

ORIGINAL RESEARCH ARTICLE

Comparative visual pathway analysis in competitive sports: A cross-sectional visual evoked potential study

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Abstract

Central visual conduction ability is crucial to human perception and visual skills. In sports, for instance, it enables athletes to gather information, predict movements, make quick decisions, and perform precise motor actions. In the present study, modern electrophysiological tools, such as visual evoked potentials (VEPs), were employed to assess central visual transmission. The goal was to analyze three VEP waveforms (N75, P100, and N145) in male athletes ($n = 100$) from cricket, yogasana, karate, and gymnastics, together with a control group of physically active boys without specific training in these disciplines. For the P100 waveform, yogasana and karateka practitioners showed significantly shorter latencies compared to all other groups ($p < 0.05$), followed by cricketers, who had latencies similar to gymnasts. The N75 waveform for yogasana and karate practitioners showed significantly faster transmission times than the cricket and control groups ($p < 0.05$). Furthermore, the N75 waveform for the left eye in gymnasts had shorter latency compared to cricketers and controls. The N145 wave for the right eye in yogasana and karate practitioners had shorter latencies compared to those of other athletes ($p < 0.05$). Meanwhile, karatekas showed higher amplitudes than those practicing yogasana and the controls, indicating that training experience might be a key factor. This study provides valuable insights into the unique visual processing demands and capabilities of athletes in various disciplines. Yogasana and karate, being gaze-oriented practices that integrate mind–body control, showed shorter latency across all groups, followed by ocularly dominant cricketers, visually trained gymnasts, and controls.

Keywords: Central visual transmission; Sports players; Visual processing demands; Gaze-oriented activity

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1. Introduction

Central visual conduction ability plays a pivotal role in human perception, particularly in athletes whose performance depends significantly on perception, interpretation, and processing of visual stimuli.¹⁻³ Visual skills enable athletes to gather essential information from their environment, predict movements, make quick decisions, and perform precise motor actions during both training and competition.⁴ Notably, specific sports require

specific visual skills, which can vary significantly depending on the nature of the sports. For example, cricket, as a popular ball game, requires players to have quicker visual reaction time for better hitting and fielding performance.⁵ In contrast, individual emerging sports, such as yogasana (yoga postures), underscore the importance of visual skills for maintaining mind–body balance.⁶ Visual skills are also crucial for karatekas for sensing opponents and identifying potential threats, along with an instinctive ability to detect hidden dangers.⁷ For the successful execution of gymnastic skills, gymnasts need to possess specific visual acuity, coordination, and visualization abilities.⁸

Traditionally, visual reaction times were denoted as a measure to understand quickness and the connection between the muscular system and the higher centers of the brain in the visual pathway, the occipital lobe.^{9–11} As technology advanced, evoked potentials (EPs), a non-invasive electrophysiological measurement, emerged and deepened our understanding of the neural mechanisms of central visual processing and its connection to sensory stimuli. Specifically, visual EPs (VEPs) are used to assess the central visual pathway.¹² In general, three standard stimulus protocols are defined for VEP recording,¹³ of which the flash VEP protocol was utilized in this comparative study. The waveforms of flash VEP consist of three distinct phases: An initial negative deflection (N75), followed by a prominent positive deflection (P100), and a later negative deflection (N145).¹⁴ Together, these phases form the negative–positive–negative (NPN) complex, and its measurements are interpreted as peak latency and peak-to-peak amplitudes.¹⁵ This VEP complex measures the conduction time from the retina to the occipital cortex through the visual optic pathway using a mid-occipital electrode. In the NPN complex, the P100 peak latency is the most pronounced and stable waveform.¹⁶ It produces little variation in latency compared to the waveforms from lateral electrodes and has a steady amplitude along with minimal intra- and inter-variability.¹⁷ Previous studies have shown differences in VEP waveforms between athletes and non-athletes, indicating variations in visuo-occipital functioning.^{11,18–22}

Considering traditional models of attention and modern VEP measures, the present study aimed to measure and analyze VEPs across athletes from cricket, yogasana, karate, and gymnastics to explore differences in visual processing. While previous research has explored VEPs in specific sports, a direct comparison across mind–body activities, team sports, and individual sports is lacking. This study fills this gap by analyzing how distinct training methods shape neural conduction and visual processing. It also highlights sport-specific neural adaptations, the contrast

between dynamic and internal focus-driven processing, and the need for long-term assessments of training effects. These insights can help refine targeted training strategies and optimize athletic performance.

2. Methods

2.1. Participants

The present cross-sectional study was conducted among the male school-going population aged 12 – 18 years, with a mean age of 15.8 ± 1.89 years, from various regions of West Bengal, India. The participants included practitioners of competitive sports, such as yogasana, karate, cricket, and gymnastics, all of whom had a minimum of state-level participation and were engaged in regular practice. Their training age ranged from 6 to 8 years, with a mean training age of 6.16 ± 1.78 years. While yogasana, karate, and gymnastics are considered art forms, and cricket is a team sport, all are currently represented as sports. All subjects were held at least state-level positions, justifying their practical applicability. On the other hand, the control group comprised healthy school-going boys who were free from disease, performed daily activities regularly, and engaged in active play without specific skill training, particularly in yogasana, karate, cricket, or gymnastics. This control group regularly participated in physical activities, such as individual or team games, for similar durations per week as the practitioner groups.

