



Visual Behavior in Inline Speed Skating: An Eye-Tracking Evaluation for Performance Analysis

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ABSTRACT

This study analyzed oculomotor behavior (fixations and saccades) in 19 competitive inline speed skaters (5 males, 14 females; aged 10–26 years) from the Aragonese Skating Federation (Spain), comparing high-performance (N1) and intermediate (N2) groups. Participants completed optometric assessments and eye-tracking during 200 m time trials on a banked oval track using a Pupil Labs Neon device, with recordings taken before (PRE) and after (POST) intensive training. Results showed visual behavior remained stable overall, but curved segments (C1, C2) required significantly more fixations and saccades than straights. Skaters consistently focused on the inner track line during curves, suggesting an optimized visual strategy. High-performance skaters (N1) demonstrated greater efficiency with fewer fixations and saccades in key segments. After training, N1 skaters showed increased fixations in C1 ($p = 0.012$) but reduced saccadic velocity (SS: PRE 8.00 deg/s vs. POST 6.82 deg/s; $p = 0.030$) and length (S1: PRE 3077.41 mm vs. POST 2564.71 mm; $p = 0.035$) on straights, consistent with fatigue. N1 exhibited different patterns of ocular abilities versus N2 pre- and post-training. Strong binocular coordination was observed (right-left eye correlations ≥ 0.85 ; $p < 0.001$). Conclusions indicate that experience enhances visual efficiency, with elite skaters showing more focused gaze patterns. Training-induced fatigue may primarily affect straight segments, reducing saccade speed and length. The finish line served as a consistent visual reference point. These findings highlight the importance of sport-specific visual training and fatigue management in inline speed skating. Future research should address study limitations including small sample size and gender imbalance.

1 | Introduction

High-performance sports provide an optimal framework for studying how gaze control and attention contribute to enhancing athletic performance. In this context, eye-tracking devices enable precise analysis of visual patterns during specific scenarios such as curves and straightaways in speed sports. These tools facilitate identification of visual demand variations across technical actions, offering valuable insights for performance optimization (Erickson 2021). High-performance sports represent an ideal setting for investigating visual mechanisms involved in motor control and decision-making. In disciplines like inline speed skating, characterized by extreme physical

demands and velocity, binocular vision and eye movements play a crucial role in athletic performance. Accurate visual perception and rapid processing of visual stimuli are critical for proper execution of technical maneuvers, particularly during high-speed curves and straight sections (Lebeau et al. 2016).

Key performance indicators in athletes include sports vision, which provides essential information for action timing and execution. The visual system's importance stems from processing approximately 80% of sensory input during athletic performance, serving as the primary guidance system in dynamic, high-demand environments (Ramaja et al. 2023). Sports vision constitutes a specialized optometry field focused on assessing

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Highlights

- Elite skaters show more efficient visual strategies, with fewer fixations than intermediate skaters, especially in curved segments.
- Training-related load may be associated with changes in oculomotor control, characterized by reduced saccade speed and length in straight sections among high-performance athletes.
- Skaters prioritize key visual references, consistently focusing on the inner track during curves and the finish line, demonstrating sport-specific gaze patterns.

and training visual skills beyond acuity, including reaction time, ocular tracking, and eye-hand/foot coordination, to maximize athletic performance. Visual perception and sensorimotor integration are particularly determinant in elite speed skating (Nascimento et al. 2020).

Binocular vision and eye movements are fundamental in highly dynamic disciplines like speed skating, where visual demands for speed and precision are exceptionally high (Buscemi et al. 2024) This three-dimensional perception enables accurate distance estimation and trajectory calculation, essential aspects of high-speed sports. In these dynamic environments, anticipatory capacity becomes particularly relevant, especially during curve negotiation where spatial perception determines both performance and safety (Erickson 2021). Binocular vision refers to the simultaneous use of both eyes to form a unified image, and proper binocular fusion requires emmetropic eyes or adequate optical correction, ensuring retinal images share similar size, shape, and color. Effective ocular motility and precise alignment of visual axes are equally essential to prevent deviations that might interfere with fusion and stereopsis (Benjamin 2006).

Eye-tracking technology has become invaluable for studying sports vision's role in athletic performance, particularly in high-speed, dynamic disciplines (Marques et al. 2018) The use of eye-tracking technologies enables detailed analysis of fixation patterns and gaze behavior, as well as variations in visual demands across different training or competition phases, allowing real-time recording of athletes' gaze direction during performance tasks in complex, high-speed environments, with successful applications including visual behavior analysis in Olympic oval speed skaters (Vickers 2006), curved trajectory assessment in cyclists at varying speeds (Vansteenkiste et al. 2014), investigation of vestibular function and oculomotor alterations in figure skaters during rotations (Menshikova et al. 2014), and observation of visual strategies in skateboarders performing acrobatic jumps of varying difficulty levels (Klostermann and Küng 2017) These studies demonstrate how eye-tracking reveals the relationship between visual perception and motor action, providing data on how athletes process visual information to control movement, maintain balance, and ultimately achieve success in their sport.

Inline speed skating, one of multiple skating disciplines, demands exceptional velocity, power, and endurance. Athletes must complete distances in minimal time, making it both physically and mentally demanding. This requires advanced

neuromotor capabilities including strength, coordination, postural control, and balance (Helda et al. 2012) The discipline's dynamic nature and high-speed motor coordination demands make binocular vision essential. It enables depth perception, balance control, movement anticipation and spatial orientation, all critical for technical and tactical performance in both training and competition. Typically conducted outdoors on hard surfaces like asphalt or vesmaco, speed skating presents unique technical and physical challenges. In short-distance events like sprints, athletes exceed 50 km/h, requiring specialized rapid visual processing capabilities (Helda et al. 2012).

This study aims to investigate changes in oculomotor behavior, specifically fixations and saccadic movements, in inline speed skaters before and after complete training sessions using eye-tracking technology. It further examines how these visual patterns vary according to athletes' experience and performance level, exploring the potential influence of physical effort and track familiarity on visual strategies in this high-speed sport. Given the limited availability of elite inline speed skaters and the complexity of in situ eye-tracking under real training conditions, the study was designed as an exploratory investigation intended to characterize visual behavior patterns rather than to provide confirmatory or causal inference.

2 | Methods

2.1 | Sample Description

The study included a sample of 19 participants (5 males and 14 females) aged between 10 and 26 years, all of whom were registered competitive speed skaters ensuring a minimum level of experience and sport-specific familiarity. The athletes were affiliated through the Aragonese Skating Federation, the official governing body for the discipline in the autonomous community of Aragón (Spain), and all belonged to the 2mil6 Skating Club (Zaragoza, Spain). Participants were divided into two performance-based groups for analysis: N1 (high-performance skaters) and N2 (intermediate competitive level) based on their competitive level within the Spanish Skating Federation, including regular participation in regional or national competitions, training volume, and objective coaching staff evaluation. Although performance level was the primary grouping variable, the authors acknowledge that age differed between groups and may partially reflect maturational differences inherent to competitive progression. The research was conducted in accordance with the ethical principles of the Declaration of Helsinki and received approval from the Research Ethics Committee of Aragón (CEICA) under reference number PI24/483. All participants (or their legal guardians for minors) provided written informed consent after receiving detailed information about study objectives and procedures. A comprehensive optometric examination was performed to assess refractive status, accommodative function, and vergence systems, followed by eye-tracking tests to record ocular movements during on-track training while performing specific visual tasks.

