Original Article

Characteristics of binocular vision and oculomotor function among sports-concussed athletes

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Purpose: To compare the binocular vision and oculomotor function between sports-concussed athletes and aged-matched controls. **Methods:** Thirty mild concussed athletes were recruited and compared with aged-matched controls. All the participants underwent a comprehensive ocular assessment followed by an oculomotor assessment which included tests for accommodation, vergence, eye movements, and reading parameters. **Results:** Three categories of oculomotor-based deficits were found: convergence insufficiency (40%), accommodative insufficiency (25%), and oculomotor-based reading dysfunctions (20%). A statistically significant reduction in the mean ± SD of the following parameters was noted in concussed athletes v/s controls:- binocular accommodative amplitude: 7.13 ± 1.59 v/s 15.35 ± 2.95 ($P < 0.001$), convergence amplitude: 14.23 ± 5.00 v/s 5.65 ± 0.90 ($P < 0.001$), positive fusional vergence for distance: 21.17 ± 8.97 v/s 31.32 ± 6.23 ($P < 0.001$), vergence facility: 6.47 ± 1.47 v/s 11.84 ± 1.00 ($P < 0.001$), accommodative facility: 7.10 ± 4.57 v/s 11.67 ± 1.83 ($P < 0.001$), reading speed: 66.97 ± 17.82 v/s 144.13 ± 24.45 ($P = 0.03$) and Developmental Eye Movement ratio: 1.40 ± 0.19 v/s 1.17 ± 0.06 ($P < 0.001$). **Conclusion:** Concussions caused by sports have a considerable impact on binocular vision and oculomotor parameters. These findings have substantial therapeutic implications in terms of establishing a periodic screening program for athletes so that essential therapy can be provided for a better outcome.

Access this article online
Website: https://journals.lww.com/ijo
DOI: 10.4103/ijo.IJO_1932_22
Quick Response Code:

Key words: Binocular vision, concussion, oculomotor

Sport-related concussion is a major public health concern. A sport-related concussion is a mild traumatic brain injury caused by biomechanical stresses to the head, face, neck – or anywhere else on the body – that are conveyed to the brain and cause a functional disturbance to the neuronal and glial networks.[1] Concussion in sports is estimated to occur at a rate of 0.1 to 21.5 per 1000 athlete exposures, depending on the sport and reporting methods.[2] Athletes, in particular, are more likely to endure many concussions during their sports careers, and the amount of subconcussive impacts can have a negative long-term effect on some players.[3]

Following a concussion, many athletes as well as adolescents end up with binocular vision disorders such as convergence and accommodative insufficiency,[4,5] which causes symptoms such as headache, asthenopia, vision blurring in and out of focus, and losing one's place while reading or copying text from a distant to a close distance.[6] Despite the association between visual disorders and neural control following a concussion,[7] oculomotor evaluation has not always been a part of concussion care protocols in the past.[1] However, in recent years, there have been numerous literature stating the role of oculomotor and binocular vision evaluation in a concussion which included accommodation, vergence, and eye movement assessments.[8-14]

There is paucity in the literature especially in terms of oculomotor and binocular vision function in sport-related concussion. Majority of the studies cited above did not have a control group included; thus, there is currently skepticism about the reported frequency of concussion-related vision problems. The purpose of this study was to compare the frequency of concussion-related oculomotor and binocular vision anomalies in a sports concussed versus a control group.

Methods

This prospective study was carried out among 30 athletes and 30 aged-matched controls. The project has been approved by the Institutional Review Board and also follows the guidelines proposed by the Declarations of Helsinki. Subjects with persistent concussive visual symptoms 6 months or more after the initial injury were recruited. The duration of 6 months was considered for the natural recovery process following the concussion. Other inclusion criteria included adequate Snellen's visual acuity of 6/9 or better and no manifest deviation of the eyes. Exclusion criteria included uncorrected refractive error, pre-existing ocular and health issues [seizures, repeated loss of consciousness following the incident, any other pre-existing health issues (coronary artery disease, asthma, mononucleosis, sickle cell anemia,

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Received: 05-Aug-2022 Revision: 27-Dec-2022
Accepted: 08-Feb-2023 Published: 17-May-2023

Cite this article as: Dutta P. Characteristics of binocular vision and oculomotor function among sports-concussed athletes. Indian J Ophthalmol 2023;71:2076-82.

