basiri et al., 2020; Hassan, 2014; Kamandi, 2019; Paul et al., 2011; Zwierko, 2008). This enhanced responsiveness is largely attributed to their greater efficiency in visual information processing and rapid cognitive decision-making, both of which are essential in a sport where ball flight times can be as short as about 800 ms during a serve (Kamandi, 2019; Paul et al., 2011). Although increasing task complexity is known to prolong reaction times, targeted perceptual-cognitive training has been shown to help counteract this effect (Kamandi, 2019; Lee et al., 2021). In the present study, however, no statistically significant differences were observed between groups in the reaction time-related parameters of saccade and fixation durations. This may suggest that other visual efficiency markers, such as fixation frequency, saccade performance, or gaze strategy, offer more sensitive indicators of expertise than duration alone.

While some studies argue that general visual functions, such as the overall peripheral field of vision, do not significantly distinguish athletes from non-athletes(Zwierko, 2008), other research highlights that the efficiency and speed with which visual information is processed, including peripheral cues, plays a critical role in elite performance (Asar et al., 2022; Zwierko, 2008). For example, in elite table tennis players, no direct correlations were found between peripheral visual field measurements and reaction times or eye-hand coordination (Asar et al., 2022). This suggests that expertise may rely less on the breadth of visual fields and more on how visual information is selectively attended to, interpreted, and integrated into motor actions. Observationally, both video analyses and live task executions in our study revealed that experienced players do not consistently track the ball with their gaze. Instead, they often fixate on the intended landing zone on the opponent's side of the table during stroke execution, indicating a strategic and anticipatory use of visual attention rather than continuous ball tracking.

An ongoing debate in sports vision research concerns whether the superior visual skills exhibited by athletes are primarily innate, stemming from genetic or anatomical advantages, or are largely acquired through systematic training and accumulated sport-specific experience (Asar et al., 2022; Basiri et al., 2020; Jafarzadehpur & Yarigholi, 2004; Zwierko, 2008). While certain foundational visual capacities may be relatively fixed and less amenable to change (Basiri et al., 2020), substantial evidence indicates that perceptual-cognitive skills, oculomotor efficiency, and overall visual processing can be significantly enhanced through targeted training and long-term engagement in sport (Altuncu & Aras Bayram, 2024; Hassan, 2014; Kamandi, 2019; Paul et al., 2011). Our findings support that visual expertise is largely shaped by practice and competitive exposure, with experienced athletes exhibiting significantly larger pupil sizes, more fixations/saccades, and distinct interocular asymmetry (LE vs. RE) compared to Amateurs and neurodiverse groups. This pupil size asymmetry, particularly notable given participants' predominant RE dominance, suggests that prolonged training induces lateralized adaptations in visual processing that override baseline ocular dominance patterns. While neurodiverse groups preserved symmetrical pupillary responses, Professionals displayed this specialized asymmetry alongside enhanced oculomotor metrics, implying that high visuomotor demand simultaneously refines both autonomic control (pupil dynamics) and conscious gaze strategies (fixations/saccades). Group differences in PD should therefore be interpreted as functional modulations during task execution rather than absolute baseline variations. The observed variability (SD) provides additional insight into cognitive and autonomic engagement: larger within-task fluctuations in the Professional and Amateur groups likely reflect adaptive modulation to visuomotor demands, whereas lower variability in the ATADES group suggests reduced pupillary responsiveness, possibly linked to age-related or cognitive factors. Future studies could normalize PD values to individual baselines or analyze percentage changes to further isolate task-specific pupillary dynamics.

A key limitation of existing eye-tracking research in high-performance sports is the frequent reliance on laboratory-based or computer-simulated settings, which, although offering high measurement precision, often fail to capture the dynamic complexity of performance in naturalistic environment (Hüttermann et al., 2018). This raises concerns regarding external validity and the practical applicability of findings. To address this, recent literature has emphasized the importance of conducting studies in naturalistic environments (Hüttermann et al., 2018; Schumacher et al., 2019). Although our study employed structured tasks, they were performed within the athletes' habitual training settings, allowing for the collection of eye movement data under valid conditions and yielding insights more representative of actual sport-specific visual demands.

In addition to differences explained by competitive experience, previous research highlights the role of cognitive profiles in shaping gaze behaviour. For instance, (Zonca, Coricelli, & Polonio, 2020) have shown in strategic decision-making tasks that higher levels of cognitive reflection are associated with gaze patterns that integrate relevant information more effectively. Although not sport-specific, these findings reinforce the idea that cognitive characteristics exert a strong influence on visual strategies. This perspective is further supported in sport contexts by studies such as Lex et al. (Lex, Essig, Knoblauch, & Schack, 2015), who demonstrated that cognitive representations and processing of team-specific tactics in soccer are crucial for anticipating play and guiding gaze toward task-relevant cues. Similarly, McPherson and Vickers (McPherson & Vickers, 2004) emphasized that cognitive control in motor expertise is fundamental for optimizing perceptual-motor coordination, with expert athletes showing superior ability to allocate attention and adjust gaze behaviour to situational demands. In interpreting the ATADES group results, it is important to consider that their oculomotor patterns may reflect the combined influence of intellectual disability and aging, since this group was significantly older than the others. Aging is known to affect gaze and hand–eye coordination strategies (Coats, Fath, Astill, & Wann, 2016). Together, these studies suggest that gaze strategies emerge from the interaction of both competitive experience and cognitive processing capacities, reinforcing our interpretation that differences observed between groups in the present study may be attributable not only to training history but also to underlying cognitive profiles. In this sense, the greater training load reported by Amateurs and especially by Professionals, who were also the only group regularly engaged in competition, could further contribute to explaining the observed performance differences.