Subjects with ophthalmic disparities and reduced visual acuity, females, and the sedentary population were excluded from the study. Diet, nutrition, and socioeconomic status were not considered criteria for inclusion or exclusion.

2.2. Study design

G*Power version 3.1.9.4 for Windows (2020) (University of Düsseldorf, Germany)²³ was used to calculate a priori sample size and determined that a total of 100 participants was sufficient, based on an error probability of 0.05, power of 0.70, and an effect size of 0.32. Based on this calculation, a subject pool of 118 individuals was formulated, and a convenience sample of 100 subjects was selected from the pool. The 100 subjects were categorized into five groups: The yogasana group, karate group, cricket group, gymnastics group, and control group, with 20 subjects in each group. [Figure 1](#) presents the flow diagram of the present study. The participants, along with their parents and trainers from their respective authorized training organizations and school authorities, attended three pre-data collection meetings and provided informed consent to participate in the study. They were guided throughout the process, and the required assent and consent forms were duly signed at the start of data collection. The research

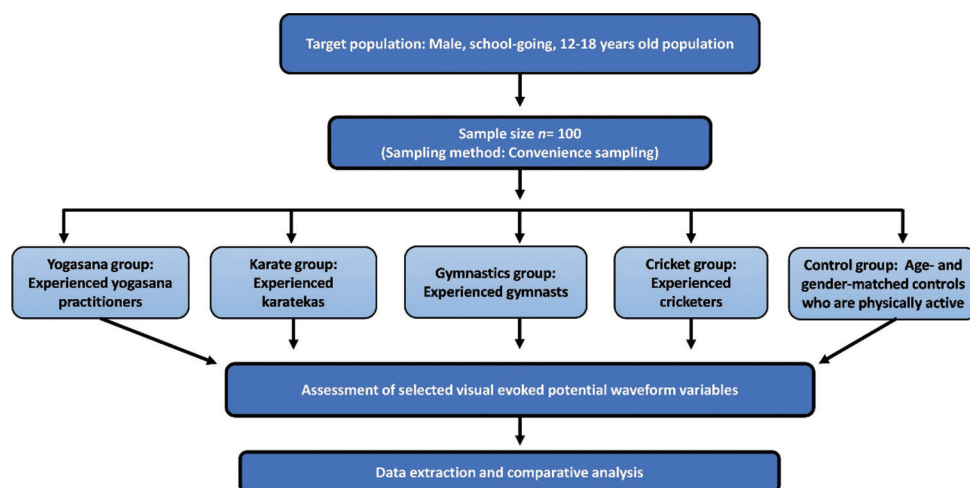


Figure 1. Study design of the cross-sectional experimentation

protocol and design were approved by the Institutional Ethics Committee for Human Research at the university where the study was performed (Approval No.: VB/IECHR/2021/9), and the study adhered to the National Ethical Guidelines for Biomedical and Health Research involving Human Participants of the Indian Council of Medical Research (ICMR).^{24,25} The study was also approved by the Clinical Trial Registry of India (CTRI; Registration No.: CTRI/2021/06/034483). The research was conducted in accordance with the Helsinki Declaration.

2.3. Visual sensory variable and data collection process

The visual sensory variable comprises VEP, measured using a goggle-based flash VEP system containing red light-emitting diodes (LEDs). The compact goggles provide a large field of stimulation, minimizing the fluttering of gaze. The RMS Salus 4C (Recorders and Medicare Systems Private Limited, India) EP recorder was used. After cleansing and degreasing the scalp with alcohol, standard disc electroencephalogram (EEG) electrodes were placed based on the 10 – 20 international system of EEG placements.^{13,26} For VEP, the standard method recommended by the International Federation of Clinical Neurophysiology and the International Society for Clinical Electro-Physiology of Vision (ISCEV)²⁶ was followed. The VEP protocol is confined to a three-channel montage, with active electrodes positioned at the midline and two lateral occipital sites. The sensitivity was set at 1 – 100 Hz while the impedance was kept below 5 k Ω . The quality of measurement was ensured by maintaining the reliability of the equipment and through critical observations by technical experts. The testers, who were part of the research core team, were well-informed and qualified to conduct data collection. They possessed full awareness

of the validation protocols and demonstrated technical responsiveness in operating the equipment. Moreover, they were assisted by experienced neurocognitive experts. Good clinical practices were adhered to during the data collection procedures. Participants were instructed to lie calmly in a quiet, sound-controlled room before data collection. Monocular recordings were conducted separately for the left and right eyes, and electrode impedance was checked after each trial. These procedures were implemented in accordance with the ICMR guidelines.^{24,25}

2.4. Psychometrics and design

EP recordings are highly subtle and sensitive neurophysiological measurements. Therefore, a critical check on technical specifications was conducted based on the RMS Salus 4C manual, expert opinions, and previous research references. The electrode impedance was calibrated daily and maintained below 5 k Ω to minimize artifacts and noise before data collection. Inter-electrode impedance was kept below 2 k Ω and checked at each subject change. For VEP recordings, data filtration took place within the range of 1 – 100 Hz, and LED luminance was maintained at 3 cd·s/m². All other detailed specifications are published in previous works.²²

2.5. Statistical analysis

Descriptive statistics were reported as mean \pm SD, with a significant level of 0.05 ($p < 0.05$) following a normality check using the Kolmogorov–Smirnov test. Group comparisons were conducted using one-way analysis of variance (ANOVA), and all statistical analyses were performed using the Statistical Package for the Social Sciences 20.0 software for Windows (IBM, USA). When the ANOVA results were significant, the least significant difference (LSD) *post hoc* test was conducted to determine

which specific group means differed significantly, allowing for assessment of intergroup significance.