diabetes, and hypertension) motor imbalances], under any ocular and systemic medications that affect the vision. The age-matched controls were those without any history of concussion with Snellen's visual acuity of 6/9 or better and stable ocular and general health. Every subject underwent a detailed history, visual acuity testing, a comprehensive ocular examination, and an oculomotor assessment. The binocular vision and oculomotor testing included the following components[15]:

- *Near point of accommodation:* using a near point card with 20/30 reduced Snellen letters and push up to blur method[15]
- *Accommodation response:* using Monocular estimate method (MEM) retinoscopy and a MEM card with 20/20 Snellen letter[16]
- *Heterophoria:* using the Modified Thorington test with a Bernell Muscle Imbalance Measure at 30 cm and 3 m[17]
- *Accommodative convergence/Accommodation ratio:* using calculated method[18]
- *Near point of convergence:* using Gulden stick with an accommodative target of 20/30 reduced Snellen letters[19]
- *Fusional step-vergence amplitude:* using a prism bar and a linear target with 20/30 reduced Snellen letters[15]
- *Positive and negative relative accommodation:* using plus/minus lenses in a stepwise manner and 20/30 reduced Snellen letters[15]
- *Accommodative facility:* using ±2.00 diopter flippers and word rock card with 20/30 reduced Snellen letters[20,21]
- *Vergence facility:* using 12 Δ base out/3Δ base in flippers and a linear target with 20/30 reduced Snellen letters[22]
- *Saccades and pursuit:* using Northeastern State University College of Optometry (NSUCO) grading[15,23]
- *Reading speed:* Standard English text with 20/30 Snellen letters
- *Developmental Eye Movement (DEM) Version 2.0 2009 test* to measure the horizontal and vertical saccadic response[24,25]

Postconcussion symptom scale (PCSS)

The PCSS questionnaire was used to assess subjective symptom evaluation. It is a 22-item scale used to assess the severity of symptoms following a concussion. This scale was developed with the goal of assigning a numerical value to each symptom in order to objectively quantify the common subjective symptoms that an individual experiences after sustaining a concussion. The purpose of designing this scale was to supplement other techniques such as neuropsychological testing. Each symptom was scored on a scale of 0 to 6, with 0 being the lowest and 6 being the highest. The higher the scores, the more severe the symptoms.

Statistical analysis

Statistical analysis was performed using Microsoft Excel 2007, SPSS version 20.0, and MedCalc Statistical Software 17.2. One sample Kolmogorov–Smirnov (K–S) test was used to check normality distribution. Since the dataset was normally distributed, further analysis was carried out using parametric