Participants were required to meet the following inclusion criteria: being registered competitive speed skaters through the

Aragonese Skating Federation, having continuous previous experience in speed skating practice, presenting monocular distance visual acuity (VA) of 0.1 LogMAR or better, attending the examination with their habitual optical correction (contact lenses or glasses for distance vision) used during training or competitions, and voluntarily agreeing to participate in the study by signing informed consent (or having legal guardians' authorization for minors). Exclusion criteria comprised subjects presenting any of these conditions: visual suppression in either eye, manifest strabismus, pre-existing ocular pathology or signs of ocular opacity that might interfere with visual function, or values outside normal ranges for their age in any binocular vision assessment parameters including accommodative dysfunctions, vergence abnormalities or ocular motility disorders that could affect visual task performance.

2.2 | Optometric Examination

The optometric examination was conducted on all 19 study participants prior to the experimental eye-tracking protocol, using each subject's habitual optical correction (glasses or contact lenses) when required, to ensure the results reflected maximum visual performance under real-world sports conditions. The assessments were performed in controlled locker room facilities adjacent to the skating rink, maintaining stable lighting and environmental conditions throughout the testing period between –6:00 p.m. and 6:30 p.m. immediately before training sessions. A single examiner conducted all measurements to ensure data collection consistency, evaluating multiple visual parameters including corrected VA, accommodative amplitude (AA), monocular (MAF) and binocular (BAF) accommodative facility at distance, vergence facility (VF) at distance, and near point of convergence (NPC). The VA was evaluated using the standardized Early Treatment Diabetic Retinopathy Study (ETDRS) chart at 4 m distance (100% contrast), with monocular and binocular measurements recorded (normal values ≥ 0.8 decimal ≤ 0.1 LogMAR). The AA was assessed monocularly via Donders' push-up method, with expected values (10–15 D) calculated using Hofstetter's equation ($AA = 18.5 - 0.3 \times \text{age}$). Accommodative facility testing involved counting lens alternation cycles (0.00D/–2.00 D) over 1-min trials, with normative values of 11 ± 5 cycles per minute (cpm) in monocular conditions and 8 cpm in binocular conditions. VF was evaluated using alternating prism trials (3 Δ base-in/12 Δ base-out), where 12–15 successful fusion cpm represented normal ranges. NPC measurements with a light stimulus showed normal break/recovery values < 4 cm. Ocular motility was quantified through the Northeastern State University College of Optometry (NSUCO) test, analyzing saccades, pursuits, and compensatory head movements to verify natural oculomotor performance during athletic tasks (Scheiman and Wick 2008; Erickson 2020).

2.3 | Experimental Protocol

Following the preliminary optometric examination, eligible participants underwent the experimental protocol using a sports eye-tracking system (Neon, Pupil Labs, Berlin, Germany).

Ocular movement data were collected at the Bozada Speed Skating Oval (41°38'32.8"N 0°54'47.5"W; 243 m above sea level, Zaragoza, Spain), a 200 m banked track, during evening sessions (6:30 p.m. to 9:30 p.m.) from November 2024 to March 2025 under standardized LED lighting conditions (four overhead fixtures). The testing protocol involved two measurement phases: baseline recordings at training initiation (PRE) and post-training recordings (POST) following complete sessions, enabling comparison of visual function parameters before and after physical exertion. Participants wore the eye tracker while completing designated high-speed skating circuits, with continuous monitoring of gaze behavior throughout both conditions.

The experimental protocol for eye movement recording consisted of four standardized phases.

1. Warm-up: participants completed a 10 min preparatory routine comprising off-skate mobility exercises followed by on-skate activation (25 laps around the 200 m track) to establish physiological readiness for testing.
2. Baseline measurement (PRE): the eye tracker was calibrated and secured to ensure unobstructed visual fields and comfort during skating. Following signal verification, gaze data were recorded during maximal effort 200 m time trials, preceded by a 100 m acceleration zone to achieve peak velocity.
3. Training intervention: athletes performed 5-7 high-intensity 1000 m interval sessions (3 min recovery periods), with total duration varying between 35 and 50 min based on individual pacing. This protocol replicated competition-level physical demands.
4. Post-training measurement (POST): identical eye-tracking procedures were repeated immediately following training completion to capture fatigue-induced oculomotor changes, maintaining consistent measurement protocols between PRE and POST conditions for direct comparison.

2.4 | Data Collection Protocol

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. For eye movement recording, the study utilized the Pupil Labs Neon sports edition eye tracker (Pupil Labs, Berlin, Germany), specifically engineered for dynamic athletic environments. 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 skater's perspective. The adjustable headband design allowed secure integration with standard skating helmets while maintaining comfort during high-speed maneuvers. The system connected via USB-C to a Motorola Edge 40 Pro mobile device (XT2301-4 model, Android 14 OS; Motorola Mobility, Wuhan, China) running Neon Companion software (v2.8.37-prod v4; Pupil Labs, Berlin, Germany), enabling real-time 2D/3D gaze

vector estimation at 200 Hz. All recordings automatically synchronized with the manufacturer's cloud platform (<https://cloud.pupil-labs.com>) for centralized data storage and processing, ensuring comprehensive analysis of fixation patterns and saccadic movements under actual training conditions (Neon n.d.). This integrated approach guaranteed precise ocular metrics while preserving natural skating kinematics throughout data collection.

All eye-tracking recordings were segmented into specific events using Pupil Cloud software (Pupil Labs, Berlin, Germany), with seven key timepoints dividing each lap into six functionally distinct segments (Figure 1A). The analysis focused on four critical phases: Curve_1 (C1), Straight_1 (S1), Curve_2 (C2), and Straight_2 (S2), corresponding to the maximal-effort timed lap. The complete segmentation protocol included: Start_C (SC: initial acceleration curve), Start_S (SS: pre-timed straight), C1 (first banked curve), S1 (subsequent straight), C2 (second banked curve), S2 (final straight), and Finish (deceleration phase). This segmentation enabled precise comparison of oculomotor behavior across different track geometries and performance conditions, with particular attention to the curve negotiation segments that presented the highest visual-motor demands.

The segmented videos were categorized into two experimental conditions: pre-training (PRE) and post-training (POST) recordings, enabling comparative analysis of visual performance before and after physical exertion. An aerial image of the speed

skating oval served as the reference framework for spatial mapping, with each recorded fixation manually plotted onto this template (Figure 1B). Heat maps (Figure 1C) were subsequently generated to visualize attention distribution patterns and identify key visual reference points used during track navigation.

For quantitative analysis of the collected data, three primary areas of interest (AOIs) were manually delineated on the speed skating track image (Figure 1D): the inner lane (Lane 1) adjacent to the inner boundary rope, the intermediate lane (Lane 2) positioned in the central zone, and the outer lane (Lane 3) near the external edge, enabling spatial contextualization of recorded visual fixations through the eye-tracking system and facilitating analysis relative to on-track movement dynamics.