3. Results

The demographic features of the participants, including age and body mass index (BMI), did not significantly differ among the five groups. The mean age of the practitioner group was 15 ± 0.40 years, whereas that of the controls was 15.4 ± 1.79 years. The BMI was consistent across groups, with the mean BMI being 19.87 ± 3.47 (yogasana), 19.14 ± 2.24 (karate), 20.22 ± 2.98 (cricket), 21.19 ± 2.01 (gymnastics), and 21.12 ± 2.09 kg/m² (controls).

For the VEP (Figure 2), specifically the P100 waveform, the yogasana practitioners (left eye: 94.47 ± 2.43 ms; right eye: 94.53 ± 2.54 ms) and karatekas (left eye: 93.60 ± 1.50 ms; right eye: 93.69 ± 3.32 ms) demonstrated significantly shorter waveform latencies than the gymnasts (left eye: 101.50 ± 6.62 ms; right eye: 103.41 ± 7.33 ms), cricketers (left eye: 97.00 ± 3.01 ms; right eye: 97.01 ± 2.84 ms), and controls (left eye: 105.07 ± 2.23 ms; right eye: 105.63 ± 3.21 ms). In addition, the cricketers recorded significantly shorter P100 latencies than the gymnasts and controls. Notably, the gymnasts showed significantly shorter P100 latency than the controls only in the left eye.

For the N75 waveform, yogasana practitioners (left eye: 61.36 ± 2.56 ms; right eye: 62.02 ± 3.67 ms) and karatekas (left eye: 62.19 ± 2.41 ms; right eye: 63.15 ± 2.84 ms) showed

significantly shorter transmission time than the cricketers (left eye: 67.41 ± 7.02 ms; right eye: 67.22 ± 7.18 ms) and controls (left eye: 65.86 ± 5.46 ms; right eye: 66.29 ± 7.13 ms). Notably, in comparison to the cricketers and controls, the gymnasts showed a markedly shorter N75 latency only in the left eye (left eye: 63.27 ± 3.76 ms).

For the N145 waveform, the yogasana practitioners (left eye: 156.4 ± 9.65 ms; right eye: 153.83 ± 10.01 ms) and karatekas (left eye: 156.56 ± 10.62 ms; right eye: 154.48 ± 14.03 ms) showed markedly shorter latencies compared to the controls (left eye: 162.53 ± 12.23 ms; right eye: 162.39 ± 10.77 ms); however, statistically significance were only seen in the right eye for both the groups.

The karatekas (3.91 ± 2.56 μ V) showed significantly lower P100 – N75 amplitude compared to the yogasana practitioners (5.79 ± 3.91 μ V) and controls (5.64 ± 2.72 μ V) (Figure 3). Table 1 presents all the variables with their descriptive statistics and one-way ANOVA parameters, whereas Table 2 presents the variables with inter-group comparisons using the LSD *post hoc* test.

4. Discussion

In a nutshell, the results revealed that among all groups, the karatekas exhibited the shortest P100 latencies, indicating the fastest visual processing times. The yogasana practitioners followed closely, also showing significantly shorter latencies compared to the cricketers, gymnasts,