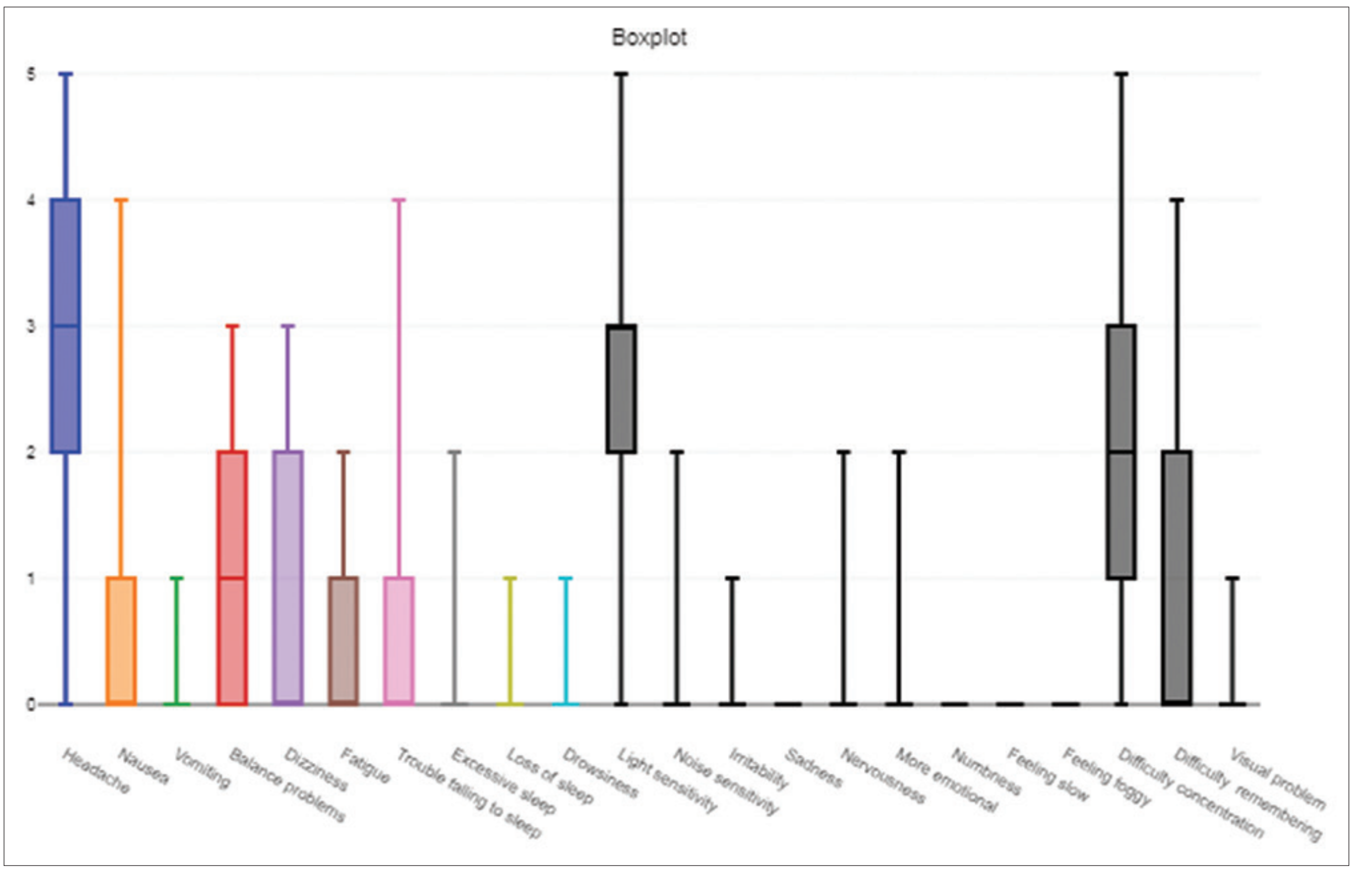

Figure 1: Postconcussion symptom scale among concussed subjects

Table 1: Accommodation parameters between concussed and aged-matched controls

Test	Group	Mean±SD	Mean difference	Std. Error difference	95% Confidence interval of the difference		*P*
					Lower	Upper	
NPA_OD in diopter	Concussed Controls	9.61±4.02 14.43±2.87	−4.82	0.89	−6.61	−3.03	<0.001
NPA_OS in diopter	Concussed Controls	9.07±3.18 14.90±2.88	−5.83	0.78	−7.41	−4.25	<0.001
NPA_OU in diopter	Concussed Controls	7.13±1.58 15.35±2.85	−8.21	0.60	−9.43	−6.99	<0.001
NRA in diopter	Concussed Controls	3.08±0.50 2.50±0.15	0.58	0.09	0.39	0.77	<0.001
PRA in diopter	Concussed Controls	−3.80±1.04 −5.30±0.18	1.49	0.19	1.11	1.88	<0.001
MEM_OD in diopter	Concussed Controls	0.85±0.21 0.67±0.11	0.18	0.04	0.09	0.27	<0.001
MEM_OS in diopter	Concussed Controls	0.86±0.23 0.62±0.12	0.23	0.04	0.14	0.33	<0.001
MAF (OD) in cycles per minute	Concussed Controls	8.18±4.02 11.45±1.60	−3.26	0.80	−4.88	−1.64	<0.001
MAF (OS) in cycles per minute	Concussed Controls	8.93±4.68 11.45±1.68	−2.51	0.89	−4.31	−0.72	0.007
BAF (OU) in cycles per minute	Concussed Controls	7.10±4.57 11.67±1.83	−4.57	0.88	−6.35	−2.80	<0.001

NPA: Near point of accommodation; NRA/PRA: Negative/positive relative accommodation; MEM: Monocular estimated method; MAF: Monocular accommodative facility; BAF: Binocular accommodative facility