Following data processing in Pupil Cloud, complete datasets from both experimental conditions were exported for specialized analysis using ETrackerParsePC 1.0 (University of Zaragoza, Spain), a custom-developed software tool for oculomotor data extraction. The program selectively processes eye-specific information from predefined track segments, generating Excel files containing quantitative parameters for saccadic movements (count, duration, velocity, length), fixations (count, duration), and pupil size of each eye, which served as the foundation for statistical analysis and graphical representation (Figure 1E). The analytical workflow initiated by importing segmented project folders into ETrackerParsePC 1.0, where the software automatically identified participants and classified the

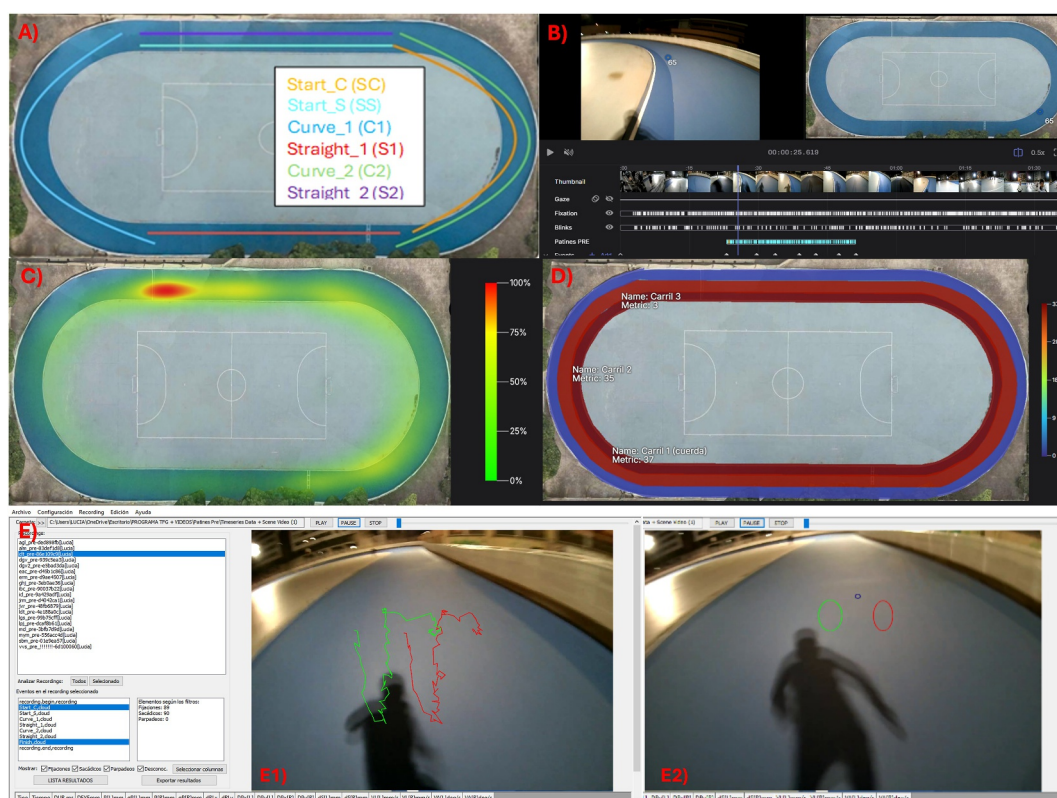


FIGURE 1 | (A) Aerial view mapping of the six analyzed segments on the speed skating oval. (B) Manual fixation mapping process overlaying eye-tracking data on the reference aerial track image. (C) Heat map visualization of aggregated fixation patterns across all participants. (D) Defined Areas of Interest (AOIs) showing the three skating lanes used for quantitative spatial analysis. (E) ETrackerParsePC 1.0 interface (University of Zaragoza, Spain) displaying: (E1) Saccadic movement patterns; (E2) Fixation distribution maps.

seven track segments. For each recording, the algorithm differentiated saccadic events (Figure 1E1) from fixations (Figure 1E2), while extracting all associated kinematic and temporal oculometric variables.

2.5 | Statistical Analysis

The study variables were extracted from Excel databases and analyzed using custom programming in Google Colab (Google LLC). After confirming non-normal distributions via Shapiro-Wilk tests, non-parametric analyses were conducted. Inter-group comparisons (N1 vs. N2) for optometric parameters and oculomotor metrics (fixations/saccades by track segment) employed Mann-Whitney U tests for independent samples, while pre-post training comparisons (PRE vs. POST) used Wilcoxon signed-rank tests for related samples, with significance set at $p < 0.05$. Binocular coordination was assessed through Spearman's rank correlation (Rho) analyzing right-left eye (RE-LE) relationships across track segments and training conditions, maintaining the $p < 0.05$ significance threshold. All statistical outputs included descriptive analyses and graphical representations of key findings. Given the exploratory nature of the study and the strong inter-dependence between oculomotor variables across track segments, formal corrections for multiple comparisons were not applied. While this approach increases the risk of Type I error, it was deemed appropriate to avoid excessive Type II error in this small, highly specific sample.

Accordingly, results are interpreted cautiously, with emphasis placed on effect sizes and consistency of patterns rather than isolated p -values.

3 | Results

3.1 | Sample Characteristics

The study included 19 young participants (mean age 15.42 ± 4.40 years, range 10–26) meeting all inclusion criteria. Table 1 presents the mean values and standard deviations of key visual parameters for the total sample and performance subgroups (N1: elite, N2: intermediate). No statistically significant differences emerged between groups ($p > 0.05$, Mann-Whitney U test) for any measured variables. While age did not differ significantly between groups, the numerical difference suggests potential maturational variability that are considered when interpreting oculomotor outcomes.

3.2 | Total Group

3.2.1 | Fixations

The average number of fixations made in six segments (SC, SS, C1, S1, C2, and S2) before (PRE) and after (POST) training is shown in Table 2 and Figure 2. Overall, no statistically

TABLE 1 | Descriptive statistics, mean value (standard deviation) for total sample and performance subgroups (N1/N2) with Mann-Whitney p -values and rank-biserial correlation coefficient (r).