Structured sports vision training, encompassing oculomotor exercises, eye-hand coordination drills, and visual stimulus-based programs, has been shown to significantly enhance multiple performance-related visual and motor skills in table tennis players (Altuncu & Aras Bayram, 2024; Basiri et al., 2020; Hassan, 2014; Paul et al., 2011). Reported improvements include faster reaction time, enhanced hand-eye coordination, greater VA, better depth perception, improved saccadic control, and increased accuracy in sport-specific actions such as the forehand drive. These findings highlight the value of integrating visual training as a complementary component in athlete development. Future initiatives aim to establish a dedicated visual training facility to further investigate its impact on oculomotor function and competitive performance. Recent advancements in table tennis research increasingly incorporate cutting-edge technologies such as binocular vision systems, deep learning models (e.g., LSTM neural networks), and smart training devices (Cai, 2022; Kamandi, 2019). These tools allow for real-time, high-precision analysis of player performance by enabling accurate detection, tracking, and prediction of ball trajectories. Beyond supporting robotic applications, these innovations could provide valuable data on the intricate visual and perceptual demands faced by human athletes during high-speed gameplay.

Several limitations of the present study should be acknowledged. First, the ATADES group included older participants compared to other groups, which may have influenced eye-hand coordination and visual-motor strategies independently of intellectual disability. Second, the sample sizes were unbalanced across groups, particularly for participants with ID. Although post-hoc power analysis indicated sufficient sensitivity for the main effects, results should be interpreted with caution, and future studies should aim for more balanced samples. Third, while the study was conducted in a realistic table tennis environment, variability in rally trajectories and ball speed may have influenced oculomotor behaviour; further research is needed to systematically examine how specific kinematic parameters of the ball, such as spin, speed, and trajectory, could modulate visual tracking and anticipatory eye movements in dynamic sports contexts. Although the head-mounted scene camera provided valuable qualitative information about each rally, its technical characteristics (30 Hz frame rate, participant-mounted perspective, and limited spatial calibration) precluded accurate quantification of the ball's 3D trajectory. The high velocity and small size of the table-tennis ball introduce motion blur and positional aliasing that cannot be corrected without a high-speed, fixed-perspective recording. Therefore, only qualitative verification of trajectory consistency was feasible, confirming that the coach maintained a uniform forehand-backhand alternation and comparable rally pace across all participants. For future work, we plan to incorporate a synchronized high-speed camera system ($\geq$ 200 Hz, global shutter) to capture precise ball kinematics and objectively confirm trajectory equivalence among trials. Fourth, certain variables such as head movements, QE, saccade onset, and reaction times were not directly measured, limiting the scope of interpretation. Fifth, understanding and executing the task may have been more challenging for participants with ID, which could have affected their performance and gaze patterns. Sixth, the temporal resolution of gaze heat maps was limited. Generating separate maps for ball reception versus return would require segmenting each trial into very short intervals, which is challenging and may reduce accuracy in defining action onsets and offsets. Although gaze patterns appeared qualitatively similar across these phases, future studies with higher temporal resolution could further explore subtle differences in visual strategies underlying sports expertise. Finally, external factors such as visual fatigue, lighting conditions, and participant familiarity with the task may have influenced results. Despite these limitations, the findings provide valuable insights into how oculomotor behaviour and visual efficiency differ across populations with varying expertise and cognitive profiles, offering directions for future research and tailored visual training interventions.

5. Conclusions

This study provides empirical evidence that differences in oculomotor behaviour and visual efficiency are associated with table tennis players' levels of experience and cognitive abilities, using wearable eye-tracking technology in a naturalistic environment. Professional athletes stood out for a higher precision in fixations and saccades, as well as significantly larger PD, suggesting greater attentional load, better visuomotor preparation, and more developed visual strategies. These characteristics were less pronounced in Amateur players and especially in groups with ID and DS, who exhibited more dispersed and less efficient visual patterns.

Although no statistically significant differences were found in fixation or saccade duration, the accuracy of these events allowed for discrimination between profiles. This finding is relevant because it suggests that dynamic variables, such as the exactitude of fixations and saccades, are more sensitive indicators of sports expertise than traditional metrics based on duration. These results align with previous research linking expertise to a more efficient and strategic use of visual attention.

Conducting the tests in real training contexts adds validity to the study, overcoming the limitations of controlled laboratory environments. This reinforces the practical usefulness of the findings, especially in planning visual training interventions. Indeed, the data support the implementation of specific programs to improve perceptual-motor integration, particularly in athletes with special needs. Finally, these results strengthen the view that visual skills in sports are highly trainable and not solely determined by innate factors. Future work should deepen this line of research by using emerging technologies (such as binocular vision systems, AI, or smart devices) to optimize visual training and evaluate its impact on competitive performance.

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Institutional review board statement

This study was conducted in accordance with the Declaration of Helsinki and approved by the Comité de Ética de la Investigación de la Comunidad de Aragón (CEICA) with reference PI24/483.

Informed consent statement

Written informed consent was obtained from all participants, or from their parents/legal guardians in the case of minors and individuals with intellectual disabilities, prior to participation in the study.

Use of artificial intelligence

Artificial intelligence (AI) tools, including large language models, were used to support the preparation of this manuscript. Specifically, AI-assisted writing tools (e.g., ChatGPT by OpenAI) were employed to refine academic language, improve structural coherence, and align the manuscript with conventional research reporting standards. All scientific content, data interpretation, and final editing were carried out and verified by the authors to ensure accuracy, originality, and integrity of the work.

CRediT authorship contribution statement

Alejandro Guiseris-Santaflorentina: Writing – original draft, Validation, Investigation, Data curation. **Ana Sanchez-Cano:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Elvira Orduna-Hospital:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare no conflicts of interest.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.humov.2025.103448.

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