Table 2: Vergence parameters between concussed and aged-matched controls

Test	Group	Mean±SD	Mean difference	Std. Error difference	95% confidence interval of the difference		*P*
					Lower	Upper	
PBCT_Dist in diopter	Concussed Controls	−1.00±1.12 0.50±2.77	−1.50	0.63	−2.79	−0.20	0.02
PBCT_Near in diopter	Concussed Controls	-5.30±3.15 -1.66±3.40	−3.63	1.42	−6.53	−0.73	0.01
NPC in cm	Concussed Controls	14.23±5 5.65±0.88	8.58	0.91	6.76	10.41	<0.001
NFV (D)-BREAK in prism diopter	Concussed Controls	9.40±2.28 10.52±2.73	−1.11	0.64	−2.41	0.17	0.09
NFV (D)-RECOVERY in prism diopter	Concussed Controls	7.27±2.18 8.45±2.66	−1.18	0.62	−2.43	0.07	0.06
PFV (D)-BREAK in prism diopter	Concussed Controls	21.17±8.87 31.32±6.23	−10.15	1.97	−14.10	−6.20	<0.001
PFV (D)-RECOVERY in prism diopter	Concussed Controls	16.87±8.45 26.42±6.01	−9.55	1.87	−13.30	−5.80	<0.001
NFV (N)-BREAK in prism diopter	Concussed Controls	14.47±2.33 12.84±3	1.62	0.69	0.24	3.00	0.02
NFV (N)-RECOVERY in prism diopter	Concussed Controls	12.33±2.87 10.84±3	1.49	0.68	0.12	2.86	0.03
PFV (N)-BREAK in prism diopter	Concussed Controls	29.90±9.97 31.13±7.27	−1.22	2.22	−5.69	3.23	0.58
PFV (N)-RECOVERY in prism diopter	Concussed Controls	25.33±9.95 26.13±7.27	−0.79	2.16	−5.12	3.53	0.71
VF (12BO/3BI) in cycles per minute	Concussed Controls	6.47±1.47 11.84±1.03	−5.37	0.32	−6.01	−4.72	<0.001

PBCT: Prism bar cover test; NPC: Near point of convergence; NFV: Negative fusional vergence; PFV: Positive fusional vergence; VF: Vergence facility

tests. Descriptive statistics were calculated using mean and SD. Independent *t*-test was used to compare the oculomotor parameters between concussed athletes and aged-matched controls with 95% Confidence intervals and α-value set at 5%.

Table 3: Eye movement parameters between concussed and aged-matched controls

Test	Group	Mean±SD	Mean difference	Std. error difference	95% confidence interval of the difference		P
					Lower	Upper	
Reading speed in words per min	Concussed Controls	66.97±17.82 144.13±24.45	−77.16	5.49	-88.15	-66.16	<0.001
DEM_Vertical in seconds	Concussed Controls	37.78±3.15 32.14±1.58	5.63	0.63	4.36	6.91	<0.001
DEM_Horizontal in seconds	Concussed Controls	52.70±5.08 37.57±1.11	15.12	1.06	13.00	17.25	<0.001
DEM_Ratio	Concussed Controls	1.40±0.19 1.17±0.06	0.23	0.03	0.15	0.30	<0.001
Saccades_NSUCO							
Ability	Concussed Controls	4.17±0.52 5.00±00	−0.83	0.10	−1.04	−0.62	<−0.001
Accuracy	Concussed Controls	4.43±0.62 4.94±0.25	−0.50	0.12	−0.74	−0.25	<−0.001
Head movement	Concussed Controls	4.80±0.40 5.00±00	−0.20	0.07	−0.34	−0.05	−0.008
Body movement	Concussed Controls	5.00±00 5.00±00	0	0	-	-	-
Pursuits_NSUCO							
Ability	Concussed Controls	4.80±0.40 4.94±0.25	−0.13	0.08	−0.30	0.03	0.12
Accuracy	Concussed Controls	4.60±0.49 4.97±0.18	−0.36	0.09	−0.55	−0.17	0.001
Head movement	Concussed Controls	4.83±0.37 5.00±00	−0.16	0.69	−0.30	−0.30	0.01
Body movement	Concussed Controls	4.97±0.18 5.00±00	−0.03	0.03	−0.09	0.03	0.31

DEM: Developmental eye movement; NSUCO: Northeastern State University College of Optometry

Results

Demographics of the subject

A total of 30 concussed athletes and 30 age-matched controls were included in the study. The mean ± SD age of the subjects was 25 ± 4 years and 24 ± 5 years in the concussed and aged-matched control group [*P = 0.34*], respectively. No statistically significant difference was noted in terms of age between both groups. All the subjects were male. The mean ± SD duration of the injury among concussed athletes was 11 ± 4 months. The concussed subjects were associated with sports like football, volleyball, and boxing. Majority of them complained of headaches (80%) followed by photosensitivity (70%). Among the concussed subjects, three major binocular vision disorders were detected based on the diagnostic criteria "Appendix 1": convergence insufficiency (40%), accommodative insufficiency (25%), and oculomotor-based reading dysfunctions (20%).