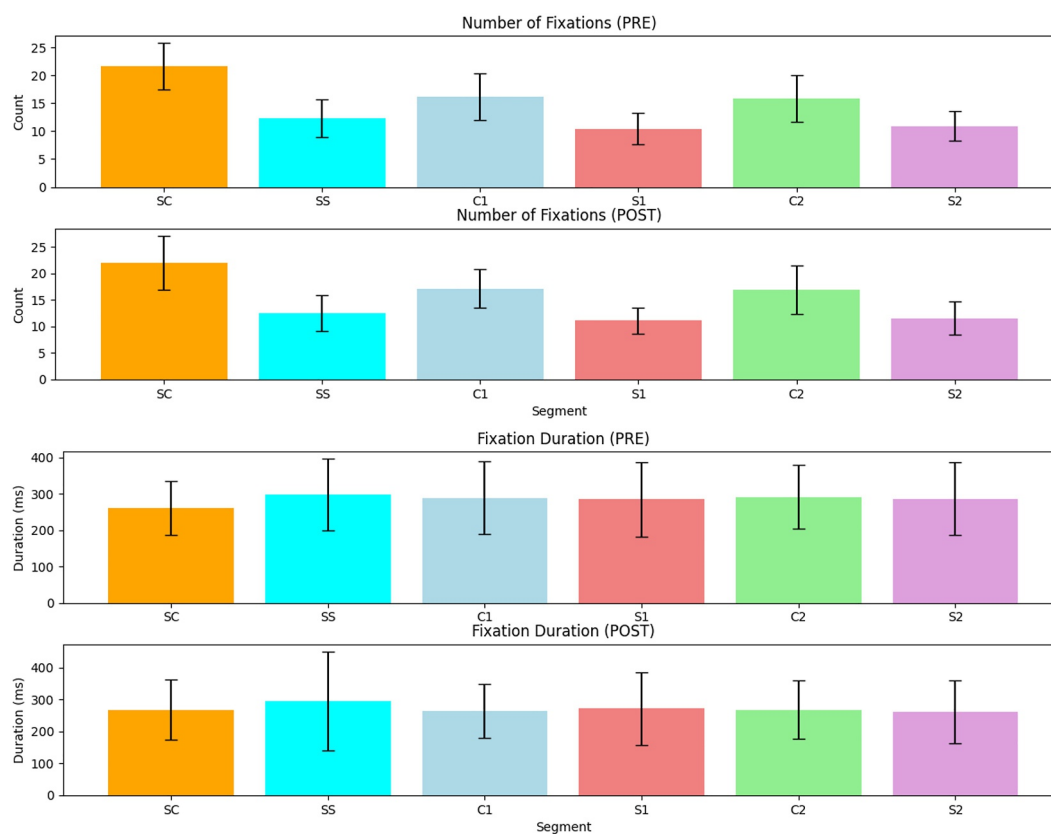
	Total sample mean value (SD)	Subgroup N1 mean value (SD)	Subgroup N2 mean value (SD)	p-value	
				N1 versus N2	r
Age (years)	15.42 (4.40)	17.10 (5.43)	13.56 (1.74)	0.216	−0.344
Rx RE (D)	−0.05 (0.31)	−0.03 (0.36)	−0.08 (0.25)	1.000	−0.011
Rx LE (D)	−0.08 (0.44)	−0.05 (0.54)	−0.11 (0.33)	1.000	< 0.001
VA RE (LogMAR)	−0.01 (0.10)	−0.04 (0.10)	0.03 (0.08)	0.264	0.311
VA LE (LogMAR)	0.00 (0.09)	−0.01 (0.12)	0.02 (0.04)	0.388	0.244
VA BE (LogMAR)	−0.01 (0.07)	−0.04 (0.09)	0.02 (0.04)	0.229	0.333
AA RE (D)	12.37 (2.52)	12.60 (2.07)	12.11 (3.06)	0.739	−0.100
AA LE (D)	13.68 (4.14)	13.90 (3.18)	13.44 (5.20)	0.534	−0.178
MAF RE (cpm)	19.53 (4.57)	21.40 (4.01)	17.44 (4.45)	0.090	−0.467
MAF LE (cpm)	17.84 (7.30)	18.20 (9.16)	17.44 (5.03)	0.389	−0.244
BAF BE (cpm)	18.58 (5.96)	19.50 (7.34)	17.56 (4.13)	0.137	−0.411
VF BE (cpm)	9.21 (6.92)	8.00 (7.50)	10.56 (6.39)	0.509	0.189
NPC break (cm)	4.26 (2.21)	3.80 (2.04)	4.78 (2.39)	0.432	0.222
NPC recovery (cm)	7.68 (2.93)	7.60 (2.72)	7.78 (3.31)	0.772	0.089

Abbreviations: AA: accommodative amplitude; BAF: binocular accommodative facility; BE: both eyes; cpm: cycles per minute; cm: centimeters; D: diopters; LE: left eye; MAF: monocular accommodative facility; NPC: near point of convergence; RE: right eye; Rx: refraction; SD: standard deviation; VA: LogMAR visual acuity; VF: vergence facility.

TABLE 2 | Comparison of fixation count and duration in milliseconds (ms) across the six visual segments (SC, SS, C1, S1, C2, S2) before (PRE) and after (POST) the training.

	SC	SS	C1	S1	C2	S2
Fixations count						
PRE mean (SD)	21.67 (4.14)	12.33 (3.41)	16.16 (4.20)	10.47 (2.87)	15.88 (4.25)	10.94 (2.65)
POST mean (SD)	22.00 (5.10)	12.52 (3.40)	17.15 (3.67)	11.10 (2.44)	16.94 (4.60)	11.52 (3.13)
PRE versus POST <i>p</i> -value	0.825	0.598	0.521	0.120	0.251	0.649
Fixations duration (ms)						
PRE mean (SD)	260.87 (74.74)	297.07 (98.69)	288.40 (100.13)	284.55 (102.77)	291.17 (87.03)	286.53 (100.68)
POST mean (SD)	268.06 (93.42)	295.45 (154.81)	263.56 (84.44)	272.15 (114.05)	268.35 (91.91)	261.68 (98.13)
PRE versus POST <i>p</i> -value	0.956	0.346	0.378	0.174	0.126	0.243

Note: Mean values, standard deviation (SD) and associated *p*-values for each metric are presented.

**FIGURE 2** | Graphical representation of the total mean count and duration in milliseconds (ms) of fixations before (PRE) and after (POST) training in each analyzed segment, with their standard deviation (in black lines) for each segment.

significant differences were found between PRE and POST conditions ($p > 0.05$).

Segment S1 showed the difference closest to significance ($p = 0.120$), with a slight increase in the number of fixations after training (from 10.47 to 11.10). Segments SC and C2 maintained high fixation levels in both conditions, while SS and S2 showed the lowest values. These results suggest overall stability in visual behavior following training, with no substantial changes in fixation distribution across segments.

Regarding fixation duration, the results indicate no statistically significant differences between PRE and POST conditions in any

of the analyzed segments ($p > 0.05$). Segment C2 showed the lowest *p*-value ($p = 0.126$), suggesting a trend toward decreased fixation duration, from 291.17 ms (PRE) to 268.35 ms (POST). Similarly, other segments such as S1 and S2 also showed slight reductions in average fixation duration, though without reaching statistical significance.

Segments like SC and SS maintained relatively stable fixation durations across conditions, likely because these speed-building zones require consistent visual attention. Globally, while no significant differences emerged, there was a slight increase in fixation count and a minor decrease in fixation duration post-training, potentially reflecting subtle improvements in visual

efficiency. However, the overall stability of these parameters suggests that training did not substantially alter oculomotor strategies or visual attention distribution, with participants maintaining similar fixation patterns before and after intervention.

The analysis revealed a clear distinction in visual fixations between straight (S1, S2) and curved segments (C1, C2), with significantly more fixations occurring during curves. This pattern likely reflects the heightened demand for trajectory adjustments during high-speed curve negotiation, necessitating greater visual control. In contrast, straights, where path stability reduces the need for active corrections, elicited fewer fixations.

3.2.2 | Saccades

The average number of saccades performed in six segments (SC, SS, C1, S1, C2, and S2) PRE and POST training is shown in Figure 3, finding no statistically significant differences between conditions ($p > 0.05$), Table 3.

Segment S1 showed the difference closest to significance ($p = 0.122$), with saccade count increasing slightly from 10.53 to 11.11 post-training. While C1 and C2 didn't reach statistical significance, they displayed the largest saccade count differences, potentially due to both their curved trajectory and increased visual control demands after physical exertion. Notably, S2 demonstrated a significant saccade duration increase ($p = 0.019$) from 101.27 to 127.74 ms, likely reflecting broader ocular tracking as athletes anticipated the lap's conclusion.

Overall, most segments showed non-significant increases in both saccade number and duration post-training, except SC where duration decreased. These subtle changes may indicate improved visual efficiency in specific phases, though the general

stability suggests training didn't substantially alter oculomotor strategies. The SC reduction (initial acceleration curve) might reflect post-training fatigue, causing delayed acceleration initiation and consequently reduced visual exploration needs in this segment.

3.2.2.1 | Correlations Between Right Eye/Left Eye in Saccadic Movements.

A significant positive correlation ($r \geq 0.85$; $p < 0.001$) was observed in all segments, both in PRE and POST conditions, between the RE and LE for saccade length, velocity, and pupil diameter (Supplementary I). Given this bilateral symmetry, mean saccadic parameters were calculated, revealing consistent length-velocity proportionality across all segments ($p < 0.05$). However, POST condition correlations were weaker in curved segments (C1: $r = 0.57$, $p = 0.011$; C2: $r = 0.61$, $p = 0.005$), suggesting curved trajectories prompt shorter-length saccades at maintained velocities as athletes make more frequent trajectory adjustments. Straight segments preserved the length-velocity relationship through more stable tracking patterns.

