Visual Functions in Post-Concussion Syndrome

by

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A thesis

presented to the University of Waterloo

in fulfillment of the

thesis requirement for the degree of

Master of Science

in

Vision Science

Waterloo, Ontario, Canada, 2018

AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

Purpose: Post-concussion syndrome (PCS) is a complex neurological disorder in which various concussion symptoms can last for weeks, months, or even years after sustaining the concussion. The PCS population has been shown to have some functional deficits such as balance and visual-motor integration issues in addition to their PCS symptoms. The current study has three main objectives as follows: 1) to establish a comprehensive visual function test battery for use in both control and PCS individuals, 2) to compare performance on the comprehensive visual function test battery in control and PCS individuals, 3) to determine if performance on the comprehensive visual function test battery is in any way related to the symptoms individuals with PCS experience.

Methods: Forty-four participants aged 18 - 35 were recruited. The study participant groups were as follows: 1) Healthy participants with no history of concussion (Controls; n=33), and 2) Participants with PCS (n=11). Participants completed two study visits separated by 2 - 7 days. The testing protocol of visit 1 consisted of the following visual function tests: static visual perception, objective refraction, ocular alignment, ocular motility, stereopsis, accommodative function, vergence function, cyclopean eye alignment position, and King-Devick. The testing protocol of visit 2 consisted of visual-motor integration tests including visual-motor reaction time and coincidence anticipation timing, and a test of dynamic visual perception.

Results: All control and PCS participants were able to complete all of the tests at each study visit. However, the PCS participants took longer time to complete the study visits as these participants needed breaks to rest between some of the tests. Control participants did not need breaks between any of the tests. A Mann-Whitney U-test was conducted to examine the difference in visual function performance between the groups. Overall, the only difference shown between the two groups was in the ocular motility, King-Devick, cyclopean eye alignment position, and the peripheral visual-motor reaction time tests. In the ocular motility test, 30% of PCS participants exhibited irregular eye movements, whereas 0% of control participants had irregular eye movements. On the King-Devick test, the control group appeared to read faster than the PCS group ($p=0.04$). On the cyclopean eye alignment position test, which is a measure of global visual function, the PCS group appear to have better performance and made fewer

errors in alignment (p=0.03). On the peripheral visual-motor reaction time test, the PCS group also appeared to have better peripheral reaction time than the control group (p=0.04).

To examine the relationship between PCS symptom severity and visual function, a Spearman correlation analysis was conducted. For the control group, stereopsis (p=0.02), distance horizontal negative fusional reserve - blur point (p=0.04), distance vertical negative fusional reserve - double point (p=0.01), and recovery point (p=0.02) were found to be significantly correlated with participant symptoms. For the PCS group, there was a statistically significant correlation for a few coincidence anticipation error measures. The vast majority of the correlations between symptom severity and visual function were not significant in either group, which suggests that performance on the visual function test battery is not predictive of participant symptoms.

Conclusion: In summary, this study has applied a comprehensive visual function testing protocol that can be used in further research and clinical practice. Eye movement tests such as the Broad H oculomotor screening test, and the King-Devick test appear to have the potential to detect lingering deficits in the PCS population. Additionally, PCS related symptoms do not appear to be related to performance on the individual visual function tests used in the test battery in either the PCS or control individuals.

Acknowledgements

- I would like to thank my supervisor, Dr. Kristine Dalton, for her continued support and guidance throughout my MSc journey. She has been a great mentor and friend.
- I would like to thank my committee member Dr. Michael Cinelli for one of the best graduate courses that expanded my knowledge and helped me to understand the field of concussion.
- I would like to thank my committee members Dr. Natalie Hutchings and Dr. Trefford Simpson for helping me with the design and statistics of this study.
- I would like to thank the Saudi Ministry of Education - King Abdullah Scholarship Program for offering me the scholarship opportunity and for their generous fund on this study.
- I would like to thank the Canadian Optometric Education (COETF) for their research grant.
- I would like thank all the study participants for making this happen.
- I would like to thank all of the Vision Science Graduate Students, staff, and faculty at the University of Waterloo School of Optometry & Vision Science for making it a pleasure to come to school every day.
- I would like to thank the graduate coordinator Stephanie Forsyth for her tremendous efforts to support all graduate students in the Vision Science Program.
- I would like to thank all the past and present members of the Vision & Motor Performance lab, thank you for your great companionship.
- I would like to thank Gayathri Premkumar for helping me with the study data. It was a pleasure to work with you.
- I would like to thank my brother - Sayaf - who supported me at the beginning of my MSc journey. Thank you for being a caring brother and a great room-mate.
- I would like to thank my family for their endless and continuous love and support even when they are miles away from me.
- I would like to thank my sisters, Sarah and Munirah; and my brothers, Suhail, Saud, and Safeer. Your love and support touched me despite the distance.
- Special thanks to my beloved friends Norah Alkanhal, Amritha Stalin, and Varadhu Jayakumar. Thank you for the tremendous support throughout this journey. I could not have done it without you.

Dedication

To my beloved parents, your love and support are the reasons behind my success.

إلى والديّ الحبيبين، حبكم ودعمكم هم أسباب نجاحي.

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Chapter 1 - Introduction

1.1 Concussion definition

Concussion is a complex pathophysiological process which impacts brain function, resulting from a biomechanical force that is directed to the head, face, neck or transmitted to the head from elsewhere in the body.[1] Concussion is considered to be a subset of mild traumatic brain injury (mTBI) although the two terms have been used interchangeably in the literature.[1,2]

1.2 Concussion pathology

Concussion is known as a short-lasting disturbance of the brain function induced by acceleration and/or deceleration of the head.[3] This neurological disturbance is thought to be due to a neurometabolic disruption rather than an obvious structural change such as swelling or bleeding of the brain. Because there are no obvious structural changes associated with concussion, concussion is typically associated with normal findings on conventional neuroimaging techniques such as computed tomography (CT) or magnetic resonance imaging (MRI).[1,3] These normal conventional neuroimaging findings distinguish concussion from other types of TBI that cause structural changes in the brain.[1,3]

In an acutely concussed individual, neuronal cell metabolism is altered. The affected neurons release potassium (K^+) and absorb toxic calcium ions (Ca^{2+}), which causes increased glucose uptake by the cells in an attempt to regulate the cell metabolic state. The resulting altered cell metabolic state results in the release of free radicals that impact the cell's DNA and the cell membrane. About 30 minutes after the concussion, the brain will begin to experience low levels of glucose uptake and cerebral blood flow, and the cell's mitochondria absorb the excess Ca^{2+} in the cell. The absorption of Ca^{2+} by cell mitochondria has a negative impact on mitochondrial function and results in an energy crisis. This metabolic imbalance affects all of the cells, even those that survived the initial insult and is thought to be the cause of the myriad of symptoms that individuals with concussion experience.[3,4]

Controversially, some research suggests that the altered neural metabolism caused by an acute concussion actually results in structural changes in the brain and leads to axonal swelling and damage, which consequently affects the neural connections. While this structural damage is not detected by conventional neuroimaging, it appears to be detectable by a technique called

magnetic resonance diffuse tensor imaging (DTI). This technique showed a potential in detecting microstructural changes in the integrity of the brain white matter after concussion.[5] Unfortunately, DTI is an expensive neuroimaging technique so there has not been widespread uptake and acceptance of this imaging technique yet in research and clinical practice.[5,6]

1.3 Concussion by the numbers

In Canada, concussion is the seventh most serious injury among individuals aged 12 and over.[7] 110 Canadians per 100,000 reported concussion as their most serious injury.[8] Of all reported concussions, 54% are sports-related and occur at sports or recreation places.[8] Concussions not related to sport have been found to occur at a number of places including the home (26%), school (7%), and streets/highways (4%).[8]

Concussion incidence rates have been found to be higher in males (140 per 100,000) than females (80 per 100,000).[8] Moreover, concussions are more common in younger adults (16 - 34 years old) than other age groups.[8] In athletes specifically, results from The National Collegiate Athletic Association (NCAA) has found concussion incidence rates are higher among collegiate athletes than high school athletes.[9]

1.4 Concussion in sport

Despite the fact that there are many causes of concussion, most of the literature on concussion focuses primarily on sports-related concussion. The preponderance of sports-related concussion literature could be because of the need for sports to have safe and clear regulations to keep athletes safe and healthy in the game.[1,10] It may also be due to the fact that sports are high-risk environments for concussions and that athletes are a relatively homogenous population to study, or that sports-related concussions seem to be associated with fewer co-morbidities at the time of injury (compared to motor vehicle accidents for example). Concussion research in sport has a long history and has paved the way for further research in many areas of concussion research. Despite differences in populations and injury mechanisms between sports-related and non-sports-related concussions, the most recent consensus statement of the International Conference on Concussion in Sport stated that there are no validated criteria to distinguish sport-related concussion from other types of head injuries[10], and that research findings on sport-related and non-sport-related concussion should be considered complimentary

to each other.[10] Therefore, the references used in this thesis are not limited solely to sport-related concussion research.

1.5 Concussion diagnosis

Previous research studies investigating biochemical markers, neuroimaging, and electrophysiological tests to diagnose concussion objectively have had unsatisfactory outcomes.[1,10] Therefore, clinicians diagnose concussion based on the patient's reported history which must include a mechanism of injury, presenting signs and/or symptoms, and neuroimaging tests to confirm that obvious structural abnormalities are absent and exclude more severe types of TBI.[1] The domains assessed in the diagnosis of concussion include screening for 1) somatic, cognitive, emotional, or sleep disturbance symptoms, 2) balance deficits, 3) behavioural changes, and 4) cognitive deficits such as slow reaction times.[1,3,10]

It is important to note that individuals do not need to lose consciousness to have a concussion, nor do they need to experience all of the symptoms / signs listed above.[1,3,10]

1.6 Concussion recovery

Clinical concussion recovery is determined by returning to normal daily life activities,[10] and involves the resolution of symptoms and the return of normal physiological functions such as balance.[10] Research has determined that the majority of concussed individuals recover within two weeks after sustaining their injury.[10] However, the concussion recovery period is still a vague and subjective phenomenon because of the lack of objective methods to monitor recovery.[1,3] In other words, it is still unclear when it is safe to permit a concussed individual to return to daily life activities including work, school, sport, etc. Defining a specific concussion recovery time frame is complicated by the fact that some concussed individuals experience symptoms and other physiological deficits that last beyond the typical two week healing period.[1,3] When concussion recovery is prolonged, it is described as Post-Concussion Syndrome, which is discussed in more detail below.[5]

1.7 Post-Concussion Syndrome (PCS)

Post-concussion syndrome (PCS) is a complex neurological disorder in which various concussion symptoms such as headache, dizziness, and loss of concentration last for weeks,

months, or even years after sustaining the concussion.[3,11] The prevalence of post-concussion syndrome varies amongst the literature. This variation may be attributed to the difference between the population samples of each study in terms of age, gender, and population size, or it may be attributed to differences in the definition of PCS, which are discussed in more detail below. Generally, somewhere between 10 to 64% of concussed individuals will develop post-concussion syndrome.[12–15] Interestingly, the percentage of individuals who suffer from PCS appears to increase when studying only a single symptom such as headache, which has been shown to persist in up to 90%[16] of individuals following a concussion.

While population differences likely contribute to some of the variability in the literature about PCS, a more notable reason that the prevalence of PCS is so variable is that there is uncertainty in literature around defining what PCS actually is. Part of this uncertainty is due to the different schools of thought about the underlying causes of PCS.[3] Some specialists believe that PCS is directly related to the sustained concussion, while others believe that PCS reflects the psychological and emotional status of the concussed individual.[3,17]

Another reason for the uncertainty around defining PCS is that the two main and widely acceptable diagnostic systems; the Diagnostic and Statistical Manual of Mental Diseases, 4th edition (DSM-IV)[3] and the World Health Organization's International Classification of Diseases, 10th edition (ICD-10),[3,18] have different definitions of and diagnostic criteria for PCS.[3]

The DSM-IV defines PCS as: 1) cognitive deficits in attention or memory and 2) at least three or more of the following concussion symptoms: fatigue, sleep disturbance, headache, dizziness, irritability, affective disturbance, apathy, or personality change, that persist for at least 3 months after the injury.[3] On the other hand, the ICD-10 defines PCS as the presence of three of the following concussion symptoms: headache, dizziness, fatigue, irritability, insomnia, concentration or memory difficulty without marked neurological impairment or reduced alcohol intolerance, that persist for at least 4 weeks after the concussion incident.[18]

In 2005, a study was conducted to determine the effectiveness of the two diagnostic systems.[19] 178 TBI patients were interviewed and evaluated using the DSM-IV and the ICD-10 systems.[19] 11% of the participants were diagnosed with PCS using the DSM-IV system compared to 64%

using the ICD-10.[19] This result demonstrates that the ICD-10 definition of PCS is more liberal and results in a higher number of PCS diagnoses.[19] Although studies such as this one have started to explain some of the variability in the incidence of PCS, the question about what the underlying cause of PCS remains unanswered.

Perhaps the greatest challenge in defining PCS lies in the fact that it is a condition based on symptoms alone. It is been argued that relying on symptoms alone to diagnose PCS is inadequate because these symptoms are prevalent in the general population as well.[20,21] In 2011, a study was conducted to compare the prevalence of PCS symptoms between a previously concussed group and a control group with no history of concussion. Interestingly, the prevalence of PCS symptoms in the control group was higher (34%) than the previously concussed group (30%).[14] Thus, it has been recommended that the PCS population should be examined using multidisciplinary approaches in order to determine objective methods to define and diagnose PCS, improve recovery monitoring, and develop intervention treatment plans.[1,14,21]

One of the earliest research studies that contributed to a better understanding of the functional recovery post-concussion was done in 2006. The study was conducted to assess visuomotor function in combination with balance function of concussed individuals at baseline (prior to concussion), and at 3, 10 and 30 days post-injury. A total of 55 participants were included in this study; 10 of these participants had a concussion after the baseline test. The test used consisted of a virtual reality moving room stimulus. The natural response to this type of stimulus is to sway in the same direction of the movement as the presented stimulus. The authors used a coherence analysis to determine whether participant's movement was at the same frequency and direction as the moving room. Participants performed as expected on the task at baseline. Interestingly, concussed participants were not able to perform the task at all on day 3 post-concussion, which was attributed to deficits in participant's visuomotor integration abilities that were attributed to the concussion incident. At day 10, the concussed participants still did not perform the task properly and displayed an abnormal sway movement in response to the presented stimulus that was significantly different compared to baseline. At day 30, no significant difference between the baseline and the day 30 results, therefore, the authors concluded that visuomotor recovery had occurred at one month after sustaining the concussion.

Based on the study described above, a number of research studies have examined PCS using the ICD-10 diagnostic criteria of 3 or more concussion related symptoms that persist for 30 days after the injury.[22–24] Interestingly, the studies conducted with this definition of PCS found that visuomotor, vestibulo-ocular, and / or balance deficits were actually present in PCS individuals one month after their injury.[22–24]

1.8 Visual function in concussion and PCS

Many of the aforementioned deficits in PCS rely heavily on vision as a main input. It has also been determined that visual pathways incorporate more than half of the brain circuits.[25] Thus, studying a wide array of different visual functions such as accommodation, eye movements, and stereopsis might contribute to a better understanding of the vision-related deficits in both PCS and concussion. Understanding how visual functions and their underlying neurological pathways are affected by concussion and PCS will help to inform how brain function is affected in PCS and concussion, especially if a comprehensive visual function battery is applied.

Visual dysfunctions have been reported in individuals with TBI since the 80's.[26–33] It is important to recognize that although the studies that have been done highlight the wide array of visual dysfunctions associated with TBI, these studies still have some limitations that need to be addressed with further research.

First of all, some of the earliest studies looked at the visual dysfunctions of individuals with all types of TBI, irrespective of the severity of the injury.[26,27,29,30] This limitation was addressed in later studies, especially when it was understood that moderate and severe TBI were associated with visual impairments such as visual field loss, whereas mild TBI and concussion where associated more with visual dysfunctions such as accommodation disorders.[27–31,33] Unfortunately, some of the later studies that examined specific TBI severities were conducted without a control group. Furthermore, several examiners often completed the visual function tests in these studies, which makes it hard to draw firm conclusions from their results because of the increased risk of inter-examiner difference bias. Additionally, the time since the initial concussion injury was not always specified, which makes it hard to understand if the reported visual dysfunctions were measured prior to, or after the 30 day time frame for PCS diagnosis.[27–31,33]

Some of the most recent research studies have focused on investigating the visual dysfunctions associated with concussion in the acute phase - prior to 30 days post injury.[34,35] However, these studies did not follow their participants out past this time point; therefore, it is still unclear if these visual dysfunctions persisted beyond the 30-day time period when the PCS occurred. It is also unclear if, or how often, visual functions recovered within the 30-day period. Moreover, the relationship between the PCS symptoms and the potential associated visual dysfunctions has not been fully studied.

Examining visual functions in PCS and accounting for the time since injury could contribute to a better understanding of the condition. Also, examining a broader range of visual functions in PCS could help explain the presence of other deficits that rely on vision such as vestibular and balance deficits. If the vision dysfunctions due to PCS help explain some of the other deficits associated with PCS then vision tests could be implemented in conjunction with other behavioural tests to provide better care to the PCS population.

In addition to the population and time since injury challenges identified above, there are some more specific challenges that researchers need to be aware of when they conduct vision research in the PCS population. These challenges are as follows:

1) There is a lack for objective and validated tests that examine specific functions such as light sensitivity which is one of the vision related symptoms associated with PCS.[36]
2) The current eye exam protocols consist of traditional visual function tests such as visual acuity, contrast sensitivity, and binocular vision tests; however, these protocols do not include novel and newly established tests such as dynamic visual acuity and visual-motor reaction time, which provide additional insight about the integrity of the brain function, but are not normally conducted in a routine eye exam.
3) As many tests such as dynamic visual acuity and visual-motor reaction time have not been studied in individuals with PCS, it is unknown how these tests will relate to the more traditional test battery, or if these tests can be done in the PCS population without provoking symptoms. Therefore, there is a need to develop test battery for the PCS population that is both applicable (measures all that is relevant) and feasible (can be completed).

4) Considering that PCS individuals experience a myriad of symptoms, they seek treatments from different clinicians such as general practitioners and physiotherapists. These treatments, whether they are medications (i.e. antidepressants) or therapy protocols (i.e. vision training) could have an effect on visual functions.[37,38] Thus, it would be better if these treatments were controlled or at least accounted for as variable in study designs.

The current study will address some of these challenges as discussed in the study objectives.

1.9 Overall objective

The overall objective of this study is to determine if the visual dysfunctions associated with PCS can be measured using a comprehensive visual function test battery. Additionally, this study will determine if the visual dysfunctions associated with PCS are related to persistent post-injury symptoms. Ultimately this study will help to inform whether or not the visual dysfunctions associated with PCS have the potential to be used as objective markers of PCS recovery.

1.9.1 Research objectives

1) To apply a comprehensive visual function test battery in both control and PCS individuals.
2) To compare performance on the comprehensive visual function test battery in control and PCS individuals.
3) To determine if performance on the comprehensive visual function test battery is in any way related to the symptoms that individuals with PCS experience.

1.9.2 Research hypotheses

1) The applied visual function testing protocol will be feasible (i.e. all tests will be able to be completed in all participants) in both the control and the PCS groups.
2) The PCS group will possess marked visual dysfunctions compared to the control group.
3) Performance on the visual function test battery will be worse in PCS individuals with more symptoms.

Chapter 2 - Methods

2.1 Study design

This observational/exploratory cohort study was primarily designed to determine the difference between PCS and control groups using a comprehensive visual function test battery. This study received ethics clearance from the Office of Research Ethics at the University of Waterloo (ORE# 20279).

2.2 Study participants

Forty-four participants between 18 - 35 year of age were recruited. The study participant groups are as follows: 1) Healthy participants with no history of concussion (Controls; n=33), and 2) Participants with PCS (n=11). One PCS participant was excluded from data analysis for not meeting the inclusion criteria, therefore (n=10) participants were included in the PCS group for analysis purposes. Participants were recruited from the University of Waterloo (UW), Wilfrid Laurier University (WLU), UW Varsity Athletics, WLU Varsity Athletics, and the Kitchener-Waterloo residential community.

2.2.1 Inclusion / Exclusion criteria of the control group

2.2.1.1 Inclusion

1) 18 - 35 years old
2) Consent of participation

2.2.1.2 Exclusion

1) A history of concussion
2) Any self-reported history of an eye problem that had an impact on the participant's vision such as glaucoma
3) Presence of a manifest binocular vision disorder such as amblyopia, nystagmus, strabismus

2.2.2 Inclusion / Exclusion criteria of the PCS group

2.2.2.1 Inclusion

1) 18 - 35 years old
2) Consent of participation
3) A history of concussion
4) A minimum of three persisted concussion symptoms 30 days after the most recent concussion

The examiner will attempt to recruit individuals in both the control and PCS groups who have similar sport backgrounds and/or physical activity levels if possible.

2.2.2.2 Exclusion

1) Any self-reported history of an eye problem that had an impact on the participant's vision such as glaucoma
2) Presence of a manifest binocular vision disorder (i.e. amblyopia, nystagmus, strabismus) that occurred before the most recent sustained concussion

2.3 Study protocol

Participants successfully completed two study visits separated by 2 - 7 days. Standardizing the days between the study visits was particularly important for the PCS group because the time between visits needed to be long enough for participants to recuperate from any symptom provocation that occurred during the study visit, without being so long that substantial injury recovery could occur. The length of the study visits was about 1 hour and 20 minutes for visit 1 and 45 to 60 minutes (1 hour) for visit 2. The tests performed as part of the comprehensive visual function test battery are listed below in (Table 2-1). More detail on how the tests were specifically conducted is available in Section 2.4, Visual function tests.

The comprehensive visual function test battery was designed based on an in-depth review of the literature. The test battery included assessments of all of the most commonly reported TBI-associated visual dysfunctions (e.g. accommodation tests), as well as a few additional novel

tests (such as dynamic visual acuity), which were thought to have potential for quantifying visual dysfunctions in the PCS population.

Table 2-1: Visual function tests conducted in each visit; tests are listed in the order they were completed for all participants

Visit 1	**Visit 2**
Visual Function Tests • King-Devick test • Static distance visual acuity test • Static near visual acuity test • Distance ocular alignment tests • Near ocular alignment tests • Contrast sensitivity test • Ocular motility test • Stereopsis test • Accommodation accuracy test • Cyclopean eye alignment position test • Amplitude of accommodation test • Near point of convergence test • Distance fusional reserve tests • Near fusional reserve tests • Negative and positive relative accommodation tests • Accommodative facility test • Vergence facility test • Objective refraction test	**Visual Function Tests** • Dynamic visual acuity tests • Visual-motor reaction time tests • Coincidence anticipation timing tests Additional tests (not included in the thesis): • Vestibulo-Ocular Motor Screening test (VOMS)

2.3.1 Study health history questionnaires

In the first study visit, all participants had to complete two health history questionnaires. The first health history questionnaire included questions about sports activities, history of concussions, and current symptoms. Control participants were asked to skip concussion related questions. The second questionnaire was an ocular health history questionnaire that included questions about eye diseases, family ocular health history, and vision training. Moreover, PCS participants had to complete an additional third questionnaire to gather more information specifically about their concussion injuries. A copy of all three questionnaires can be found in Appendix A.

In the second visit, participants were asked to repeat the current symptoms section of the first health questionnaire. This was done in order to look at the relationship between the reported symptoms and the visual function in each visit.

2.4 Visual function tests

All tests were performed under full room illumination (400 lux) unless indicated otherwise. Also, all tests were performed with participants' habitual vision. In other words, participants were asked to wear their current refractive correction (if they had one). For all monocular tests, right eye (OD) and left eye (OS) were tested, respectively. If a binocular test was performed, then both eyes (OU) were tested after the OS. All tests were done while the participant was comfortably seated except for coincidence anticipation timing and visual-motor reaction time, which were done with the participant standing.

2.4.1 Static visual perception

2.4.1.1 Visual acuity

Visual acuity (VA) is defined as the ability of the eye to detect fine details.[39] It is the most commonly used measurement in the assessment of the visual perception. Visual acuity is an indicator of the presence of ocular diseases that affect the central retina or its representation in the visual pathway and uncorrected refractive errors. Visual acuity can be used to monitor the progression of certain ocular diseases and to monitor the effectiveness of prescribed medication.[39]

Habitual static visual acuity was measured for all participants at distance (4m) and at near (40cm) both monocularly and binocularly.

2.4.1.1.1 Static distance visual acuity (Visit 1)

In 1982, Ferris et al. developed the Early Treatment Diabetic Retinopathy Study chart (EDTRS chart).[40] It is considered as one of the most precise methods to score VA and it is widely used in research settings. The EDTRS chart was designed based on the 0.1 logMAR progression of letter size suggested by Bailey and Lovie in 1976.[41] Each line of the EDTRS chart has a step size of 0.1 and five letters. This means each letter has an equal weight of 0.02 logMAR, which is the value of the step size divided by the number of letters.[40] Thus, per-letter VA scoring of the EDTRS chart is precise and effective for clinical research.[41]

Static distance visual acuity was measured using a set of EDTRS charts. The charts were placed at 4 m from the participant. The luminance on the chart was set to be 320 cd^2/m. The test was performed monocularly then binocularly, each test being done with a different letter chart. Then, VA was calculated with a per-letter scoring system using the following formula:

VA = the number of the lowest line – (-0.02 X number of wrong answers).

The mean static distance VA for (20 - 49) years old adult is -0.14 logMAR with a range of -0.02 to -0.26 logMAR.[39,42]

2.4.1.1.2 Static near visual acuity (Visit 1)

Near visual acuity can be measured with various types of near charts such as continuous near text charts.[39] Many scientists have suggested that continuous text near charts are effective tools for measuring near visual acuity as it relates to everyday tasks because continuous text charts mimic, in a controlled way, commonly used reading materials.[43,44]

Near visual acuity was measured using the Lighthouse Continuous Text Card - Bee chart at a test distance of 40 cm. The card consists of simple sentences designed in lines. The acuity ranged from 8.0 to 0.4 M units, which is the text size unit. Monocular and binocular VA tests were performed and the results were recorded as the acuity level in M units of the smallest line the participant was able to read.

2.4.1.2 Contrast sensitivity (Visit 1)

Contrast sensitivity (CS) is a crucial test for the assessment of visual function. In the real-world, we see objects in different contrasts, not just black and white. Thus, the CS test provides useful information about real-world vision that is not provided by the VA test. Moreover, the CS test is sensitive enough to detect subtle vision changes or losses as is the case in post-refractive surgery and multiple sclerosis patients.[39,45,46] Therefore, assessment of CS has become standard in many clinical research studies.

CS was measured using the Pelli-Robson letter contrast sensitivity chart at a 1 m test distance while participants were comfortably seated. The luminance on the chart was set to be 120cd^2/m. CS was measured binocularly, and the test score was recorded on the Pelli-Robson recording sheet in CS log units. In normal, healthy 20 to 50 years old adults, CS should be 1.80 logCS or greater.[39,47]

2.4.2 Dynamic visual perception

2.4.2.1 Dynamic visual acuity (Visit 2)

In this study, moV& (V&mp Vision Suite, Waterloo, Canada), a specific dynamic visual acuity test was performed for all participants. This test was developed and validated in the Vision & Motor Performance Lab at the School of Optometry and Vision Science at the University of Waterloo, and has been shown to demonstrate good test - retest repeatability.[48,49]

DVA was measured binocularly using a Tumbling E target presented on an LED monitor screen 4 m away from the participant. In this test, three different DVA motion types were used: 1) random motion, where the target moved on the screen in a Brownian motion type pattern to ensure that the target path was unpredictable, 2) horizontal motion, where the target crossed the center of the screen horizontally from left to right, and 3) jitter motion, where the target was presented at the centre of the screen and quickly shifted in all directions around the centre.

The maximum VA, or starting place for the test, was set to be 0.4 logMAR larger than participants' static VA. The letter speed was 1 m/s for the random and horizontal motions, and the minimum jitter standard deviation was 1 mm. The target exposure time was a maximum of

20 sec. display time for all motion types. Dynamic visual acuity was measured in logMAR using a per-letter scoring system. Data were electronically recorded and saved to excel sheets.

2.4.3 Refractive status

2.4.3.1 Objective refraction (Visit 1)

Objective refraction test provides an insight about the eye's refractive status. The test provides a primary measurement of the eye's refractive error that can be refined later with a subjective refraction.[39] In this study, an auto-refractor was used to determine the objective refractive status. Then, the spherical equivalent was calculated for the OD and OS (right and left eyes, respectively) with the following formula:

$$\text{Spherical equivalent} = \text{spherical power} + (0.5 * \text{cylindrical power})$$

2.4.4 Binocular vision

2.4.4.1 Ocular alignment (Visit 1)

The cover test is a routine binocular vision test that determines the presence, type, direction, and amount of any ocular misalignment. There are two types of the ocular misalignment: 1) Tropia (manifest misalignment) which also called squint, or strabismus, and 2) Phoria (hidden misalignemt). In the presence of an ocular misalignment, an eye can deviate inward (eso), outward (exo), upward (hyper), or downward (hypo). There are three basic types of the cover test as follows: the unilateral cover test which determines the presence of tropia, the alternating cover test which determines the presence of phoria in the absence of a positive result on the unilateral cover test (i.e. no tropia), and the simultaneous prism cover test which determines the amount of the misalignment.[39,50] In this study, all of these tests were conducted in: primary, left, and right gazes at distance (4m) and near (40cm).

For distance and near cover tests, the targets used were one line better than the participant's best static VA. Unilateral and alternating cover tests were conducted, respectively. If a deviation was found, the simultaneous cover test was done using prism bars. Results were recorded as the type and amount of deviation determined in prism diopters (PD), or as (Ortho) if no deviation was found.

2.4.4.2 Ocular motility (Visit 1)

Ocular motility testing, or the Broad H test, provides insight into the integrity of the six extra-ocular muscles and their nerve supply.[39] During this test, participants were asked to track a moving target with their eyes while the examiner watches the eyes to observe for any irregular eye movements. The target used in this test was a black (z) letter, printed in 14-point font size on white paper and glued to a stick that was held at a 40cm test distance. The examiner moved the target into the six cardinal gaze positions (in the form of an (H) shape) while observing the participants' eye movements. Any irregular eye movements in the form of jerky eye movements, overactions, or underactions were recorded with the accompanied position of gaze.

A scale of -1 (lowest) to -4 (greatest) was given to mark the degree of underaction of the eye movements. Conversely, a scale of +1 (lowest) to +4 (greatest) was given to mark the degree of overaction of the eye movements. If there was no underaction or overaction of the eye movements, a score of 0 was given. Reported symptoms such as double vision or discomfort in any of the six-cardinal positions were also recorded.

2.4.4.3 Stereopsis (Visit 1)

Stereopsis, or depth perception, is a fundamental component of binocular vision. Under normal binocular viewing conditions, the visual system captures two images (one from each eye). These two images are slightly different due to the fact that the human eyes are separated horizontally. The outcome of this disparity is binocularly detectable patterns and perceived depth.[51] Stereopsis measures the ability of the visual system to combine the two monocular images to form a single three-dimensional, binocular view of the environment.[51,52] There are two stereopsis mechanisms in the visual system; local and global stereopsis.[51] Local stereopsis depends on horizontally separated patterns that are detectable with monocular viewing. Global stereopsis is a binocularly detectable pattern that cannot be detected when viewed monocularly.

Global and local stereopsis were measured in this study using the Randot stereo-acuity test at 40 cm. The test was repeated three times and the average stereopsis was calculated in seconds of arc.

2.4.4.4 Accommodative function

2.4.4.4.1 Amplitude of accommodation (Visit 1)

Accommodation is the ability of the eye to obtain focus on targets over a large range of distances. Amplitude of accommodation (AA) is a visual function that normally decreases with age.[39,53] There are several techniques to quantify AA and it is measured in diopter units (D).

The pull-away technique was used in this study and values were measured with the Royal Air Force (RAF) rule. The RAF rule is a standard tool for measuring near visual functions such as accommodation. It consists of 50 cm rule with a movable and rotatable cube. The cube has four sides each with different viewing targets. For this test, the chosen target was one line better than the participant's near VA. Initially, the participant was asked to close both eyes. The eye not being tested was covered with an eye patch. Then, the target was placed close to the participant's eyes, in front of the eye being tested. After that, the participant was asked to open the uncovered eye and look at the target; if the target was blurry it was pulled away until the participant reported the target was clear. The distance from the participant to the target was measured and recorded as the test endpoint in dioptric units. The test was conducted monocularly and repeated three times for each eye.

The minimum AA expected based on age was calculated using the Duane-Hofstetter formula: minimum AA= 15.0 – 0.25 x age. Then, the resultant AA value was calculated by subtracting the minimum AA expected based on age from the participant's average measured AA. If the total was positive that indicated better AA average than expected for the participant's age and vice versa. Additionally, the monocular difference in accommodation between the two eyes was measured by calculating the absolute difference of the AA (|OD – OS|). This method was followed since there is a lack of established normative data on the pull-away technique in the literature to rely on.

2.4.4.4.2 Accommodation accuracy (Visit 1)

In daily life activities, accommodation of the eyes is needed to perform different near tasks such as reading and writing. For these kinds of tasks, some eyes exert more accommodation (lead) than needed, while others produce an insufficient amount of accommodation (lag).

Accommodation accuracy is an eye test that determines the individual's accommodative posture when performing a near task.[39,50]

Accommodation accuracy can be tested with different methods. In this study, the Monocular Estimated Method (MEM) was conducted using a Welch Allyn fixation card attached to a retinoscope at the examiner's working distance of 54 cm. Room lighting was decreased by two-thirds for all participants to allow for better observation of the light reflection in the eye being tested while ensuring participants could still view the words on the card. Participants were asked to read the words on the card out loud, while the examiner performed MEM retinoscopy and neutralised the retinal reflex seen. The result was recorded as the dioptric power of the lens needed to neutralize the light reflex in each eye. A plus value indicated a lag of accommodation and a minus value indicated lead of accommodation. Additionally, the monocular difference in accommodation accuracy between the two eyes was measured by calculating the absolute difference of the accommodation accuracy (|OD – OS|).