Binocular vision and oculomotor parameters among concussed v/s aged-matched controls

"Tables 1–3" show the mean difference in all the parameters between concussed and aged-matched controls. The analyzed data were normally distributed [*P = 0.05, K–S test*]. The comparison between both the groups was analyzed using an independent *t*-test with a 95% confidence interval. The concussed subjects showed a statistically significant reduction in accommodative amplitude ($P < 0.001$), accommodative response ($P < 0.001$), relative accommodation ($P < 0.001$), convergence amplitude ($P < 0.001$), positive fusional vergence for distance ($P < 0.001$), vergence facility ($P < 0.001$), DEM test components ($P < 0.001$), and reading speed ($P < 0.001$) when compared with the control group.

Postconcussion symptom scale in concussed subjects

The median interquartile range (IQR) scores of the most common PCSS among the concussed subjects are as follows: headache 3 (5), balance problem 1 (2), light sensitivity 3 (3), difficulty concentrating 2 (0), and others [Fig. 1].

Discussion

This paper illustrates the characteristic features of binocular vision function in concussed athletes. Concussed athletes in this study had a reduction in convergence, accommodation, and eye movement parameters, which affected their daily lives as well as their sporting endeavors. A neural connection is involved in producing accommodation, which consists of stimulation of retinal photoreceptors, i.e., the cones by defocus blur which gets disseminated through the magnocellular layer of the geniculate nucleus to the primary visual cortex.[26,27] In the case of concussion, the blur-related information and the entire processing are transmitted inefficiently and ineffectively along the neural pathways, thus producing an imbalance in accommodative function.[27]

Previous studies have shown a long-term effect in the accommodative amplitude reduction inconcussion.[27,28] A study by Ciuffreda *et al*. aimed at retrospectively analyzing the common occurrence of oculomotor disorders following mild traumatic brain injury where accommodative insufficiency was a major finding for most of the subjects. The susceptibility of accommodative pathways and the neural motor innervation to axonal injury resulting in neurological insulting in accommodative insufficiency was also being described.[29] Moreover, these disturbances in the neurological process of accommodation lead to common visual symptoms such as blurred vision, eyestrain with associated near task avoidance, and headache.[27,29] Using reduced accommodative amplitude as the diagnostic criteria, previous investigations found a 10% to 33% incidence of accommodative insufficiency following a concussion.[30,31] The reduction in accommodative indices in this study, on the other hand, is consistent with past findings. The accommodative amplitude of the concussed athletes was significantly lower than that of the controls, thus affecting the near triad.

A concussion can cause widespread axonal damage, making the vergence and accommodative pathways more vulnerable to the effects.[32] Ciuffreda *et al*.[29] found that convergence insufficiency was one of the most prevalent vergence defect following a concussion in a retrospective study of 300 subjects with oculomotor dysfunction. The finding of the present study, however, is consistent with it. When populations with concussion were compared to control groups, prior research have found substantial variations in near phoria, near point of convergence break, recovery values, and vergence ranges.[33] Berne, Scheiman, and Gallaway both observed considerably increased exophoria in the mild traumatic brain injury group.[33] This study also supports this finding since the concussed subjects exhibited increased near exophoria compared to the controls, which possibly led as a factor toward receded convergence amplitude. Near point of convergence is also being used more frequently in postconcussion examinations, with nearly 42% of instances documented at the 1-month interval following a sports-related concussion.[34,35] Furthermore, exposure to a competitive season in contact sports tends to affect near point of convergence results, as a recent study found that even heading a soccer multiple times can cause a convergence issue.[36]

An observation in the reduced vergence facility among concussed athletes was also made in this study. This test's performance is closely connected with reading efficiency (using infrared eye-tracking methods) making it a reasonable oculomotor test to use as a measure of reading efficiency, a problem that is frequently reported after a concussion.[37] Given the inherent link between near-distance visual system "flexibility," which is vital in sports, vergence facility testing is likely more sensitive for detecting overall oculomotor dysfunction.[38] Our findings underscore the need of future research exploring vergence infacility in this population, as well as the evaluation of vergence facility testing at a distance, which eliminates the confound of accommodation at close range, which can sometimes disguise vergence dysfunction.