TABLE 3 | Summary of p -values for saccadic metrics (Count, Velocity (deg/s), Length (mm), and duration (ms)) comparison between PRE and POST training for each visual segment (SC, SS, C1, S1, C2, S2).

Segment	Count	Velocity (deg/s)	Length (mm)	Duration (ms)
SC	0.875	0.030	0.030	0.609
SS	0.627	0.034	0.325	0.899
C1	0.439	0.766	0.966	0.702
S1	0.122	0.020	0.035	0.678
C2	0.392	0.145	0.890	0.378
S2	0.711	0.329	0.611	0.019

Note: Statistically significant differences ($p < 0.05$) are highlighted in red.

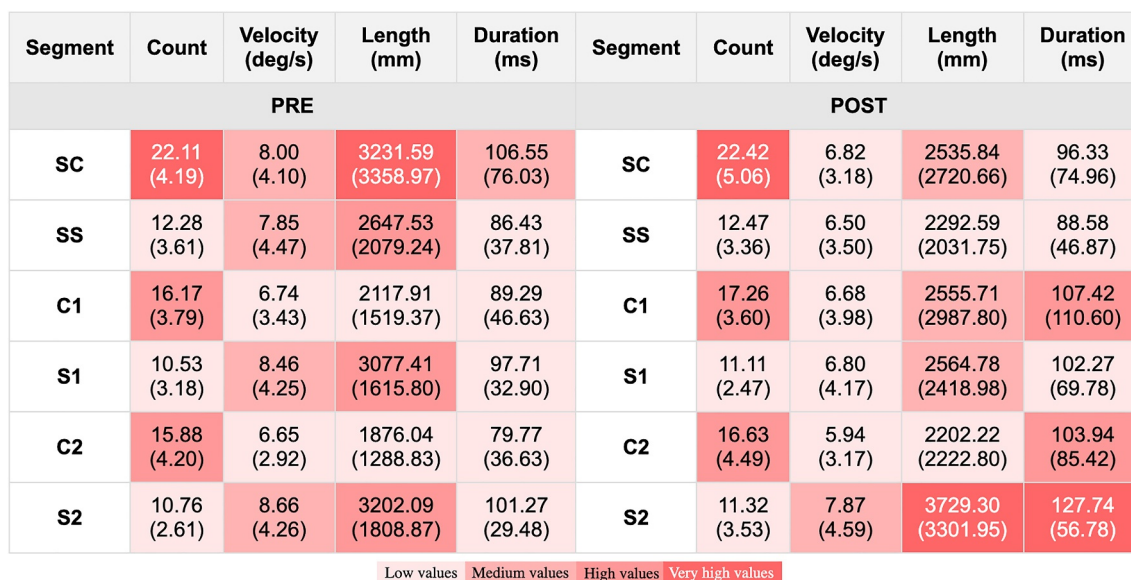


FIGURE 3 | Summary heatmap of means and standard deviations (in parentheses) for key saccadic metrics where Count is the number of saccades, Velocity (deg/s) is angular velocity, Length (mm), and Duration (ms) for each visual segment (SC, SS, C1, S1, C2, S2) in PRE and POST conditions.

Significant differences in saccadic parameters were observed in specific segments. SC showed reduced mean velocity (PRE: 8.00 deg/s vs. POST: 6.82 deg/s; $p = 0.030$) and shorter mean length (PRE: 3231.59 mm vs. POST: 2535.84 mm; $p = 0.030$), a pattern that replicated in S1 (velocity: 8.46 deg/s vs. 6.80 deg/s, $p = 0.020$; length: 3077.41 mm vs. 2564.71 mm, $p = 0.035$). SS displayed only mean velocity reductions (PRE: 7.85 deg/s vs. POST: 6.50 deg/s, $p = 0.034$). While other segments showed no statistically significant differences, C2 and S2 exhibited a consistent trend toward slower but longer saccades post-training (Figure 3 and Table 3). These selective modifications suggest training-induced adaptations in oculomotor strategies, particularly in entry (SC) and transitional segments (S1, SS), where high-speed control is most critical.

This pattern may be explained by the fact that during curves, athletes execute a greater number of saccadic movements to adjust their trajectory, preserving velocity while producing shorter-length saccades. In contrast, during straight segments, velocity remains proportional to saccade length because athletes maintain their trajectory and perform fewer tracking movements.

3.3 | Division Into Two Performance Categories

3.3.1 | Fixations

The analysis of fixation count, Table 4 and Figure 4, reveals differences according to athletes' performance level and the evaluated segment. In group N1, statistically significant differences were observed between PRE and POST conditions in segment C1 ($p = 0.025$), corresponding to the first curve of the circuit. In this case, the number of fixations increased after training, which could be interpreted as a greater need for visual control and spatial awareness regarding trajectory, possibly motivated by physical fatigue induced by training exertion. Furthermore, the comparison between N1 versus N2 revealed significant differences during segment SC before training ($p = 0.008$) and SC after training ($p = 0.034$). These results indicate that more experienced skaters performed fewer fixations in the initial curve compared to the lower-level group. This difference could be explained by greater spatial knowledge and optimal trajectory awareness, allowing them to adopt more efficient visual strategies less dependent on frequent visual

TABLE 4 | Fixation counts and duration in milliseconds (ms) before (PRE) and after (POST) training for each analyzed segment and performance category (N1 and N2), showing mean values, standard deviations (in parentheses), and corresponding p -values for between-group comparisons of each track segment.

		SC	SS	C1	S1	C2	S2
Fixations count							
N1	PRE mean (SD)	19.50 (3.10)	11.50 (2.17)	14.50 (2.76)	9.60 (1.26)	14.50 (2.76)	10.10 (1.91)
	POST mean (SD)	19.70 (4.87)	11.70 (2.62)	16.60 (3.13)	10.60 (2.59)	14.70 (2.90)	9.40 (2.32)
	PRE versus POST p -value	0.887	0.780	0.025	0.160	0.794	0.390
N2	PRE mean (SD)	24.37 (3.77)	13.37 (4.47)	18.25 (4.92)	11.71 (4.07)	17.85 (5.40)	12.14 (3.23)
	POST mean (SD)	24.55 (4.21)	13.44 (4.06)	17.77 (4.29)	11.66 (2.29)	19.44 (4.98)	13.89 (2.02)
	PRE versus POST p -value	0.875	0.649	0.665	0.815	0.278	0.219
N1 versus N2	PRE p -value	0.008	0.259	0.057	0.140	0.111	0.122
	POST p -value	0.034	0.277	0.501	0.401	0.020	< 0.001
Fixations duration (ms)							
N1	PRE mean (SD)	283.86 (72.19)	294.93 (80.97)	300.86 (89.60)	290.93 (74.48)	284.32 (69.67)	284.92 (92.21)
	POST mean (SD)	289.15 (95.22)	303.58 (131.78)	263.49 (74.15)	279.76 (139.01)	274.11 (76.65)	289.10 (121.89)
	PRE versus POST p -value	0.835	0.699	0.056	0.432	0.292	0.884
N2	PRE mean (SD)	232.13 (71.88)	299.74 (123.32)	272.82 (116.31)	275.44 (140.29)	300.97 (112.82)	288.83 (119.44)
	POST mean (SD)	244.62 (90.90)	286.42 (184.97)	263.66 (99.29)	263.70 (85.87)	261.96 (110.95)	231.20 (54.47)
	PRE versus POST p -value	0.937	0.205	0.835	0.330	0.201	0.075
N1 versus N2	PRE p -value	0.150	0.922	0.571	0.771	0.711	0.940
	POST p -value	0.313	0.817	0.997	0.967	0.783	0.208

Note: Statistically significant differences ($p < 0.05$) are highlighted in red.