2.4.4.4.3 Accommodation facility (Visit 1)

An individual's ability to rapidly change focus is called accommodation facility (AF). This characteristic has been determined to be related to other vision symptoms especially those associated with near tasks.[39] Scientists have concluded that accommodation facility is an independent measure which means 'accommodation infacility' can occur even with normal results on other accommodation tests.[39]

A $\pm$ 2.00 diopter lens flipper was used in this test. Participants were instructed to place the Bee near VA chart at a 40 cm distance and focus on the line above their best near VA. Participants were instructed to try to make the target clear when one of the lenses was placed in front of the eye, and report when the target was clear by saying 'clear'. Then, the lenses were "flipped" and the opposite lens was presented. The process continued for one minute and the number of cycles completed was recorded. A cycle was counted when the participants report a clear target for both lenses. This test was performed monocularly. Each eye was tested three times and the average was calculated and recorded in cycles per minute (cpm) units. Additionally, the monocular difference between the two eyes was measured by calculating the absolute average facility difference (|OD – OS|).

2.4.4.4.4 Negative relative accommodation (NRA) and positive relative accommodation (PRA) (Visit 1)

Negative and positive relative accommodation tests determine the accommodation range of the individual relative to their vergence function.[54] Along with other accommodation tests, NRA and PRA give insight into the accommodation system and its function.[54,55] Individual's ability to relax accommodation is examined with NRA and PRA tests the individual's ability to exert accommodation.[54]

The target used in this test was one line better than the participant's near VA using the near Bee VA chart at 40 cm. First, the NRA test was performed with a plus lens bar placed in front of the participant's eyes to avoid the influence of accommodation on the measurement. Participants were asked to keep the target clear while examiner gradually increased the power of the lenses and to report when the target was blurry. Then, the PRA test was performed with a negative lens bar and the same instructions were given. The PRA and NRA test results were recorded as the dioptric power of the first lens that caused sustained blur.

2.4.4.5 Vergence function

2.4.4.5.1 Near point of convergence (Visit 1)

Vergence is a voluntary eye movement. It involves either a convergence or a divergence of the eyes' visual axes to maintain a single image while focusing on a near or distance target.[39,50] When performing a near task, three ocular responses take place; convergence, accommodation, and pupil constriction.[39,50] The near point of convergence (NPC) is the point where the visual axes intersect under the maximum effort of convergence while maintaining single vision.[39,50]

In this study, the RAF rule was used to measure NPC. The target was a vertical line with a central black dot. Participants were asked to focus on the black dot and report when the dot split into two or went double (break point), and then when the black dot became single again (recovery point). The break point was measured when either the participant reported seeing the black dot doubled (subjective NPC) or when the examiner observed the eye drifted out (objective NPC); the recovery point was measured when the participant reported seeing the

black dot single again. Break and recovery points were measured in centimeters (cm). The test was repeated three times and the average was calculated. Also, the difference between the two points was calculated (recovery point - break point).

In the literature, there is diversity around the normative data for NPC based on the population studied and the target used when testing NPC.[39,50,56,57] There tends to be an agreement that NPC in adults should be about 7 cm and 10 cm for break and recovery points, respectively.

2.4.4.5.2 Fusional reserve (Visit 1)

Fusional reserve (FR) is also known as fusional amplitude, and is the amount of prism power the eyes can tolerate while still maintaining single vision before fusion breaks, resulting in double vision.[39,50] Fusional reserve can be assessed at distance and at near, both horizontally (H) and vertically (V). The ability of the eyes to overcome the power of base-out or base-up prism over the right eye is known as positive fusional reserve (PFR). Negative fusional reserve (NFR) is obtained with base-in or base-down prism over the right eye.[39,50]

This test was performed binocularly using hand-held prism bars to introduce prisms in front of one eye. Distance (6m) PFR and NFR were measured using the 6/12 line of the EDTRS chart printed on A4 paper as a target. Near (40cm) PFR and NFR were measured using isolated lines of a near Hart card (approximately 0.50 M size). The FR assessment was conducted both horizontally and vertically at both distances. A vertical target was used for the horizontal FR testing and a horizontal target was used for the vertical FR testing. Participants were instructed to look at the target and report when it got blurry, double, and single again. The resultant prism in front of the eye at each point (blur, double, and single) was recorded in prism diopters (PD).

2.4.4.5.3 Vergence facility (Visit 1)

As described earlier, there are two types of vergence eye movements: convergence and divergence. Tests of vergence facility are designed to examine the ability of the vergence system to perform rapid convergence and divergence eye movements over a specific period of time.[39,50] This test is conducted by placing prisms of different powers and base directions in front of one eye (under binocular conditions) to stimulate the two different vergence eye movements.

In addition to the fusional reserves vergence test, vergence facility testing is useful in diagnosing binocular vision problems.[39,50]

A 3 base-in / 12 base-out prism flipper was used in this study, and the target was an isolated vertical line from a near Hart chart card at a 40 cm distance. The test began with placing the 3 base-in prism in front of the right eye. Participants were asked to report if the target was seen as one, by saying 'single'; if the target was seen as double, participants were encouraged to try and make it single, and then to report when it was single. Once the target was seen as single with the 3 base-in prism in place, then a 12 base-out prism was introduced and the participant was asked to indicate when the line was single again. The test continued for one minute, and successful target fusion of both prisms was considered as one cycle; the number of completed cycles was recorded. The test was repeated three times and the average was calculated and recorded in cycles per minute (cpm) units.

2.4.5 Global visual function

2.4.5.1 Visual spatial awareness - cyclopean eye alignment position (Visit 1)

Conventionally, binocular visual direction was believed to be the average of the visual direction from both eyes. Currently, scientists determined that binocular visual direction originates from a reference point that falls midway between the eyes; the cyclopean eye (CE).[58–60] In other words, the CE provides a unified visual direction using the information from both eyes. The assessment of visual direction is important because individuals with head injuries have demonstrated shifts in their perceptions of visual direction.[61]

A rod with a 50 cm length and a 4 mm diameter was placed 50 cm from the bridge of the participant's nose. The rod was rotated from the participant's right side on the 180 plane (Figure 2-1),[58] and the participant was asked to say 'stop' when the rod was centred. Then, a picture was taken from above the instrument to determine the visual direction angle; however, after testing a few participants the examiner noted that the measurement could be improved. Therefore, a printed protractor was centred underneath the rod to specify the visual direction angle. The test was repeated three times and the average was calculated in degree units.

Figure 2-1: Cyclopean eye alignment position instrument

2.4.5.2 King-Devick (Visit 1)

The King-Devick (KD) test is a neuropsychological test that is based on measuring the speed of rapid number naming. The KD test examines suboptimal brain function by detecting deficits of language, eye movements, and attention.[62,34] Research studies determined that the KD test is a useful tool for concussion screening.[62,34] In this study, a software version of the KD test was used on an iPad (Figure 2-2). The KD test consists of three cards of numbers arranged in different configurations. Participants were asked to hold the iPad at a distance of 40 cm and read each of the three test cards as fast and accurate as possible. The total time to read all three cards was automatically measured by the iPad and recorded on the testing sheet. The number of errors participants made was also recorded. Errors were based on participant's first response, and an error was recorded if the participant skiped or misnamed a number.

Figure 2-2: King-Devick (KD) test on iPad

2.4.5.3 Visual motor integration

2.4.5.3.1 Visual-motor reaction time (Visit 2)

Visual-motor reaction time (VMRT) is defined as the time the visual system requires to process a visual stimulus plus the time needed from the neuromuscular motor system to give a motor response for that particular stimulus.[63]

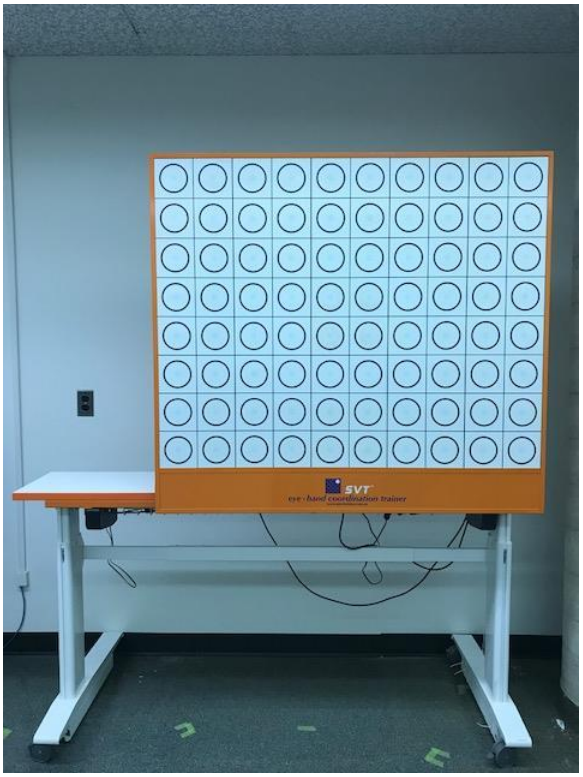
In this study, an eye-hand reaction time test was used to assess the VMRT. Despite the fact that eye-hand coordination has been studied in different contexts such as sports, there is a lack of a standardized and validated tools to examine eye-hand reaction time.[64] The Sports Vision Trainer (SVT) is a tool that has been developed by scientists at The New South Wales Institute of Sport in Sydney, Australia to measure eye-hand reaction time (Figure 2-3).[65] Scientists have established the test-retest reliability of the specific SVT protocol that was followed in this study.[64]

The SVT board is about 114 cm height and 125 cm width, and rests on a height adjustable table. The board consists of a matrix of 80 circular lights targets. Each light target consists of a touch pad (2 cm diameter), centered in a circle (8 cm diameter).

Participants were asked to stand in front of the reaction time board at a distance where they could easily reach the side, lower, and upper lights. The board's height was then adjusted to be in line with the participant's eye level in primary gaze.

The test was run in proactive mode, which means the light stayed on the board until the participant responded by hitting it. Central and peripheral reaction times were each assessed with 4 trials (one practice and three test trials). The lights were shuffled before starting each trial so the lights appeared in a randomized manner. The total reaction time was recorded in milliseconds (ms) for each trial. The average reaction time per light was calculated based on the three test trials only (ignoring the practice trial). All results were automatically saved by the SVT software and exported for analysis.

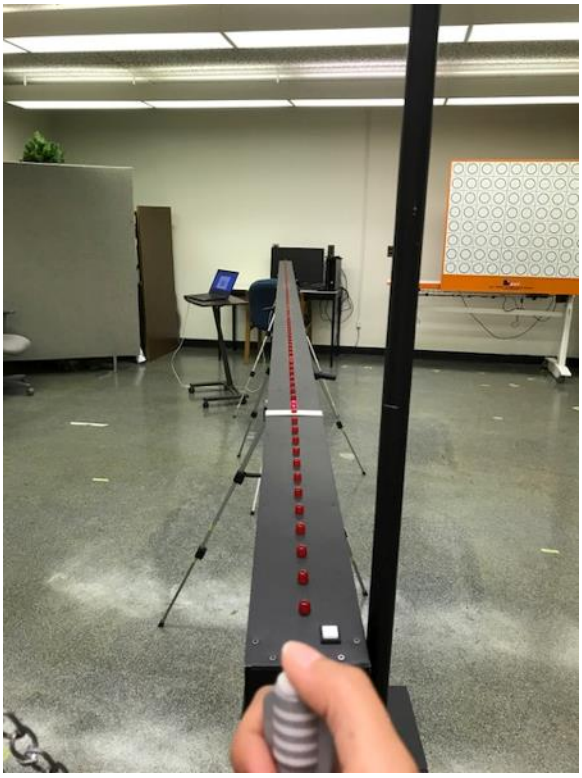
Figure 2-3: Sports Vision Trainer (SVT)



2.4.5.3.2 Coincidence anticipation timing (Visit 2)

Coincidence anticipation timing (CAT) is defined as the ability to judge when a moving object will arrive at a designated point.[63,66] CAT is a cognitive task that incorporates different parts of the brain to deliver the required response.[63,66–68] The task involves a combination of visual input processing, decision making, and motor response delivery.[66–68] Hence, it has the potential to provide significant insight into both brain function and cognitive capability.[66] The Bassin Anticipation Timer (BAT) is a common application used in clinical research to assess coincidence anticipation timing. The BAT consists of a long track of light-emitting diodes (LEDs) that can be programmed to travel at different speeds and trajectories (i.e. constant motion or acceleration).[63]

Figure 2-4: Bassin Anticipation Timer (BAT)



Participants were asked to respond by pressing a button when they thought the light would arrive at a specific location on the track. For this study, the test was designed so that the light traveled with a constant motion at speeds ranging from 5mph to 40mph (in 5mph steps). Each

speed presentation was repeated for 5 trials before the next speed was presented. The 5 repeated trials were used to compute 3 different average error values as follows: 1) Constant error (CE) which provided a measure of how early (positive value) or late (negative value) the participant tended to respond on average, 2) Absolute error (AE) which was an average of the absolute error magnitude, and 3) Variable error (VE) which provided a measure of the average variability of the accuracy values across all 5 trials.

2.5 Statistical analysis

Overall, normal distribution of the data was tested using the Shapiro-Wilk test with SPSS analysis software (Version 25, New York, USA). The data was not normally distributed in the majority of tests; therefore, non-parametric analysis tests were chosen. All data were analyzed using non-parametric analyses, and no additional data transformations were performed on the data that was normally distributed prior to analysis.

2.5.1 Descriptive statistics and group comparison

The study data was presented as the descriptive statistics (mean, standard deviation (SD), and median) of each visual function for each group. Descriptive statistics were calculated with Microsoft Office Excel software (Version 16.16.2, Redmond, USA). Additionally, scatter plots were presented for visual inspection of all the data. All scatter plots were graphed using GraphPad Prism software (Version 7.0d, La Jolla, USA), and all the correlation plots were graphed using RStudio (Version 1.1.456, Boston, USA).

A Mann Whitney U-test was conducted to identify the difference in symptoms and visual functions between the two groups using SPSS. Statistical test results were presented as level of significance represented by the p-value. All p-values <0.05 were considered to be significant.

2.5.2 Correlation analysis

A Spearman non-parametric correlation test was conducted with SPSS to examine the correlation between symptom severity and visual functions in both study groups. Correlations were considered to be significant when the p-value was <0.05.

Chapter 3 - Results: Comparison of Control and PCS groups

3.1 Sample

Forty-four participants aged 18 to 35 years old were recruited for, and successfully completed the two study visits. The study participant groups are as follows: 1) Healthy participants with no history of concussion (Controls; n=33), and 2) Participants with PCS (n=11). One PCS participant was excluded from data analysis for not meeting the inclusion criteria, therefore (n=10) participants were included in the PCS group for analysis purposes. All PCS participants were athletes who played recreational sports (n=3) or varsity sports (n=7). Sixteen control participants were athletes, and all but one of these participants played recreational sports. The remaining 17 control participants did not play any sports (Table 3-1).

3.2 Test battery feasibility

The test battery appears to be feasible in both the control and PCS group. All participants successfully completed all of the tests in the battery and the two study visits and no participants withdrew from the study. While all of the participants enrolled in the study were able to complete the test battery, many of the PCS participants took more time than expected to complete the battery because their symptoms were exacerbated by some of the tests conducted. While this finding suggests that the test battery was not actually feasible in the PCS population, the examiner would disagree, because the symptom exacerbation triggered by certain tests in the battery is an interesting finding of itself. The PCS participant's symptom exacerbation during testing will be discussed further in Section 4.7.

3.3 Health history questionnaire

As mentioned in the Methods chapter, participants were asked to complete health history questionnaires to gain an insight on the participants' well-being, activity levels, and symptoms on the days of testing. For the purpose of this thesis, the number of symptoms reported, the severity of symptoms reported, and the number of previous concussions (in the PCS group only) were examined (Tables 3-2 and 3-3). Overall, participants were healthy; no participants reported a history of an eye problem or manifest binocular vision problem that would have excluded them from participation in this study.

Table 3-1: Overview of demographic data of the control and PCS group

<table>
<tr><th>Group</th><th colspan="2">Controls (n=33)</th><th>PCS (n=10)</th></tr>
<tr><td>Gender</td><td colspan="2">Females (n= 19)
Males (n=14)</td><td>Females (n=5)
Males (n=5)</td></tr>
<tr><td>Age</td><td colspan="2">23 ± 3.8</td><td>24 ± 3.1</td></tr>
<tr><td>Athletic background</td><td colspan="2">Non-athletes (n=16)
Athletes (n=17)</td><td>Athletes (n=10)</td></tr>
<tr><td rowspan="3">Level and type of sports</td><td colspan="2">Recreational sports (n=15)
Badminton, swimming, tennis, Muay Thai, yoga, rock climbing, hockey, baseball, skating, volleyball, and soccer.</td><td>Recreational sports (n=3)
Skiing, soccer, and hockey.</td></tr>
<tr><td colspan="2" rowspan="2">Varsity sports (n=2)
Cricket, field hockey</td><td>Varsity sports (n=6)
Rugby, swimming, badminton, soccer, track and field.</td></tr>
<tr><td>International competitive level (n=1)
Equestrian</td></tr>
<tr><td rowspan="4">Sport practice (hr/week)</td><td>Mean ± SD</td><td>3.8 ± 3.6</td><td rowspan="4">Only 3 PCS participants reported their sport practice (hr/week) as 2,5, and 6, respectively.
One participant reported sport activity cessation since the concussion incident. The rest of the group reported irregular practice based on their symptoms.</td></tr>
<tr><td>Median</td><td>2.5</td></tr>
<tr><td>Minimum</td><td>1</td></tr>
<tr><td>Maximum</td><td>15</td></tr>
</table>

3.3.1 Symptoms

Participant symptoms were assessed using the health history questionnaire in two ways: 1) a total number of symptoms and 2) a symptom severity score. Participants were asked to score their symptoms on a 7-point Likert scale ranging from 0 (no symptoms) to 6 (severe symptoms) based on how they felt “now” at each study visit. Each symptom scored at a value of 1 or more was counted as symptom. The total number of symptoms that could be reported was 22 symptoms. Symptom severity score was calculated by summing up all of the individual severity scores across all 22 symptoms. Symptom severity score had minimum value of 0 and a maximum value of 132 (Table 3-2).

As expected, the PCS group reported more symptoms than the control group at both visits ($p<0.0001$; Table 3-2). The PCS group also reported more severe symptoms than the control group at both visits ($p<0.0001$; Table 3-2). It is interesting to note that, despite the control group not having any history of concussion, some participants in the control group reported experiencing some level of symptoms, as shown in (Table 3-2). While the presence of symptoms in the control group was an interesting finding, it was not unexpected. The symptoms assessed with the health history questionnaire are not concussion specific and it is not uncommon for healthy, non-concussed university students to routinely demonstrate some of these symptoms.

Although the analysis in this study was done considering both symptom measures, number of symptoms and symptom severity scores, the primary measure of participant’s symptoms chosen for the purpose of this thesis was the symptom severity score. From the descriptive statistics presented below (Table 3-2, Figures 3-1 and 3-2), it is obvious that symptom severity values were more prominent in the PCS group. Also, symptom severity appeared to change more between study visits, especially in the PCS group, and the examiner felt that the changes in symptom severity scores better represented participant’s symptoms on each day of testing, which was important for the correlation analysis between symptoms and visual functions. For these reasons, symptom severity was prioritized over the number of symptoms. The examiner recognizes that analyses based on symptom severity are limited to some extent as symptom severity scores are subjective and have a greater scale (score out of 132) than the number of

symptoms (score out of 22), however this was still the metric chosen for use in this particular analysis.

Please note, in all of the tables presented below, p-values marked with a * are significant at least p<0.05. On all the presented scatter plots, ● = control group data, and ▲ = PCS group data, unless specified otherwise.

Table 3-2: Symptom data of the control and PCS group at visits 1 and 2

	Mean	SD	Median	p-value
Number of Symptoms				
Control – visit 1	3.5	4.8	1	<0.0001
PCS – visit 1	13.8	4.6	15	
Control – visit 2	2.8	4.1	1	<0.0001
PCS – visit 2	13.2	6.3	11.5	
Symptom Severity				
Control – visit 1	6.8	11.0	2.0	<0.0001
PCS – visit 1	39.4	24.0	39.5	
Control – visit 2	4.3	6.8	1.0	<0.0001
PCS – visit 2	28.4	21.3	19.5	

Figure 3-1: Symptom severity scatter plot

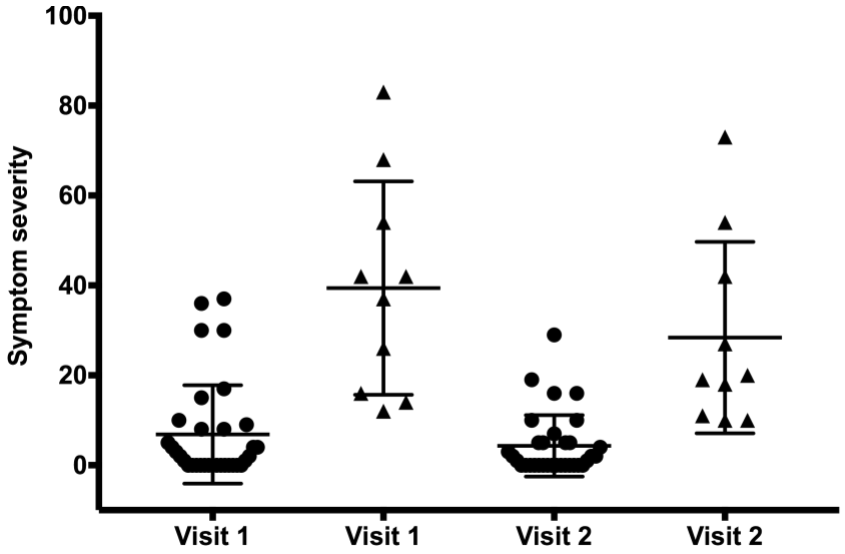
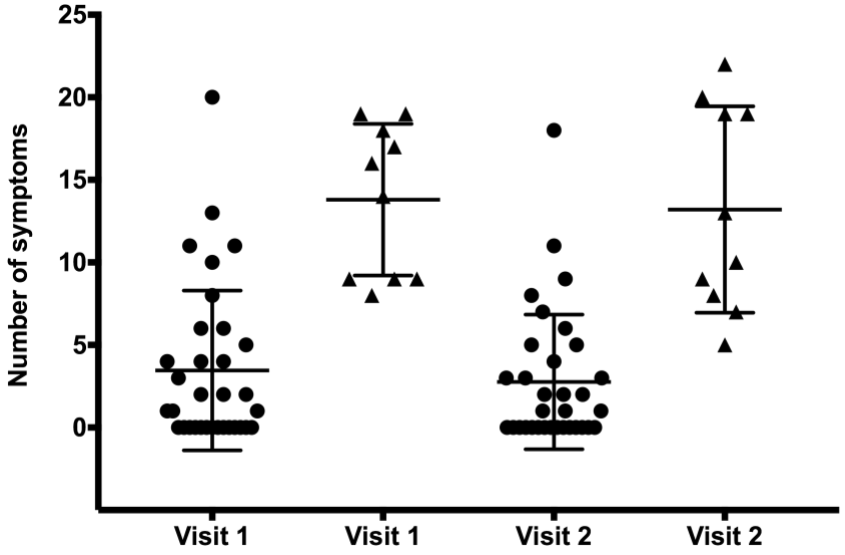


Figure 3-2: Number of symptoms scatter plot



3.3.2 Number of previous concussions (PCS group)

In addition to assessing the number of symptoms participants experienced as well as the severity of symptoms experienced, all participants in the PCS group were asked to report how many previous concussions they had had (Table 3-3). On average participants had 3.9 previous concussions (range 1 to 11 previous concussions).

Table 3-3: Previous concussions data (PCS group)

Mean ± SD	3.9 ± 3.2
Median	2.5
Minimum	1.0
Maximum	11.0

3.4 Comparing visual function between groups

A Mann Whitney U-test was conducted to identify differences in visual function performance between the control and the PCS groups. The p-values of all test comparisons are presented, along with the descriptive statistics (mean, standard deviation (SD), median values) in the tables below. In addition, scatter plots and/or graphs of all tests are presented.

Overall, there was no statistically significant differences in performance between the two groups on any of the visual functions measured except for the following tests: King-Devick test

(p=0.04), cyclopean eye test (p=0.03), and peripheral visual-motor reaction time test (p=0.04). Further information about all of the visual function tests completed is presented in the following sections.

3.4.1 Static visual perception

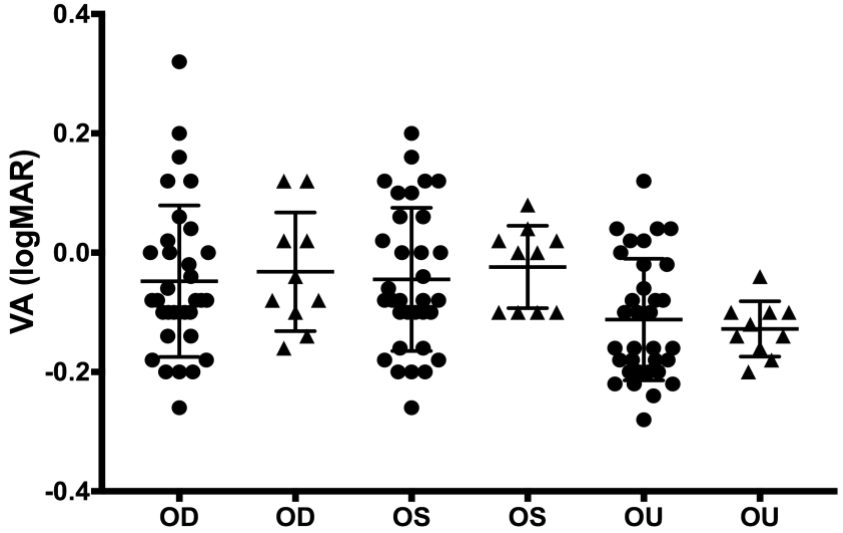
3.4.1.1 Static distance visual acuity

There was no statistically significant difference in static distance visual acuity between the two groups in OD (p=0.54), OS (p=0.64), or OU (p=0.97). Although not compared statistically, the SD values of both groups also appear to be similar for OD, OS, and OU.

Table 3-4: Distance static visual acuity (4m; logMAR)

	Eye tested	Mean	SD	Median	p-value
Control	OD	-0.04	0.13	-0.08	0.54
PCS		-0.03	0.10	-0.06	
Control	OS	-0.04	0.10	-0.08	0.64
PCS		-0.02	0.07	0.00	
Control	OU	-0.11	0.10	-0.16	0.97
PCS		-0.13	0.05	-0.13	

Figure 3-3: Distance static visual acuity scatter plot



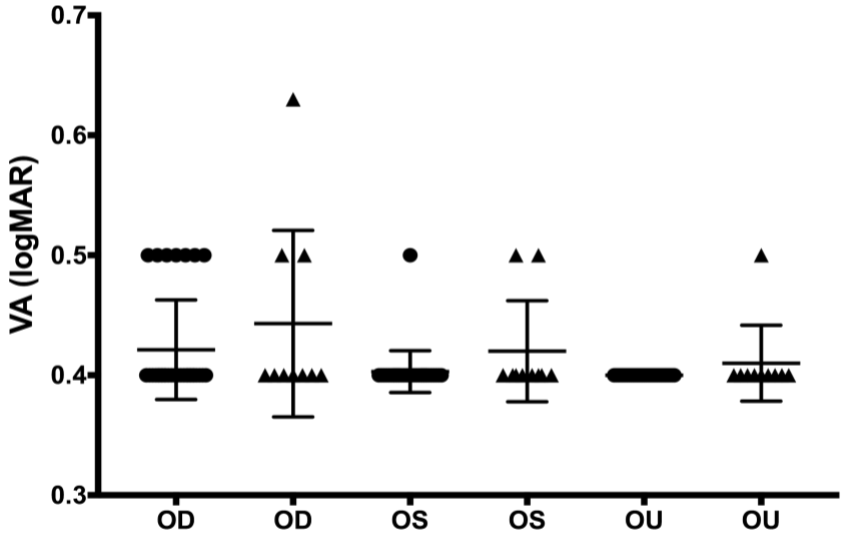
3.4.1.2 Static near visual acuity

There was no statistically significant difference in static near visual acuity between the two groups in OD (p=0.62), OS (p=0.44), or OU (p=0.64). Although not compared statistically, the PCS group's performance appeared to be less consistent than the control group, as demonstrated by the larger SD values. This observation was particularly apparent in the OU data.

Table 3-5: Near static visual acuity (40 cm; M unit)

	Eye tested	Mean	SD	Median	p-value
Control	OD	0.42	0.04	0.40	0.62
PCS		0.44	0.08	0.40	
Control	OS	0.40	0.02	0.40	0.44
PCS		0.42	0.04	0.40	
Control	OU	0.40	0.00	0.40	0.64
PCS		0.41	0.03	0.40	

Figure 3-4: Near static visual acuity scatter plot



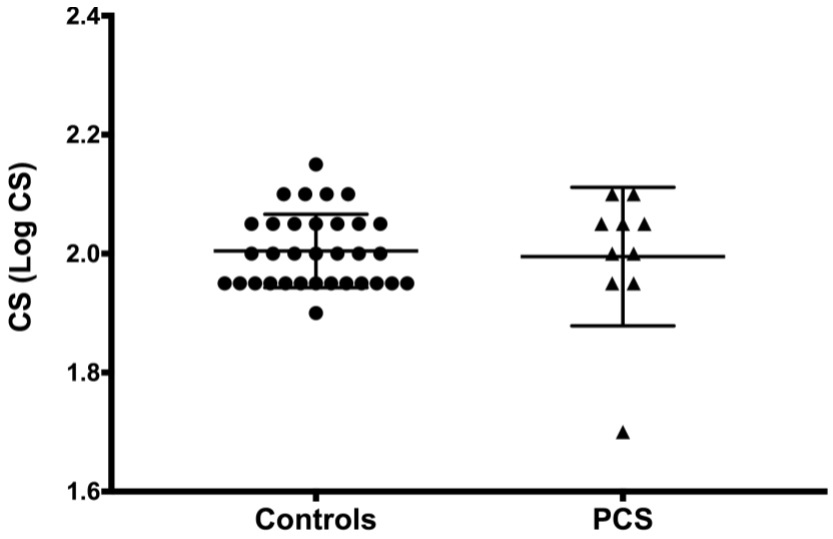
3.4.1.3 Contrast sensitivity

There was no statistically significant difference in the contrast sensitivity between the two groups in contrast sensitivity (p=0.60). Based on visual evaluation there was also no difference between the SD values of both groups.

Table 3-6: Contrast sensitivity (1m; logCS)

	Eye tested	Mean	SD	Median	p-value
Controls	OU	2.00	0.06	1.99	0.60
PCS		1.99	0.11	2.02	

Figure 3-5: Contrast sensitivity scatter plot



3.4.2 Dynamic visual perception

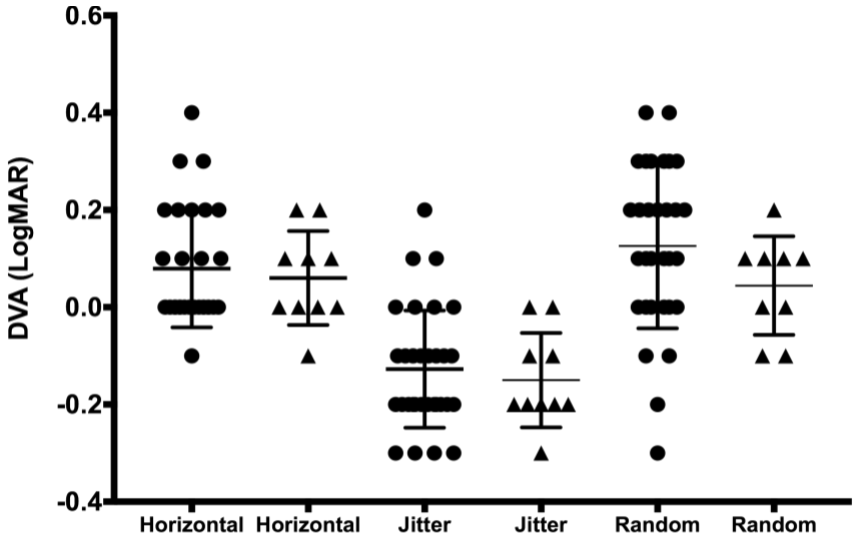
3.4.2.1 Dynamic distance visual acuity

There was no statistically significant difference in the dynamic distance visual acuity between the two groups in horizontal (p=0.89), jitter (p=0.68), and random (p=0.12) motions. The SD values of both groups also appear to be similar based on visual inspection, except for the random motion task on which controls appeared to demonstrate greater variability.

Table 3-7: Dynamic distance visual acuity (4m; logMAR)

	Motion type	Mean	SD	Median	p-value
Controls	Horizontal	0.08	0.12	0.00	0.89
PCS		0.06	0.10	0.05	
Controls	Jitter	-0.13	0.12	-0.10	0.68
PCS		-0.15	0.10	-0.20	
Controls	Random	0.13	0.17	0.10	0.12
PCS		0.04	0.10	0.10	

Figure 3-6: Dynamic distance visual acuity scatter plot



3.4.3 Refractive status

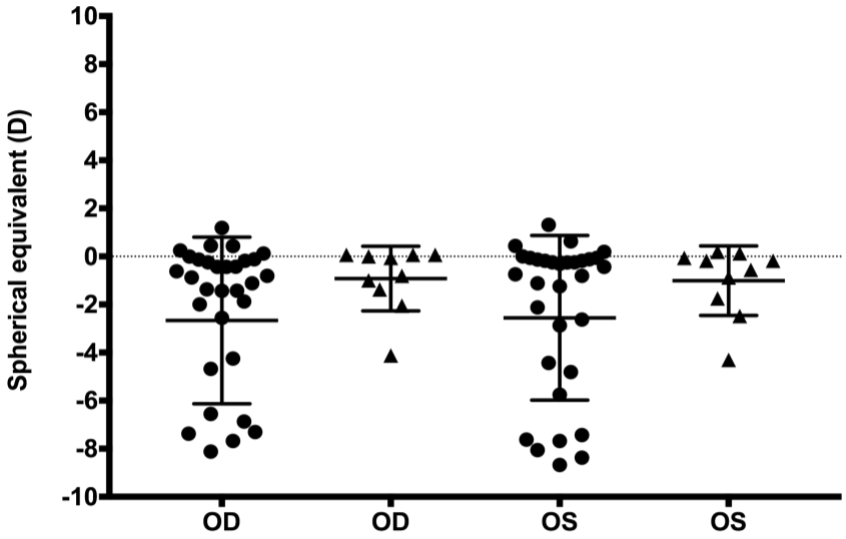
3.4.3.1 Objective refraction

There was no statistically significant difference in the objective refraction spherical equivalent between the two groups in either the right (p=0.20) or left eyes (p=0.37). The lack of statistical difference between the two groups was probably due to the high variability of this parameter in the control group.

