RESEARCH PROJECT IN MECHATRONICS ENGINEERING

EYE-TRACKING SYSTEM FOR DIAGNOSIS OF VISUAL DEFICITS

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ABSTRACT

Millions of adults and children around the world suffer from visual deficits. When left untreated these visual deficits can cause severe vision loss and psychosocial issues [1]. This study pursues the design, build, and testing of an eye-tracking system for the diagnosis of strabismus, allowing for successful classifying and quantifying of strabismus.

The trials include a head mounted eye-tracker (the Jazz-novo), a CRT monitor, and dichroic filters (red and blue) for dichoptic presentation. Two sets of tests were carried out; firstly the 9-point fixation test, then the smooth pursuit tracking test. The visual stimuli was presented dichoptically such that at any one time, monocular perception was engaged whilst fixating or tracking. The stimuli was a circular, blue or red point which was only perceived through the right colour filter (blue for blue, red for red).

The fixation test stimulus oscillated 10 times (blue and red) with a frequency of 1 HZ at each of the nine locations on the grid. The tracking test stimulus travelled across both the horizontal and vertical meridians twice (once with blue stimulus and once with red stimulus). The tracking motion was a sinusoidal function, with a frequency of 0.12 Hz.

Eight subjects participated in the formal trials of this experiment. Fast Fourier Transform (FFT) analyses were computed on the data from these subjects to acquire amplitudes, gains, and phases for the different sets of tests.

Results in this report outline two subjects who showed interesting results, one for fixation and one for tracking, and separate group analyses were also carried out. The results revealed distinct oscillations in the 1 Hz component of the eye-tracking data in either X or Y displacement for the fixation test. These amplitudes were compared relative to each subject's calibration point and a relative gain was established for each subject. A larger gain meant larger magnitude of deviations which led to potential signs of strabismus. The tracking test results portrayed the gain and phase of the subject's ability to track a moving stimuli. Higher gains meant there were overshoots from the relative gaze position, whilst lower gain corresponded to undershoots. Group results for the difference between Dominant Eye (DE) and Non-dominant Eye (NDE) gains and phases were also retrieved which revealed a possibility of diagnosing strabismus.

The results open an opportunity to diagnose and quantify strabismus with improving eye-tracking technology. These could one day lead to mobile eye-tracking systems in clinical practices for efficient use of time, resources, and introduce a level of autonomy.

DECLARATION

Student

I hereby declare that:

1. This report is the result of the final year project work carried out by my project partner (see cover page) and I under the guidance of our supervisor (see cover page) in the 2019 academic year at the Department of Mechanical Engineering, Faculty of Engineering, University of Auckland.

2. This report is not the outcome of work done previously.

3. This report is not the outcome of work done in collaboration, except that with a potential project sponsor (if any) as stated in the text.

4. This report is not the same as any report, thesis, conference article or journal paper, or any other publication or unpublished work in any format.

In the case of a continuing project, please state clearly what has been developed during the project and what was available from previous year(s):

Signature: 27/09/19

Date:

Supervisor

I confirm that the project work undertaken by this student in the 2019 academic year is / is not (strikethrough as appropriate) part of a continuing project, components of which have been completed previously. Comments, if any:

Signature: 27/9/19

Date:

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Glossary of Terms

Visual Deficit	Visual impairments leading to decreased vision
Eye Tracking	Measurements denoting the horizontal and vertical positions of a subject's gaze
Dichoptic Presentation	Presenting a stimulus to one eye at a time
Monocular Perception	Seeing the visual stimulus through a single eye
Binocular Perception	Seeing the visual stimulus via both eyes simultaneously

Abbreviations

VA	Visual Acuity
ADC	Analogue to Digital Converter
FFT	Fast Fourier Transform
DE	Dominant Eye
NDE	Non-dominant Eye

1. Introduction

Millions of adults and children around the world suffer from visual deficits. When left untreated these can cause severe vision loss and psychosocial issues [1]. Adverse psychosocial effects consist of problems in childhood and education, job prospects, interaction with peers, may manifest more seriously as psychiatric disorders, and may also be detrimental to the general quality of life [2]. According to the American Academy of Pediatrics, early diagnosis and intervention is necessary in preschool and early childhood to reduce these risks by more than 50%, by the age of 7. Children with first-degree relatives with similar conditions should also be referred to testings early on [3].