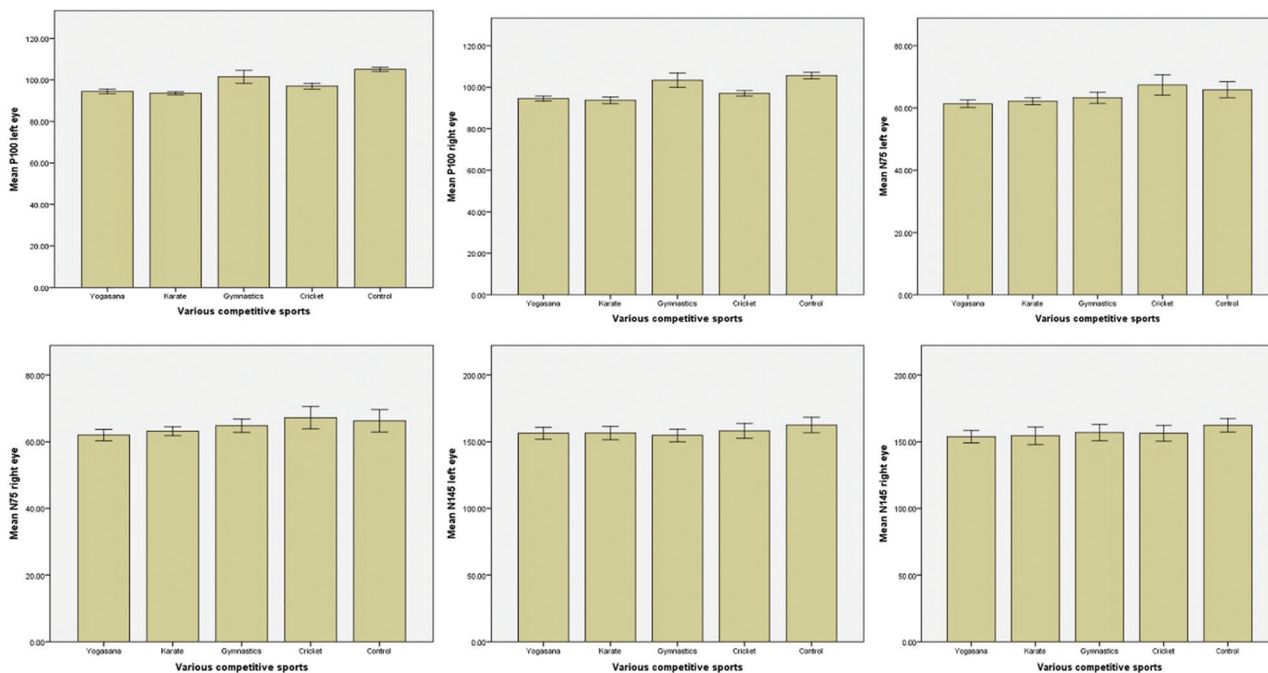


Figure 2. Visual evoked potential latencies of the negative–positive–negative complex across the five groups

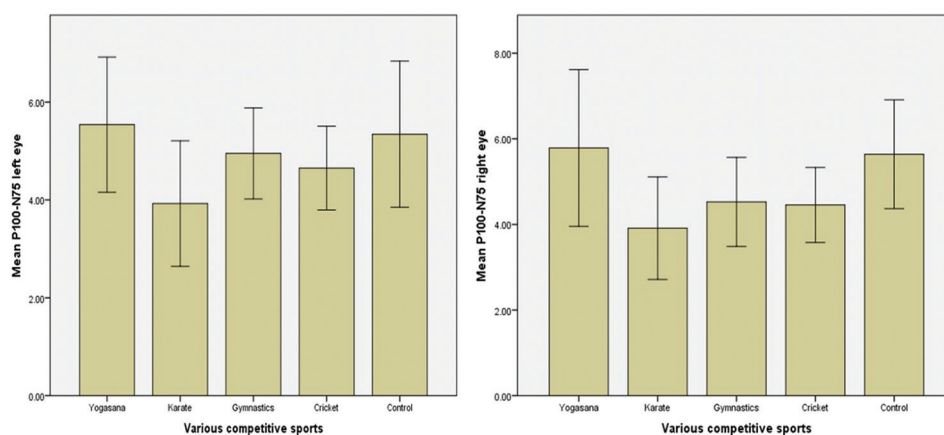


Figure 3. Visual evoked potential amplitude across the five groups

and controls. The cricketers, while not as rapid as the karatekas or yogasana practitioners, demonstrated faster visual transmission times than the gymnasts and controls. In contrast, the gymnasts and controls demonstrated the longest latencies, indicating slower visual processing speeds. These findings highlight the positive impacts of specific physical activities, particularly martial arts and yogasana, on enhancing visual response times.

4.1. Visuo-motor neural response mechanism and its variations among sports players

Advancements in technology have introduced improved methods of measurement, such as VEP recording. The P100 component of VEPs reflects the brain's response to visual stimuli, providing insights into the speed of information processing and selective attention. VEPs measure the electrical signals elicited by visual stimulation, with responses recorded from the visual cortex in the occipital lobes. The anterior visual pathway signaling was quantified through the flash VEP setup, based on ISCEV.^{13,26} Latency, measured in milliseconds, indicates the time taken for a visual stimulus to travel from the retina to the occipital cortex, and is typically represented through the NPN complex waveform. Although less effective for detecting training effects, amplitude was also recorded in this study.¹² This study focuses on visual evoked responses to assess the functional integrity of the visual pathway from the retina, via the optic nerves, to the visual cortex. Compared to scanning techniques, such as magnetic resonance imaging (MRI), VEPs provide a more quantifiable measure of the functional integrity of the optic pathways.²⁷

The most common approach for assessing the visual-sensory-motor abilities relevant to sports performance involves comparing athletes from different sports with non-athletes, a method employed in the present study.

Various mechanisms have been proposed by previous researchers, some of which are discussed here.

Athletes may possess inherently superior visual-system physiology, termed “visual hardware,” which allows for more efficient reception of visual information. Alternatively, they may develop enhanced perceptual-cognitive abilities, or “visual software,” through practice involving visual information processing.^{28,29} Neural responses to visual stimuli consist of bottom-up and top-down processes. Bottom-up mechanisms involve initial visual information processing, beginning with light entering the eye, stimulating the photoreceptors, and transmitting information through the optic nerve to the brain, leading to motor output. In contrast, top-down mechanisms involve the brain's processing of visual information, incorporating previous experiences from training, competition, or visual skills to influence the interpretation of new information and determine appropriate responses.^{30,31} These mechanisms prioritize specific regions or objects within the visual scene for processing while filtering out irrelevant information.

Attention can be driven by both endogenous factors (intrinsically generated goals and expectations) and exogenous factors (stimulus-driven cues).³² In addition, the magnocellular pathway, a key component of the visual system responsible for motion detection and processing low spatial frequencies, may be enhanced through regular sports training. This enhancement can lead to sharper visual perception, faster reaction times, and improved motor coordination, ultimately refining an athlete's ability to track moving objects and anticipate motion dynamics more effectively.^{33,34}

4.2. Sports training and vision among athletes from different sports

Sports training aims to enhance perceptual mechanisms by improving the visual skills necessary for optimal sports

Table 1. Descriptive statistics of the visual evoked potential tests across five groups