Table 3-8: Objective refraction (spherical equivalent; D)

	Eye tested	Mean	SD	Median	p-value
Controls	OD	-2.70	3.50	-1.12	0.20
PCS		-0.92	1.34	-0.44	
Controls	OS	-2.60	3.40	-0.75	0.37
PCS		-1.00	1.45	-0.40	

Figure 3-7: Objective refraction (spherical equivalent) scatter plot



3.4.4 Binocular vision

3.4.4.1 Ocular alignment

For the ocular alignment tests, no tropia (strabismus) was found in either group. The ocular misalignment findings that were present included exophoria (represented by a minus sign), esophoria (represented by a plus sign), or orthophoria (represented by zero).

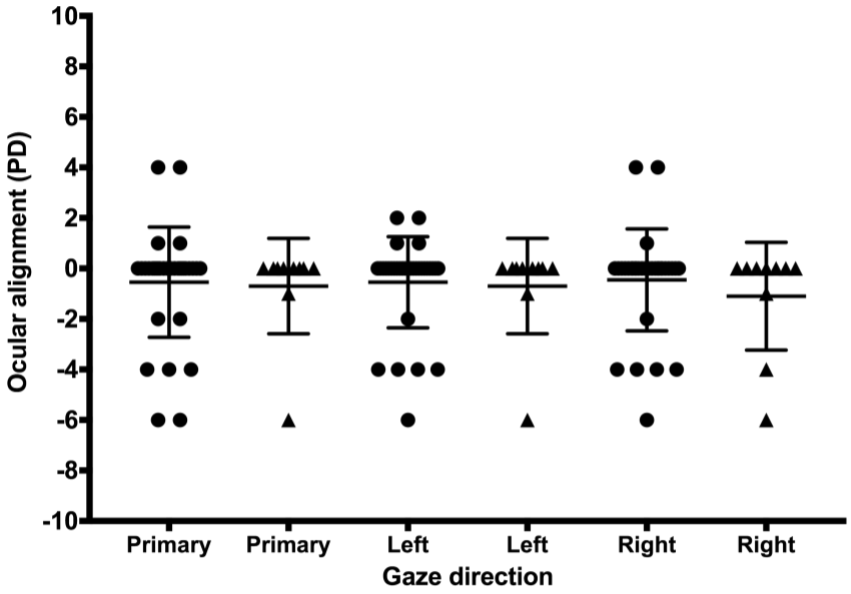
3.4.4.1.1 Distance ocular alignment

There was no statistically significant difference in the mean distance ocular misalignment test between the two groups in primary (p=0.72), left (p=0.60), or right (p=0.40) gazes. Visual observation suggests that both the SD and median values of both groups were also similar.

Table 3-9: Distance ocular alignment (4m; PD)

	Gaze	Mean	SD	Median	p-value
Controls	Primary gaze	-0.6	2.2	0.0	0.72
PCS		-0.7	1.9	0.0	
Controls	Left gaze	-0.6	1.8	0.0	0.60
PCS		-0.7	1.9	0.0	
Controls	Right gaze	-0.5	2.0	0.0	0.40
PCS		-1.1	2.1	0.0	

Figure 3-8: Distance ocular alignment scatter plot



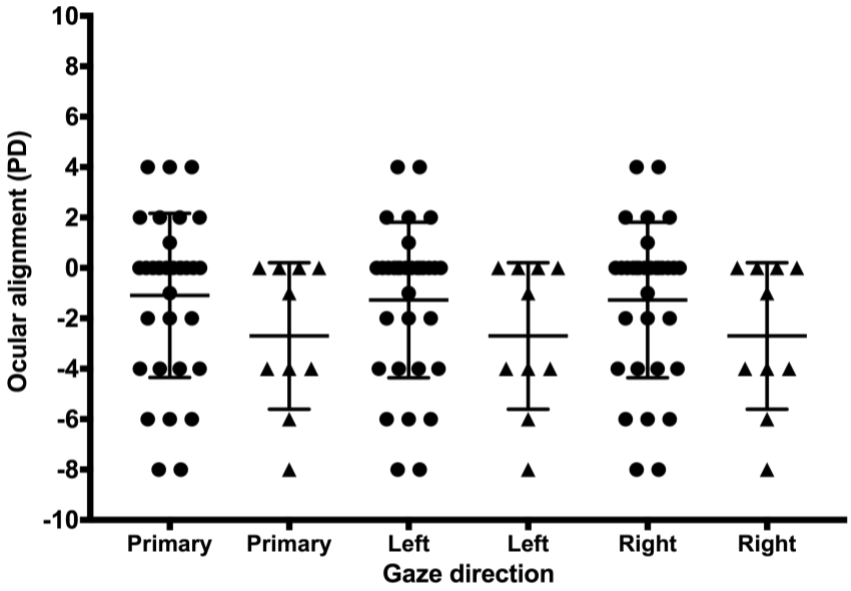
3.4.4.1.2 Near ocular alignment

There was no statistically significant difference in the mean near ocular misalignment test between the two groups in primary (p=0.14), left (p=0.18), or right (p=0.18) gazes. Based on visual inspection, there does not appear to be a difference in SD values between groups, however, visual inspection of the median values suggests that there was more exophoria in the PCS group than the control group in all gazes.

Table 3-10: Near ocular alignment (40cm; PD)

	Gaze	Mean	SD	Median	p-value
Controls	Primary gaze	-1.1	3.3	0.0	0.14
PCS		-2.7	2.9	-2.5	
Controls	Left gaze	-1.3	3.1	0.0	0.18
PCS		-2.7	2.9	-2.5	
Controls	Right gaze	-1.3	3.1	0.0	0.18
PCS		-2.7	2.9	-2.5	

Figure 3-9: Near ocular alignment scatter plot



3.4.4.2 Ocular motility

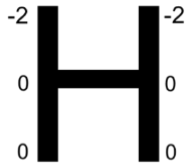
As described in the methods chapter, ocular motility assessment was performed using the Broad H method. All the control participants in addition to seven participants of the PCS group had normal eye movements with no observed abnormalities or reported symptoms. Only three participants from the PCS group had abnormal findings as described in the following sections.

3.4.4.2.1 Participant 1

This participant had restricted binocular eye movements in the upper left and right cardinal gazes. Also, nystagmus was noted in both eyes in the upper left and right cardinal gazes only.

The nystagmus was accompanied with eyeball strain, forehead pain, and headache reported by the participant.

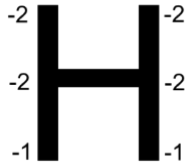
Figure 3-10: Ocular motility test result - Participant 1



3.4.4.2.2 Participant 2

This participant had restricted eye movement in all six cardinal positions. In the upper and middle positions, the restricted eye movements were graded as (-2) for both left and right sides. However, in the lower left and right cardinal positions, the eye movement restrictions were recorded as (-1). This participant reported symptoms of headache, irritation, and difficulty in concentrating on the target while moving their eyes.

Figure 3-11: Ocular motility test - Participant 2



3.4.4.2.3 Participant 3

This participant had no restricted eye movements. However, the participant had jerky eye movements while following the target in all positions of gaze. Furthermore, the participant reported the target appeared to be flickery throughout the test.

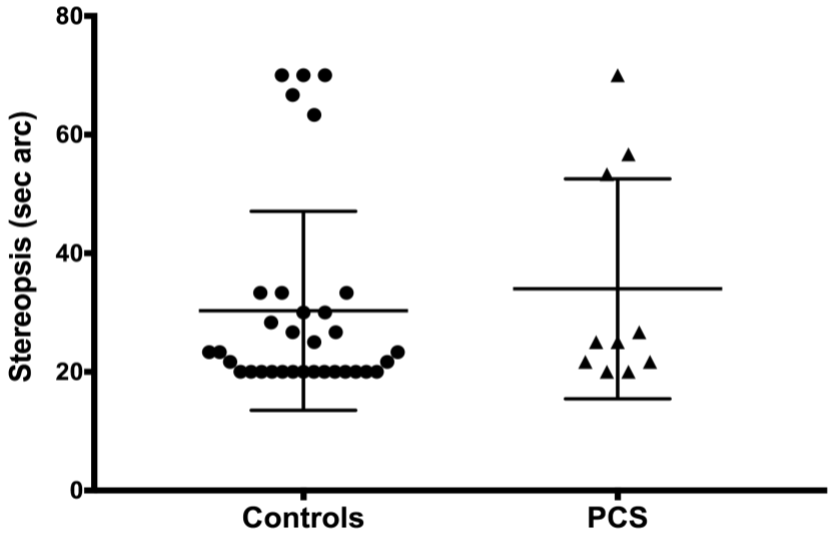
3.4.4.3 Stereopsis

There was no statistically significant difference in the stereopsis test between the two groups ($p=0.45$). Visual inspection of the SD values suggests that the variability in stereopsis was also similar between the two groups.

Table 3-11: Stereopsis (40cm; arc sec)

	Mean	SD	Median	p-value
Controls	30.3	16.8	22.7	0.45
PCS	34.0	18.6	25.0	

Figure 3-12: Stereopsis scatter plot



3.4.4.4 Accommodation function

3.4.4.4.1 Amplitude of Accommodation

There was no statistically significant difference in the amplitude of accommodation between the two groups in OD (p=0.31), OS (p=0.52), or the absolute difference between the two eyes (p=0.21). SD values also appear similar between the groups; however, this was not tested statistically.

Table 3-12: Amplitude of accommodation (40cm; D)

	Eye tested	Mean	SD	Median	p-value
Control	OD	0.8	1.8	0.8	0.31
PCS		1.4	1.7	1.3	
Control	OS	1.2	2.0	0.8	0.52
PCS		1.5	2.0	1.3	
Control	Absolute difference	0.8	0.8	0.7	0.21
PCS		0.5	0.6	0.3	

Figure 3-13: Amplitude of accommodation scatter plot

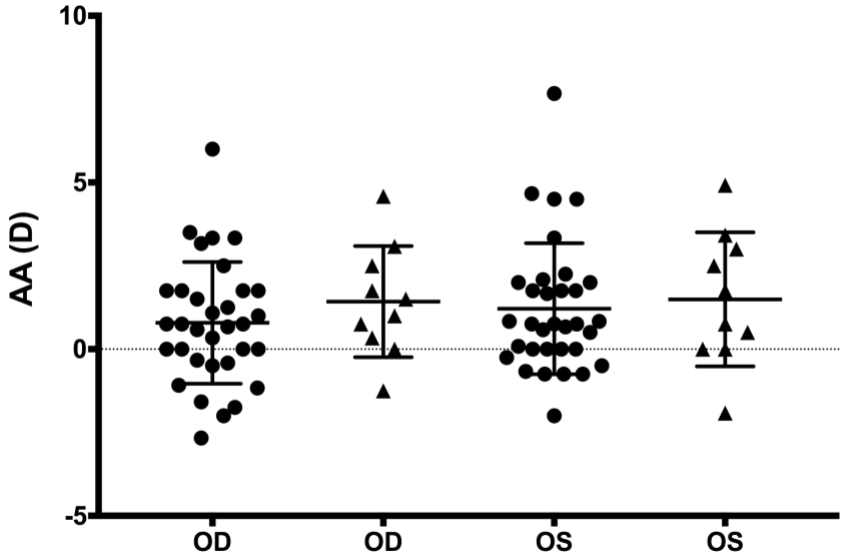
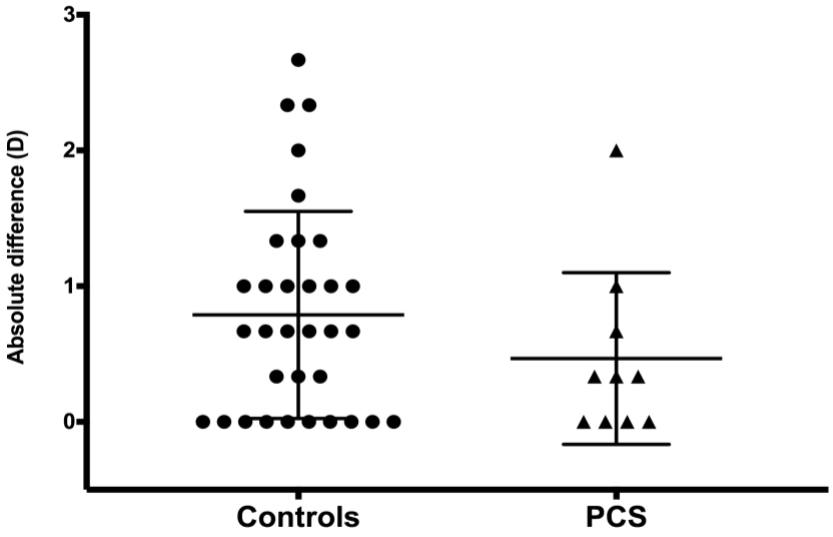


Figure 3-14: Amplitude of accommodation (absolute difference) scatter plot



3.4.4.4.2 Accommodation accuracy

There was no statistically significant difference in the accommodation accuracy between the two groups in OD (p=0.84), OS (p=0.41), or the absolute difference (p=0.14) between the two eyes. Also, visual inspection suggested that the SD values of both groups were similar. However, there were three PCS participants who demonstrated abnormal behavior on this test by having one eye with lag (plus value) and the other eye with lead (minus value) of accommodation as shown in the scatter plot (Figure 3-16). Conversely, this abnormality was not found in the control group (Figure 3-15).

Table 3-13: Accommodation accuracy (54cm; D)

	Eye tested	Mean	SD	Median	p-value
Control	OD	0.63	0.57	0.75	0.84
PCS		0.70	0.71	0.75	
Control	OS	0.56	0.51	0.50	0.41
PCS		0.80	0.68	0.75	
Control	Absolute difference	0.14	0.18	0.25	0.14
PCS		0.38	0.41	0.25	

Figure 3-15: Accommodation accuracy scatter plot for the control group

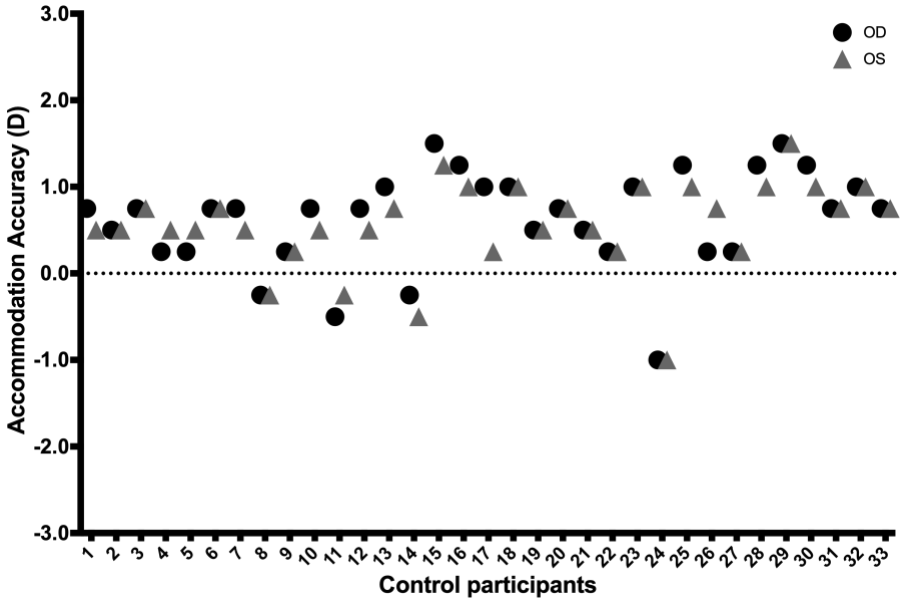


Figure 3-16: Accommodation accuracy scatter plot for the PCS group

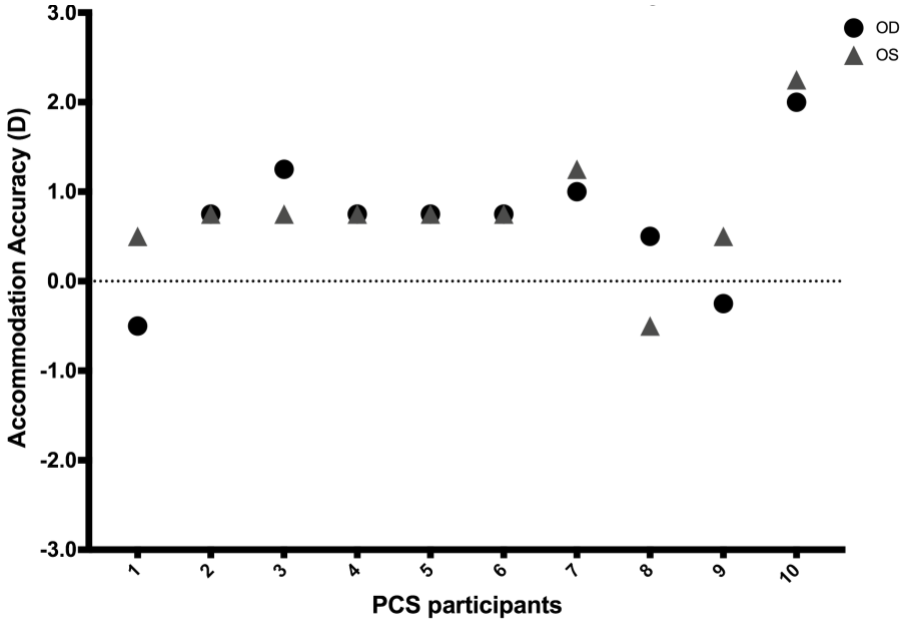
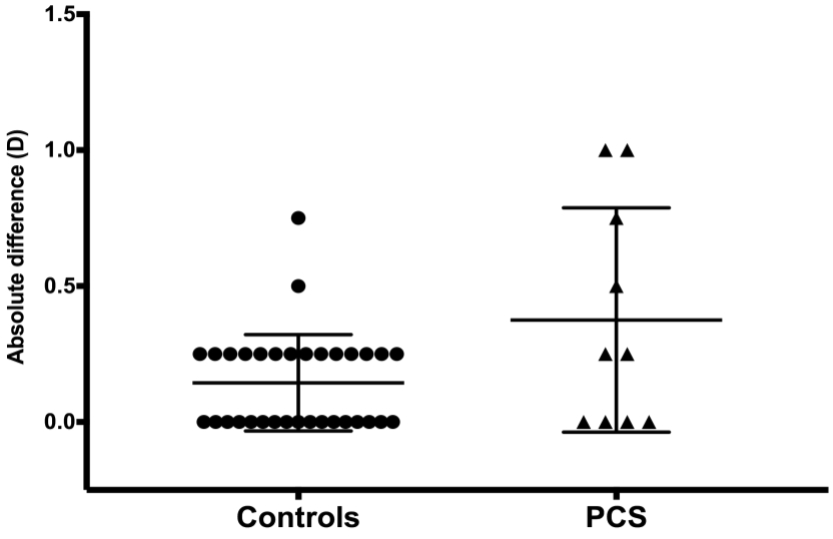


Figure 3-17: Accommodation accuracy (absolute difference) scatter plot



3.4.4.4.3 Accommodation facility

There was no statistically significant difference in the accommodation facility between the two groups in OD (p=0.37), OS (p=0.48), or in the absolute difference between the two eyes (p=0.61). The SD values of both groups appear to be similar upon visual inspection.

Table 3-14: Accommodation facility (40cm; cpm)

	Eye tested	Mean	SD	Median	p-value
Control	OD	9.9	6.4	9.3	0.37
PCS		7.7	6.4	9.7	
Control	OS	11	6.8	11.0	0.48
PCS		9.4	6.1	10.3	
Control	Absolute difference	2.4	2.5	1.7	0.61
PCS		2.0	2.2	1.0	

Figure 3-18: Accommodation facility scatter plot

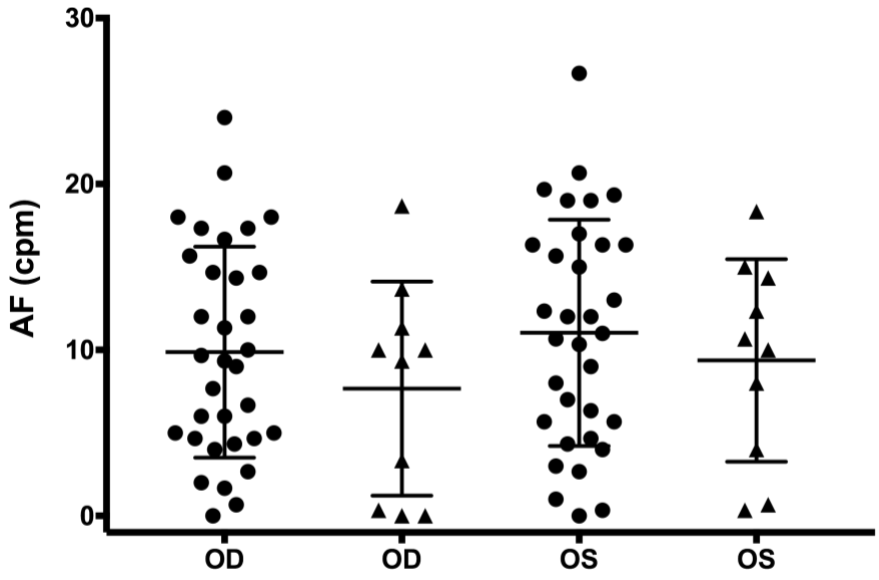
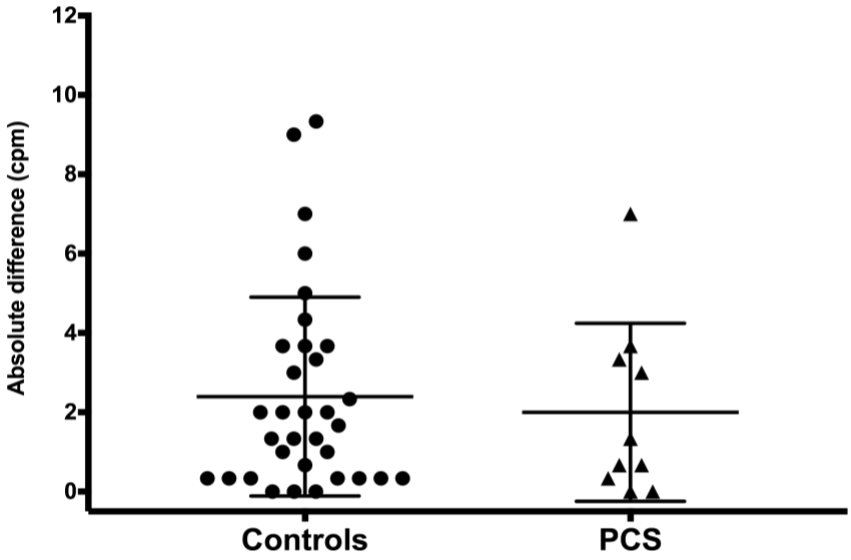


Figure 3-19: Accommodation facility (absolute difference) scatter plot



3.4.4.4.4 Negative and positive relative accommodation

This test was added to the testing protocol part way through the study. Therefore, there were fewer participants who completed this test (control n=10, PCS n=8).

There was no statistically significant difference in the NRA (p=0.60) and PRA (p=0.81) values between the two groups, and visual inspection of the SD values of these measures suggest that the variability of the results in both groups was similar.

Table 3-15: Negative and positive relative accommodation (40cm; cpm)

	Test	N	Mean	SD	Median	p-value
Control	NRA	10	2.6	0.7	3.0	0.60
PCS		8	2.7	0.7	2.0	
Control	PRA	10	-3.3	1.8	-3.0	0.81
PCS		8	-3.8	1.8	-3.8	

Figure 3-20: Negative relative accommodation scatter plot

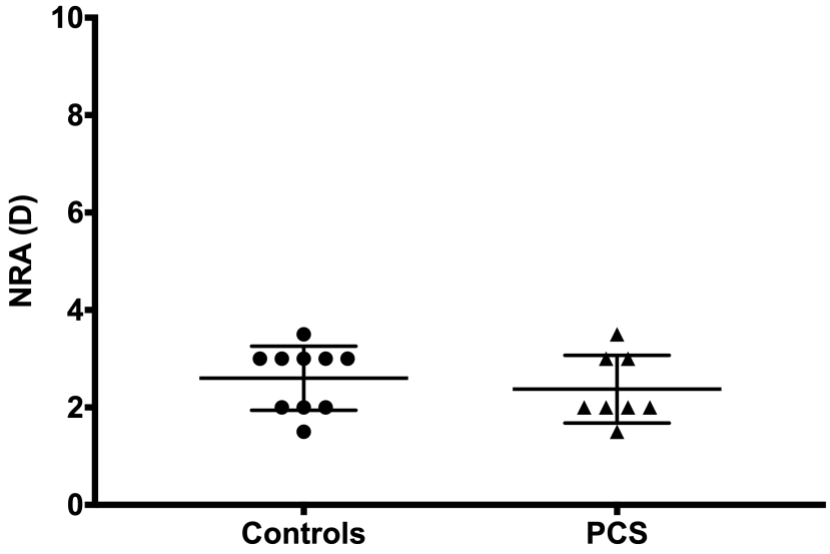
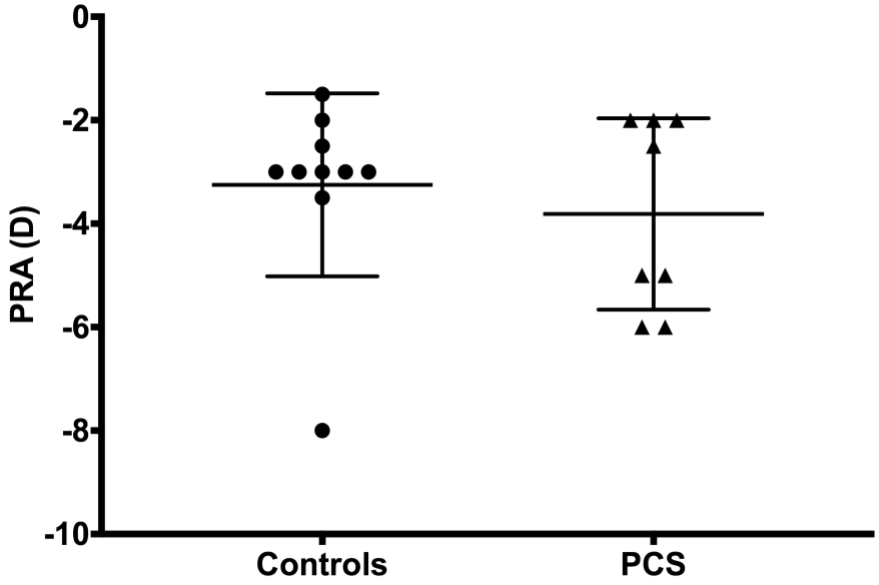


Figure 3-21: Positive relative accommodation scatter plot



3.4.4.5 Vergence function

3.4.4.5.1 Near point of convergence

There was no statistically significant difference in the near point of convergence between the two groups in break (p=0.99) and recovery (p=0.83) points, and in the difference between the two points (p=0.34). Visual inspection of the SD values of both groups suggests that the variability in each group was similar.

Table 3-16: Near point of convergence (40cm; cm)

		Mean	SD	Median	p-value
Control	Break point	5.3	2.9	5.3	0.99
PCS		5.4	2.7	6.0	
Control	Recovery point	6.4	3.3	7.0	0.83
PCS		6.9	3.1	7.6	
Control	Difference	1.1	0.9	1.1	0.34
PCS		1.5	0.9	1.4	

Figure 3-22: Near point of convergence scatter plot

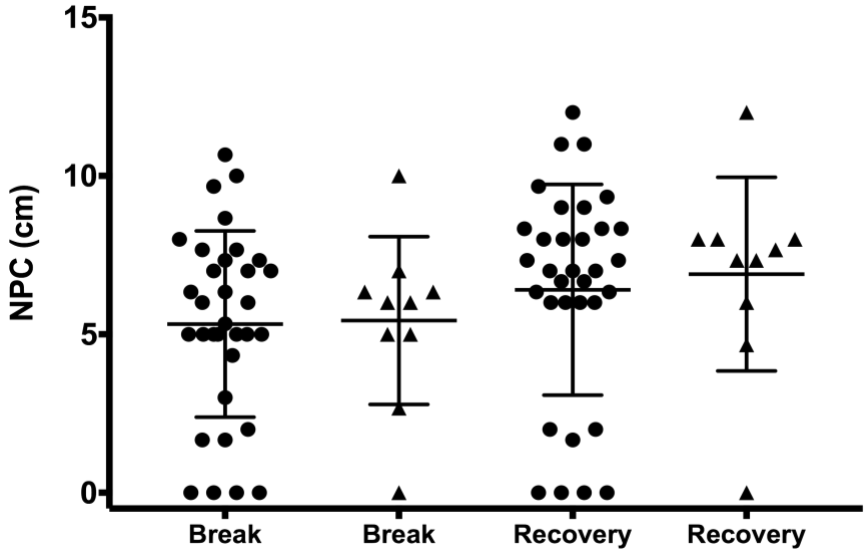
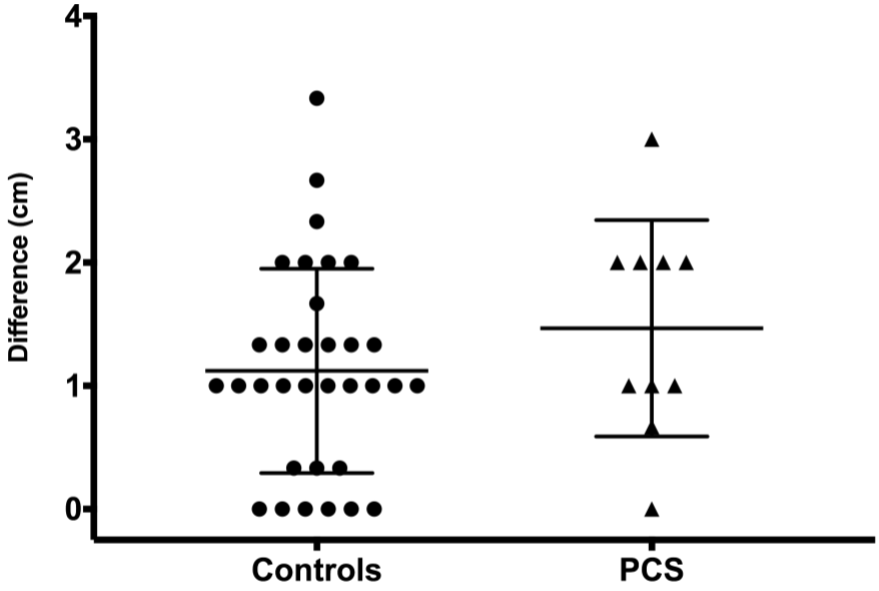


Figure 3-23: Near point of convergence (difference) scatter plot



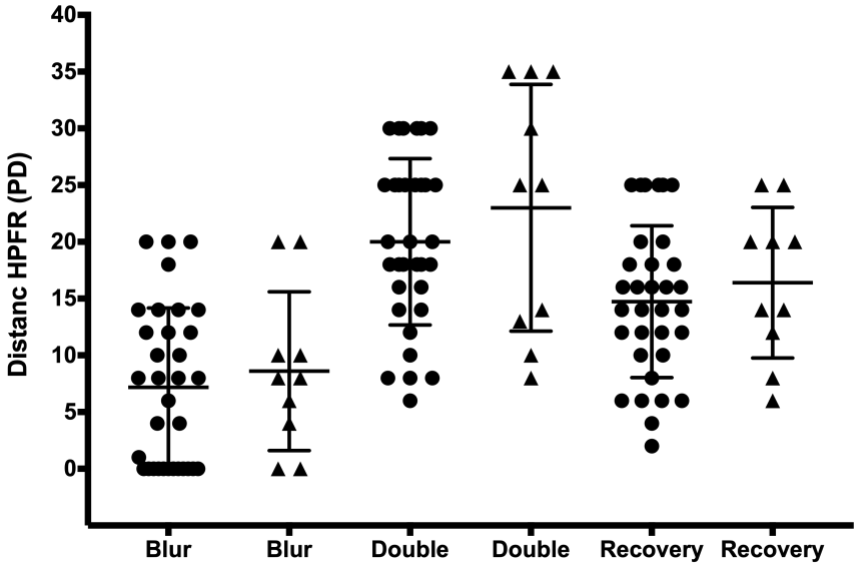
3.4.4.5.2 Distance horizontal positive fusional reserve

There was no statistically significant difference in the distance HPFR between the two groups in blur (p=0.62), double (p=0.40), or recovery (p=0.48) points. Although not tested statistically, there does not appear to be a difference in SD values between groups, except in the double point where the PCS group appears do demonstrate slightly more variability. Interestingly, based on visual inspection of the median values, the PCS group appear to perform better than the controls across all points.