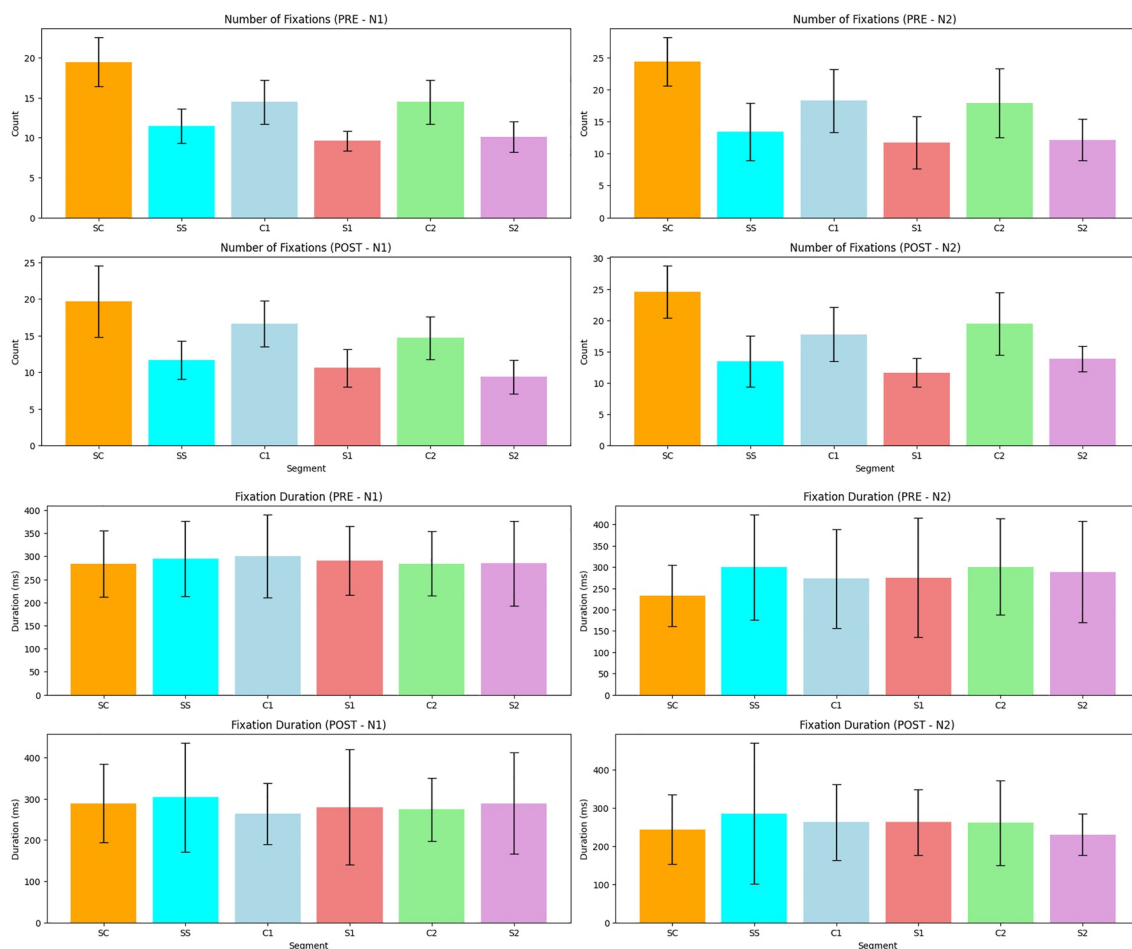


FIGURE 4 | Graphical representation of the total mean number and duration in milliseconds (ms) of fixations before (PRE) and after (POST) training in each analyzed segment and performance category (N1 and N2), with their standard deviation (in black lines).

explorations. Another statistically significant difference when comparing N1 versus N2 was found in segment S2 ($p < 0.001$) after training, corresponding to the second fast straight of the lap. In this case, a different number of fixations was observed between higher and lower-level athletes, most likely because of better control and familiarity with the high-speed final trajectory among high-performance skaters. This difference suggests a more efficient oculomotor strategy in group N1, possibly associated with their competitive experience and mastery of the environment.

Fixation duration analysis (Table 4 and Figure 4) showed no significant differences by experience level (N1 vs. N2) or segment geometry, with stable PRE-POST values across all segments ($p > 0.05$). This consistency suggests visual processing time remains unaffected by athlete expertise or track configuration.

3.3.2 | Saccades

The analysis of saccade count, Table 5 and Figure 5, reveals differences according to the performance level of the athletes and the evaluated segment. In group N1, statistically significant differences were observed between PRE and POST conditions in segment C1 ($p = 0.012$), with increased saccades post-training,

suggesting greater visual control needs for trajectory adjustment, possibly due to training-induced fatigue. Significant pre-training differences were observed between N1 and N2 skaters in saccade count for SC ($p = 0.012$) and C1 ($p = 0.046$), with fewer saccades in the higher-level N1 group. This pattern persisted post-training, revealing significant differences in the number of saccadic movements during segments C2 ($p = 0.024$) and S2 ($p < 0.001$) after training. Higher-level skaters showed fewer saccades in curves and final straights than less-experienced athletes, suggesting more efficient trajectory control despite fatigue. This reflects their ability to maintain optimized visual strategies during high-demand competitive situations. The analysis of saccade duration did not reveal relevant differences either based on participants' experience level or in relation to the geometry of the analyzed segments. Neither in group N1 nor in group N2, nor in comparisons between them, were significant differences observed between PRE and POST conditions in any of the evaluated segments. These results suggest that saccade duration remains stable regardless of the skater's experience level or the type of circuit segment.

Saccadic velocity analysis (Figure 5) revealed limited differences by experience level or segment type. In experienced skaters, velocity significantly decreased post-training in straights (N1, SS: $p = 0.014$; S1: $p = 0.037$), these differences may reflect training-induced changes in visual control; however, in the

TABLE 5 | Summary of p -values for saccadic metrics (count, velocity (deg/s), length (mm), and duration (ms)) comparison between PRE and POST training for each category group (N1 and N2), and comparison between N1 and N2 before (PRE) and after (POST) training in each visual segment (SC, SS, C1, S1, C2, S2).

p-values	SC	SS	C1	S1	C2	S2
Saccades count						
PRE versus POST (N1)	0.837	0.794	0.012	0.178	1.000	0.373
PRE versus POST (N2)	1.000	0.734	0.739	0.838	0.376	0.238
PRE N1 versus N2	0.012	0.857	0.046	0.156	0.106	0.104
POST N1 versus N2	0.051	0.303	0.488	0.647	0.024	< 0.001
Saccades duration (ms)						
PRE versus POST (N1)	0.314	0.557	0.841	0.272	0.294	0.074
PRE versus POST (N2)	0.844	0.690	0.945	0.938	0.688	0.178
PRE N1 versus N2	0.203	0.146	0.164	0.242	0.623	0.512
POST N1 versus N2	0.838	0.038	0.270	0.307	1.000	0.439
Saccades velocity (deg/s)						
PRE versus POST (N1)	0.064	0.014	0.770	0.037	0.492	0.375
PRE versus POST (N2)	0.563	0.742	0.945	0.408	0.469	0.728
PRE N1 versus N2	0.315	0.173	0.360	0.055	0.133	0.417
POST N1 versus N2	0.111	0.037	0.153	0.066	0.596	0.936
Saccades length (mm)						
PRE versus POST (N1)	0.131	0.010	0.922	0.049	0.846	0.922
PRE versus POST (N2)	0.148	0.902	1.000	0.469	0.688	0.561
PRE N1 versus N2	0.101	0.274	0.203	0.280	0.962	0.801
POST N1 versus N2	0.236	0.025	0.094	0.094	0.713	0.967