Variables	Groups	n	Mean±standard deviation	ANOVA groups	Sum of squares	df	Mean square	F-ratio	p-value
P100 latency, left eye (ms)	Yogasana	20	94.47±2.43	Between groups	1890.548	4	472.637	35.842	<0.001***
	Karate	20	93.60±1.50	Within groups	1252.738	95	13.187		
	Gymnastics	20	101.50±6.62	Total	3143.286	99			
	Cricket	20	97.00±3.01						
	Control	20	105.07±2.23						
	Total	100	98.33±5.63						
P100 latency, right eye (ms)	Yogasana	20	94.53±2.54	Between groups	2308.984	4	577.246	32.190	<0.001***
	Karate	20	93.69±3.32	Within groups	1703.584	95	17.932		
	Gymnastics	20	103.41±7.33	Total	4012.567	99			
	Cricket	20	97.01±2.84						
	Control	20	105.63±3.21						
	Total	100	98.85±6.37						
N75 latency, left eye (ms)	Yogasana	20	61.36±2.56	Between groups	517.264	4	129.316	6.121	<0.001***
	Karate	20	62.19±2.41	Within groups	2007.068	95	21.127		
	Gymnastics	20	63.27±3.76	Total	2524.331	99			
	Cricket	20	67.41±7.02						
	Control	20	65.86±5.46						
	Total	100	64.02±5.05						
N75 latency, right eye (ms)	Yogasana	20	62.02±3.67	Between groups	369.987	4	92.497	3.264	0.015*
	Karate	20	63.15±2.84	Within groups	2691.88	95	28.336		
	Gymnastics	20	64.80±4.21	Total	3061.868	99			
	Cricket	20	67.22±7.18						
	Control	20	66.29±7.13						
	Total	100	64.69±5.56						
N145 latency, left eye (ms)	Yogasana	20	156.40±9.65	Between groups	705.363	4	176.341	1.457	0.222
	Karate	20	156.56±10.62	Within groups	11501.31	95	121.066		
	Gymnastics	20	154.73±10.18	Total	12206.673	99			
	Cricket	20	158.11±11.99						
	Control	20	162.53±12.33						
	Total	100	157.66±11.10						
N145 latency, right eye (ms)	Yogasana	20	153.83±10.01	Between groups	913.813	4	228.453	1.539	0.197
	Karate	20	154.48±14.03	Within groups	14105.33	95	148.477		
	Gymnastics	20	156.93±13.02	Total	15019.143	99			
	Cricket	20	156.36±12.65						
	Control	20	162.39±10.77						
	Total	100	156.80±12.32						
P100–N75 amplitude, left eye (µV)	Yogasana	20	5.54±2.95	Between groups	32.284	4	8.071	1.197	0.317
	Karate	20	3.93±2.74	Within groups	640.614	95	6.743		
	Gymnastics	20	4.95±1.99	Total	672.899	99			
	Cricket	20	4.65±1.83						
	Control	20	5.34±3.19						
	Total	100	4.88±2.61						

(Cont'd....)

Table 1. (Continued)

Variables	Groups	n	Mean±standard deviation	ANOVA groups	Sum of squares	df	Mean square	F-ratio	p-value
P100-N75 amplitude, right eye (µV)	Yogasana	20	5.79±3.91	Between groups	52.773	4	13.193	1.751	0.145
	Karate	20	3.91±2.56	Within groups	715.714	95	7.534		
	Gymnastics	20	4.53±2.22	Total	768.487	99			
	Cricket	20	4.45±1.87						
	Control	20	5.64±2.72						
	Total	100	4.86±2.79						

Notes: Statistical analysis conducted using one-way ANOVA; *p<0.05, **p<0.01, ***p<0.001. Abbreviation: ANOVA: Analysis of variance.

Table 2. Pairwise comparison of the visual evoked potential variables across five groups

Groups	n	Left eye				Right eye			
		Mean±SD	Mean difference	Standard error difference	p-value	Mean±SD	Mean difference	Standard error difference	p-value
P100 latency (ms)									
Yogasana	20	94.47±2.43	0.87000	1.14833	0.451	94.53±2.54	0.84000	1.33912	0.532
Karate	20	93.60±1.50				93.69±3.32			
Yogasana	20	94.47±2.43	7.03150	1.14833	<0.001***	94.53±2.54	8.88150	1.33912	<0.001***
Gymnastics	20	101.50±6.62				103.41±7.33			
Yogasana	20	94.47±2.43	2.53000	1.14833	0.030*	94.53±2.54	2.48000	1.33912	0.067
Cricket	20	97.00±3.01				97.01±2.84			
Yogasana	20	94.47±2.43	10.60000	1.14833	<0.001***	94.53±2.54	11.10000	1.33912	<0.001***
Control	20	105.07±2.23				105.63±3.21			
Karate	20	93.60±1.50	7.90150	1.14833	<0.001***	93.69±3.32	9.72150	1.33912	<0.001***
Gymnastics	20	101.50±6.62				103.41±7.33			
Karate	20	93.60±1.50	3.40000	1.14833	0.004**	93.69±3.32	3.32000	1.33912	0.015*
Cricket	20	97.00±3.01				97.01±2.84			
Karate	20	93.60±1.50	11.47000	1.14833	<0.001***	93.69±3.32	11.94000	1.33912	<0.001***
Control	20	105.07±2.23				105.63±3.21			
Gymnastics	20	101.50±6.62	4.50150	1.14833	<0.001***	103.41±7.33	6.40150	1.33912	<0.001***
Cricket	20	97.00±3.01				97.01±2.84			
Gymnastics	20	101.5±6.62	3.56850	1.14833	0.002**	103.41±7.33	2.21850	1.33912	0.101
Control	20	105.07±2.23				105.63±3.21			
Cricket	20	97.00±3.01	8.07000	1.14833	<0.001***	97.01±2.84	8.62000	1.33912	<0.001***
Control	20	105.07±2.23				105.63±3.21			
N75 latency (ms)									
Yogasana	20	61.36±2.56	0.83000	1.45351	0.569	62.02±3.67	1.13500	1.68332	0.502
Karate	20	62.19±2.41				63.15±2.84			
Yogasana	20	61.36±2.56	1.91100	1.45351	0.192	62.02±3.67	2.78150	1.68332	0.102
Gymnastics	20	63.27±3.76				64.80±4.21			
Yogasana	20	61.36±2.56	6.05000	1.45351	<0.001***	62.02±3.67	5.20500	1.68332	0.003**
Cricket	20	67.41±7.02				67.22±7.18			
Yogasana	20	61.36±2.56	4.50000	1.45351	0.003**	62.02±3.67	4.27500	1.68332	0.013*
Control	20	65.86±5.46				66.29±7.13			
Karate	20	62.19±2.41	1.08100	1.45351	0.459	63.15±2.84	1.64650	1.68332	0.330
Gymnastics	20	63.27±3.76				64.80±4.21			
Karate	20	62.19±2.41	5.22000	1.45351	0.001**	63.15±2.84	4.07000	1.68332	0.018*
Cricket	20	67.41±7.02				67.22±7.18			