Table 3-17: Distance horizontal positive fusional reserve (4m; PD)

		Mean	SD	Median	Min	Max	p-value
Control	Blur point	7.2	7.0	6.8	0	20	0.62
PCS		8.6	7.0	8.0	0	20	
Control	Double point	20.0	7.3	19.6	6	30	0.40
PCS		23.0	10.9	25.0	8	35	
Control	Recovery point	14.7	7.0	14.7	2	25	0.48
PCS		16.4	6.6	16.4	6	25	

Figure 3-24: Distance horizontal positive fusional reserve scatter plot



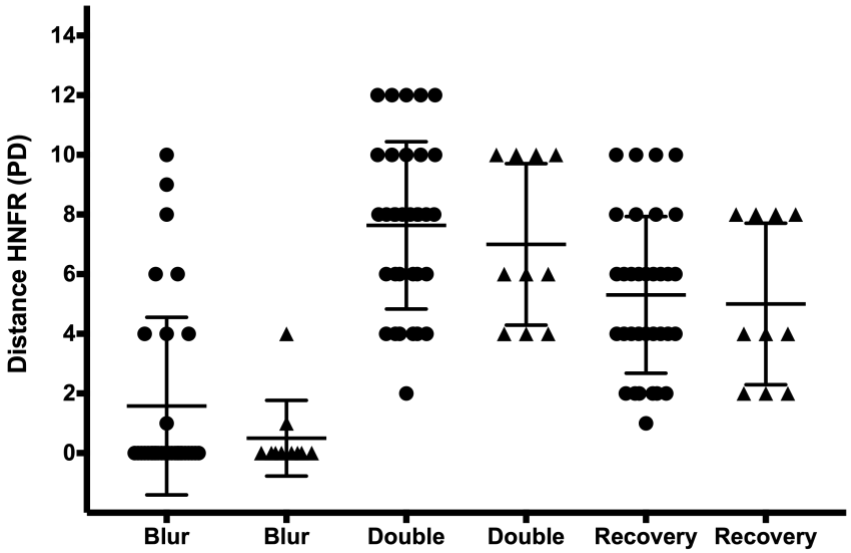
3.4.4.5.3 Distance horizontal negative fusional reserve

There was no statistically significant difference in the distance HNFR between the two groups in blur (p=0.62), double (p=0.56), and recovery (p=0.77) points. Also, both the SD and median values of these measures appear to be similar between the groups based on visual inspection.

Table 3-18: Distance horizontal negative fusional reserve (4m; PD)

		Mean	SD	Median	p-value
Control	Blur point	1.6	3.0	0.4	0.62
PCS		0.5	1.3	0.2	
Control	Double point	7.6	2.8	7.6	0.56
PCS		7.0	2.7	6.6	
Control	Recovery point	5.3	2.6	5.1	0.77
PCS		5.0	2.7	4.6	

Figure 3-25: Distance horizontal negative fusional reserve



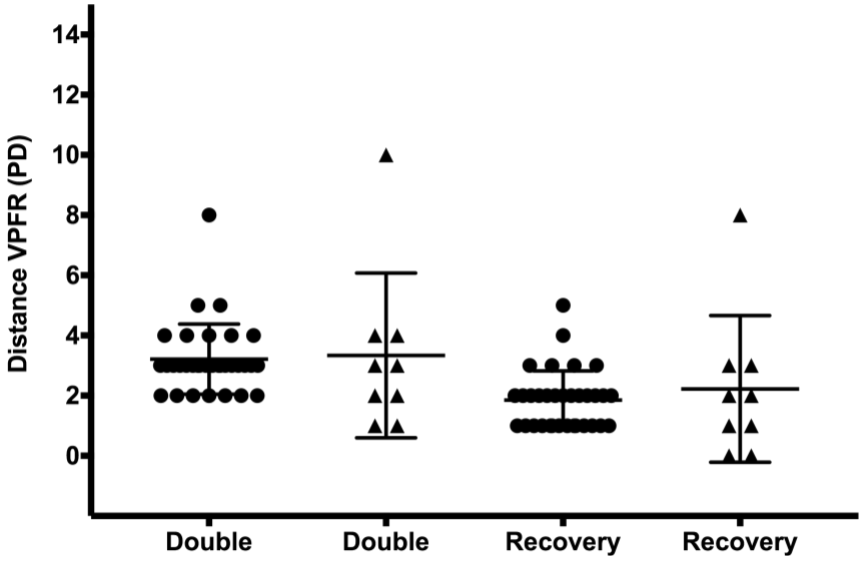
3.4.4.5.4 Distance vertical positive fusional reserve

There was no statistically significant difference in the distance VPFR between the two groups in double (p=0.77), and recovery (p=0.78) points. Both the SD and median values of these measures appear to be similar between the groups based on visual inspection.

Table 3-19: Distance vertical positive fusional reserve (4m; PD)

		Mean	SD	Median	p-value
Control	Double point	3.2	1.2	3.0	0.77
PCS		3.4	2.6	3.0	
Control	Recovery point	1.9	1.0	1.7	0.78
PCS		2.3	2.3	2.0	

Figure 3-26: Distance vertical positive fusional reserve



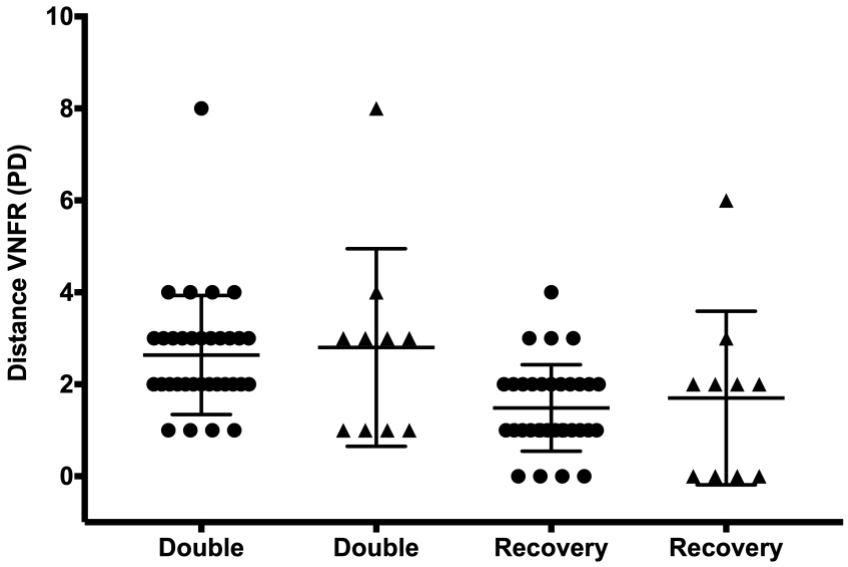
3.4.4.5.5 Distance vertical negative fusional reserve

There was no statistically significant difference in the distance VNFR between the two groups in double (p=0.89), and recovery (p=0.99) points. The SD and median values of both groups also appear to be similar based on visual inspection.

Table 3-20: Distance vertical negative fusional reserve (4m; PD)

		Mean	SD	Median	p-value
Control	Double point	2.6	1.3	2.5	0.89
PCS		2.8	2.2	2.5	
Control	Recovery point	1.5	0.9	1.4	0.99
PCS		1.7	1.9	1.5	

Figure 3-27: Distance vertical negative fusional reserve scatter plot



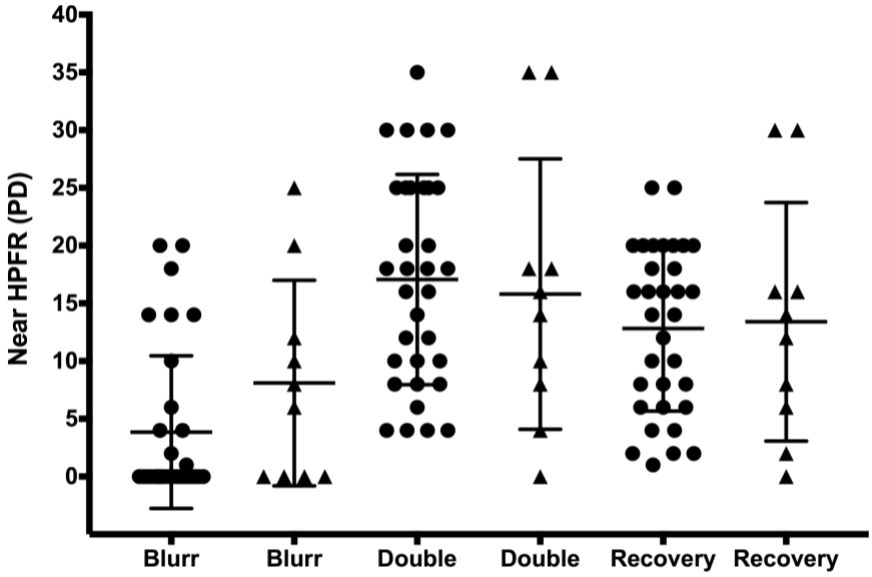
3.4.4.5.6 Near horizontal positive fusional reserve

There was no statistically significant difference in the near HPFR between the two groups in blur (p=0.85), double (p=0.72), and recovery (p=0.38) points. Visual inspection of the median values also suggests that the groups behaved similarly. However, based visual inspection of the SD values, the PCS group appeared to demonstrate more variability than the control group, as the standard deviation of the mean was larger in the PCS group than the control group.

Table 3-21: Near horizontal positive fusional reserve (40cm; PD)

		Mean	SD	Median	p-value
Control	Blur point	3.9	6.6	0.6	0.85
PCS		8.1	8.9	7	
Control	Double point	17.6	9.1	17.0	0.72
PCS		15.8	11.7	15.0	
Control	Recovery point	12.8	7.2	14.3	0.38
PCS		13.5	10.3	13.0	

Figure 3-28: Near horizontal positive fusional reserve scatter plot



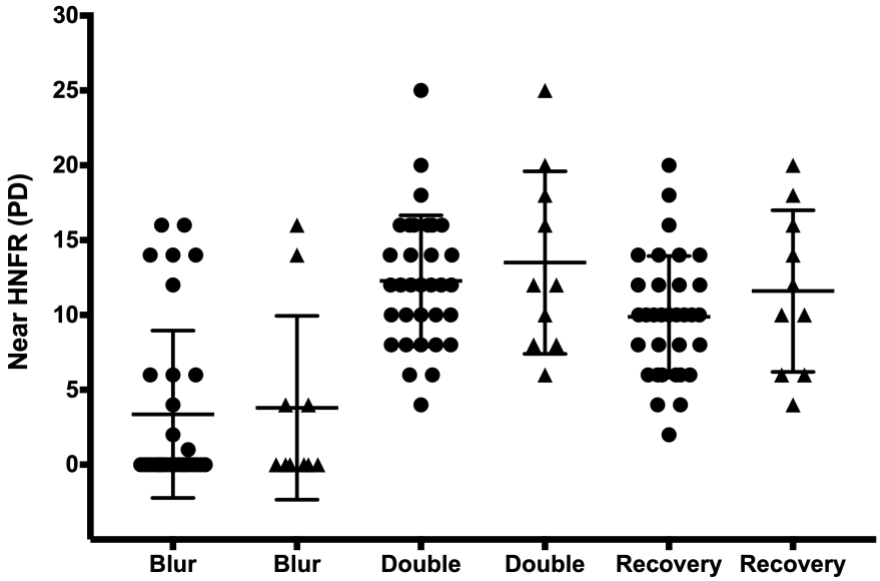
3.4.4.5.7 Near horizontal negative fusional reserve

There was no statistically significant difference in the near HNFR between the two groups in blur (p=0.85), double (p=0.72), and recovery (p=0.39) points. There were no obvious differences in the SD or median values of both groups upon visual inspection of these values either.

Table 3-22: Near horizontal negative fusional reserve (40cm; PD)

		Mean	SD	Median	p-value
Control	Blur point	3.4	5.59	0.6	0.85
PCS		3.8	6.14	2.0	
Control	Double point	12.3	4.38	12.0	0.72
PCS		13.5	6.16	12.0	
Control	Recovery point	9.9	4.1	9.7	0.39
PCS		11.6	5.5	11.3	

Figure 3-29: Near horizontal negative fusional reserve



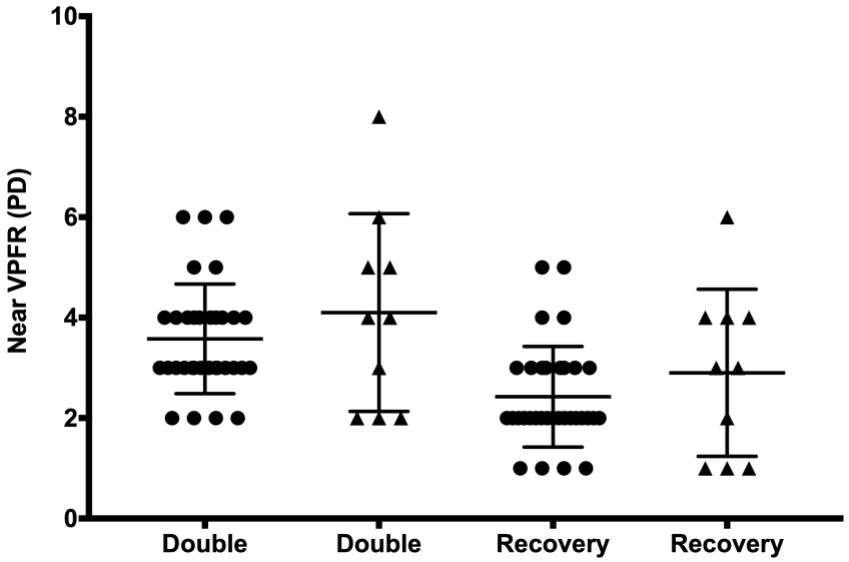
3.4.4.5.8 Near vertical positive fusional reserve

There was no statistically significant difference in the near VPFR between the two groups in double (p=0.56) and recovery (p=0.45) points. While not tested statistically, the SD and median values of both groups also appear to be similar.

Table 3-23: Near vertical positive fusional reserve (40cm; PD)

		Mean	SD	Median	p-value
Control	Double point	3.6	1.1	3.5	0.56
PCS		4.1	2.0	4.0	
Control	Recovery point	2.4	1.0	2.3	0.45
PCS		2.9	1.7	3.0	

Figure 3-30: Near vertical positive fusional reserve scatter plot



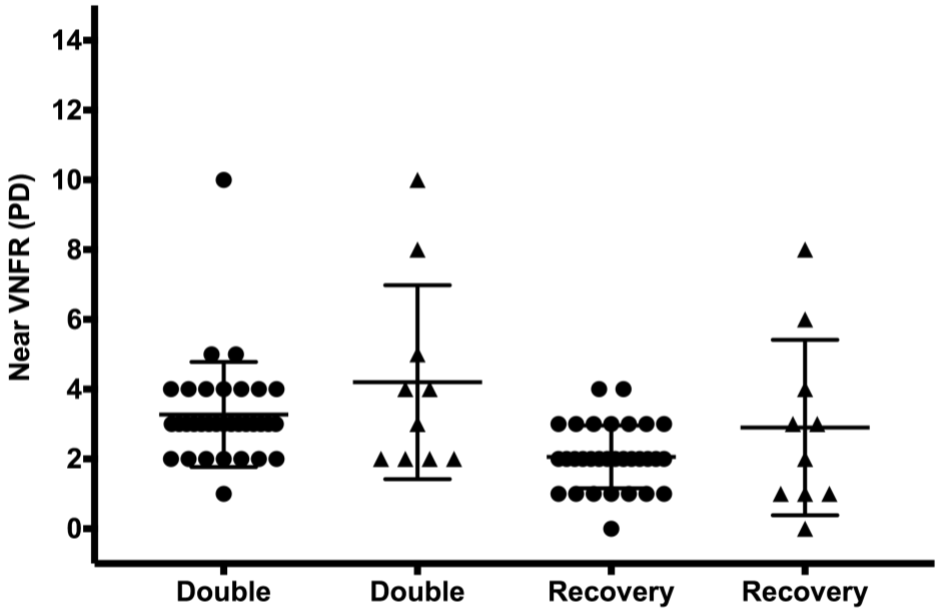
3.4.4.5.9 Near vertical negative fusional reserve

There was no statistically significant difference in the near VNFR between the two groups in double (p=0.64) and recovery (p=0.62) points. The SD and median values of both groups also appear to be similar, although this was not tested statistically.

Table 3-24: Near vertical negative fusional reserve (40cm; PD)

		Mean	SD	Median	p-value
Control	Double point	3.3	1.5	3.1	0.64
PCS		4.2	2.8	3.3	
Control	Recovery point	2.1	1.0	2.0	0.62
PCS		2.9	2.5	2.3	

Figure 3-31: Near vertical negative fusional reserve scatter plot



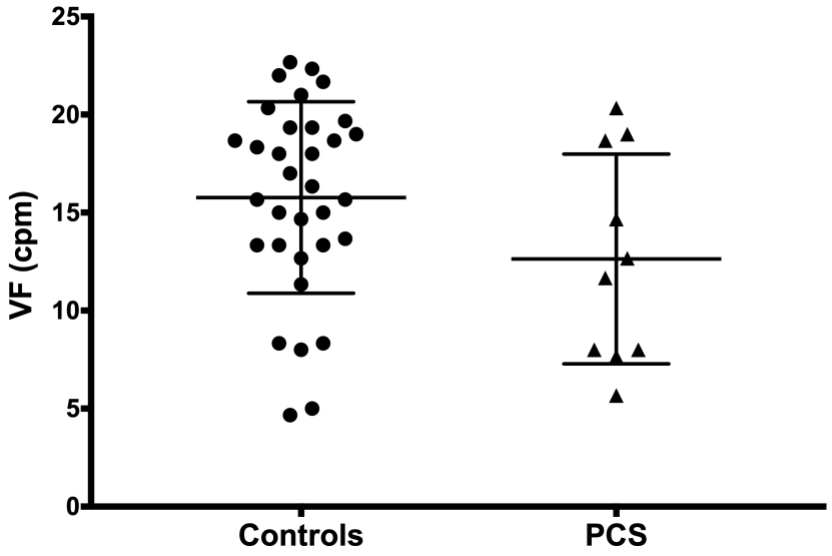
3.4.4.5.10 Vergence facility

There was no statistically significant difference in the vergence facility between the two groups (p=0.09), although interestingly there was a trend towards vergence facility being worse in the PCS group. Visual inspection of the median values also suggests that the control group appears to have higher (better) median value than the PCS group. Visual inspection of the SD values revealed no obvious differences between groups.

Table 3-25: Vergence facility (40cm; cpm)

	Mean	SD	Median	p-value
Controls	15.8	4.9	16.3	0.09
PCS	12.6	5.4	12.2	

Figure 3-32: Vergence facility scatter plot



3.4.5 Global visual function tasks

3.4.5.1 Visual spatial awareness - cyclopean eye alignment position

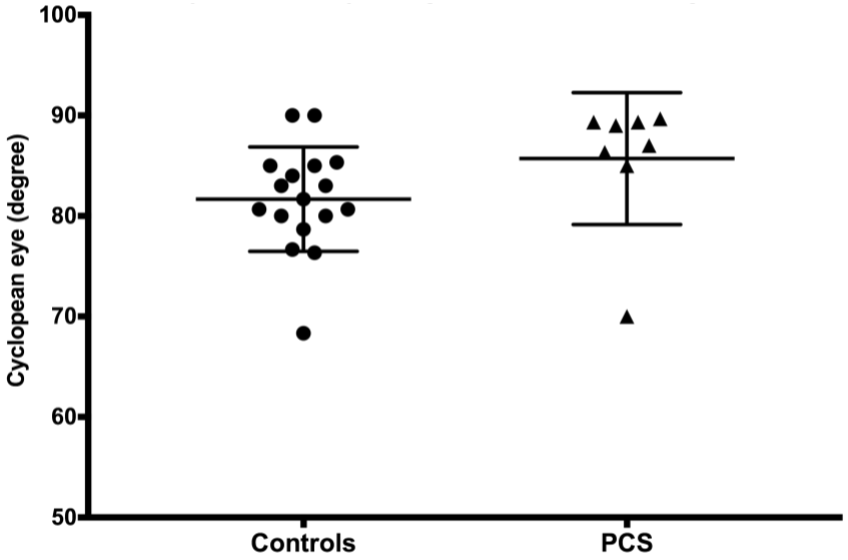
As mentioned in the methods chapter, the technique of measuring the cyclopean eye was modified part way through the study. Therefore, there were fewer participants who performed the test after the modification was completed (control n=17, PCS n=8).

There was statistically significant difference in the cyclopean eye position between the two groups (p=0.03). And the mean cyclopean eye position of the PCS group was closer to the midline (90 degrees) than the control group. This result was supported by observational analysis of the median values, which also appeared to be closer to the midline in the PCS group. There was no visually observable difference between the SD values of both groups.

Table 3-26: Visual spatial awareness - cyclopean eye alignment position (50cm; degrees)

	N	Mean	SD	Median	p-value
Controls	17	81.7	5.2	80.7	0.03*
PCS	8	85.7	6.6	88.0	

Figure 3-33: Visual spatial awareness - cyclopean eye alignment position scatter plot



3.4.5.2 King-Devick

There were two outcome measures recorded on the KD test: 1) reading time and 2) number of errors made. There was statistically significant difference in the reading time between the two groups (p=0.04), and the control group appeared to read faster (took less time to complete the task), than the PCS group. There was no statistically significant difference in the number of errors made between the two groups.

Table 3-27: King-Devick (40cm)

		Mean	SD	Median	p-value
Controls	Reading time (seconds)	48.1	13.7	42.2	0.04*
PCS		61.0	20.0	60.1	
Controls	Error (number of errors)	0.3	1.6	0.0	>0.99
PCS		0.1	0.3	0.0	

Figure 3-34: King-Devick (time) scatter plot

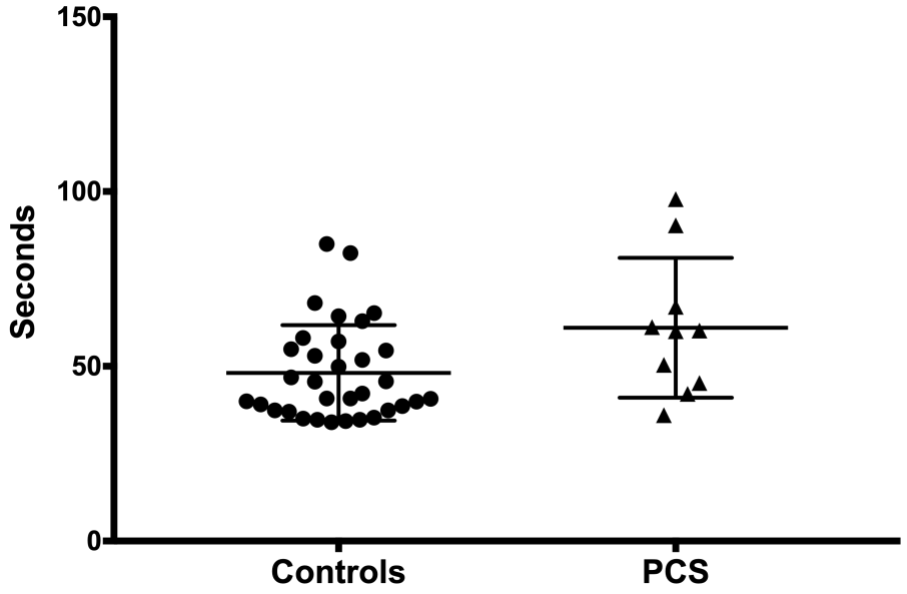
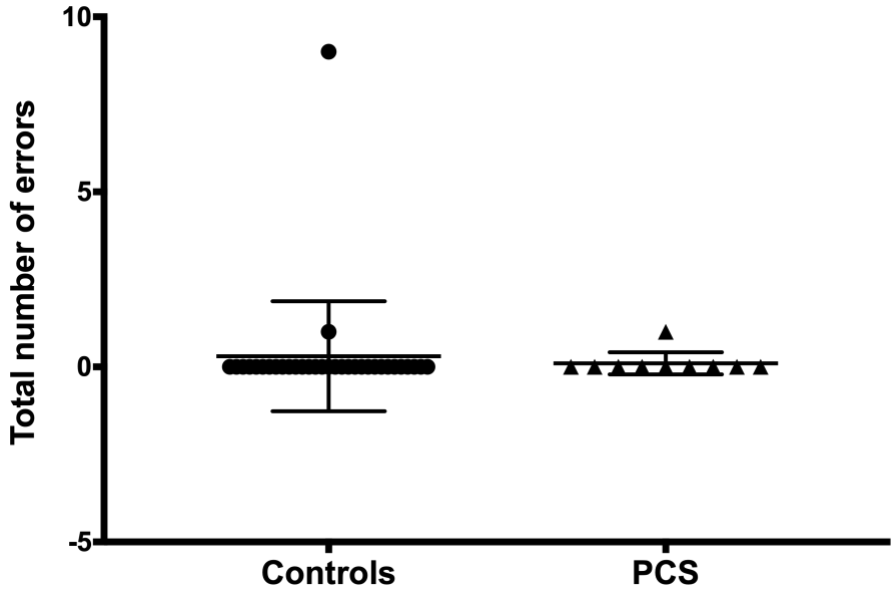


Figure 3-35: King-Devick (errors) scatter plot



3.4.6 Visual motor integration

3.4.6.1 Visual-motor reaction time

In this test**,** central and peripheral VMRT were measured. There was a statistically significant difference between the two groups in the peripheral VMRT only (p=0.04). Interestingly, the PCS group had a better peripheral VMRT compared to the control group. The PCS group also appeared to have a better central VMRT as well, although there was no statistical difference in central VMRT between groups. Furthermore, visual observation of the SD values suggests that the control group appeared to have higher (more variable) SD value in the central and peripheral VMRT tasks than the PCS group. The apparent increased variability in the control group likely contributed to the lack of a significant difference being found on the central VMRT task.

Table 3-28: Visual-motor reaction time (ms)

		Mean	SD	Median	p-value
Control	Central	509.1	115.2	492.6	0.58
PCS		476.1	74.9	477.3	
Control	Peripheral	960.3	236.6	905.7	0.04*
PCS		810.0	136.0	812.7	

Figure 3-36: Visual-motor reaction time (central) scatter plot

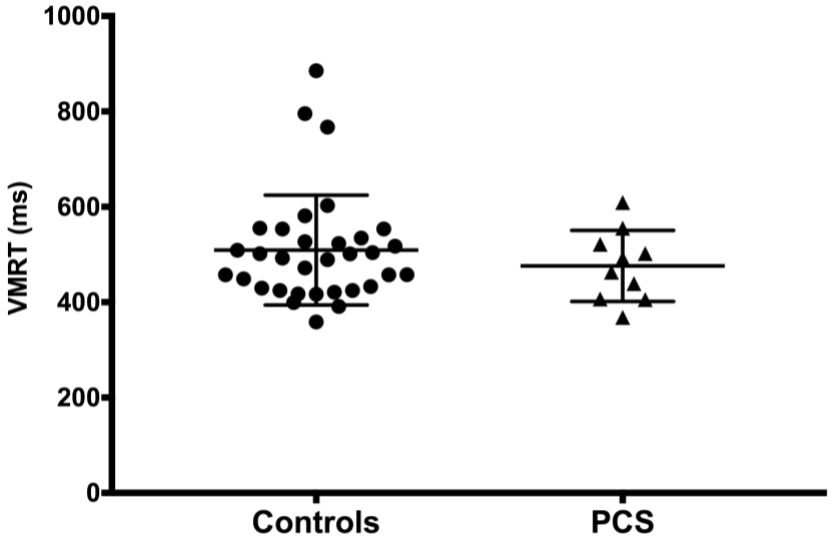
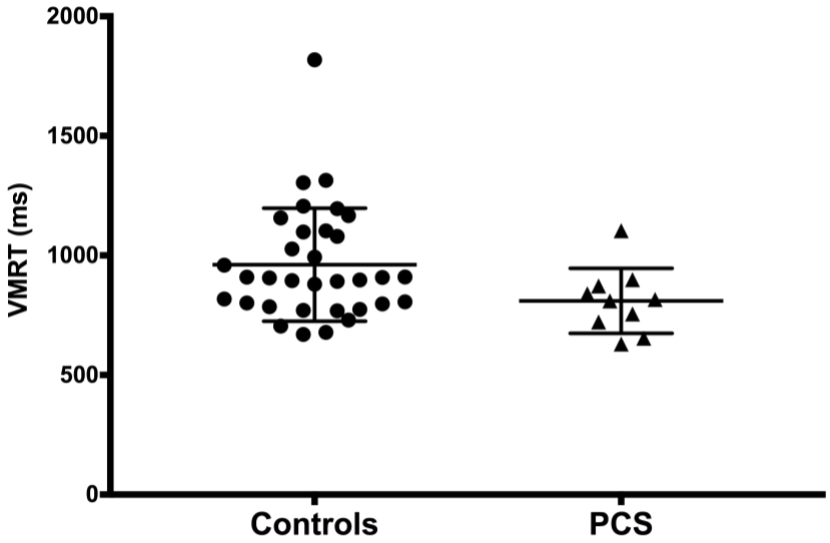


Figure 3-37: Visual-motor reaction time (peripheral) scatter plot



3.4.6.2 Coincidence anticipation timing

Overall, there were no statistically significant differences between the two groups at any of the speeds (5 - 40 mph) tested on any of the outcome measures (constant, absolute, and variable errors). Also, visual inspection suggests that there were no specific or consistent trends in the mean and SD values amongst the groups.

Table 3-29: Coincidence anticipation timing (mph)

	CE					AE				VE			
	Speed	**Mean**	**SD**	**Median**	**p-value**	**Mean**	**SD**	**Median**	**p-value**	**Mean**	**SD**	**Median**	**p-value**
Control	5	-24.2	31.6	-11.0	0.23	47.3	23.1	37.8	0.52	42.3	17.4	39.9	0.66
PCS		-35.6	33.7	-37.5		52.5	25.4	39.5		45.0	20.1	43.2	
Control	10	-13.6	26.6	-7.2	0.27	34.7	18.7	30.6	0.64	32.8	16.9	29.5	0.22
PCS		-2.6	16.6	-1.7		38.9	20.3	33.5		42.1	20.9	35.95	
Control	15	-14.7	26.3	-15.8	0.96	47.0	24.3	42.4	0.83	49.8	32.1	38.8	0.85
PCS		-14.9	23.5	-18.8		41.6	11.8	41		44.6	11.3	46.0	
Control	20	-9.1	18.1	-10.4	0.49	47.1	19.3	46.2	0.16	52.2	25.6	49.7	0.39
PCS		-5.9	26.3	2.7		55.0	16.9	54.6		58.5	21.0	59.6	
Control	25	-1.3	21.8	-0.8	0.18	40.8	16.6	39.4	0.09	45.8	18.5	44.7	0.12
PCS		-11.2	20.9	-15.7		50.5	12.1	47.4		55.4	13.2	50.7	
Control	30	11.9	23.52	13.8	0.47	40.0	15.7	36.2	0.44	40.2	15.1	38.0	0.62
PCS		6.0	19.2	3.6		43.3	15.0	44.5		43.4	18.8	49.4	
Control	35	11.6	21.3	11.6	1.00	33.1	18.3	28.0	0.97	35.0	19.5	30.1	0.75
PCS		10.8	22.5	11.0		31.4	13.8	29.0		31.7	14.8	29.2	
Control	40	19.0	17.3	14.2	0.50	32.3	18.7	29.6	0.19	32.1	20.3	30.2	0.12
PCS		16.3	22.8	13.4		25.0	19.2	16.8		22.2	12.1	19.0	

Figure 3-38: Coincidence anticipation timing (CE) scatter plot of the control group

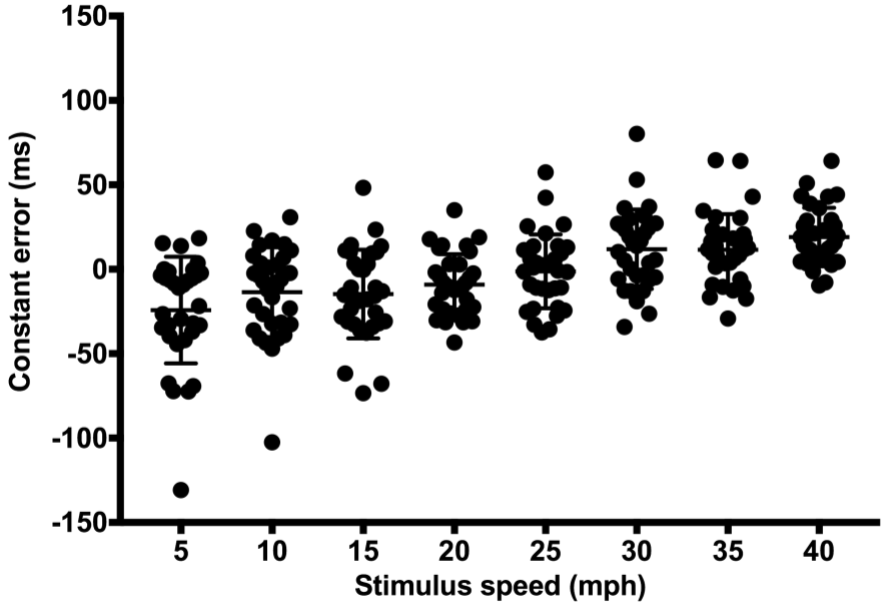


Figure 3-39: Coincidence anticipation timing (CE) scatter plot of the PCS group

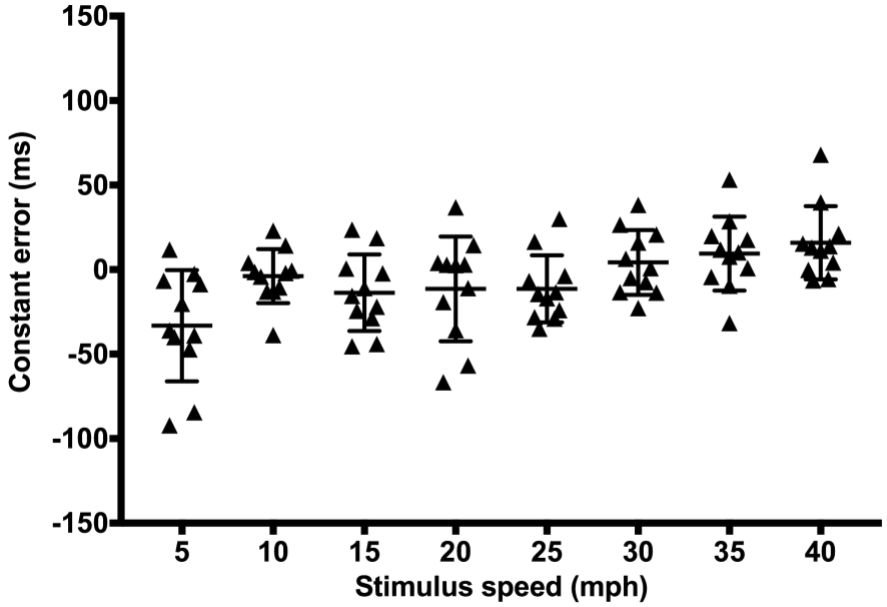


Figure 3-40: Coincidence anticipation timing (AE) scatter plot of the control group