There are many shortcomings to the manual visual diagnostic methods currently in use. Majority of the current visual diagnostic methods require a professional or specialist to conduct the vision screening tests. These are manual and lack quantitative measures. They use resources and time from the facility as well as the patients, making them expensive and undesirable. Furthermore, the conducting of the screening tests is often difficult and subjective, and predominantly requires communication between the patient and ophthalmologist. This can lead to a communication barrier with young or non-verbal children. In these cases specifically, observational methods are favourable and should be conducted.

Eye-tracking is a non-invasive method currently used for detecting visual abnormalities in patients. Eye-tracking is a relatively new area of research but becoming increasingly popular as technology advancements occur with cheaper, more reliable eye-trackers being more readily available - thanks to the gaming industry. These new devices can slowly minimise the subjectivity of tests and bring in more accurate measurements. There are multiple areas in life where research is being done using eye-tracking devices including; medical research, marketing and social applications, education, and gaming/VR [4]. In this paper, we focus on the medical research and usage of eye-trackers; specifically, the diagnosis of visual deficits using an eye-tracking system.

We propose to develop a test for diagnosing strabismus using eye-tracking. Our test must, for the most part, be automatic and objective when detecting strabismus in subjects. We will acquire gaze position using fixation points for the subject to observe on screen, and a set of horizontal and vertical traversals to track. Through our trials and testing, the data gathered and analysed should give us a better understanding of visual acuity in strabismic subjects and potentially lead to developing a quick-and-easy, mobile system for use by ophthalmologists or paediatricians in visual screening tests.

2. Literature Review

2.1 Visual Deficits

There are a number of visual deficits which affect visual acuity and many of these can have potentially adverse effects on the patient. Strabismus is one of the most commonly diagnosed visual abnormalities which could lead to visual deficits. Fortunately, treatment of strabismus has high success rate if treated early. Therefore, we are focusing our study on diagnosing patients with strabismus.

Adult strabismus is present in approximately 4% of the adult population [2,3,5]. Strabismus, sometimes known as squint or heterotropia, is the irregular alignment of one (or in rare cases, both) of the visual axes of the eye; a measurable relative deviation between the visual axes is thus observed. This abnormality is caused by weakened motor fusion mechanism or neuromuscular anomalies in the eye [6].

There are two classifications of strabismus; comitant and incomitant. The former resulting in deviation within physiological limits and same in all directions of gaze. Whilst in the case of the latter, the extraocular muscles show signs of paralysis and hence the magnitude of deviation varies at different directions of gaze [6]. There are also four types of strabismic deviations in the eye, as shown in *Figure 1* and explained below:

- Esotropia - Horizontal convergence (inwards displacement) of visual axis
- Exotropia - Horizontal divergence (outwards displacement) of visual axis
- Hypertropia - Vertical upwards displacement of visual axis
- Hypotropia - Vertical downwards displacement of visual axis