Note: Statistically significant differences ($p < 0.05$) are highlighted in red.

absence of direct physiological or perceptual fatigue markers, this interpretation remains inferential. No changes occurred in lower-level skaters (N2), suggesting experienced athletes show greater oculomotor adaptability to demanding training. Furthermore, the comparison between N1 versus N2 groups revealed a statistically significant difference in segment SS ($p = 0.037$) after training, indicating that experienced skaters performed significantly slower saccades compared to the lower-level group in the acceleration-initiation straight section. This difference could be related to greater training intensity in the N1 group, which would have generated a higher degree of fatigue. Consequently, high-performance athletes may have adopted slower or more conservative oculomotor patterns in this straight segment, where complex trajectory adjustments are not required to maintain performance.

In N1 skaters, saccadic length analysis (Figure 5) revealed statistically significant differences between PRE and POST conditions in segments SS ($p = 0.010$) and S1 ($p = 0.049$), both corresponding to straight sections. In these cases, saccadic length decreased after training, which could be interpreted as an optimization of visual exploration patterns in the straight parts of the circuit, possibly due to increased automation or precision in visual environment recognition. In contrast, no significant differences between PRE and POST conditions were observed in any segment for N2 participants, suggesting reduced visual

adaptation to training and supporting the hypothesis that experience influences either the efficiency or modification of oculomotor patterns. Furthermore, the N1 versus N2 comparison revealed a significant difference in segment SS ($p = 0.025$) post-training, indicating that experienced skaters executed saccades significantly shorter from those of the less-trained group during gentle straight sections. This difference may result from either enhanced visual anticipation capabilities or greater familiarity with the track configuration in elite performers.

4 | Discussion

Inline speed skating is considered one of the fastest human-powered sports without mechanical assistance or inclined surfaces. As described by (Vickers 2006), skaters train and compete on banked oval tracks requiring precise control through high-speed curves and straightaways. In this demanding context, visual behavior and perception are essential components of athletic performance. The present study, using eye-tracking technology, highlights the critical role of gaze positioning along the track trajectory as a key factor in maintaining perceptual control and optimizing technical execution during both training and competition. Notably, our analysis revealed that athletes predominantly fixate on the finish line, suggesting this location

PRE - CATEGORY N1					POST - CATEGORY N1				
Segment	Count	Velocity (deg/s)	Length (mm)	Duration (ms)	Segment	Count	Velocity (deg/s)	Length (mm)	Duration (ms)
SC	20.00 (3.16)	7.70 (4.95)	2472.34 (2340.49)	82.75 (31.96)	SC	20.30 (4.81)	6.12 (3.99)	1868.45 (1420.74)	77.32 (23.87)
SS	11.50 (2.27)	7.41 (5.38)	2257.51 (2127.07)	72.59 (27.28)	SS	11.70 (2.79)	5.39 (3.99)	1480.35 (1552.35)	67.83 (32.83)
C1	14.60 (2.46)	6.47 (4.18)	1780.36 (1492.63)	75.42 (41.04)	C1	16.70 (2.87)	6.39 (5.34)	1869.55 (1770.75)	77.15 (22.99)
S1	9.60 (1.51)	7.88 (5.39)	2712.97 (1892.01)	89.69 (31.46)	S1	10.60 (2.41)	6.01 (5.27)	1917.16 (2010.59)	82.33 (38.37)
C2	14.50 (2.72)	6.23 (3.38)	1880.19 (1378.46)	83.60 (40.16)	C2	14.50 (2.92)	5.82 (4.11)	2073.00 (1626.34)	97.41 (59.57)
S2	9.90 (1.66)	8.66 (5.15)	3299.24 (2042.50)	105.35 (26.89)	S2	9.00 (2.87)	7.95 (6.06)	4145.14 (4236.09)	137.64 (63.42)
PRE - CATEGORY N2					POST - CATEGORY N2				
Segment	Count	Velocity (deg/s)	Length (mm)	Duration (ms)	Segment	Count	Velocity (deg/s)	Length (mm)	Duration (ms)
SC	24.75 (3.92)	8.38 (3.01)	4180.65 (4301.73)	136.29 (104.43)	SC	24.78 (4.44)	7.60 (1.90)	3277.39 (3634.33)	117.46 (105.11)
SS	13.25 (4.80)	8.41 (3.26)	3135.06 (2047.75)	103.72 (43.59)	SS	13.33 (3.87)	7.73 (2.52)	3195.09 (2199.10)	111.64 (50.94)
C1	18.12 (4.39)	7.08 (2.43)	2539.85 (1541.29)	106.63 (49.97)	C1	17.89 (4.37)	7.00 (1.84)	3318.10 (3913.53)	141.06 (156.56)
S1	11.86 (4.49)	9.29 (1.83)	3598.05 (1027.12)	109.16 (33.79)	S1	11.67 (2.55)	7.67 (2.52)	3284.35 (2740.66)	124.43 (90.83)
C2	17.86 (5.30)	7.24 (2.22)	1870.11 (1256.69)	74.31 (33.16)	C2	19.00 (4.87)	6.07 (1.90)	2345.79 (2845.56)	111.21 (110.95)
S2	12.00 (3.32)	8.67 (2.93)	3063.29 (1558.68)	95.43 (34.14)	S2	13.89 (2.15)	7.77 (2.47)	3267.26 (1971.72)	116.74 (49.71)

Low values Medium values High values Very high values

FIGURE 5 | Summary heatmap of means and standard deviations (in parentheses) for key saccadic metrics where Count is the number of saccades, Velocity (deg/s) is angular velocity, Length (mm), and Duration (ms) for each visual segment (SC, SS, C1, S1, C2, S2), comparing PRE and POST conditions and dividing by category group (N1 and N2).

serves as a vital visual reference point, likely tied to the strategic demands of concluding a race.