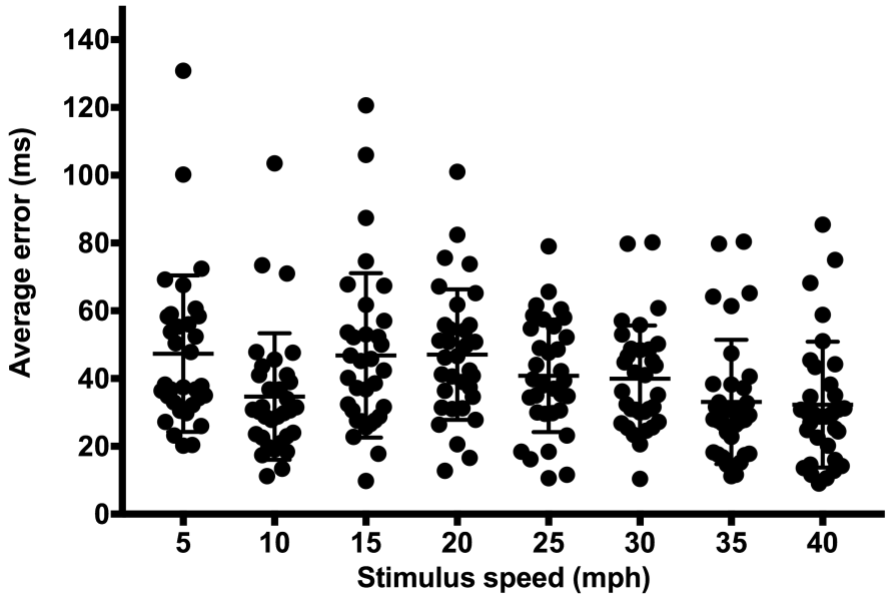


Figure 3-41: Coincidence anticipation timing (AE) scatter plot of the PCS group

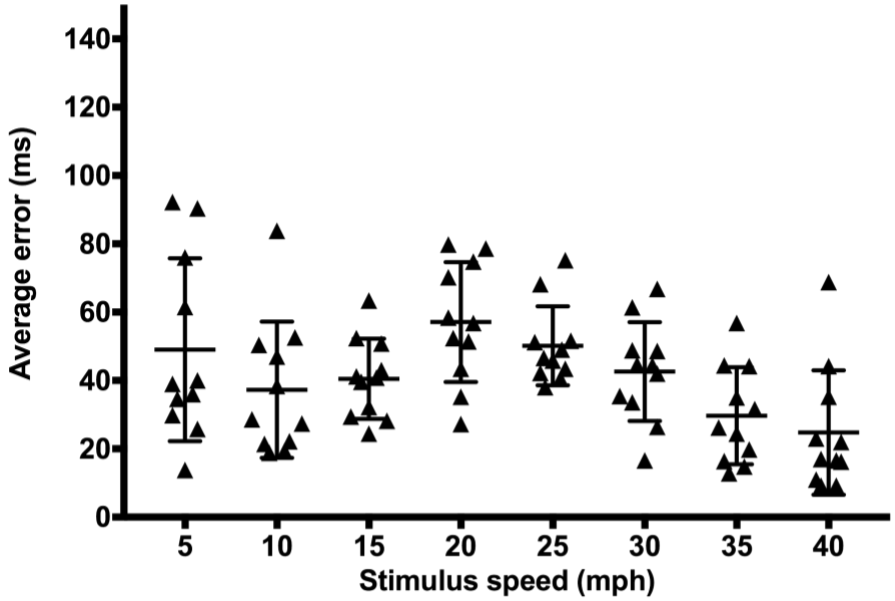


Figure 3-42: Coincidence anticipation timing (VE) scatter plot of the control group

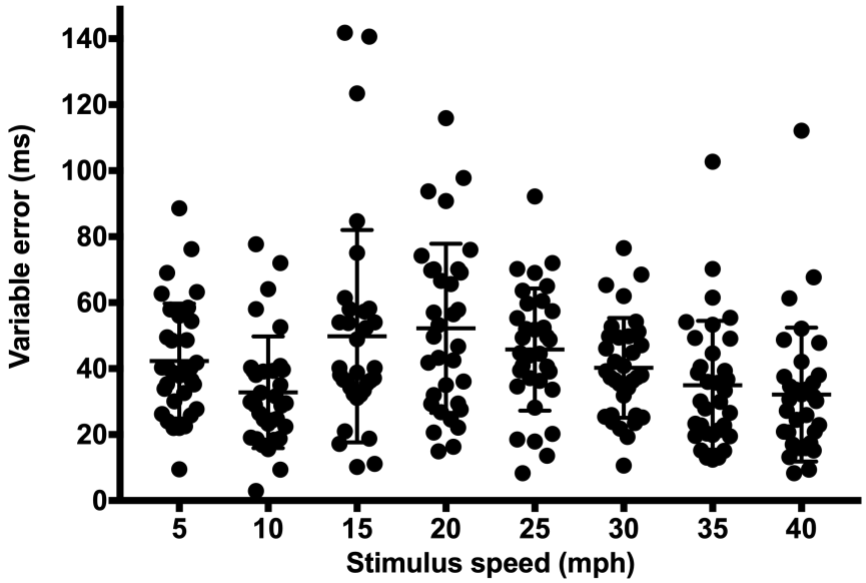
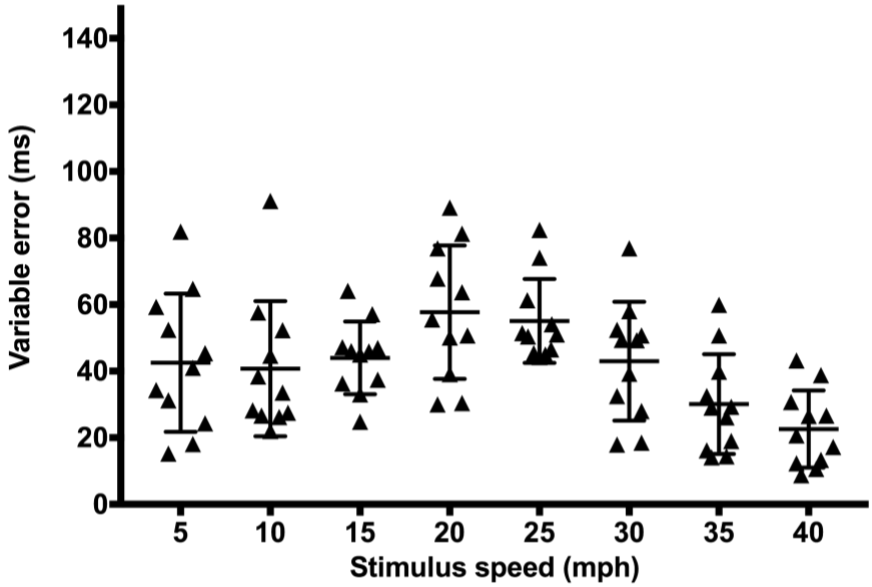


Figure 3-43: Coincidence anticipation timing (VE) scatter plot of the PCS group



Chapter 4 - Results: Symptoms and visual function

In order to look at the relationship between symptoms and visual functions, Spearman correlations were used to compare symptom severity scores and performance on each of the visual function tests in each visit for each group. The results of these correlation analyses are presented in (Tables 4-1 to 4-26). The significance levels of the correlations between the symptom severity and each visual function test are represented by the (p-value) whereas the spread of the data is represented by Spearman's rho (ρ-value) - (Tables 4-1 to 4-26).

Please note, in all of the tables presented below, p-values marked with a * are significant at least $p<0.05$. On all of the following graphs, grey data represents the control group and black data represents the PCS group.

4.1 Static visual perception

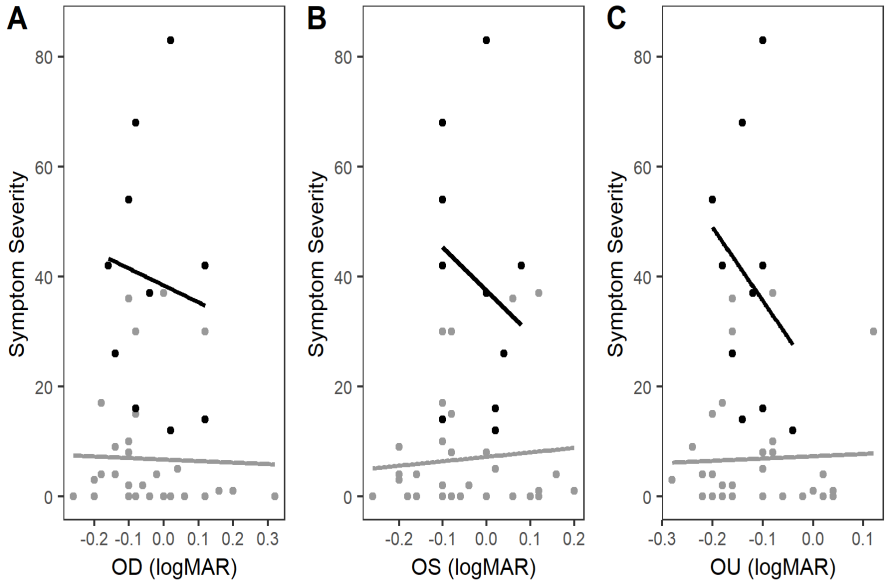
4.1.1 Static distance visual acuity

There was no significant correlation between symptom severity and static distance visual acuity for either groups.

Table 4-1: Correlation of symptom severity and static distance visual acuity

	Control		**PCS**	
	p-value	ρ-value	p-value	ρ-value
OD	0.45	-0.14	0.57	-0.21
OS	0.93	-0.02	0.37	-0.32
OU	0.80	-0.05	0.41	-0.30

Figure 4-1: Correlation of symptom severity and static distance visual acuity



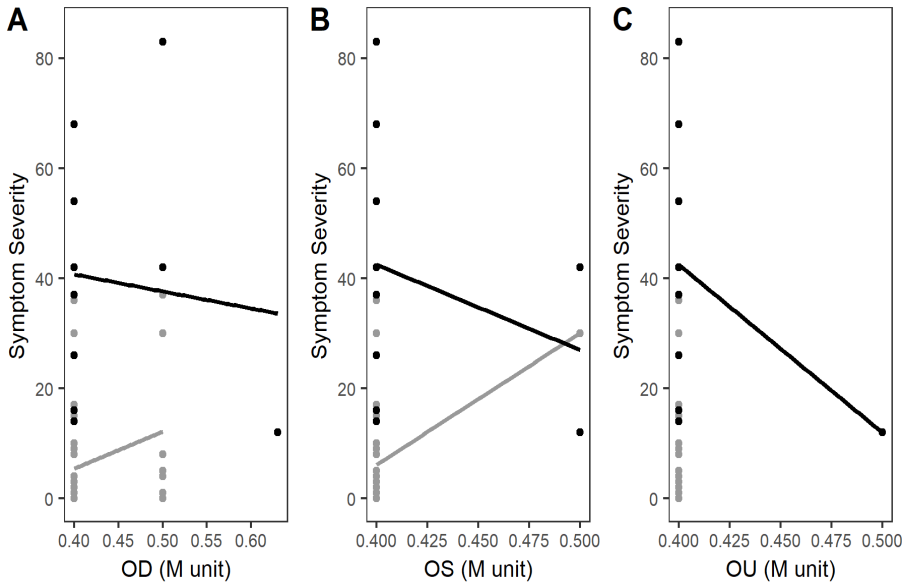
4.1.2 Static near visual acuity

There was no significant correlation between the symptom severity and the static near visual acuity for both groups.

Table 4-2: Correlation of symptom severity and static near visual acuity

	Control		**PCS**	
	p-value	ρ-value	p-value	ρ-value
OD	0.10	0.29	0.93	-0.03
OS	0.14	0.26	0.39	-0.31
OU	NA	NA	0.12	-0.52

Figure 4-2: Correlation of symptom severity and static near visual acuity



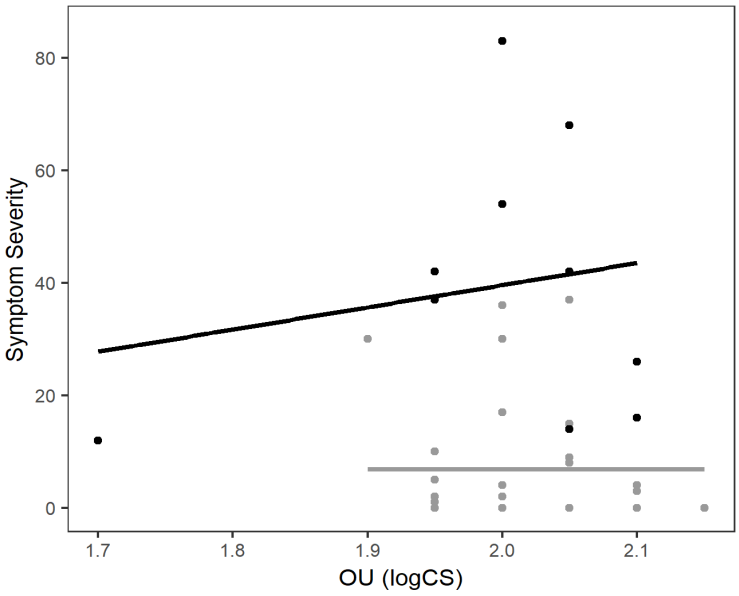
4.1.3 Contrast sensitivity

There was no significant correlation between symptom severity and contrast sensitivity for either both groups.

Table 4-3: Correlation of symptom severity and contrast sensitivity

	Control		**PCS**	
	p-value	ρ-value	p-value	ρ-value
OU	0.33	0.18	0.93	-0.03

Figure 4-3: Correlation of symptom severity and contrast sensitivity



4.2 Dynamic visual perception

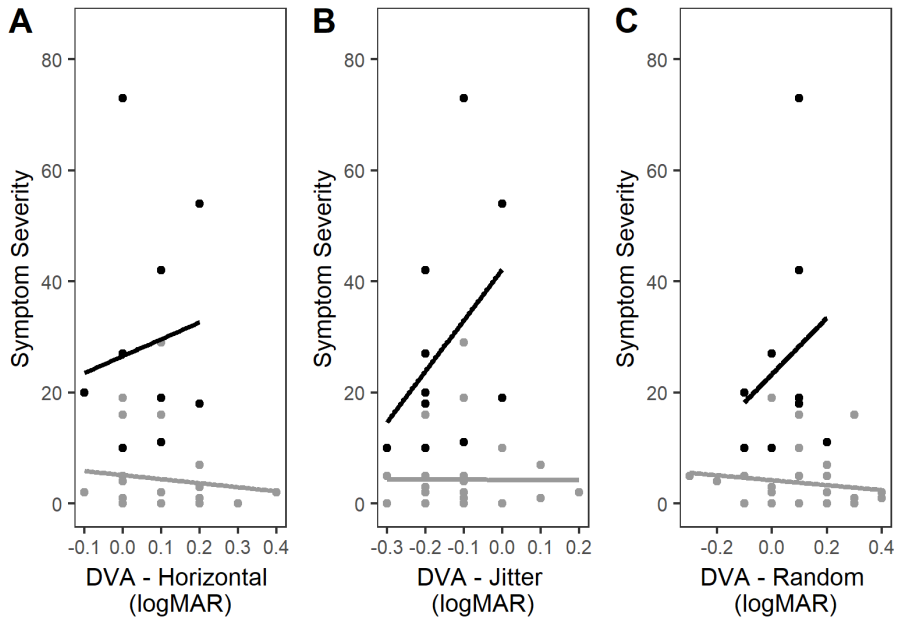
4.2.1 Dynamic distance visual acuity

There was no significant correlation between symptom severity and dynamic visual acuity for both groups.

Table 4-4: Correlation of symptom severity and dynamic distance visual acuity

	Control		**PCS**	
	p-value	ρ-value	p-value	ρ-value
Horizontal	0.54	-0.12	0.75	0.46
Random	0.29	-0.20	0.59	0.21
Jitter	0.86	0.03	0.18	0.12

Figure 4-4: Correlation of symptom severity and dynamic visual acuity



4.3 Refractive status

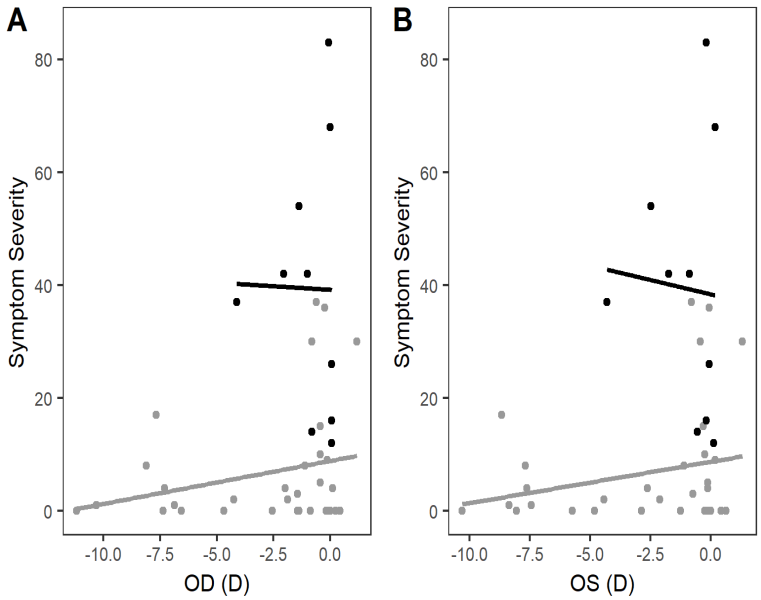
4.3.1 Objective refraction

There was no significant correlation between symptom severity and refractive error for both groups.

Table 4-5: Correlation of symptom severity and objective refraction (spherical equivalent)

	Control		**PCS**	
	p-value	ρ-value	p-value	ρ-value
OD	0.67	0.08	0.20	-0.44
OS	0.74	0.06	0.20	-0.45

Figure 4-5: Correlation of symptom severity and objective refraction (spherical equivalent)



4.4 Binocular vision

4.4.1 Ocular alignment

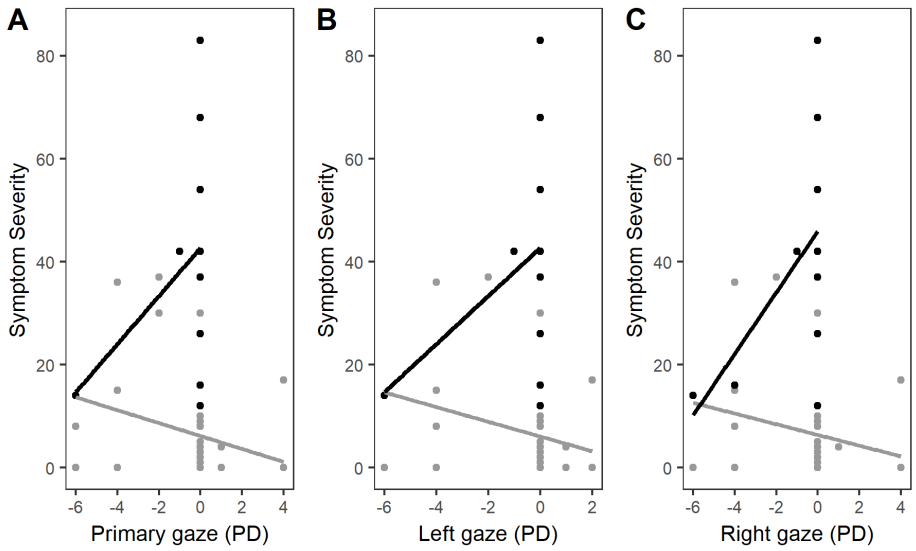
4.4.1.1 Distance ocular alignment

There was no significant correlation between symptom severity and distance ocular alignment for either group.

Table 4-6: Correlation of symptom severity and distance ocular alignment

	Control		PCS	
	p-value	ρ-value	p-value	ρ-value
Primary gaze	0.17	-0.25	0.48	0.26
Left gaze	0.33	-0.18	0.48	0.26
Right gaze	0.45	-0.14	0.20	0.44

Figure 4-6: Correlation of symptom severity and distance ocular alignment



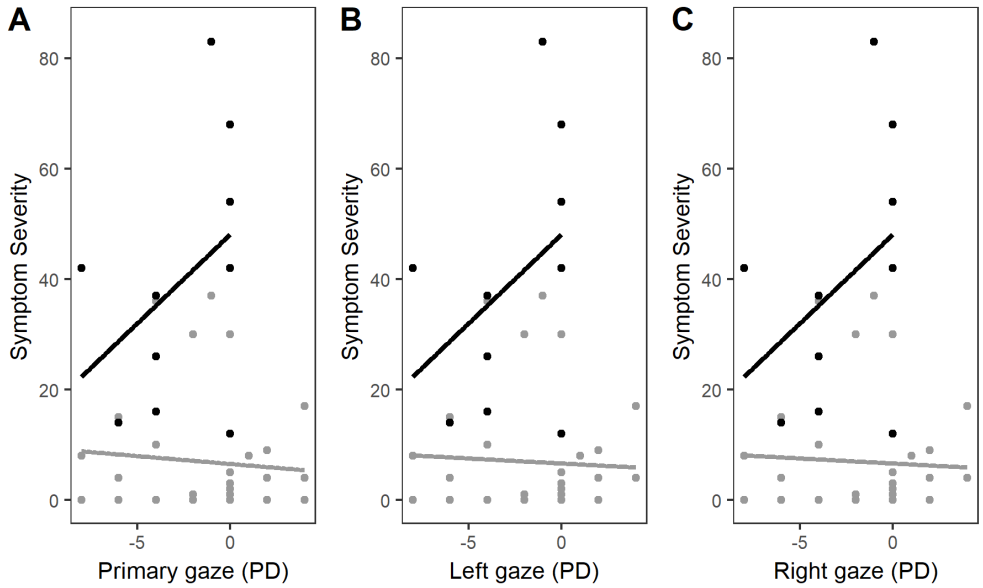
4.4.1.2 Near ocular alignment

There was no significant correlation between symptom severity and near ocular alignment for either group.

Table 4-7: Correlation of symptom severity and near ocular alignment

	Control		**PCS**	
	p-value	ρ-value	p-value	ρ-value
Primary gaze	0.74	-0.06	0.39	0.31
Left gaze	0.99	0.00	0.39	0.31
Right gaze	0.99	0.00	0.39	0.31

Figure 4-7: Correlation of symptom severity and near ocular alignment



4.4.2 Stereopsis

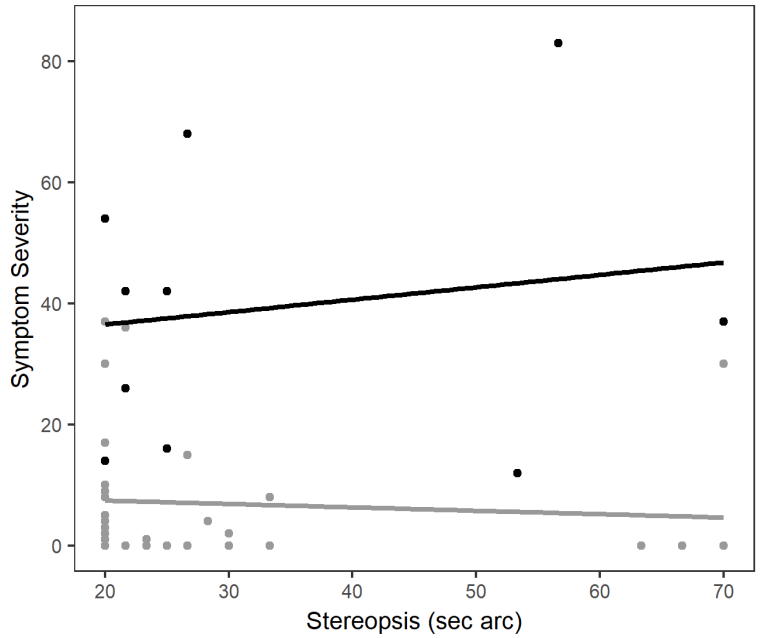
There was a significant negative correlation between symptom severity and stereopsis for the control group and an increase in symptom severity was found to be associated with less (better) stereopsis. Even though this correlation was significant, stereopsis measures could only account for or be explained by 41% of the symptom severity score.

No significant correlation between symptom severity and stereopsis was found for the PCS group.

Table 4-8: Correlation of symptom severity and stereopsis

	Control		**PCS**	
	p-value	ρ-value	p-value	ρ-value
Stereopsis	0.02*	-0.41	0.67	0.15

Figure 4-8: Correlation of symptom severity and stereopsis



4.4.3 Accommodation function

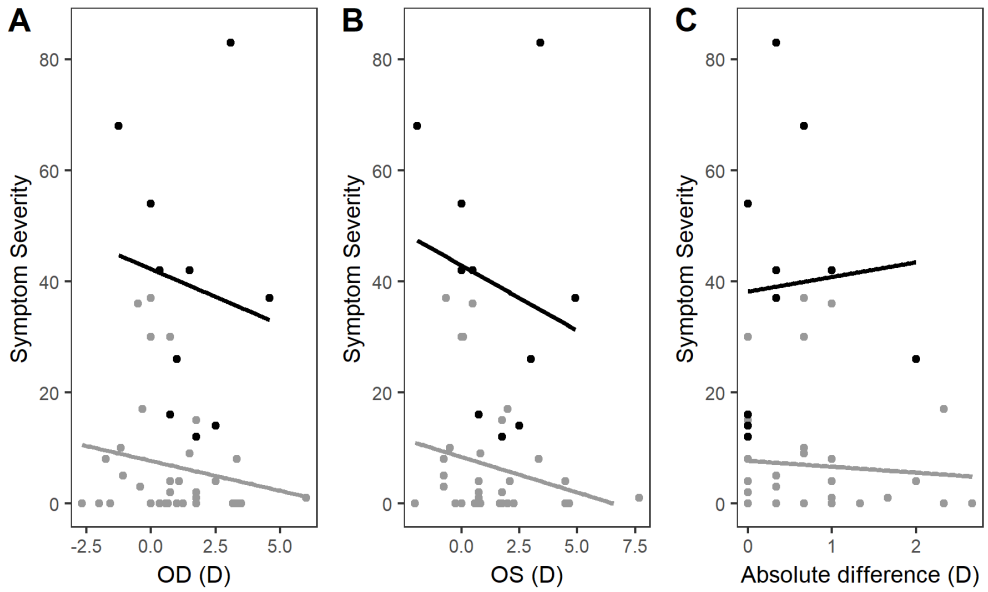
4.4.3.1 Amplitude of accommodation

There was no significant correlation between symptom severity and the amplitude of accommodation for both groups.

Table 4-9: Correlation of symptom severity and amplitude of accommodation

	Control		**PCS**	
	p-value	ρ-value	p-value	ρ-value
OD	0.46	-0.13	0.41	-0.29
OS	0.37	-0.16	0.41	-0.30
Absolute difference	0.45	-0.14	0.27	0.39

Figure 4-9: Correlation of symptom severity and amplitude of accommodation



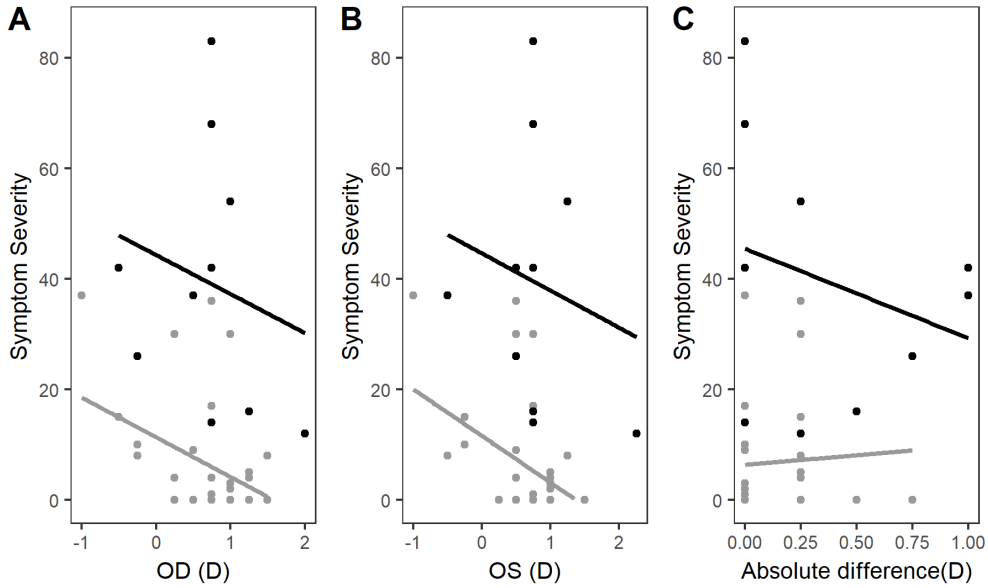
4.4.3.2 Accommodation accuracy

There was no significant correlation between symptom severity and the accommodation accuracy for both groups.

Table 4-10: Correlation of symptom severity and accommodation accuracy

	Control		**PCS**	
	p-value	ρ-value	p-value	ρ-value
OD	0.32	-0.18	0.47	-0.26
OS	0.42	-0.15	0.82	-0.08
Absolute difference	0.52	0.12	0.44	-0.28

Figure 4-10: Correlation of symptom severity and accommodation accuracy



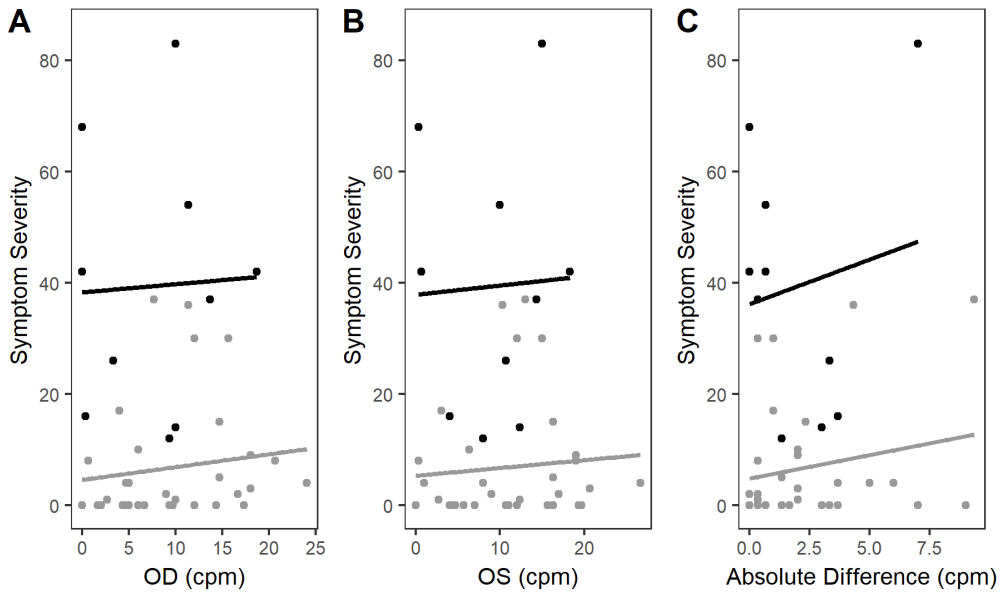
4.4.3.3 Accommodation facility

There was no significant correlation between symptom severity and the accommodation facility for both groups.

Table 4-11: Correlation of symptom severity and accommodation facility

	Control		PCS	
	p-value	ρ-value	p-value	ρ-value
OD	0.17	0.25	0.93	0.03
OS	0.44	0.14	0.85	0.07
Absolute difference	0.69	0.07	0.48	-0.25

Figure 4-11: Correlation of symptom severity and accommodation facility



4.4.3.4 Negative and positive relative accommodation

There were no significant correlations between symptom severity and the negative and positive relative accommodation measures for both groups.