(Cont'd....)

Table 2. (Continued)

Groups	n	Left eye				Right eye			
		Mean±SD	Mean difference	Standard error difference	p-value	Mean±SD	Mean difference	Standard error difference	p-value
Karate	20	62.19±2.41	3.67000	1.45351	0.013*	63.15±2.84	3.14000	1.68332	0.065
Control	20	65.86±5.46				66.29±7.13			
Gymnastics	20	63.27±3.76	4.13900	1.45351	0.005**	64.80±4.21	2.42350	1.68332	0.153
Cricket	20	67.41±7.02				67.22±7.18			
Gymnastics	20	63.27±3.76	2.58900	1.45351	0.078	64.80±4.21	1.49350	1.68332	0.377
Control	20	65.86±5.46				66.29±7.13			
Cricket	20	67.41±7.02	1.55000	1.45351	0.289	67.22±7.18	0.93000	1.68332	0.582
Control	20	65.86±5.46				66.29±7.13			
N145 latency (ms)									
Yogasana	20	156.40±9.65	0.15850	3.47946	0.964	153.83±10.01	0.65500	3.85327	0.865
Karate	20	156.56±10.62				154.48±14.03			
Yogasana	20	156.4±9.65	1.67200	3.47946	0.632	153.83±10.01	3.10150	3.85327	0.423
Gymnastics	20	154.73±10.18				156.93±13.02			
Yogasana	20	156.40±9.65	1.71000	3.47946	0.624	153.83±10.01	2.53500	3.85327	0.512
Cricket	20	158.11±11.99				156.36±12.65			
Yogasana	20	156.40±9.65	6.12500	3.47946	0.082	153.83±10.01	8.56500	3.85327	0.029*
Control	20	162.53±12.33				162.39±10.77			
Karate	20	156.56±10.62	1.83050	3.47946	0.600	154.48±14.03	2.44650	3.85327	0.527
Gymnastics	20	154.73±10.18				156.93±13.02			
Karate	20	156.56±10.62	1.55150	3.47946	0.657	154.48±14.03	1.88000	3.85327	0.627
Cricket	20	158.11±11.99				156.36±12.65			
Karate	20	156.56±10.62	5.96650	3.47946	0.090	154.48±14.03	7.91000	3.85327	0.043*
Control	20	162.53±12.33				162.39±10.77			
Gymnastics	20	154.73±10.18	3.38200	3.47946	0.334	156.93±13.02	0.56650	3.85327	0.883
Cricket	20	158.11±11.99				156.36±12.65			
Gymnastics	20	154.73±10.18	7.79700	3.47946	0.027*	156.93±13.02	5.46350	3.85327	0.159
Control	20	162.53±12.33				162.39±10.77			
Cricket	20	158.11±11.99	4.41500	3.47946	0.208	156.36±12.65	6.03000	3.85327	0.121
Control	20	162.53±12.33				162.39±10.77			
P100–N75 amplitude (µV)									
Yogasana	20	5.54±2.95	1.61150	0.82118	0.053	5.79±3.91	1.87400	0.86798	0.033*
Karate	20	3.93±2.74				3.91±2.56			
Yogasana	20	5.54±2.95	0.58850	0.82118	0.475	5.79±3.91	1.25900	0.86798	0.150
Gymnastics	20	4.95±1.99				4.53±2.22			
Yogasana	20	5.54±2.95	0.88700	0.82118	0.283	5.79±3.91	1.33100	0.86798	0.128
Cricket	20	4.65±1.83				4.45±1.87			
Yogasana	20	5.54±2.95	0.19450	0.82118	0.813	5.79±3.91	0.14650	0.86798	0.866
Control	20	5.34±3.19				5.64±2.72			
Karate	20	3.93±2.74	1.02300	0.82118	0.216	3.91±2.56	0.61500	0.86798	0.480
Gymnastics	20	4.95±1.99				4.53±2.22			
Karate	20	3.93±2.74	0.72450	0.82118	0.380	3.91±2.56	0.54300	0.86798	0.533
Cricket	20	4.65±1.83				4.45±1.87			
Karate	20	3.93±2.74	1.41700	0.82118	0.088	3.91±2.56	1.72750	0.86798	0.049*
Control	20	5.34±3.19				5.64±2.72			
Gymnastics	20	4.95±1.99	0.29850	0.82118	0.717	4.53±2.22	0.07200	0.86798	0.934
Cricket	20	4.65±1.83				4.45±1.87			
Gymnastics	20	4.95±1.99	0.39400	0.82118	0.632	4.53±2.22	1.11250	0.86798	0.203
Control	20	5.34±3.19				5.64±2.72			
Cricket	20	4.65±1.83	0.69250	0.82118	0.401	4.45±1.87	1.18450	0.86798	0.176
Control	20	5.34±3.19				5.64±2.72			