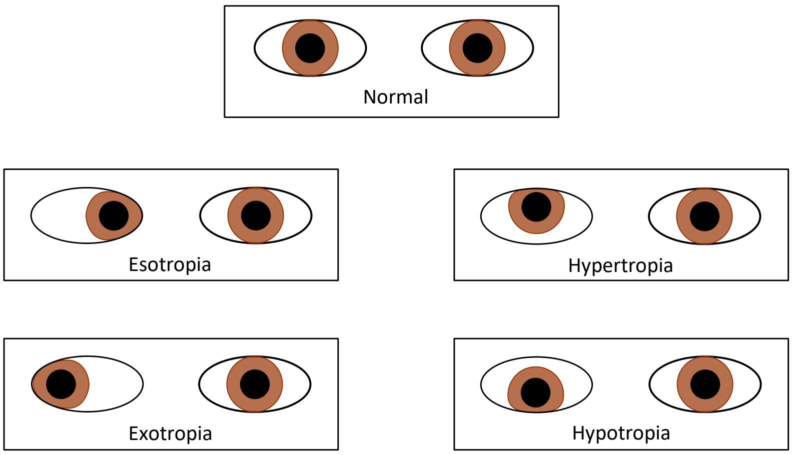


Figure 1 Four types of strabismic deviations

Those who acquire ocular misalignment as adults usually report diplopia (double vision) and visual confusion. When strabismus occurs earlier, in childhood, these symptoms are absent as the visual system learns to suppress images from the deviated eye when viewing binocularly [7]. However, untreated strabismus has still been found to lead to amblyopia (decreased vision), weakened three-dimensional perception [5], as well as the psychosocial effects mentioned earlier - problems in education and job prospects, interaction with peers, and detrimental to general quality of life. Therefore, early diagnosis and treatment is vital. It has shown to provide improved outcomes and prevent the degradation of visual acuity and other aforementioned problems. This is why there is a key focus on diagnosis of strabismus in our research.

2.2 Current Test Methods

2.2.1 Eye Movements (Smooth Pursuits/Saccades)

Part of the eye-tracking method is to design and implement gaze tracking of the eyes when following a target point. In target tracking there are two forms of movements of the eyes, smooth pursuit and saccadic eye movement. Smooth pursuit is the gradual tracking of a target to keep the target on the fovea, where speeds of the observed moving object are less than 30°/s with reference to the observing eye. Saccadic movements are short and fast transitions of the eye from one viewpoint to another, and generally occur above the mentioned speed. A [saccadic] latency of 100-200 ms can also be expected to 'catch up' to the moving target [8].

2.2.2 Manual Tests

Manual tests carried out by ophthalmologists are laborious and time consuming. These tests include the Cover-Uncover test, Prism and Cover test, and Maddox Cross test, and others [6]. They require equipment such as occluders, prisms, filters and other apparatuses which are brought close to the face and eyes of the subject - requiring a high level of trust between patient and clinician. This would cause unrest in many young children or those with other behavioural issues. The tests require input from the subject and/or clinician in order to correctly test and diagnose signs of strabismus - making them highly subjective. Most of these tests also lack quantitative and accurate measures of deviation (other than the Maddox Cross test) which we hope to overcome using our system. An example of the Prism-Cover test is shown in *Figure 2*. Depicting how the prism and occluder are used conjointly to detect signs of strabismus in an esotropic subject.

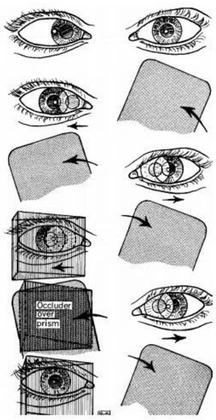


Figure 2 Example of Prism-Cover test and the signs of esotropic strabismus

2.2.3 Eye-tracking Tests

Eye-tracking during fixation tasks has recently been used to quantify visual deficits. Using a 9-point grid of fixation points equally spaced across the screen, similar to that used by ophthalmologists, subjects carried out a digitised eye-tracking test. In the paper by Hafed et al. [9], a 9-point fixation test was conducted with blind patients - with subretinal visual implants - using eye-tracking. Similarly, in the paper by Chen et al. [5], the researchers used a Tobii X2-60 connected to a laptop for an eye-tracking system, with the subject seated 50 cm away. Using their Tobii eye tracker, they retrieved X and Y coordinates of each eye and hence determined the Euclidean distances between a gaze pair and the fixation point. Using these Euclidean distances, four weighting coefficients, and a bias, they computed the strabismus occurence feature, f_{so}. If f_{so} was greater than 0 than the subject was deemed to be strabismic, whilst 0 and lower meant subject was visually normal. They observed in strabismic subjects that one eye has a gaze point close to the target whilst the other eye (the strabismic eye) is, relatively, further away. They also observed on certain points on the screen, the strabismic subject could fixate precisely whereas for points in other directions the gaze data did not align as well. This can be explained by the case of incomitant strabismus. Their results from the data analysis was accurate in diagnosing strabismus, as they correctly classified strabismic and visually normal subjects. This is an important leap forward in this area of research as they were able to objectively, and with minimum input from subject or clinician, predict strabismus in the subject.