Table 4-12: Correlation of symptom severity and NRA and PRA

	Control		PCS	
	p-value	ρ-value	p-value	ρ-value
NRA	0.31	-0.36	0.06	0.68
PRA	0.32	0.35	0.97	0.02

Figure 4-12: Correlation of symptom severity and negative relative accommodation

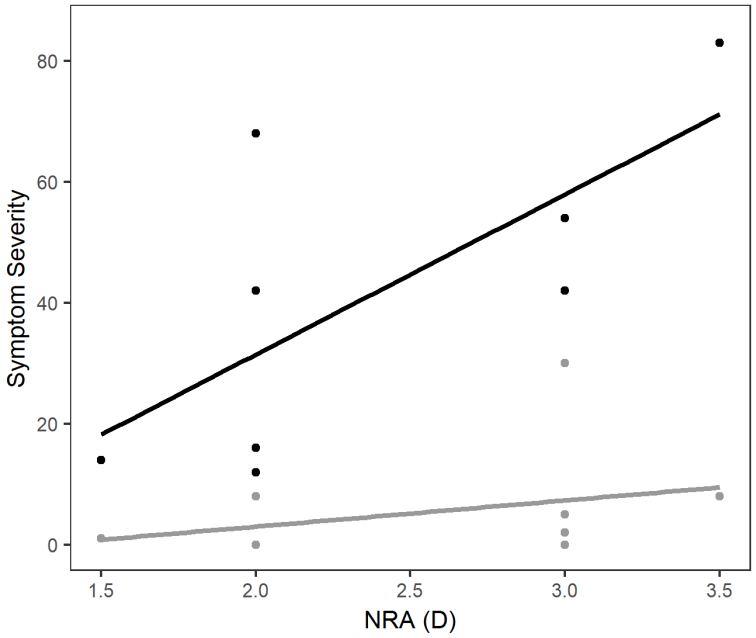
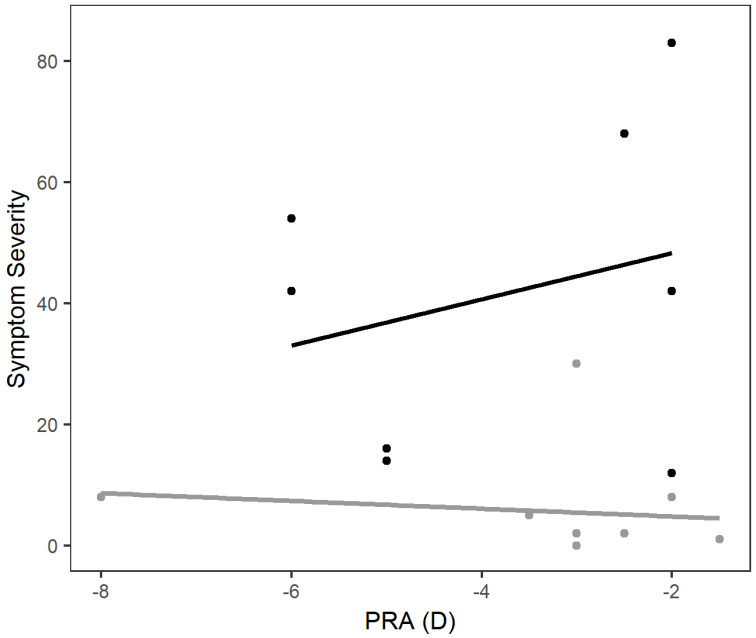


Figure 4-13: Correlation of symptom severity and positive relative accommodation



4.4.4 Vergence function

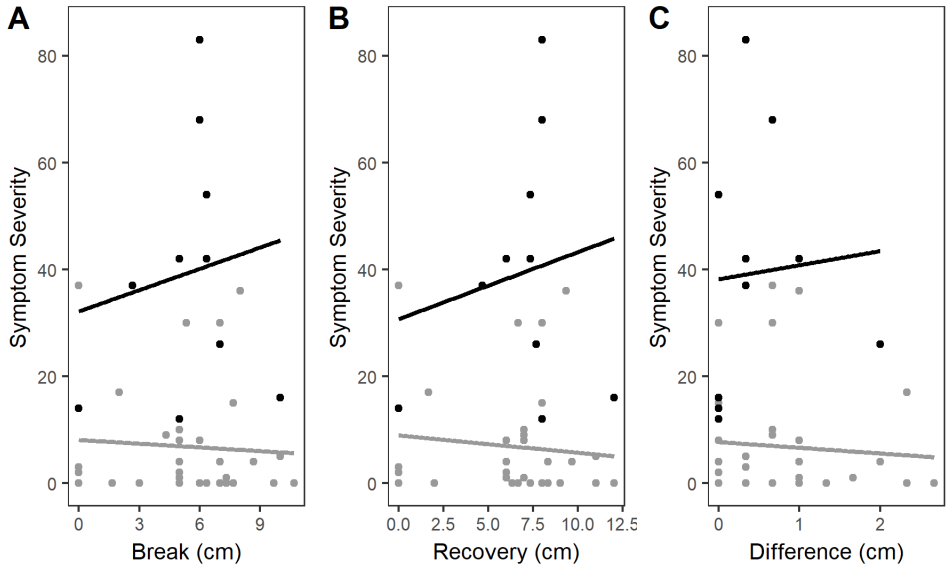
4.4.4.1 Near point of convergence

There was no significant correlation between symptom severity and the near point of convergence for both groups.

Table 4-13: Correlation of symptom severity and near point of convergence

	Control		PCS	
	p-value	ρ-value	p-value	ρ-value
Break point	0.88	-0.03	0.61	0.18
Recovery point	0.47	-0.13	0.78	0.10
Difference	0.16	-0.25	0.89	0.05

Figure 4-14: Correlation of symptom severity and near point of convergence



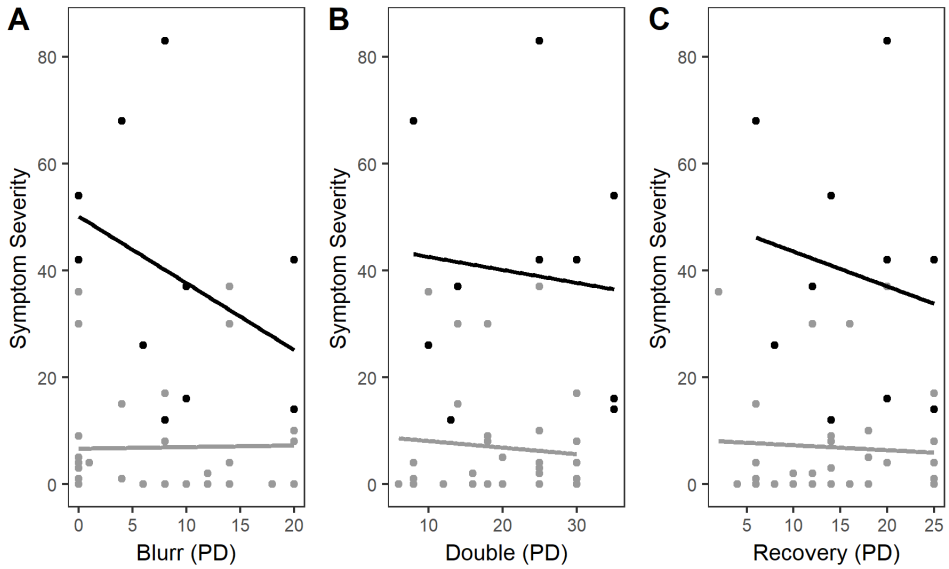
4.4.4.2 Distance horizontal positive fusional reserve

There were no significant correlations between symptom severity and the distance horizontal positive fusional reserve measures for either group.

Table 4-14: Correlation of symptom severity and distance HPFR

	Control		PCS	
	p-value	ρ-value	p-value	ρ-value
Blur point	0.89	0.03	0.19	-0.45
Double point	0.91	0.02	0.75	-0.11
Recovery point	0.64	0.08	0.66	-0.16

Figure 4-15: Correlation of symptom severity and distance HPFR



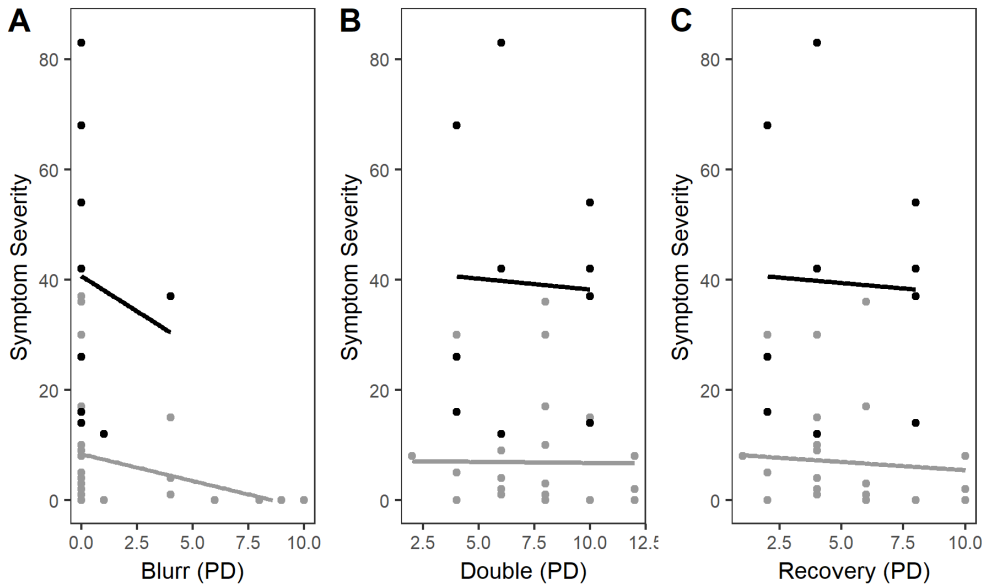
4.4.4.3 Distance horizontal negative fusional reserve

Except from the blur point in the control group, there were no significant correlations between symptom severity and the distance horizontal negative fusional reserve for both groups. The blur point in the control group demonstrated a significant negative correlation with symptom severity, whereby an increase in symptom severity was associated with a lower (worse) blur point value. Even though this correlation was significant, the blur point measure could only account for or be explained by 36% of the symptom severity score.

Table 4-15: Correlation of symptom severity and distance HNFR

	Control		PCS	
	p-value	ρ-value	p-value	ρ-value
Blur point	0.04*	-0.36	0.25	-0.40
Double point	0.55	-0.11	0.99	-0.003
Recovery point	-0.29	-0.19	0.99	-0.003

Figure 4-16: Correlation of symptom severity and distance HNFR



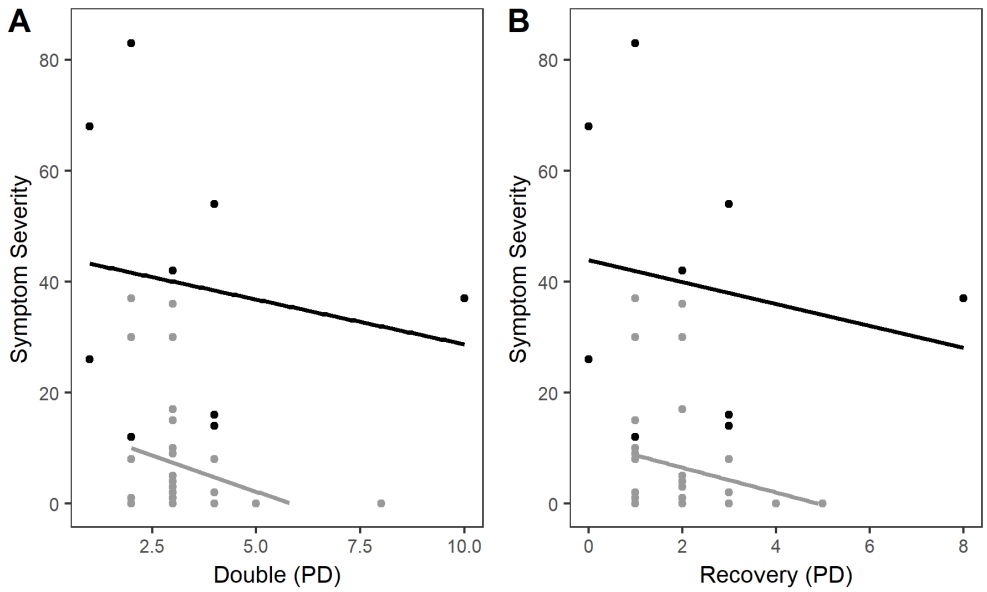
4.4.4.4 Distance vertical positive fusional reserve

There were no significant correlations between symptom severity and the distance vertical positive fusional reserve measures for either group.

Table 4-16: Correlation of symptom severity and distance VPFR

	Control		PCS	
	p-value	ρ-value	p-value	ρ-value
Double point	0.10	-0.29	0.51	-0.24
Recovery point	0.37	-0.16	0.51	-0.24

Figure 4-17: Correlation of symptom severity and distance VPFR



4.4.4.5 Distance vertical negative fusional reserve

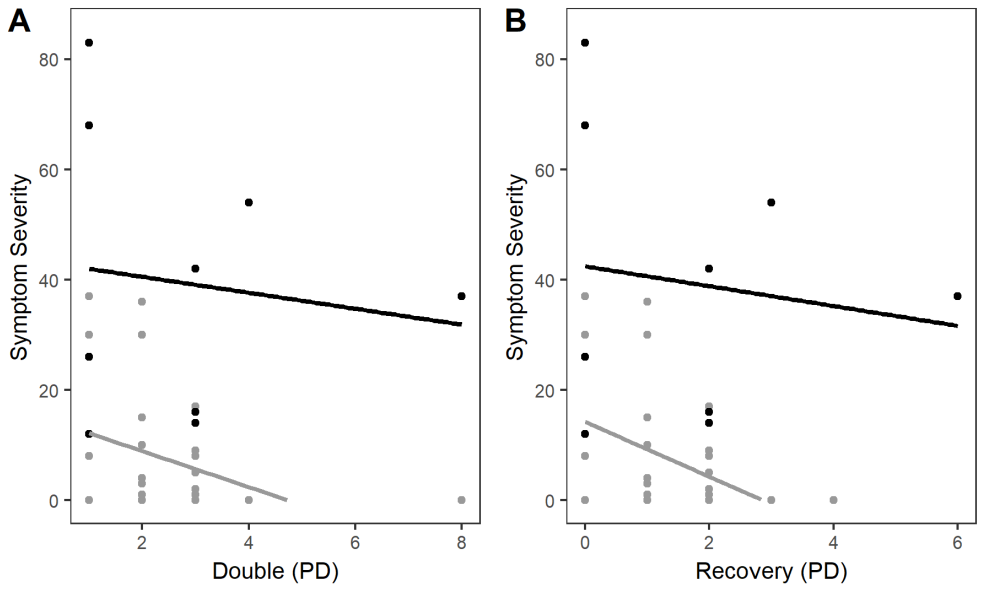
There were significant negative correlations between symptom severity and the distance vertical negative fusional reserve double point and recovery point measures in the control group. As symptom severity increased, the distance vertical negative fusional reserve double point and recovery point values decreased indicating poorer distance VNFR. There was no significant correlation between symptom severity and the distance vertical negative fusional reserve measures in the PCS group.

Even though the double and recovery point correlations were significant in the control group, the double and recovery points could only account for or be explained by 45% and 39% of the symptom severity score, respectively.

Table 4-17: Correlation of symptom severity and distance VNFR

	Control		**PCS**	
	p-value	ρ-value	p-value	ρ-value
Double point	0.01*	-0.45	0.90	-0.05
Recovery point	0.02*	-0.39	0.90	-0.05

Figure 4-18: Correlation of symptom severity and distance VNFR



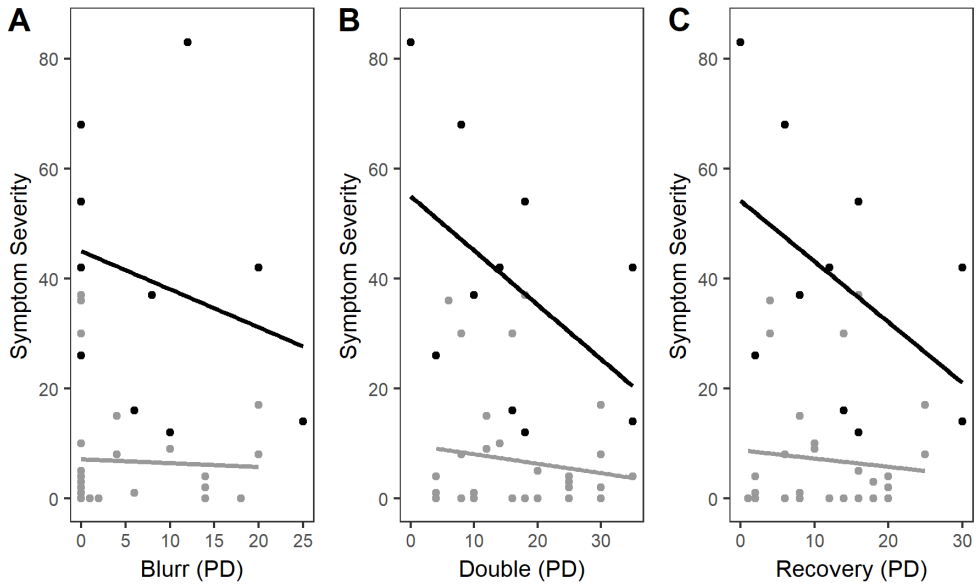
4.4.4.6 Near horizontal positive fusional reserve

There were no significant correlations between symptom severity and the near horizontal positive fusional reserve measures for either group.

Table 4-18: Correlation of symptom severity and near HPFR

	Control		PCS	
	p-value	ρ-value	p-value	ρ-value
Blur point	0.51	0.12	0.41	-0.29
Double point	0.92	-0.02	0.17	-0.47
Recovery point	0.99	-0.001	0.17	-0.47

Figure 4-19: Correlation of symptom severity and near HPFR



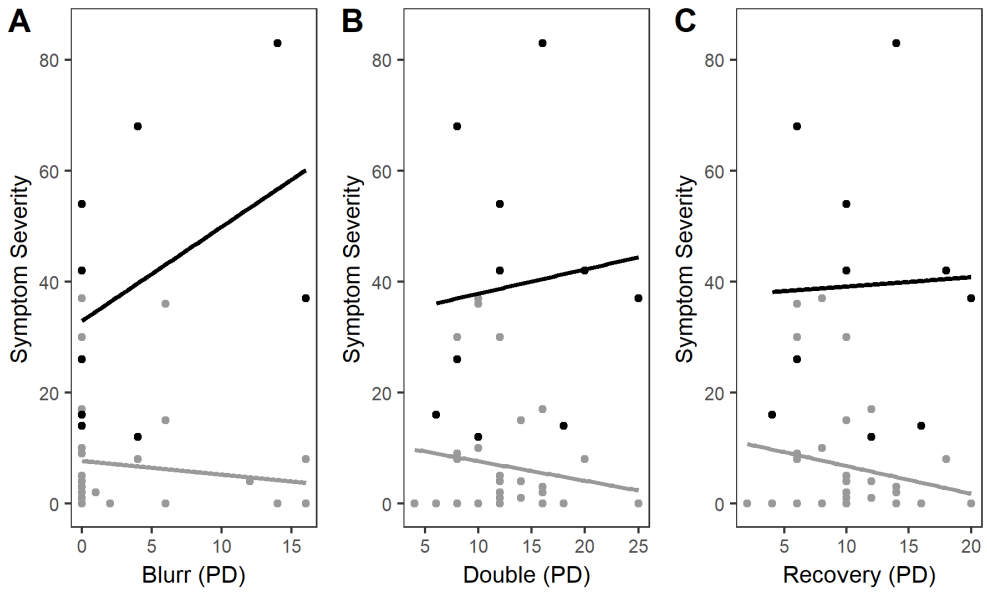
4.4.4.7 Near horizontal negative fusional reserve

There were no significant correlations between symptom severity and the near horizontal negative fusional reserve measures for either group.

Table 4-19: Correlation of symptom severity and near HNFR

	Control		PCS	
	p-value	ρ-value	p-value	ρ-value
Blur point	0.53	-0.11	0.50	0.24
Double point	0.92	-0.02	0.71	0.14
Recovery point	0.84	-0.04	0.97	-0.02

Figure 4-20: Correlation of symptom severity and near HNFR



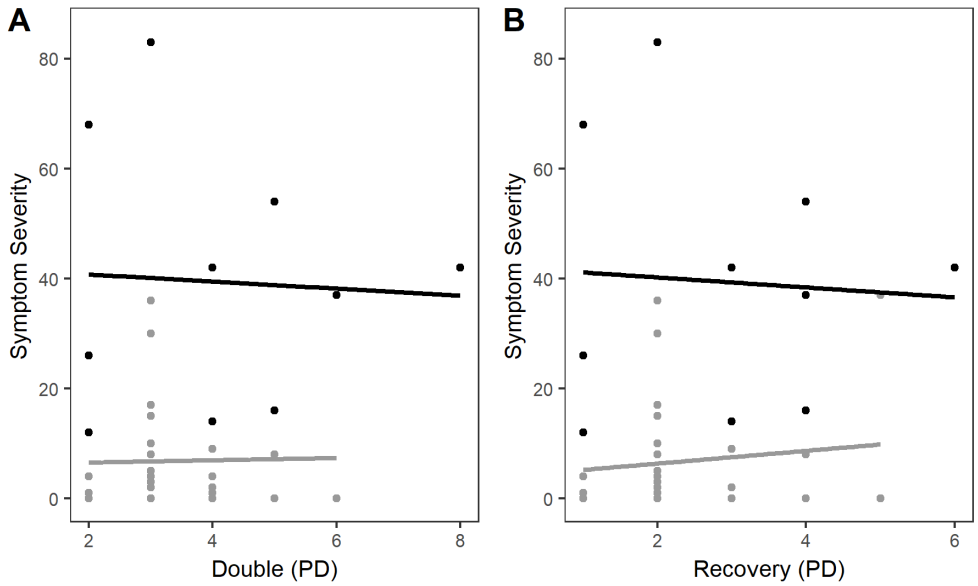
4.4.4.8 Near vertical positive fusional reserve

There were no significant correlations between symptom severity and the near vertical positive fusional reserve measures for either group.

Table 4-20: Correlation of symptom severity and near VPFR

	Control		PCS	
	p-value	ρ-value	p-value	ρ-value
Double point	0.32	-0.18	0.87	0.06
Recovery point	0.49	-0.12	0.86	0.07

Figure 4-21: Correlation of symptom severity and near VPFR



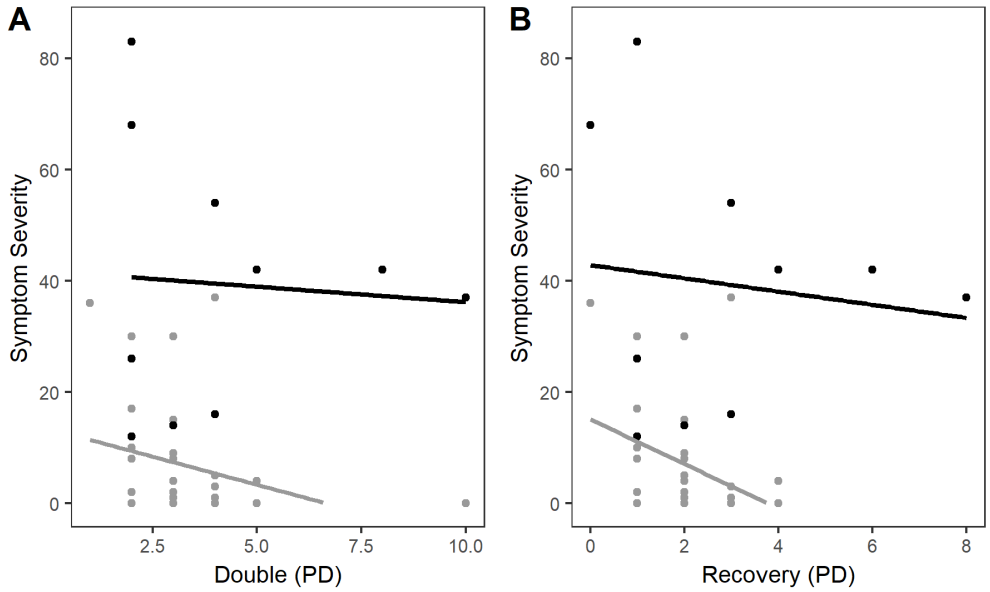
4.4.4.9 Near vertical negative fusional reserve

There were no significant correlations between symptom severity and the near vertical negative fusional reserve measures for either group.

Table 4-21: Correlation of symptom severity and near VNFR

	Control		PCS	
	p-value	ρ-value	p-value	ρ-value
Double point	0.09	-0.10	0.99	-0.006
Recovery point	0.07	-0.32	0.83	-0.08

Figure 4-22: Correlation of symptom severity and near VNFR



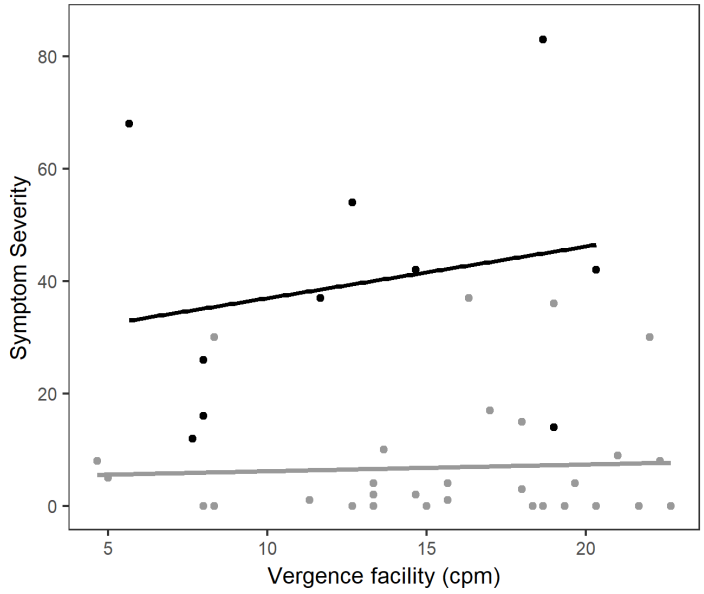
4.4.4.10 Vergence facility

There was no significant correlation between symptom severity and vergence facility for both groups.

Table 4-22: Correlation of symptom severity and vergence facility

	Control		PCS	
	p-value	ρ-value	p-value	ρ-value
Vergence facility	0.90	-0.02	0.63	0.18

Figure 4-23: Correlation of symptom severity and vergence facility



4.5 Global visual function tasks

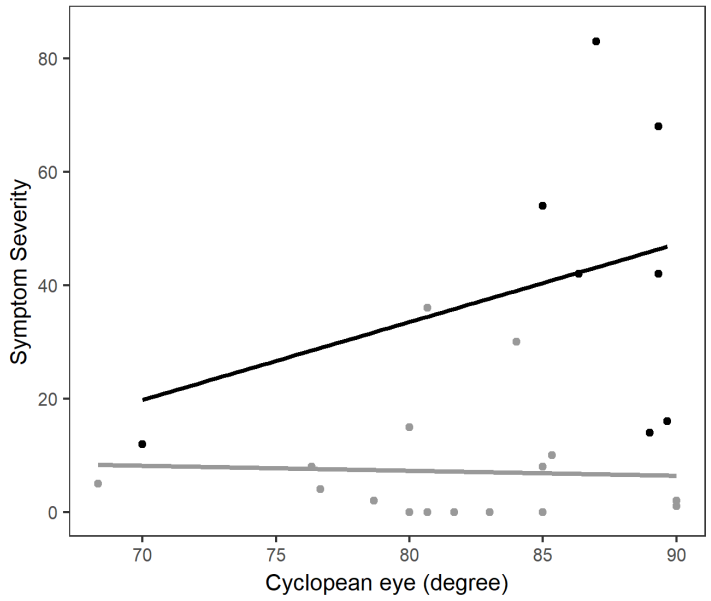
4.5.1 Visual spatial awareness - cyclopean eye alignment position

There was no significant correlation between symptom severity and the cyclopean eye position result for both groups.

Table 4-23: Correlation of symptom severity and cyclopean eye alignment position

	Control		**PCS**	
	p-value	ρ-value	p-value	ρ-value
Cyclopean eye alignment	0.68	-0.11	0.77	0.13

Figure 4-24: Correlation of symptom severity and cyclopean eye alignment position



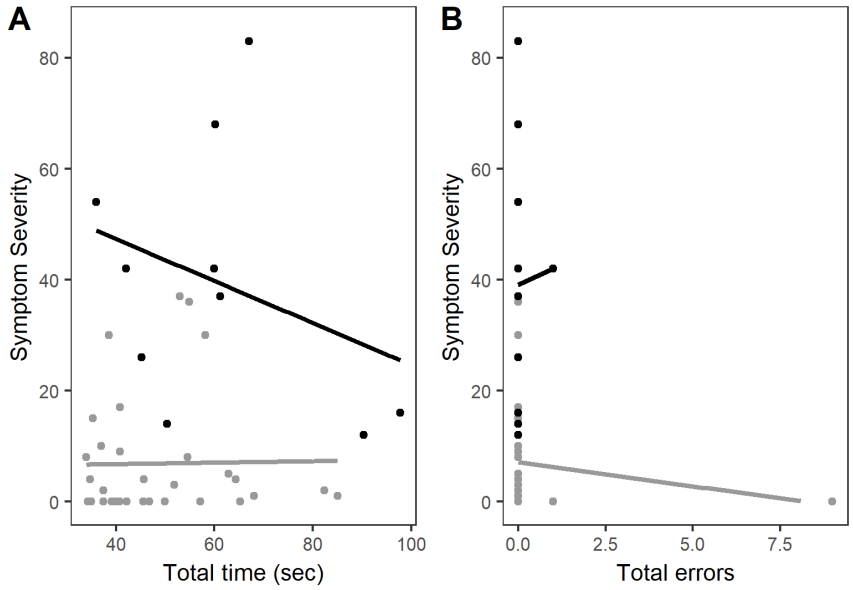
4.5.2 King-Devick

There were no significant correlations between the symptom severity and either the KD time or KD errors results for either group.

Table 4-24: Correlation of symptom severity and King-Devick

	Control		**PCS**	
	p-value	ρ-value	p-value	ρ-value
Time	0.53	0.11	0.48	-0.25
Errors	0.14	-0.26	0.75	0.12

Figure 4-25: Correlation of symptom severity and King-Devick



4.6 Visual motor integration

4.6.1 Visual-motor reaction time

There were no significant correlations between symptom severity and visual-motor reaction times (central and peripheral) for both groups.

Table 4-25: Correlation of symptom severity and visual-motor reaction time

	Control		**PCS**	
	p-value	ρ-value	p-value	ρ-value
Central	0.20	-0.23	0.19	-0.24
Peripheral	0.80	0.09	0.35	0.33

Figure 4-26: Correlation of symptom severity and central visual-motor reaction time

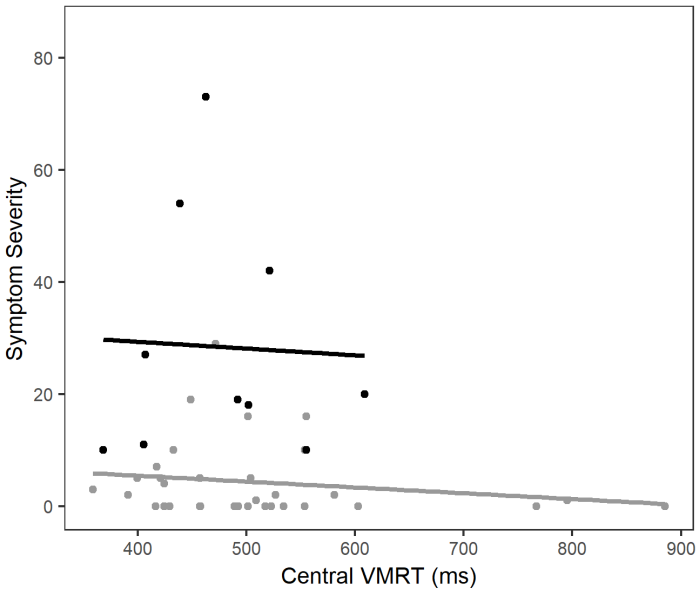
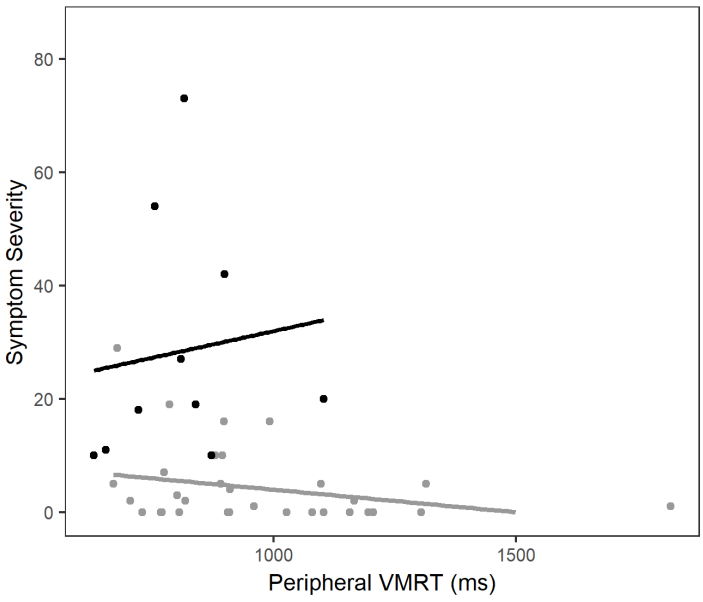


Figure 4-27: Correlation of symptom severity and peripheral visual-motor reaction time



4.6.2 Coincidence anticipation timing

For the most part there were no significant correlations between symptom severity and the coincidence anticipation timing measures for both groups except the following outcome measures, which were significant correlated in the PCS group only:

1) Constant error - speed 35 (mph): a significant negative correlation was present. This indicates that PCS participants with more severe symptoms tended to have later responses to the stimulus at this particular speed.
2) Variable error - speed 35 (mph): a significant negative correlation was present. This indicates that PCS participants with more severe symptoms tended to have more variable, inconsistent responses at this stimulus speed.
3) Absolute error - speed 10 (mph): a significant positive correlation was present. This indicates that PCS participants with more severe symptoms tended to have higher absolute error values (or were more inaccurate overall) when responding to the stimulus at this stimulus speed.

One possible explanation for the poorer performance in the PCS participants with more symptoms is that these participant's symptoms were associated with slower reaction times and / or difficulty attending to the task. An alternative explanation, at least for the poorer performance at 35 mph in the PCS group was that this task was just more challenging than some of the other speeds and the participants did not do as well on it.