Eye-tracking devices have been previously used in elite ice hockey to study gaze patterns, including fixation and tracking (involved sustained gaze on elements such as the puck, opponent, stick, boards, or net), and the “quiet eye”, defined as the final fixation on a specific location prior to a critical movement (Vickers et al. 2017). Our results in inline speed skating are consistent with previous studies since most participants directed their gaze toward the inner boundary line of the curve during curved segments of the circuit, indicating a consistent movement path or habitual visual trajectory (Vickers 2006; Vickers et al. 2017). The curved segments of the circuit, such as the first curve (C1), showed a higher number of fixations compared to straight sections. This difference is directly related to the visual strategy of the skaters, who predominantly direct their gaze toward the inner boundary line of the curve, identified as Lane 1 (Figure 1C and 1D). This concentration of visual attention on the inner portion of the curve, crucial for adjusting trajectory and counteracting forces, explains why the curved segments, and specifically the inner lane, present greater visual processing demands and consequently a higher number of fixations. This visual strategy could allow skaters to optimize their performance, as maintaining gaze orientation toward the inner part of the track rather than the outer part facilitates speed increase and more effectively counteracts the centrifugal forces that act to displace the athlete toward the outer part of the track. It also could help manage potential imbalances, such as significant one-sided dominance, which can cause lateral deviation in the

skating trajectory and could increase the total distance skated (Jin et al. 2025). This tactic of directing gaze toward the inner curve also serves an anticipatory function in trajectory guidance, since vision constitutes the primary sensory system for planning and adjusting future movements. Unlike other skating disciplines, such as skateboarding, where athletes tend to direct their gaze toward the board during certain movements to maintain control (Klostermann and Küng 2017), in speed skating the gaze is oriented toward a point ahead of the skates' position. This divergence likely reflects fundamental control differences: skateboarders require continuous visual foot monitoring to compensate for non-attached board dynamics, whereas inline speed skaters' inherent postural stability permits gaze allocation toward trajectory anticipation rather than equipment tracking. In contrast to our results, research on the “look-up line” in ice hockey showed that players fixated more on the orange warning line, they looked down more during critical phases, skated slower, and moved farther from the boards (Vickers et al. 2017). Athletes tend to fixate their gaze on an area ahead of their current position, like how they use saccadic movements, which allows them to anticipate the direction and trajectory they will follow (Vansteenkiste et al. 2014). This anticipation is essential for maintaining control during high-speed movement execution. These different results suggest that visual cues can unintentionally alter motor behavior, and different sports may require tailored visual and mood-regulation strategies (Barkhoff and Heiby 2004).

These identified patterns indicate that athletes employ focused visual strategies, guided both by physical references in the

environment and by tactical needs and specific movement routines in key areas. In short track speed skating, success depends on sharp visual perception and quick decision-making in key areas such as starting position, overtaking, and drafting. An inner start offers an advantage in short races (e.g., 500 m) by enabling faster access to the first turn and early control. In contrast, longer races (e.g., 3000 m) support a more conservative start and strategic drafting to conserve energy for a final sprint. The influence of starting position on results becomes more pronounced in later rounds, where competition is tighter and margins are smaller (Muehlbauer and Schindler 2011). Because of the visual strategy used as a guiding method during curve execution, in our study significant differences were observed in the number of fixations made depending on the geometry of the analyzed segment. Specifically, curved sections required a greater number of fixations and saccadic movements compared to straight sections. This pattern suggests that curves involve a higher demand for visual processing and trajectory control, whereas, in straight sections, since they do not require constant adjustment of movement direction, athletes significantly reduce oculomotor activity, except for the final segment where they are focused on the finish line, showing the “quiet eye” phenomena.

Our high-performance athletes (N1) made fewer fixations compared to our intermediate-level skaters (N2) in certain segments of the race. This result may be interpreted as a reflection of greater experience and familiarity with the environment by the higher-level group, as well as a greater awareness of the optimal trajectory to follow. In experienced skaters, these adaptations may represent a strategic recalibration of visual behavior under load rather than a simple decrement in oculomotor performance. This difference in the efficiency of visual skills based on experience level has also been described in previous research, demonstrating that elite athletes tend to adopt more efficient visual strategies that are less dependent on frequent ocular explorations (Silva et al. 2022). Differences were also observed in fast eccentric-concentric muscle actions and vigorous physiological responses, which vary between competitive and recreational levels (Radman et al. 2016; Orepic et al. 2014).

As observed in the videos analyzed in this study, saccadic movements play a fundamental role in decision-making and trajectory orientation, being particularly relevant during curved segments of the course. These eye movements may be modulated by neural plasticity mechanisms localized in specific cerebellar regions (vermal lobes VI-VII), which are associated with the regulation of such ocular movements (Park et al. 2012). In this context, expanding research to explore this relationship could provide significant contributions to the field of visual training in sports with high perceptual demands.

Regarding saccade length, the results indicate that after physical effort, the high-performance athletes (N1) showed a significant reduction in the length of these movements, as well as in their velocity, while maintaining a speed similar to that recorded before training. This finding suggests that more experienced athletes may thereby reduce sensory conflicts caused by external stimuli, particularly in situations of high physical demand. This hypothesis aligns with the findings described in other study (Menshikova et al. 2014), which analyses saccade amplitude during the training of figure skaters.

Overall, the results of this study suggest that training had a greater impact on the more experienced skaters, both in straight segments, where automation and visual precision play a key role, and in curved trajectories, where fatigue induced by training load appears to have influenced certain oculomotor parameters. Although the training protocol was physically demanding, no direct markers of fatigue as heart rate, perceived exertion, or neuromuscular measures in this study were recorded. Consequently, observed pre- and post-changes cannot be attributed exclusively to fatigue. Alternative mechanisms such as sensory reweighting, attentional narrowing, or increased movement automation following intensive effort may also account for the observed oculomotor adaptations. However, the high variability observed across all analyzed segments indicates that visual strategies may be highly influenced by individual factors, justifying future studies with greater control or profile segmentation.

Among the main limitations of this study is the small sample size, constrained by the limited number of athletes practicing this discipline at a federated level, thereby limiting the generalizability of the findings. The large number of comparisons performed across performance level, track segment, eye-movement variables, and training condition increases the probability of Type I error. Therefore, statistically significant findings should be interpreted as indicative trends rather than definitive effects. Additionally, male representation was limited, reflecting the higher female participation in this sport, which may have influenced the homogeneity of certain results and their applicability to mixed populations. On the other hand, the mean age of participants was relatively low, as the team where the study was conducted had a higher proportion of athletes belonging to junior categories. Additionally, age and maturational status may represent confounding factors, particularly in oculomotor control and fatigue responses, as visual and neuromotor systems continue to develop throughout adolescence. Due to sample size constraints, age could not be included as a covariate, and future studies should incorporate age-matched designs or longitudinal approaches. In this regard, including participants from different clubs, as well as greater representation of categories in future research, would allow for a more balanced and representative sample, thereby reducing the impact of these limitations.

5 | Conclusions

This study analyzed visual behavior patterns in speed skaters before and after training, revealing several performance-related trends. The overall visual behavior remained stable across the group, with no statistically significant differences in fixation counts or saccadic movement duration in most track segments pre- and post-training. Curved segments demanded greater visual processing, showing increased fixations and saccades compared to straight sections. Skaters consistently employed an inward gaze strategy during curves, optimizing performance by counteracting centrifugal forces. High-performance athletes demonstrated superior visual efficiency through fewer fixations and saccades than intermediate skaters, particularly in the initial curve and second straight segments, suggesting experience-driven optimization of visual strategies. Training impacts were

more pronounced in N1 skaters, showing significant post-exercise changes including increased fixations in C1 and reduced saccadic velocity/length in straight segments (SS, S1), potentially indicating fatigue effects. Strong binocular coordination was evidenced by significant correlations between RE-LE saccadic parameters and pupil metrics. Spatial analysis revealed two key focal points: concentrated attention on the finish line as a tactical reference, and preferential visual monitoring of both inner lanes which provide competitive distance advantages over outer lanes. These findings collectively demonstrate how expertise level, track geometry, and training load interact to shape oculomotor strategies in elite inline speed skating.

Author Contributions

Conceptualization, methodology, software, validation, formal analysis, resources, writing (review and editing), visualization, supervision, and project administration: A.S.-C. and E.O.-H. Investigation, data curation, writing (original draft preparation): L.M.-G., A.S.-C., and E.O.-H. All authors have read and agreed to the published version of the manuscript.

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Ethics Statement

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

Consent

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

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.

Supporting Information S1: ejsc70171-sup-0001-suppl-data.docx.