Notably, among the concussed athletes, the DEM test revealed a slowed vertical and horizontal test response, as well as an abnormal ratio score. During reading, the eyes move swiftly in a sequence of saccades. These are interspersed with fixations where information is gathered. Learning impaired and generally poor readers were seen in several studies to have insufficient ocular movements, resulting in increased regression and fixation, as well as additional, although transient left to right saccades.[39] The majority of saccadic eye movement research focuses on horizontal saccades; however, it is crucial to look at both horizontal and vertical saccades because the neuroanatomical control of both eye movements comes from various parts of the brain. A concussion can damage distinct neuroanatomical regions of the brain, resulting in differences in saccade reaction times. Furthermore, horizontal saccades are slower than vertical saccades in terms of saccadic fixation, which happens as the individual evaluates the number.[40] Because it analyzes both horizontal and vertical saccades, the DEM test may contribute extra information to concussion assessment. The quantification of saccadic and smooth-pursuit eye movements, in particular, has been the focus of several concussion studies and is now incorporated in Ciuffreda's conceptual model for concussion evaluation and vision rehabilitation.[41] In DEM test, the automaticity of number naming ability is determined by the Vertical time score. The Horizontal subtest assesses number naming in a reading-like task with a significant oculomotor component. The Ratio score is a method for directly comparing test performance levels in the vertical (automaticity) and horizontal (automaticity plus oculomotor control) directions. When the Ratio scores are much higher than expected, it indicates that oculomotor control is more difficult when horizontal eye movements are necessary. However, the poor DEM test results in the concussed athletes in this study gives estimation about their poor oculomotor control, which occurred as a result of concussion. Furthermore, Badovinac *et al*. found that 21.7 and 9.7% of concussed athletes had abnormal horizontal and vertical saccades, respectively, in a recent study.[42] However, as compared to the controlled group in their investigation, DEM test levels were not significantly reduced. The source and site of concussion, the period of injury, and the limited number of individuals included in this study could all be contributing factors.

It is widely considered that postinjury oculomotor abnormalities are triggered by the concussion. Although this is primarily relevant, growing incidence of oculomotor and basic visual acuity difficulties among athletes in this study, premorbid oculomotor dysfunction must be factored as a variable. As a result, knowing an athlete's premorbid oculomotor status would likely be immensely helpful during a postconcussion evaluation. With the heightened understanding of sports-related concussions, there is a need to establish reliable and efficient testing protocols for sideline concussion diagnosis so that players can be withdrawn from play as soon as possible.

Conclusion

Oculomotor and binocular vision dysfunction affect a large number of athletes after concussion. Many go undetected in the initial phases due to a lack of understanding of postconcussion symptoms. However, every athlete who is at risk of concussion at any point throughout their sport should follow a consistent procedure and have their oculomotor and binocular vision function screened periodically to benefit from timely rehabilitation and referrals.

Financial support and sponsorship

Nil.

Conflicts of interest

There are no conflicts of interest.

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DOI: 10.4103/ijo.IJO_1932_22

Appendix 1

Diagnostic criteria used in the study to diagnose the oculomotor conditions[15]

1. **Convergence insufficiency**

Symptoms:

Worse at the end of the day and associated with reading or other close tasks. Asthenopia, migraines, and intermittent diplopia are the most prevalent symptoms.

Signs:

1. Greater exophoria for close proximity than for distance
2. Receded NPC (near point of convergence) break with accommodative target greater than 6 cm
3. Difficulty with base out prisms/low PFV (positive fusional vergence) not meeting Morgan's expected values (or) failure to meet Sheard's Criteria (PFV less than twice the near phoria)
4. Difficulty clearing + 2.00 DS with binocular accommodative flippers

2. **Accommodative insufficiency**

Symptoms

Symptoms include blurred near vision, discomfort and strain from near tasks, fatigue with prolonged near works, and difficulty focusing and paying attention when reading.

Signs:

1. Reduced accommodation amplitude relative to expected normal amplitudes for age based on Hoffstetter's formula for average or minimum accommodation
2. Difficulty with accommodating monocular and binocular facility with − 2.00 DS
3. High lag of accommodation in MEM

3. **Oculomotor dysfunction**

Symptoms

Head movement that is excessive, skipping letters while reading, getting around lines, slow intensive reading, comprehension issues, limited attention span, problems with copying from the chalkboard, having trouble using computer scan sheets when taking standardized psychological or educational assessments

Signs

1. Score of 15% or below on the Developmental Eye Movement Test
2. Reduced reading rate on English text
3. Reduced NSUCO results compared to age normative values