Table 4-26: Correlation of symptom severity and coincidence anticipation timing

	Control		PCS	
Speed	p-value	ρ-value	p-value	ρ-value
Constant error				
5	0.670	-0.077	0.738	-0.122
10	0.186	0.236	0.763	-0.109
15	0.431	-0.142	0.532	0.225
20	0.384	-0.157	0.521	0.231
25	0.997	0.001	0.868	-0.061
30	0.086	-0.304	0.614	0.182
35	0.876	-0.028	0.04*	-0.663
40	0.541	-0.110	0.947	-0.024
Variable error				
5	0.501	-0.121	0.947	-0.024
10	0.173	-0.243	0.336	0.340
15	0.486	0.126	0.751	-0.116
20	0.822	0.041	0.763	0.109
25	0.433	0.141	0.250	-0.401
30	0.833	0.038	0.663	-0.158
35	0.277	0.195	0.01*	-0.742
40	0.538	-0.111	0.614	-0.182
Absolute error				
5	0.097	0.294	0.934	-0.030
10	0.223	-0.218	0.04*	0.644
15	0.819	0.041	0.960	-0.018
20	0.523	0.115	0.555	-0.213
25	0.470	0.130	0.521	0.231
30	0.555	0.107	0.763	-0.109
35	0.091	0.299	0.166	-0.474
40	0.610	-0.092	0.861	-0.064

Figure 4-28: Correlation of symptom severity and coincidence anticipation timing - 5 mph

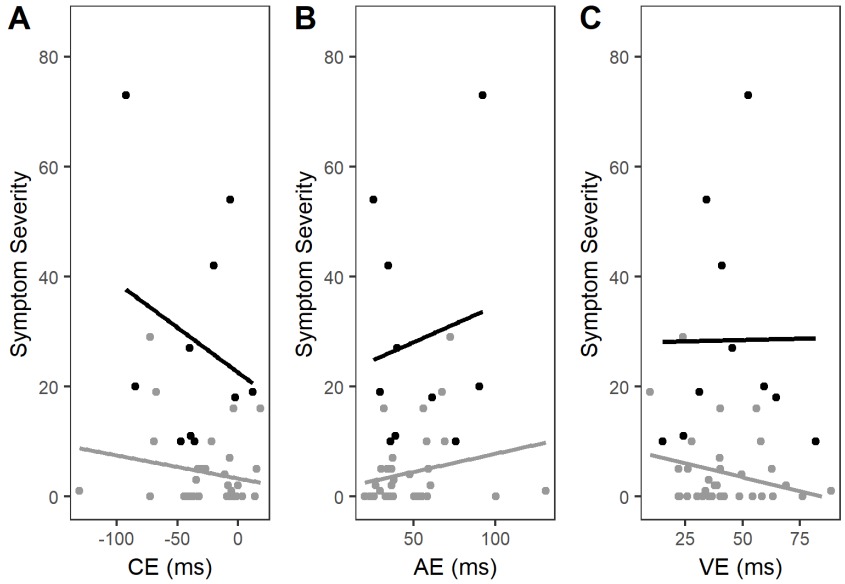


Figure 4-29: Correlation of symptom severity and coincidence anticipation timing - 10 mph

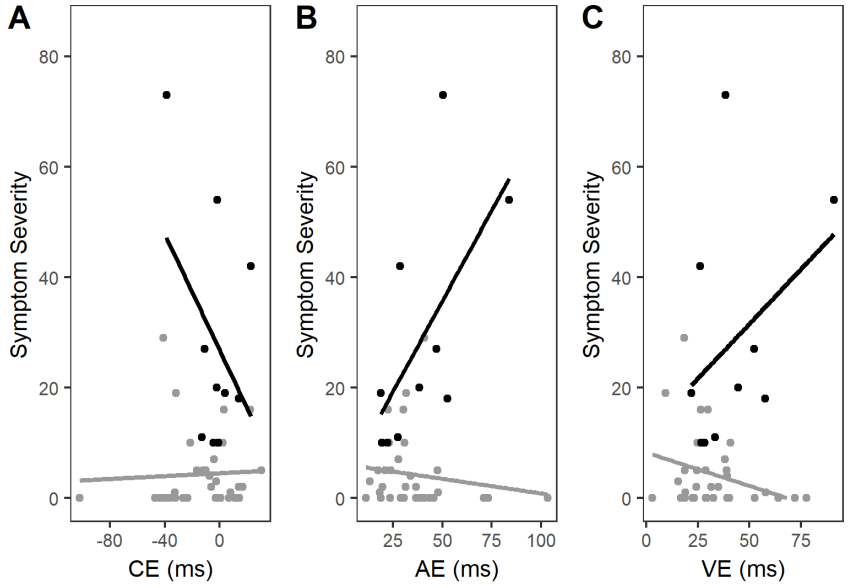


Figure 4-30: Correlation of symptom severity and coincidence anticipation timing - 15 mph

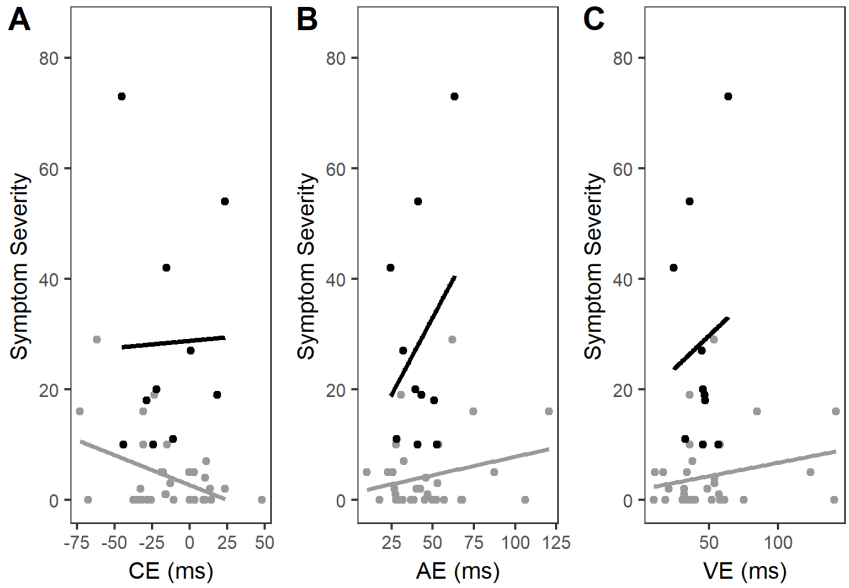


Figure 4-31: Correlation of symptom severity and coincidence anticipation timing - 20 mph

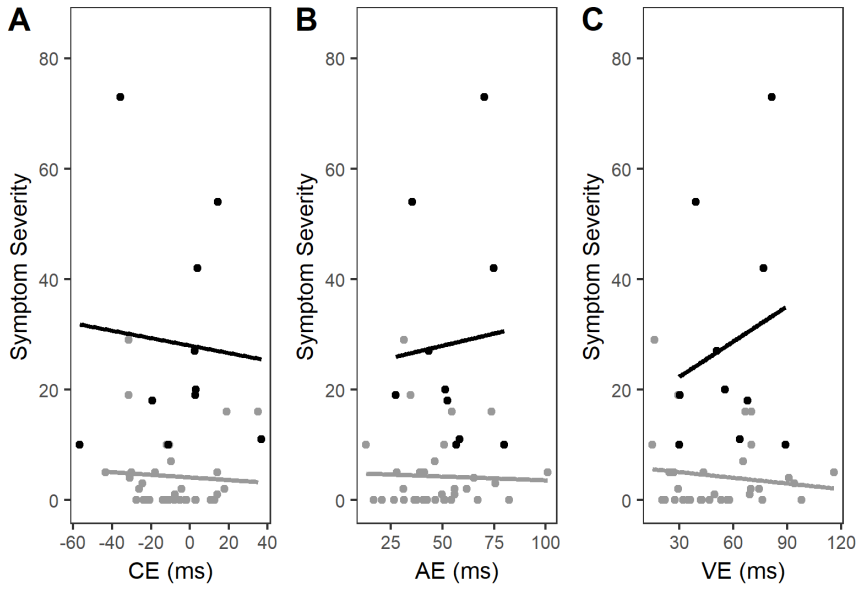


Figure 4-32: Correlation of symptom severity and coincidence anticipation timing - 25 mph

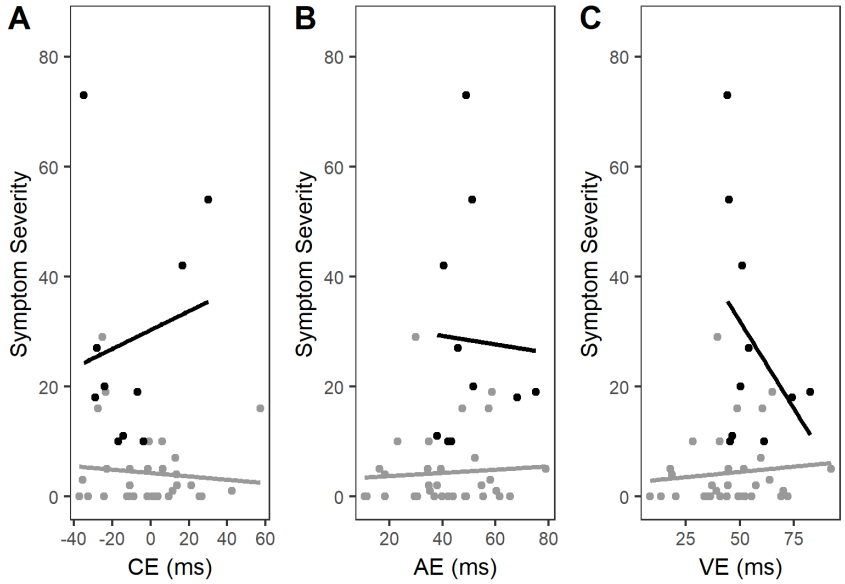


Figure 4-33: Correlation of symptom severity and coincidence anticipation timing - 30 mph

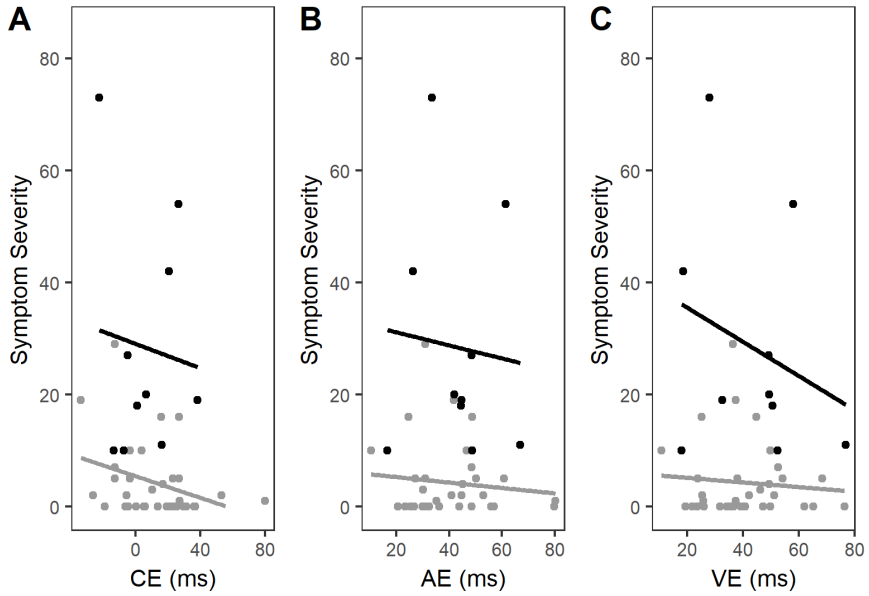


Figure 4-34: Correlation of symptom severity and coincidence anticipation timing - 35 mph

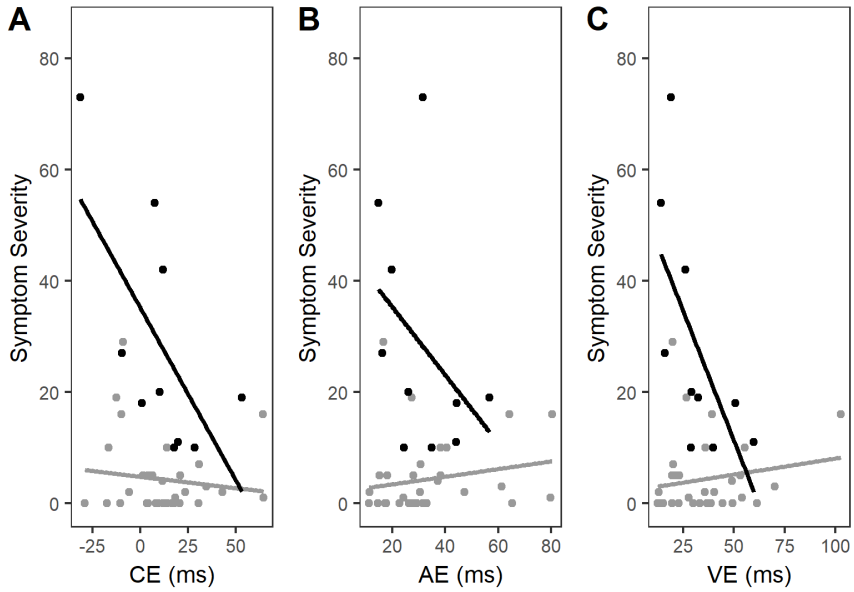
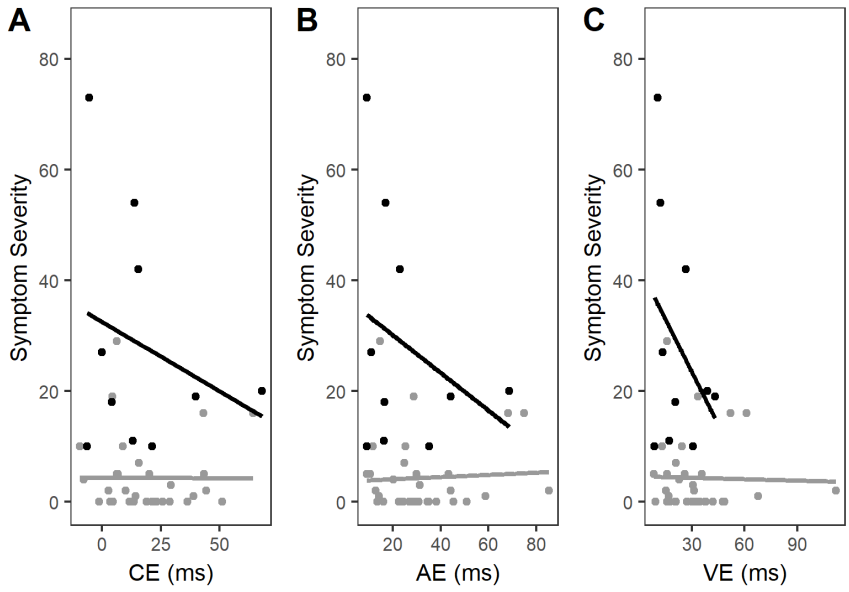


Figure 4-35: Correlation of symptom severity and coincidence anticipation timing - 40 mph



4.7 Other observations: symptoms and examination length

As mentioned in the methods chapter, the length of the study visits was about 1 hour and 20 minutes for visit 1 and 45 to 60 minutes for visit 2. However, some of the PCS participants experienced symptom exacerbation during the assessments and required breaks, which prolonged the length of the visits. None of the control participants experienced symptom exacerbation during the study visit.

It is worth mentioning that a break from testing was given whenever the participant asked for one, and testing only continued when the participant was ready. Although the study protocol was not designed to look at test breaks or symptoms exacerbation during testing, the examiner thought it was an important behavioral difference between the groups and should be recorded, especially as this study was exploratory in nature. Therefore, the study examiner recorded the breaks given along with the participant's reported symptoms every time a break was given. Unfortunately, neither the length of the break nor the overall length of the study visit was recorded.

The process of recording test breaks and symptoms started with the second PCS participant who took part in the study. This participant also happened to be the first participant who experienced symptom exacerbation and the first participant to ask for a break. There were only two PCS participants who did not experience symptom exacerbation during testing. On the other hand, there were eight PCS participants who did experience symptom exacerbation. Of the eight PCS participants who experienced symptom exacerbation, only one participant reported light sensitivity but never asked for a break (Participant 10). All of the other PCS participants who reported symptom exacerbation asked for breaks. It is important to mention that Participant 10 wore tinted non-prescription glasses between tests, but not during the tests. Table 4-27 highlights the symptoms reported by each PCS participant and the visual function tests associated with symptom exacerbation. If symptoms were recorded, then a break was given (except for Participant 10's light sensitivity symptoms).

Overall, only nine tests of the tests conducted in this study seemed to provoke symptoms in the PCS group. These tests are as follows: near ocular alignment, ocular motility, amplitude of accommodation, near point of convergence, accommodation facility, vergence facility, dynamic visual acuity, distance horizontal positive fusional reserve, and visual-motor reaction time.

Near point of convergence and accommodation facility tests appeared to be the most provocative, because these two tests triggered symptoms that caused the highest number of participant breaks. On the contrary, the near ocular alignment and the distance horizontal positive fusional reserve tests triggered the lowest number of participant breaks (Table 4-27).

Table 4-27: Breaks and symptoms of the PCS group

Participant	Near ocular alignment	Broad H	AA	NPC	AF	VF	DVA	HPFR	VMRT
1	No break needed								
2		Hard to concentrate + irritation			Nausea				
3	Aching behind the eye + flickering sensation - only with the left gaze			Trouble focusing					

4						Fatigue + pressure on the head			
5		Target flickers	Dizziness and fogginess	Dizziness and fogginess			Dizziness and fogginess - only with the random motion		
6		Eyeball strain + forehead pain + headache	Headache	Headache	Headache		Headache - only with the random and horizontal motions	Headache	Headache – only with the peripheral lights
7					Nausea	Tired			

8	No break needed								
9				Pressure on the head + fatigue + nausea	Pressure on the head + fatigue + nausea		Headache + difficulty concentrating - only with the random motion		Blurry vision + vertigo + seeing dark spots
10	Sensitivity to light and flickering sensation of the room lights during all tests (no breaks)								
Total breaks per test	1	3	2	4	4	2	3	1	2

Chapter 5 - Discussion

The objectives of the current study were as follows: 1) to apply a comprehensive visual function test battery in both control and PCS individuals 2) to compare performance on the comprehensive visual function test battery between control and PCS individuals 3) to determine if performance on the comprehensive visual function test battery was in any way related to the symptoms individuals with PCS experience. In this chapter, the discussion will be structured around the study objectives to determine if the study was able to fulfill its objectives.

5.1 Establishment of the visual function test battery

A comprehensive visual function test battery was applied in this study. The test battery consisted a number of assessments that were completed across two study visits. The assessments completed included health history questionnaires, static visual perception tests, dynamic visual function tests, binocular vision tests, global visual function tests, and visuomotor integration tests. The tests conducted in each visit were listed in Table 2-1.

The test battery appears to be feasible in both the control and PCS groups, and all of the participants successfully completed all of the tests in the battery and the two study visits. It is interesting to note that a number of the PCS participants took longer to complete the study visits than the control participants, because some of the tests in the battery caused an increase in participant symptoms that required breaks to be taken during the exam. This finding is interesting in its own right, and will be discussed in more detail below.

It is important to mention there was one PCS participant who was excluded from the study. When this participant contacted the study examiner, the participant was eligible to participate in this study and was an excellent candidate for the PCS group (see 2.2.2 Inclusion/Exclusion criteria of the PCS group). The only time that worked for the participant to join the study was about a month after contacting the study examiner at which time, the participant successfully joined the study and completed the study visits. At the time of data entry, the study examiner realized that this participant reported only one symptom on the day of testing and.no longer met the study inclusion criteria. Therefore, this participant was excluded from the study.

5.2 Comparing performance on the comprehensive visual function test battery between control and PCS groups

5.2.1 Static visual perception

5.2.1.1 Static distance visual acuity

In this study, the mean and median values of static distance VA of both groups fall within the established normal range[39,42] and were not different between groups. Testing static distance visual acuity did not provoke any participant symptoms either. These findings suggest that static distance visual acuity is less likely to be affected in individuals with concussion or PCS, and that this test has less utility for providing an objective measure of concussion and PCS recovery.

5.2.1.2 Static near visual acuity

There was no difference in the static near VA between the groups in OD, OS, or OU. Mean and median values for both groups were (0.40 M) which is the smallest print on the chart. This finding indicates excellent static near VA among groups. However, the PCS group as a whole was less consistent on this test than the control group. Examination of the scatter plot for static near VA, reveals that the observed inconsistency in the PCS group was caused by an outlier. Upon further examination of this particular PCS participant, there did not appear to be a major refractive error issue that caused this reduction in near VA (OD: 0.12-0.12x104 - OS: 0.25-0.25x38). However, this participant was the only participant that reported experiencing a loss of consciousness for >1 minute at the time of their concussion incident. It is well-known that concussion is rarely accompanied with loss of consciousness.[1,3,10,69] Loss of consciousness has not been proven to be a risk factor for significant deficits post-concussion,[3,70] but it was the only compelling factor for the observed decrease in near VA for this case. This case highlights the importance of studying the PCS population as individual cases[3] to look at other potential confounding factors that may explain specific deficits and/or behaviours.

5.2.1.3 Contrast sensitivity

In this study, contrast sensitivity was found to be similar between groups, and consistent with the established CS normal values for this age group.[39,47] Like static visual acuity, it appears that CS did not differentiate between healthy controls and PCS participants in this study. Previous

research has shown that contrast sensitivity is reduced in individuals following TBI, so the findings of this study may suggest that the test used was not sensitive enough to detect differences in CS between groups.[71,72] The study findings could also suggest that the population sample studied was not either large enough to detect differences in CS, or that the injury population in particular did not have severe enough injuries to affect their contrast sensitivity values. An alternative explanation is that most of the PCS group was high-level athletes, while most of the control group were recreational or non-athletes. It is possible that CS was reduced in the high-level athletes with PCS compared to other high-level athletes, but not reduced compared to the controls. While it was not possible to examine this last explanation within the current study sample, it is important to consider matching the athletic background of participants in future studies.

5.2.2 Dynamic visual perception

5.2.2.1 Dynamic visual acuity

DVA was similar between the two groups in horizontal, jitter, and random motions. It is important to mention that DVA for the jitter motion of both groups appeared to be better than for the random and horizontal motions. This could be due to the fact that during the jitter movement, participants were required to make fewer eye movements to find the target than during the horizontal and random motion tasks. This was because the target in the jitter motion task stayed at the centre of the screen; therefore, the image fell on the foveal area with minimal effort, and likely made it easier to recognise. This finding is similar to the results found in the validation study of the same DVA test (moV&).[48] The population samples studied here, DVA tests did not appear to be effective measures for distinguishing visual function deficits in normal and PCS individuals. DVA has been shown to be better in healthy dynamic sport athletes than controls[73]; therefore, it is possible that the athletic background of the PCS participants may have masked any deficits in performance when comparing this group to the control group of mainly recreational athletes and non-athletes.

5.2.3 Refractive status

5.2.3.1 Objective refraction

Spherical equivalent refractive errors were found to be similar between groups, and objective, non-cycloplegic refraction does not appear to be a strong measure for identifying visual dysfunction associated with PCS. It is important to mention that 18 control participants (55%) and 4 PCS participants (40%) wore prescription glasses or contact lenses on the days of testing. The remainder of the participants did not have refractive corrections.

5.2.4 Binocular vision

5.2.4.1 Ocular Alignment

5.2.4.1.1 Distance ocular alignment

The distance ocular alignment test was similar between the groups in the primary, left, and right gazes, and the distance ocular alignment of both groups appeared to be similar to the established normal values of distance phoria.[50,74] Additionally, there was no incomitancy (≥5 PD difference in the ocular misalignment between gazes[75]) found between the primary, left, and right gazes among participants in both groups. Therefore, in this study, the distance ocular alignment test had less utility in distinguishing visual dysfunctions in the PCS group as a whole.

5.2.4.1.2 Near ocular alignment

The near ocular alignment test was also similar between the groups in the primary, left, and right gazes and no incomitant deviations were noted. Near ocular alignment was similar to the established normal values of near phoria in both groups,[50] however, the normative values used for comparison were reported in children, which is a different population than the population of this study.

Although not significantly different from the controls, the PCS group appeared to have slightly more near exophoria at near than the control group. Additionally, the mean and median values of the PCS group suggested that the PCS group had higher exophorias at near compared to distance, which can be an indicator of convergence insufficiency.[26,76,77] This finding suggests

that the near ocular alignment test has the potential to distinguish lingering visual dysfunctions in PCS individuals. Hence, it is worth including this test in visual function assessments of individuals with PCS.

5.2.4.2 Ocular motility

There were no abnormalities found in the control group participants in terms of eye movements. Conversely, irregular eye movements were found in three participants of the PCS group. The irregular eye movements in the PCS participants were accompanied with symptoms of irritation, and aching behind the eyes.

The abnormal, irregular eye movements could be due to impaired nervous innervation of the eye muscles or due to deficits in the eye muscles themselves.[50] Additionally, these abnormalities could be attributed to higher order processing deficits of the brain stem.[50] It is unclear whether or not the abnormalities observed in this study were caused by a pre-existing structural abnormality in the nerves or the eye muscles that manifested after the concussion incident,[78] or if they were new abnormalities that had just developed. In 2010, a study was conducted to investigate the presence of cranial nerve injuries after mTBI, and determined that cranial nerve injuries occurred in number of the cranial nerves including the oculomotor nerve (III), trochlear nerve (IV), and abducens nerve (VI), which are the main nerves that control eye movements. As part of this 2010 study, a follow-up assessment was conducted one year after the initial assessment, and 3 out of 10 cases demonstrated persistent cranial nerve deficits that were present despite no associated abnormalities being found on the CT scan.[79] The findings of this study suggest that functional abnormalities of the cranial nerves can exist in the absence of any obvious structural abnormalities as detected by current conventional neuroimaging techniques. This argument is supported by another study that determined eye movement impairments were present in a PCS sample who did not have any obvious structural neurological deficits.[80]

It is well-known that eye movements determine the visual information received by the retina and processed by the visual cortex. Therefore, eye movements are an important part of visually guided functions such as balance.[81] Determining that eye movement deficits exist in PCS individuals with the Broad H, which is considered an eye movement screening test,

demonstrates that it is important to study eye movement functions in PCS in more sophisticated way. In studying eye movements more precisely, it would be important to determine if deficits in eye movements correlate with deficits in balance. This would be an interesting study to complete because it would build on previous research which has shown that deficits of balance,[81] the vestibulo-ocular reflex,[22] and visual-motor coordination[24] exist in the PCS population.

5.2.4.3 Stereopsis

Stereopsis was similar between the groups, and the findings in both groups were consistent with the normal stereopsis values in a similar age group.[82] In this particular study, stereopsis did not differentiate between the control and PCS groups, suggesting that stereopsis might not be an effective objective measure of visual dysfunction in PCS. However, stereopsis is an excellent tool to rapidly assess global binocular vision at near, and so may still have some clinical utility in the PCS population.

5.2.4.4 Accommodation function

5.2.4.4.1 Amplitude of accommodation

In this study, AA was measured following Hofstetter's formula for the minimum age expected AA. If the total was positive that indicates the participant had a better AA than average and vice versa. The majority of participants in this study had better than average AA for OD, OS, and the absolute difference between the two eyes, and there was no difference in AA between groups on any of the parameters measured. The results of the AA tests suggest that AA may be less able to differentiate PCS individuals with visual dysfunction from normal, non-concussed individuals.

5.2.4.4.2 Accommodation accuracy

Accommodation accuracy was similar between the two groups for OD, OS, and the absolute difference between the two eyes. There is lack of normative data on the accommodation accuracy data. However, there was one study conducted by Ma et al. (1999) that examined accommodation accuracy with the MEM technique in participants of similar age to the current study participants. Ma et al.'s study examined the OD only (neither the OS nor the absolute

difference between the eyes was examined), however, the OD accommodation accuracy found in the current study were similar to the OD accommodation accuracy found by Ma et al. (1999).[83]

Although there was no statistically significant difference found between groups in this test, there were unusual behaviours in the accommodation of three participants from the PCS group. These participants had a lag of accommodation in one eye and a lead of accommodation in the other eye. To our knowledge, this imbalance in the accommodation behaviour has not been reported in any other study.

Participants were examined with their habitual correction, if they had one, and it is possible that the retinoscopy reflex seen was an overcorrection and/or under-correction of the participant's own refractive correction.[50] Also, it is possible that the retinoscopy reflex seen was an uncorrected refractive error.[50] The table below presents information on the refractive error and the accommodation accuracy findings for these three PCS participants (Table 5-1). With that being said, improper correction of participant's own refractive error is less likely to be the cause of this unusual finding because this finding was not found in the control group as well. Moreover, these three participants had excellent near VA (0.40M) in OD, OS, and OU. For participant 1 and 3 particularly, it is even more unlikely that what was seen in the retinoscopy was refractive errors. Although these participants had lead of accommodation in the OD, they had no minus spherical refractive error in the same eye. Furthermore, they had an astigmatic refractive error on the horizontal axis (opposite to the axis of the retinoscopy streak, which was vertical). For these reasons, it is less likely that these abnormal findings were due to refractive errors.

Therefore, because this abnormal finding was not found in the control group and it is not commonly seen in healthy populations, it could be a visual dysfunction that resulted specifically from these participant's concussions. It is possible the initial concussion injury resulted in an insult to the corresponding visual pathway responsible for accommodation, which includes the oculomotor nerve (III), and resulted in the deficits observed in this study.

However, the question becomes why this abnormality occurred in only a few participants. That could be attributed to different reasons such as injury mechanism and/or medication side-effects

which are beyond the scope of this thesis. It could also have been associated with the number of previous concussions participants had or the time since their injury, although neither of these relationships were explored in this thesis either. These results do suggest that the accommodation accuracy test appears to be a valuable objective measure in the assessment of visual dysfunction in PCS. In addition, these findings again highlight the importance of studying the PCS participants as separate cases and investigating the potential contributing factors to each presented abnormality, rather than studying them as a homogenous group.

Table 5-1: Refractive error of the three PCS participants

Participant	Participant wearing refractive correction	Objective refraction OD	Objective refraction OS	Accommodation accuracy OD	Accommodation accuracy OS
1	Yes	0.25	0.25	-0.50	0.50
		-0.50x171	-0.12x176		
2	Yes	-3.75	-4.00	0.50	-0.50
		-0.75x172	-0.62x159		
3	No	0.12	0.37	-0.25	0.50
		-0.12x178	-0.87x177		

5.2.4.4.3 Accommodation facility

The mean monocular AF values of both groups were consistent with established AF mean values in the literature,[50,84] and were similar between groups. Therefore, AF does not appear to demonstrate utility in differentiating individuals with PCS visual dysfunction from controls.

5.2.4.4.4 Negative and positive relative accommodation

NRA and PRA were similar between the two groups and consistent with established values in the literature.[50] Therefore NRA and PRA appear to have less potential to differentiate visual dysfunction in PCS from normal visual function in controls, especially when compared to other test such as accommodation accuracy and oculomotor control.

5.2.4.5 Vergence function

5.2.4.5.1 Near point of convergence

In this study, the mean NPC break and recovery point values for both groups were similar to the established norms in the literature,[39,50,56,57] and were not different between groups. In the current study, the NPC test does not seem to be a strong objective measure for visual dysfunctions in PCS, however the findings of this study are inconsistent with previous literature in the TBI and PCS populations, which has found that reduced NPC and convergence insufficiency are very commonly associated with visual dysfunction following concussion.[28,31,78,85] The small sample size of our PCS group may be one of the reasons behind the lack of significant difference in NPC values between groups. Another possibility is that many of the controls were tested during the university exam period, and may have had some mild visual dysfunction as a result of fatigue from studying, however the NPC values in both groups were normal so this may be less likely.

5.2.4.5.2 Distance horizontal positive and negative fusional reserve

Distance HPFR results were similar between groups, and both groups had higher (better) values for the blur point which resulted in higher (better) values for the break and recovery points; values for all three points were all slightly higher (better) than clinically accepted norms.[39,50]

For the distance HNFR test, both groups had similar break and recovery values, and these values were within the clinical accepted norms for this test.[50,75]

These findings suggest that both distance horizontal fusional reserve tests may have less potential to make a distinction between control and PCS participants.

5.2.4.5.3 Distance vertical positive and negative fusional reserve

It is important to mention that there is no established normative data on vertical fusional reserves in general. However, it is known that vertical FR values are usually less than horizontal FR values[75], which is consistent with the findings in this study. In this study, the distance vertical

fusional reserve tests were not different between groups and do not appear to be capable of differentiating controls from PCS participants.

5.2.4.5.4 Near horizontal positive and negative fusional reserve

In this study, the near HPFR and HNFR the mean and median values of both groups were similar and were within the clinical accepted norms.[50]

However, the PCS group appeared to demonstrate more variability on the near HPFR test than the controls (Figure 3-28). This variability again suggests that the PCS cases be considered individually in order to look for potential confounding factors that generated the variability. For instance, recurrent concussions have been a proposed as a factor associated with slower recovery, longer lasting PCS symptoms, and other clinically significant conditions such as depression.[86–88] By looking at the test data closely, it appears that the PCS participant with the highest number of concussions (11 sustained concussions) had the lowest near HPFR values among PCS participants. Conversely, another PCS participant with only one sustained concussion had the highest values in this test. The wide variety in the number of previous concussions within the PCS population studied (range 1 – 11, median 2.5; see Table 3-3) may be a possible explanation for the high variability within the PCS group in this study.

With that being said, it is difficult to draw this conclusion based on observations from two PCS participants. However, these are still interesting observations that should be further studied to better understand the effect of recurrent concussions on visual function performance. Furthermore, this preliminary finding strongly suggests that PCS individuals are different and they should be studied individually rather than a whole group, and that the near horizontal fusional reserve tests have strong potential to uncover visual dysfunctions associated with PCS.

5.2.4.5.5 Near vertical positive and negative fusional reserve

The near VPFR and VNFR were similar between the two groups. Similar to the comment made on the distance VPFR and VNFR tests, there is no established norms to look at in parallel to the results in this study, but the near vertical FR values found in this study were less than the near horizontal FR values as expected.[75] Similar to the distance vertical fusional reserve tests, near

vertical fusional reserve tests do not appear to be capable of differentiating controls from PCS participants.

5.2.4.5.6 Vergence facility

Although there was no significant difference in VF between the two groups, the control group appeared to have better mean and median values than the PCS group, but not to an extent that made a significant difference.

VF depends on rapid change in vergence, which is a type of bilateral eye movement that typically occurs when both eyes turn nasally or both eyes turn temporally. The results of this study suggest that vergence facility might have been slightly affected in the PCS group, but it was not affected as much as other eye movement tests (i.e. Broad H) and the King-Devick test (global reading ability that utilises eye movements) that were significantly worse in the PCS group. Furthermore, this finding suggests that the VF test is worth considering in the assessment of visual function in individuals with PCS.

5.2.5 Global visual function

5.2.5.1 Visual spatial awareness - cyclopean eye alignment position

Interestingly, on this test, the PCS group exhibited significantly less visual direction shift (performed better) than the control group. As mentioned earlier, about half of the control participants were involved in different recreational sport activities whereas most of the PCS participants practiced sports at a higher level. It has been determined that experienced athletes often provide more precise feedback on visual-spatial awareness tasks compared to the non-athletes,[89,90] therefore it is possible that the PCS group's athletic background level enhanced their visual function in this test to the extent that their performance surpassed the control group. Once again, this test results highlights the importance of comparing healthy athletes with PCS athletes in future studies in order to understand how athletic background affects test outcomes.