Notes: Statistical analysis conducted using the least significant difference *post hoc* test; **p*<0.05, ***p*<0.01, ****p*<0.001. Abbreviation: SD: Standard deviation.

performance. The primary goal of any sports training program is to help athletes process larger quantities of information in a shorter time, while priming the perceptual and effector mechanisms for subsequent information.³⁵ This process ultimately improves the speed and efficiency of the decision-making process, which is further enhanced by feedback on visual attention and the use of mental imagery techniques.³⁶

Training methods that simulate sports-related conditions provide additional benefits by facilitating the transfer of perceptual and cognitive improvements to real performance settings. Figure 4 describes the processing of various feedback based on perceptual, decision-making, and effector mechanisms, each of which varies depending on the sport. Focusing specifically on individual sports, the results of the present study provide a clearer picture regarding the visual sensory reception and central cognitive processing mechanisms of the brain.

First, considering yogasana and karate, the yogasana practitioners demonstrated the shortest P100 latencies – the most reproducible component of the VEP – for both the left and right eyes compared to other sports, apart from karate, which showed similar results. These results align with previous studies on yogasana, karate,³⁷⁻⁴¹ and other mind–body activities.⁴² A possible explanation lies in the neural processing of visual stimuli, wherein signals travel from the retina through the lateral geniculate nucleus to the primary visual cortex, and their divergence into two neural pathways that provide additional signal processing: the dorsal pathway, which provides information about spatial properties; and the ventral pathway, which provides further information about object detailing and identification, through the inferior temporal cortex. These

pathways converge in the areas of the prefrontal cortex and posterior parietal cortex, which are both key areas for decision-making and perceptual integration, offering advantages in these sports.^{43,44} In addition, one common factor in both yogasana and karate is the use of *drishti* (gaze), a focal point to deepen the primary movement of the yogic pose and to keep away the mind from wandering so that it is tamed and engaged inward. *Drishti* is a natural eye movement directed by the alignment of the body in a given posture.⁴⁵ Previous research on *drishti*, scientifically known as focal point concentration of gazing, has demonstrated improvements in neural processing and enhanced visual cognition through yogic activity.^{46,47}

Similarly, karate training involves various components, including *kihon*, *kata*, and *kumite*, with *kihon* being the basics of karate – e.g., punches, blocks, kicks, and stances. *Kata* involves the performance of predefined sequences of offensive and defensive movements in a standardized order, while *kumite* refers to free fighting or sparring. In all these practices, movements of the eye are highly pertinent. Direct gaze shifts toward a visual target are known as overt attention, and the ability to attend to peripheral targets without shifting gaze is known as covert attention. These visual attention mechanisms, combined with neural conduction to attain optimum transient and spatial attention, are the prime neurocognitive requirements in martial arts, such as karate.²² Other studies on martial meditative art forms, such as *qigong*, have shown similar results.⁴² Over time, the development of such techniques, along with mental rehearsal through mental imagery, enhances the ability to accurately locate and interpret advanced visual cues. This offers significant potential advantages in real-life situations for karatekas and supports meditative indications for yogasana practitioners.