5.2.6 King-Devick

On the KD test, the control group performed significantly better and had a shorter (faster) reading time than the PCS group by about 18 seconds. Although KD is a simple reading task, it

captures underlying brain deficits that correlate with functions such as saccadic eye movements.[34,62] Research studies have determined that the KD test is a useful tool for concussion screening and as a sideline concussion assessment in sports.[34,62] The finding of the current study, that reading time is faster in the control group is similar to other studies that compared KD test results between control and PCS groups and found that reading time in PCS groups was longer than in controls.[91,92] It is suggested that the longer reading time in the PCS population may indicate the presence of some underlying subcortical brain damage that affects eye movements.[91,92] In this study, KD reading time appeared to be a strong objective measure of visual dysfunction in the PCS group, and the KD test should be included in the assessment of visual function in PCS individuals.

Despite the longer reading time in the PCS group, there was no difference in the KD number of sustained error results between the two groups in this study, which suggests that aspects of the KD task involved in processing visual information accurately were functioning equally in both groups.

5.2.7 Visual-motor integration

5.2.7.1 Visual-motor reaction time

Peripheral VMRT is usually higher (slower) than central VMRT because the peripheral VMRT targets are further apart than the central targets. The peripheral VMRT targets are further apart because they need to be separated by a larger visual angle than the central targets, and this means they take more time to be hit.[93,94] The results of the current study are consistent with this previous literature, and in both groups, the peripheral VMRT was higher than the central one.

Although there was no statistical difference between the two groups in the central VMRT, the PCS group had a faster central VMRT than the control group. Additionally, peripheral VMRT in the PCS group was significantly faster than in the control group. These differences in VMRT are likely a result of the differences in sports activity between the two groups. As mentioned earlier, about half of the control participants were involved in different recreational sport activities whereas most of the PCS participants practiced sports on a higher level of competition. Some studies suggest that athletes have superior VMRT compared to non-athletes.[95,96] Therefore, the

observed difference in peripheral VMRT might be related to participants athletic backgrounds. If so, it might be possible that the PCS group had peripheral VMRT deficits compared to healthy athletes, even though the PCS group was still better than the controls. In future studies it would be good to compare athletes with PCS to healthy athletes without PCS, as this would inform whether or not athletic background should be accounted for in future studies.

5.2.7.2 Coincidence anticipation timing

The CAT test did not differentiate healthy controls from PCS individuals. This finding suggests that the CAT test may has less potential to assess visual dysfunctions associated with PCS. It is important to mention that there is no established normative data on the CAT test in the literature. The data available in the literature varies based on the population, stimulus speed, and the testing method,[63,67,68,97,98] which makes it impossible to compare the literature with the results of the current study.

5.3 Correlation of symptom severity and visual function

A correlation statistical analysis was conducted to gain an insight into whether or not performance on the visual function tests correlated with symptom severity in each group and to understand if these correlations were different between the two groups in any way. This understanding could help in explaining the visual function performance in relation to the symptoms in the PCS group specifically.

5.3.1 Correlation of symptom severity and visual function in the control group

As mentioned in the introduction chapter, PCS symptoms have been found in individuals with no history of head injuries.[14] In this study, the control population was also found to have some PCS symptoms despite not having a history of head injury. Hence, it would not be surprising to find some correlations between symptoms and visual functions in the control group.

For the control group, significant correlations between symptom severity and most of the visual function tests were not found. Significant correlations were only found for the following tests:

1) a negative significant correlation was found between symptom severity and stereopsis. In other words, the increase of symptom severity was associated with less (better) stereopsis and vice versa.

2) a negative significant correlation was found between symptom severity and the blur point in the distance HNFR. In other words, increased symptom severity was associated with a lower (worse) blur point value. It is important to mention that in all the HFR tests a blur point is not always reported. In this study, only 8 out of the 33 control participants reported a blur point in the HNFR test. Therefore, a value of zero was given if the participant did not report blur point. This might have caused the negative significant correlation in this test.

3) a negative significant correlation was found between distance VNFR and symptom severity on both the break and recovery points. In other words, the increase of symptom severity was associated with reduced (poorer) VNFR results. Generally, vertical negative fusional reserve values are lower in magnitude than the horizontal negative fusional reserve values[99], which might have caused the negative significant correlation. Yet, it is also possible that the VNFR results were affected by symptom severity in the control group.

The aforementioned significant correlations do not provide enough evidence to suggest that overall visual function performance is affected by the severity of symptoms in the control participants. This is supported by the fact that no significant correlations were found between most of the visual function tests and symptom severity. In addition, it is clear from the scatter plot of symptom severity (Figure 3-1) that only few participants in the control group reported high symptom severity, which may have also affected the correlation results. Based on these results, it can be concluded that the visual function performance does not appear to have been affected by symptom severity in controls.

5.3.2 Correlation of symptom severity and visual function in the PCS group

For the PCS group, no significant correlations were found between symptom severity and performance on most of the visual function tests. Significant correlations were found for the following tests only:

1) a negative significant correlation was found between the constant and variable errors of the CAT test for the 35mph speed only. This indicated that PCS participants with more symptom severity tended to have late responses to the stimulus at this particular speed. In a similar fashion, PCS participants had more variable responses at the same speed. This might indicate a fatigue effect since it occurred towards the end of the test. Yet, this observation did not occur in the following and final speed, 40mph.

2) a positive significant correlation was found between the absolute error of the CAT test for the 10mph speed only, which meant that PCS individuals with more severe symptoms had higher absolute error values, or were less accurate, when responding to this particular stimulus.

Overall, the visual function test performances that correlated with symptom severity were different between the two groups. This might be due to the discrepancy in the number of participants between the two groups. Also, this might indicate functional differences between the groups despite the presence of symptoms in both of them. It is important to remember that most of the PCS symptoms reported were not specifically related to vision, which may explain lack of correlation between symptom severity and visual function.

5.4 Other observations: symptoms and examination length

As mentioned earlier, there are two school of thoughts about defining PCS. Some specialists believe that PCS is directly related to underlying pathophysiological changes in the brain caused by the sustained concussion, while others believe that PCS reflects the psychological and emotional status of the concussed individual.[3,17] It has been proposed that if the PCS symptoms get triggered or exacerbated by performing a certain task that requires cognitive and/or physical efforts and go away with minimal rest, then, the PCS symptoms would be more likely to reflect pathophysiological changes in the brain.[3]

The PCS participants were recruited based on specific inclusion criteria that were chosen to try and ensure that the PCS group was homogenous in their PCS condition to some extent. However, by looking at the breaks needed and tests causing symptom exacerbations (Table 4-27), only two participants out of ten did not require breaks nor experience symptom exacerbation with the tests. The question then becomes if the PCS group is homogenous, why did these two PCS participants not experience worsening of symptoms like the rest of the group? Other factors such as adjunct therapies, medications, or time since injury, might have an impacted individual's performances and are harder to account for in a population of PCS individuals because there are so many variables that need to be considered. Therefore, for the time being at least, it is very important to consider PCS individuals as single cases, especially in studies such as this one with a smaller PCS sample.

Based on the notion that PCS symptoms could be exacerbated by exerting effort, the eight PCS participants who experienced symptoms exacerbation and required breaks during the visual function assessments are good candidates to support the argument that PCS reflects pathophysiological changes in the brain. Particularly because taking rests between tests that exacerbated their symptoms helped them recover and continue through the rest of the study visit. The breaks participants needed varied in length and also significantly increased the length of their study visits. These breaks may have been a better indicator of symptom severity than the individual visual function performance measures, especially if the break and exam durations had been documented more completely. In future studies it will be important to learn from this observation so that visual functions in PCS are not be studied as the test result only. Rather the test result, time required to complete the task, and the symptom change associated with the task should all be considered.

The interesting questions that arise from this subjective observation that could be examined in future studies include, why did only a few tests exacerbate symptoms out of the wide array of visual function tests conducted in this study? Additionally, would the symptom severity or number of symptoms change prior to and after conducting these specific tests? Also, is the change in symptoms going to be consistent if these tests are performed over a number of visits?

Chapter 6 - Conclusion

6.1 Conclusion

In summary, this study has applied a feasible and a comprehensive visual function testing protocol that could be applied in future research and clinical practice.

The visual function comparison between the two groups demonstrated that some eye movement tests (i.e. Broad H) and the King-Devick test have the potential to detect lingering deficits in the PCS population. Conversely, PCS individuals still possess what appear to be normal to excellent visual functions (i.e. visual-motor reaction time) that might not have been affected by the PCS condition. There is a caveat to this conclusion though, which is that high-level PCS athletes appear to have normal to excellent visual functions when compared to recreational and non-athlete controls. In future research, it will be important to compare high-level PCS athletes with high-level athlete controls to see if the groups' performance on the visual function tests are still comparable.

Despite meeting strict inclusion criteria, it appears that the PCS population is not homogenous and that individuals with PCS need to be considered as single cases in addition to being considered as a population. The detailed health history used in the PCS group specifically helped with linking some of the PCS details with the abnormal results on visual functions and should be collected in future studies as well. Using statistical analysis techniques such as multivariate regression may also help account for the wide variability in this population, however larger population samples would make this type of analysis more meaningful.

Moreover, symptom severity on the testing day does not appear to be a predictive variable of visual function performance in either the PCS or control individuals. On the other hand, specific visual function tests appear to provoke symptoms in the PCS individuals, which affects the time required to complete the visual function task. Accounting for symptom changes following tests, the need for and duration of breaks between tests, and the overall test and visit durations may provide important insight into the relationship between symptom severity and overall visual function in PCS individuals.

6.2 Limitations

The window for recruiting participants was open for about 9 months. Initially, the intention was to collect PCS participants first, then, match them with control participants with the same age, gender, and sports activity level for a well-controlled study. However, this could not be achieved. In the first 4 months of the recruitment process, only one PCS participant took part in the study despite concentrated recruitment efforts that included advertising the study in concussion management centres, the University of Waterloo and Wilfrid-Laurier University accessibility centres, physiotherapy clinics, and with PCS support groups. Due to the shortage of PCS participants recruited, recruitment of control participants was started while taking in any prospective PCS participants who came along. Eventually, 10 PCS participants completed this study. The number of the PCS group participants was almost one third of the control group participants, and resulted in a lack of power in the PCS group that may have affected the ability to find differences between the two groups. Another likely reason that differences were not found between the two groups was the high amount of variability found within the PCS group itself. However, the study still applied a comprehensive and feasible visual function test protocol that could be applied on larger group in future research or even to in Optometry clinics to assess PCS patients.

Although the control and the PCS group ended up being fairly well matched with regards to age and gender, there was a difference in terms of the sport activity background between the two groups that might have affected the study outcomes. The vision in sports literature recommends using well-controlled and sport matched study samples, because differences in visual performance between different sports and activity levels are present.[95,98,100–103] Unfortunately, sport and activity level matching created a recruitment challenge that could not be overcome in this particular study.

Another important participant-related limitation of this study was that most of the study participants were UW and WLU students. The majority of these students were able to join the study between the ends of April and May - right after the final exam period. This time period involves tremendous studying efforts, which are visually demanding and may have resulted in exhaustion of visual function. The timing of the study visits might also have had an effect on the

study outcome, particularly in the control group, and might explain some of the symptoms of the control participants as well as some of the unusual behaviours of some of the outliers in the control group.

6.3 Future work

To continue this study, the PCS participants will be studied as separate cases as was recommended earlier. Studying PCS participants as individual cases will allow for accounting for different variables such as effect of medications, number of concussions, and time since injury, etc. Additionally, statistical analysis will be conducted on selected tests that were repeated three times to look for fatigue and/or learning effects over the test trials in both groups.

Furthermore, this study included the development of an objective VOMS test (Table 2-1) using a force plate to measure balance and an eye tracker to measure gaze control. While control and PCS data has been collected with this test, the data still needs to be analysed. Examining the preliminary results of this objective VOMS test will help to increase our understanding of the relationship between balance and eye movement in both groups.

In future studies it would be good to explore the change in symptoms prior to, during, and after testing for the specific visual function tests that provoked symptoms in PCS individuals, and to determine if the change in symptoms would affect the test result if the test was repeated. It would also be good to examine how long each specific visual function test took to complete for each individual. It may be possible that test time (including time needed for breaks) may be a better indicator of PCS recovery than simply visual function tests alone.

Finally, eye movements appear to be a sensitive measure of the visual dysfunction in PCS and they may help researchers to detect potential lingering brain deficits associated with PCS. Therefore, eye movements should be assessed in an objective and accurate way in all future studies of PCS.

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Appendix A - Health questionnaire forms

Health History Questionnaire

Participant ID: M/F Date:

D.O.B.: (mm/dd/yyyy) Team:

1. At what age did you begin playing organized sport? _____

2. How many years have you played your sport? _____

3. Do you wear a mouth guard while playing?
___yes ___no
If yes, what kind?
___stock ___boil & bite
___custom, front teeth ___custom, all

4. Have you suffered from neck pain within the past 6 months? ___yes ___no

5. Have you suffered a concussion?
___yes ___no ___not sure

6. If yes to #5,
a) How many times total? _____
b) How many times while playing sport in the past 6 months? _____
c) Date of last concussion? _____
d) How long did the symptoms last (for last concussion)?
___1-3 days ___4-7 days ___8-10 days
___11-14 days ___more than 2 weeks
e) After the last concussion, how long did you refrain from physical activity?
___4-7 days ___8-10 days ___11-14 days
___15-21 days ___more than 3 weeks

7. Have you ever been knocked unconscious?
___yes ___no

8. If yes to #7,
a) How many times in the past 6 months? __
b) What is the longest duration you've been knocked unconscious? _____

9. In the past 6 months, after being hit in the head in sports, have you experienced any of the following symptoms:

___confusion ___getting 'dinged'
___headaches ___balance problem
___nausea ___getting 'bell rung'
___dizziness ___ringing in the ears
___blurry vision ___poor memory
___other:_____

10. In regards to how you feel NOW, please rate the following:

	None			Mild			Severe
Headache	0	1	2	3	4	5	6
"Pressure in head"	0	1	2	3	4	5	6
Neck pain	0	1	2	3	4	5	6
Nausea/vomiting	0	1	2	3	4	5	6
Dizziness	0	1	2	3	4	5	6
Blurred vision	0	1	2	3	4	5	6
Balance problems	0	1	2	3	4	5	6
Sensitivity to light	0	1	2	3	4	5	6
Sensitivity to noise	0	1	2	3	4	5	6
Feeling slowed down	0	1	2	3	4	5	6
"Don't feel right"	0	1	2	3	4	5	6
Hard to concentrate	0	1	2	3	4	5	6
Feeling "in a fog"	0	1	2	3	4	5	6
Trouble remembering	0	1	2	3	4	5	6
Fatigue/low energy	0	1	2	3	4	5	6
Confusion	0	1	2	3	4	5	6
Drowsiness	0	1	2	3	4	5	6
Trouble falling asleep	0	1	2	3	4	5	6
More emotional	0	1	2	3	4	5	6
Irritability	0	1	2	3	4	5	6
Sadness	0	1	2	3	4	5	6
Nervous/anxious	0	1	2	3	4	5	6

11. Do the above symptoms get worse with physical activity? ___yes ___no

12. Do the above symptoms get worse with mental activity? ___yes ___no

CONCUSSION SAFETY PROGRAM INJURY REPORT

Participant ID: _____ Birthdate: ____/____/____ Sex: (M) (F)

Sport: _____ Date of Injury: _____

INJURY CONDITIONS
□ Practice □ Warm-up □ Game □ Other: _____

CAUSE OF INJURY *(check box and circle object)*
□ Hit by object (puck, stick, ball) □ Collision with object (boards, net) □ Fall
□ Collision with opponent □ Fight □ Other _____

DESCRIBE INJURY *(check all that apply)*
□ Concussion □ Fracture □ Joint/ligament □ Muscle/tendon
□ Contusion □ Laceration □ None □ Other _____

LOSS OF CONSCIOUSNESS
□ None □ 1-20 seconds □ 21-59 seconds □1-2 minutes
□ 3-5 minutes □ > 5 minutes

CONFUSION/DISORIENTATION
□ None □ 1-59 seconds □ 1-2 minutes □ 2-3 minutes
□ 3-5 minutes □ > 5 minutes

AMNESIA
□ None □ 1-10 seconds □ 11-59 seconds □ 1-5 minutes
□ 6-15 minutes □ > 15 minutes

RETURNED TO ACTIVITY
□ after 0-15 min □ after 16-30 min □ after 30-60 min □ did not return
□ taken to hospital

REASON FOR RETURN
□ Stayed on for rest of shift □ Waited for whistle/stoppage of play □ Did not report symptoms

SYMPTOMS AT The Time of The Injury *(check all that apply)*
□ Fatigue □ Headache □ Dizziness □ Balance problems □ Visual changes
□ Nausea □ Vomiting □ Personality change □ Numbness/Tingling

SIDE OF IMPACT
□ Left □ Right

POINT OF IMPACT
□ Frontal □ Parietal □ Temporal □ Occipital
□ Nasal □ Jaw □ Body

MOUTH GUARD
□ Yes □ No

HELMET WORN
□ Yes □ No/Not required for sport □ Came off due to impact

DESCRIBE INJURY

AUTHOR _____ **DATE** _____

Ocular Health Questionnaire

Participant:_____ M/F Date:_____
D.O.B.:_____(mm/dd/yyyy) Team/Position:_____

1- Do you wear any type of vision correction (i.e. glasses, contact lenses)? if yes please specify.
2- Have you been diagnosed with any eye problem? (If your answer is NO please go to question 6)
3- Could you specify what was the problem?
*This question is only for individuals who have had concussion. 4- Could you specify if this problem was prior or after the concussion?
5- Have you ever received a vision therapy (orthoptic treatment)?
6- Do you have a family history of eye problem? if yes please specify.
7- Are you on medication right now? if yes please specify.

Appendix B - Does athletic background affect visual function?

B.1 Introduction

As discussed previously (see Chapter 5 - Discussion), the control and PCS groups performed almost equally on all of the visual function measures tested. The differences in performance on the visual function test could not be fully explained by the symptoms of either group. One possibility is that athletic background had some impact on visual performance as previous research has demonstrated that in some aspects of visual function, athletes perform better than non-athletes [93,95,104–109] (Table B.1).

All of the PCS participants in this study were athletes, whereas only about half of the control group was athletes (see Chapter 3, Table 3-1). Perhaps the reason for the lack of obvious difference in visual function between the two groups was because the athletic background of the PCS group made up for their visual function deficits compared to controls. To investigate whether this might be a factor impacting the results of this thesis, the decision was made to compare performance on the visual function measures between the non-athlete control participants and the athlete control participants. If the athlete controls performed significantly better on the visual function tests than the non-athlete controls, than it might be more appropriate to compare the PCS athletes with the control athletes only in future studies.

In order to have a better understanding about the relationship between athletic background and performance on the visual function measures, participants within the control group were split into two subgroups: 1) non-athletes (n=16) 2) athletes (n=17). It is important to mention that this comparison was not intended when this study was designed. Therefore, athletic participants were not recruited based on a specific criterion, and they were simply assigned to one of the groups based on whether the participant practice sport or not. Although this analysis was not intended when this study was designed, the athletic background remain an interesting variable to look at. Hence, this part was added as an appendix rather than embedded within the thesis.

A Mann-Whitney U-test was performed to look at the difference in the visual functions between the two groups. Also, the mean ± (SD), and median values were calculated for both groups.

Table B-1: Literature review of visual functions in athlete versus non-athlete populations

Study	Study Sample	Visual Function	Methods		Conclusion	Significance
Omar et al, (2017)[104]	Athletes (n=107); age (14.9 ± 1.0) years Non-athletes (n=107); age (15.0±1.0) years	Amplitude of Accommodation	Push-up technique with RAF rule		Athletes significantly better	OD - p=0.02 OS - p=0.05 OU - p=0.03
		Accommodation Facility	Using ±2.00 D lens flipper		No significant difference	OD - p=0.38 OS - p=0.32
		Ocular misalignment	Horizontal ocular misalignment measured at distance with prism bar and Howell card as a target		No significant difference	p=0.44
		Near point of convergence	Subjective / objective break points measured		Non-athletes significantly better	p<0.001
		Vergence facility	Using 12 base-out/3 base-in prism flipper		Athletes significantly better	p=0.01
		Horizontal fusional reserve (HFR)	Positive HFR - break point		Non-athletes significantly better	p=0.03
			Positive HFR - recovery point		No significant difference	p=0.44
			Negative HFR - break point		Non-athletes significantly better	p=0.001
			Negative HFR - recovery point		Non-athletes significantly better	p=0.001
Vera et al, (2017)[105]	Basketball players (n=18); age (23.3 ± 2.4)	Accommodation accuracy	Using MEM technique		No significant difference	p=0.16
		Near point of convergence	a fixation stick with 20/30 single letter target	Break point	Athletes significantly better	p=0.004
				Recovery point		p=0.014

	Non-athletes (n=15); age (22.3 ± 2.1)	Distance horizontal fusional reserve	Positive HFR - break point	Athletes were significantly better	p=0.01
			Positive HFR - recovery point		p=0.01
			Negative HFR - break point	No significant difference	p=0.76
			Negative HFR - recovery point		p=0.81
		Near horizontal fusional reserve	Positive HFR - break point	Athletes had marginally significant higher values	p=0.06
			Positive HFR - recovery point		p=0.06
			Negative HFR - break point	No significant difference	p=0.67
			Negative HFR - recovery point		p=0.93
		Accommodation facility	By shifting vision from distance (5 m) to near (40 m) using Hart charts as targets	No significant difference	p=0.12
		Stereo acuity	Distance stereo acuity	No significant difference	p=0.81
			Near stereo acuity		p=0.13
		Reaction time	Eye-hand coordination was measured using Wayne saccadic fixator	No significant difference	p=0.02
Babu et al, (2005)[106]	Badminton and squash players (n=27); Non-athletes (n=14)	Saccadic adaptation	Eye movements were recorded using 120 Hz eye tracker	No significant difference	p=0.93
Ishigaki et al, (1993)[107]	Baseball, tennis, or badminton players (n=53); age (20.1 ± 1.0) Non-athletes (n=46); age (21.6 ± 1.5)	Dynamic visual acuity	Using Landolt C as a target with the following gap sizes 8', 14', 28', and 42'. The target speed range was 300 - 200°/sec.	Athletes were better than non-athletes only in identifying small C gaps at higher velocities	p<0.05

Schneiders et al., (2010)[108]	Motorsport athletes (n=9); Non-athletes (n=9) - Mean age (17.6)	Dynamic visual acuity	Head moved in horizontal metronome of 150°/sec. for OD and OS	No significant difference	OD - p=0.74 OS - p=0.52
Boden et al, (2009)[109]	Baseball players (n=51); mean age 14.2 years Non-athletes (n=52); mean age 13.8 years	Static near stereo acuity	Randot stereo-acuity test (circles)	Athletes significantly better	p<0.0001
Dunham, (1989)[67]	Athletes (n=10); Non-athletes (n=10) - age (17 -18 years)	Coincidence anticipation	Pitching ball machine at the following speeds 35, 40, 45, and 50	No significant difference	p>0.05
Ando, et al. (2001)[93]	Soccer players (n=6); age (21.5 ± 1.4) Non-athletes (n=6); age (22.8 ± 0.8)	Central and peripheral reaction time	Stimulus presented on a computer screen with different stimulus sizes and different distances. Response given using the computer space key.	No significant difference found between the groups. Therefore, groups were combined together to look at the difference between size of the stimulus at different distances.	Not provided

Paterson (2010)[95]	Netball and hockey players (n=33); age (21.7 ± 2.1) Non-athletes (n=84); age (22 ± 1.9)	Visual motor response time	40 random lights on the Sport Vision Trainer board	No significant difference between athletes and non-athletes neither males and females	p>0.05

B.2 Results

Overall, there was no significant difference between the athlete and non-athlete groups (Table B.2) on most of the visual functions except for the following:

4) Accommodation accuracy: OS (p=0.04). The non-athletes appear to have better accommodation accuracy (less lag of accommodation at near) than the control group.
5) Distance horizontal negative fusional reserve: Break point (p=0.02) and recovery point (p=0.03). The non-athlete group appear to have better distance HNFR in break and recovery points than the athlete group.

Additionally, there was marginally significant difference between the groups in the distance vertical positive fusional reserve (recovery point p=0.05). The non-athlete group appear to have better distance VPFR in recovery points than the athlete group.

Table B-2: Results of athlete and non-athlete groups

	Athlete		Non-athlete		p-value
	Mean ± SD	Median	Mean ± SD	Median	
Number of symptoms					
Visit 1	4.6 ± 6.0	2.5	2.4 ± 3.3	1.0	0.47
Visit 2	3.6 ± 4.9	2.0	2.0 ± 3.1	0.0	0.20
Symptom severity					
Visit 1	4.4 ± 7.8	1.0	9.4 ± 13.2	4.0	0.43
Visit 2	3.3 ± 5.8	0.0	5.4 ± 7.8	2.5	0.22
Objective refraction					
OD	-2.9 ± 3.7	-1.1	-2.4 ± 3.4	-1.1	0.44
OS	-2.9 ± 3.7	-0.6	-2.3 ± 3.2	-0.7	0.48
Distance visual acuity					
OD	-0.04 ± 0.13	-0.09	-0.05 ± 0.01	-0.08	0.98
OS	-0.04 ± 0.11	-0.08	-0.05 ± 0.13	-0.08	0.74
OU	-0.10 ± 0.10	-0.10	-0.12 ± 0.10	-0.16	0.69
Near visual acuity					
OD	0.41 ± 0.03	0.40	0.43 ± 0.05	0.40	0.40
OS	0.40 ± 0.00	0.40	0.41 ± 0.03	0.40	>0.99
OU	0.40 ± 0.00	0.40	0.40 ± 0.00	0.40	>0.99
Dynamic visual acuity					
Horizontal	0.06 ± 0.1	0.00	0.1 ± 0.1	0.00	0.58
Jitter	-0.13 ± 0.1	-0.10	0.12 ± 0.1	-0.20	0.93
Random	0.11 ± 0.2	0.10	0.1 ± 0.1	0.15	0.70
Contrast sensitivity					
OU	1.99 ± 0.06	2.00	2.01 ± 0.06	2.00	0.59
Distance cover test					
Primary	-1.2 ± 2.7	0.0	0.1 ± 1.4	0.0	0.11
Left	-1.1 ± 2.2	0.0	-0.1 ± 1.1	0.0	0.19
Right	-1.1 ± 2.2	0.0	-0.1 ± 1.1	0.0	0.19
Near cover test					
Primary	-1.9 ± 3.9	-1.50	-0.3 ± 2.3	0.0	0.20
Left	-2.2 ± 3.7	-1.50	-0.4 ± 2.2	0.0	0.14
Right	-2.2 ± 3.7	-1.50	-0.4 ± 2.2	0.0	0.14
Stereopsis					
	25.4 ± 12.5	20.0	34.9 ± 19.2	26.7	0.06
Amplitude of accommodation					
OD	0.9 ± 1.8	0.8	0.7 ± 2.0	0.7	0.82
OS	1.3 ± 1.7	0.8	1.1 ± 2.2	0.8	0.42
Absolute difference	0.9 ± 0.9	0.8	0.6 ± 0.7	0.7	0.38
Accommodation accuracy					
OD	0.45 ± 0.65	0.25	0.80 ± 0.44	0.75	0.08

OS	0.39 ± 0.61	0.50	0.72 ± 0.34	0.75	0.04*
Absolute difference	0.19 ± 0.21	0.25	0.10 ± 0.13	0.00	0.30
Cyclopean eye					
	n=6		n=11		
	80.4 ± 6.3	81.9	82.4 ± 4.7	81.7	0.94
Relative accommodation					
	n=4		n=6		
NRA	2.90 ± 0.60	3.00	2.40 ± 0.70	2.50	0.33
PRA	-4.40 ± 2.40	-3.25	-2.50 ± 0.60	-2.75	0.07
Accommodative facility					
OD	10.7 ± 6.3	10.5	9.1 ± 6.5	9.0	0.49
OS	12.1 ± 6.9	11.3	10.0 ± 6.8	11.0	0.47
Absolute difference	2.9 ± 3.0	1.5	1.9 ± 2.0	2.0	0.33
Near point of convergence					
Break	5.7 ± 2.8	5.2	5.0 ± 3.1	6.0	0.57
Recovery	6.9 ± 3.2	7.2	6.0 ± 3.5	7.0	0.36
Difference	1.2 ± 0.7	1.2	1.1 ± 0.9	1.0	0.47
Distance horizontal positive fusional reserve					
Blur	7.2 ± 7.4	7.0	7.2 ± 6.8	8.0	0.98
Double	19.0 ± 7.0	19	21.0 ± 7.7	25	0.49
Recovery	1.9 ± 3.3	16	1.3 ± 2.7	14	0.54
Distance horizontal negative fusional reserve					
Blur	1.9 ± 3.3	0.0	1.3 ± 2.7	0.0	0.54
Double	8.8 ± 2.3	8.0	6.6 ± 2.9	6.0	0.02*
Recovery	6.3 ± 2.3	6.0	4.4 ± 2.7	4.0	0.03*
Distance vertical positive fusional reserve					
Double	3.6 ± 1.4	3.0	2.9 ± 0.9	3.0	0.07
Recovery	2.2 ± 1.1	2.0	0.2 ± 0.7	1.0	0.05
Distance vertical negative fusional reserve					
Double	3 ± 1.6	3.0	2.3 ± 0.8	2.0	0.18
Recovery	1.7 ± 1.0	1.5	1.3 ± 0.8	1.0	0.33
Near horizontal positive fusional reserve					
Blur	3.7 ± 7.8	0.0	4 ± 5.5	0.0	0.37
Double	17.6 ± 8.8	18.0	16.5 ± 9.6	16.0	0.69
Recovery	13.5 ± 7.3	15.0	12.2 ± 7.2	14.0	0.71
Near horizontal negative fusional reserve					
Blur	5.4 ± 6.9	0.0	1.5 ± 6.9	0.0	0.16
Double	13.3 ± 5.0	12.0	11.3 ± 3.6	12.0	0.33
Recovery	10.6 ± 4.5	10.0	9.2 ± 3.5	10.0	0.51
Near vertical positive fusional reserve					
Double	4.0 ± 1.3	4.0	3.2 ± 0.7	3.0	0.07
Recovery	2.8 ± 1.2	2.0	2.1 ± 0.7	2.0	0.16

Near vertical negative fusional reserve					
Double	3.3 ± 2.0	3.0	2.9 ± 0.7	3.0	0.13
Recovery	2.3 ± 1.1	2.0	1.9 ± 0.7	2.0	0.21
Vergence facility					
	15.1 ± 5.3	16.0	16.4 ± 4.5	18.0	0.61
King-Devick					
Time	49.18 ± 10.53	48.35	47.08 ± 16.34	39.90	0.22
Errors	0.63 ± 2.25	0.00	0.00 ± 0.00	0.00	0.23
Visual-motor reaction time					
Central	510.7 ± 118.1	502.7	507.6 ± 116.1	489.1	0.91
Peripheral	995.5 ± 268.7	908.9	850.8 ± 159.7	785.2	0.06
Constant error					
Speed	Mean ± SD	Median	Mean ± SD	Median	p-value
5	-25.3 ± 38.4	-9.7	-23.1 ± 24.8	-26.6	0.84
10	-5.2 ± 20.3	-2.4	-21.5 ± 29.8	-23.2	0.11
15	-10.0 ± 24.9	-14.1	-19.2 ± 27.5	-23.4	0.34
20	-8.3 ± 19.6	-10.6	-9.8 ± 17.1	-9.8	0.79
25	-2.7 ± 19.5	0.8	0 ± 24.3	-1.6	0.82
30	16.5 ± 23.9	16.3	7.5 ± 23.0	5.2	0.32
35	11.3 ± 19.8	9.8	11.9 ± 22.7	11.8	0.84
40	19.7 ± 19.1	13.9	18.4 ± 16.1	15.6	0.74
Average error					
5	46.8 ± 28.2	36.6	47.8 ± 18.0	37.8	0.44
10	30.6 ± 15.4	30.0	38.5 ± 21.0	31.6	0.23
15	46.5 ± 20.0	46.3	47.13 ± 28.3	38.6	0.53
20	50.8 ± 20.4	50.3	43.6 ± 18.0	40.8	0.26
25	41.4 ± 17.2	37.5	40.3 ± 16.5	39.8	0.99
30	39.8 ± 17.5	33.8	40.1 ± 14.4	41.0	0.98
35	37.3 ± 23.1	35.0	29.1 ± 11.8	27.8	0.51
40	29.1 ± 18.3	24.8	35.3 ± 19.0	30.8	0.26
Variable error					
5	40.0 ± 18.2	36.6	44.5 ± 16.8	40.2	0.27
10	30.2 ± 15.6	27.7	35.3 ± 18.2	29.9	0.45
15	51.2 ± 26.4	47.0	48.5 ± 37.6	37.1	0.39
20	57.1 ± 28.4	53.4	47.6 ± 22.6	41.8	0.31
25	47.3 ± 19.8	42.7	44.3 ± 17.7	49.7	0.99
30	39.3 ± 15.4	38.3	41.1 ± 15.2	38.0	0.85
35	41.3 ± 24.5	36.4	29.0 ± 11.0	26.6	0.23
40	27.9 ± 16.3	23.7	36.2 ± 23.2	32.2	0.20

*indicates a significant difference ($p<0.05$)

B.3 Discussion

As it is clear from the results, the athlete group's performance on the visual function tests was not significantly better than the non-athlete group on any of the tests. On the other hand, the non-athlete group visual function performance was better in the accommodation accuracy (OS) and distance horizontal negative fusional reserve (double and recovery points) tests. Although this finding is not consistent with the previous literature (Table B-1), it indicates that the athletic background was not the reason behind the lack of difference between the control and PCS analysis in this study.

One possible explanation for the lack of difference between the athlete and non-athlete control groups in this study is that most of the athlete group participants (15 out of 17) were involved in recreational sports (Table 3-1). In other words, their sport practice may have been irregular and was not at a high enough level to allow for the development of superior visual functions (unlike the more elite and competitive athletes studied in the previous literature).