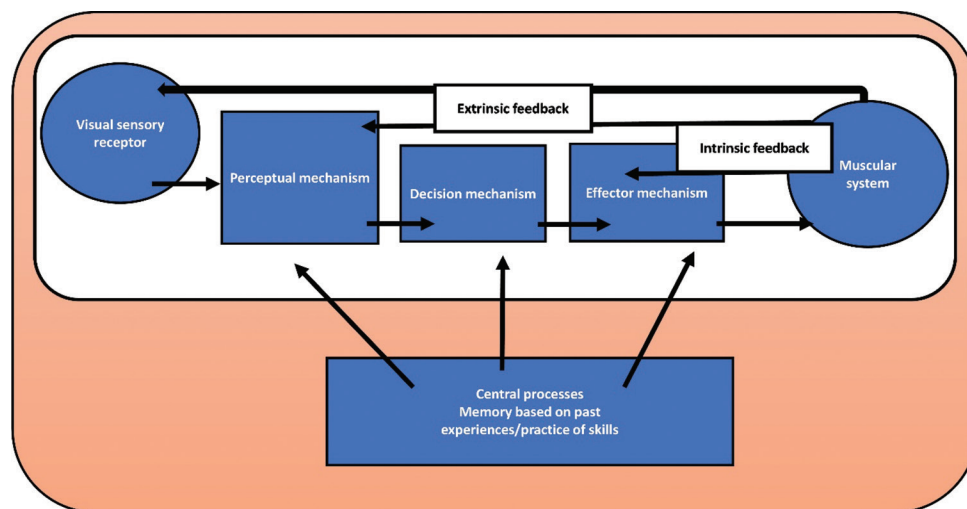


Figure 4. Sports performance training and its visual sensory mechanism

The next group exhibiting shorter visual transmission times was the cricket group. The underlying reasons could be ocular dominance – the preference for visual input from one eye over the other, similar to handedness. Previous studies have suggested similar reasons.^{48,49} While handedness typically aligns with the dominant cerebral hemisphere, ocular dominance does not necessarily follow the same pattern, as each eye projects to both cerebral hemispheres. Nevertheless, previous research has demonstrated the effects of handedness on cognition in the general population and athletes such as baseball players.^{50,51} A short visual transmission time is crucial in high-speed sports, such as cricket, where athletes must coordinate their eyes, hands, and body.^{5,11} Notable cross-dominant athletes are recognized for their exceptional hand–eye coordination. It is possible that consistent exposure to sport-specific demands contributes to improved visual transmission latency. Similar findings have been reported in table tennis players, where enhanced neural efficiency along visual pathways was observed using functional MRI, and more recently in skeet shooters, where rapid visual processing was also evident.^{52,53}

Gymnastics, as an individual sport, requires athletes to develop specific visual acuity, coordination, and visualization skills to perform intricate movements with precision and elegance. It relies less on immediate visual feedback from teammates or opponents, instead emphasizing skills such as visual acuity, field of vision, and visual imagery – skills essential for executing movements gracefully and with balance.⁸ As a result, the frontal cortex may be less involved in visual object discrimination in gymnasts.⁵⁴ This could be a reason for this group to exhibit longer P100 latencies compared to other athletes in this study.

Previous VEP analyses have revealed a relationship between training experience and the N75–P100 amplitude. Specifically, more experienced athletes were characterized by a lower amplitude of this parameter, regardless of the type of stimulation and the viewing conditions during the tests. In the present study, the lowest amplitude was observed in the karatekas, who were the most experienced group among all other sports groups. Conversely, other findings suggest that spatial stimuli, when visually activated and trained accordingly, could lead to heightened N75–P100 amplitude.⁵⁵ This may explain the higher amplitude observed in the yogasana group in the present study, as such yogic practices often involve spatial awareness for improved body alignment and posture, as well as a reduced risk of injury.

Research has shown that the traditional theory of sensory processing demonstrates how visual stimuli are transmitted from muscles to the brain's processing

lobes, supporting memory and attention development. In addition, sports training has been found to enhance the speed of visually stimulated responses compared to non-athletes or active, age- and gender-matched controls. Recent studies have highlighted the use of various sports-visual-training techniques to further improve visual latency, ultimately enhancing on-field or on-court performance.^{53,56} Emerging evidence has also shown how sports visual training is being used to enhance motor efficiency and performance.^{56,57}

While previous studies have compared VEP measures between athletes and non-athletes, or between one or two sports and controls, the present study expands this scope by examining VEP measurements across four practitioner groups. The aim was to understand the mechanisms underlying visual stimulus transmission and to compare these with active, gender-matched controls. Despite certain limitations, the study offers valuable insights into the relationship among VEP measures, visual perception mechanisms, types of sport, training modalities, training experience, and training age. The findings indicate that mental imagery and gaze skills, most practiced by yogasana practitioners and karatekas, are associated with the fastest visual transmission. Cricketers exhibited the next fastest response time, followed by gymnasts, who still outperformed the controls.

The study excluded sedentary children and female participants, with the latter omitted due to post-pandemic disruptions in their respective training regimens, which could be a limitation. Furthermore, post-pandemic parental concerns limited female participation in laboratory tests more than male participation, contributing to their exclusion. To address socioeconomic and nutritional variability, all participating schools were chosen from similar socioeconomic backgrounds in West Bengal, and all students received mid-day meals, ensuring a degree of homogeneity. However, certain factors such as diet, nutritional status, socioeconomic status, and sleep profiles were not directly controlled. Despite this, the study maintained highly specific inclusion criteria, minimizing potential confounding effects across the selected groups. As a cross-sectional study, certain limitations exist. Future research should consider longitudinal or intervention-based designs, while also accounting for potential sources of measurement error (e.g., VEP waveform variability and electrode impedance fluctuations).

5. Conclusion

Different sports demand specific visual skills, such as shorter reaction time in cricket, mind–body balance in yogasana, opponent sensing in karate, and visual acuity in gymnastics. The variability in bioelectrical function along

the visual pathway – across central and peripheral locations under monocular and binocular conditions – is interrelated with the perceptual requirements specific to each sport. This functional variability is more pronounced in athletes with more training experience and mind–body activities than those in other team-based or individual sports.

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Conflict of interest

The authors declare they have no competing interests.

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Ethics approval and consent to participate

The research protocol and design were approved by the Institutional Ethics Committee for Human Research at the university where the study was performed (Approval No.: VB/IECHR/2021/9). The study was approved by the Clinical Trial Registry of India (Regn. No: CTRI/2021/06/034483). The research was conducted in accordance with the Helsinki Declaration. The written consent to participate form was acquired from the participants at the start of data collection.

Consent for publication

Complete written and verbal informed consent was obtained from the subjects and parents for the publication of this study.

Availability of data

Not applicable.

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