Eye-tracking has also been used in tracking tasks to detect strabismus. In the paper, “Strabismus Screening by Eye Tracker and Games” [10], the researchers used a Gazepoint GP3 Desktop Eye Tracker connected to a desktop monitor with the subject 33 cm from the eye-tracker. On the screen were 5 points, in the shape of a ‘plus sign’, and the subject was to follow a series of tasks which required traversing multiple times from top to bottom, then traversing from left to right of the screen. This was done to simulate smooth pursuit of the eye’s motion. They retrieved gaze data of each eye and determined the Euclidean distance and compute a threshold distance which they would use to predict strabismus (similar to the last study). An Euclidean distance threshold, $D_{\text{threshold}} \geq 0.05$, was considered as the limit for determining the subject as strabismic. Their predictions were all accurate in determining their controlled visually normal group, and the strabismic patients’ group, totalling 50 subjects.

We propose to confirm and extend the results described above, by Chen et al. [5] and Saisara et al. [10], by measuring both fixation and smooth pursuit in visually normal and strabismic subjects. Using a similar fixation test in conjunction with a smooth pursuit tracking test, gaze point data will be gathered from the subject. We hope to observe changes in the average gaze points of the eyes when tracking a point horizontally, and similarly with vertical tracking. This could potentially aide us in detecting strabismus through the deviation of the eyes, as they had done, in quantifying the amount of deviation in the strabismic eye, and potentially the classification of the strabismus; comitant or incomitant.

2.2.4 Stimulus Shape

An inappropriate stimulus presented can introduce unwanted saccades or microsaccades during testing. It is critical to present stimulus with minimal bias towards these saccadic motions. Hafed et al. [9] reasoned that shapes with larger horizontal dimensions (rectangle) introduced predominantly horizontal saccades. Therefore, an equilateral shape such as a circle, with no hard edges, should be used to present stimuli.

2.3 Eye-tracking Devices

There are multiple eye-tracking devices on the market many of which provide adequate data in numerous areas of research. They can also be crossed into medical research as required in our study. We had two devices available to us, the Tobii Eye Tracker 4C and the Jazz-novo SN 1060.

2.3.1 Tobii Eye Tracker 4C

The Tobii Eye Tracker 4C is a plug-and-play device which is compatible with Windows 7 and above. Originally intended for gaming purposes, the Tobii allows the user to perceive their gaze on their screen and is a useful tool for use with assistive gaming features (with compatible games only). The Tobii Eye Tracker 4C is a USB (2.0) powered device which can be mounted on top of a monitor or connected to a laptop. It uses two near-infrared illuminators to track the eyes at an operational frequency of 90 Hz [11]. Setup is straightforward and requires the company’s proprietary software for calibration (during setup and initialisation) and use, but a separate SDK and license is required for acquiring gaze point data - used by researchers and developers.

A similar eye-tracker from Tobii, the Tobii Pro TX300, was used in a study conducted at the University of Melbourne [12]. The objective of the study was on nystagmus identification using the acquired gaze data. The results indicated that it is possible to distinguish between congenital (developed in infancy) and acquired (developed later through illness/brain damage) nystagmus through the gaze data alone, and other observations in eye movement in the subject were also made which are not easily seen using manual testing procedures. This is a clear advantage of eye-tracking, over manual tests, that has not been available until recent developments in eye-tracking technology. However, a downfall of this, and the Tobii Eye Tracker 4C, is that monocular calibration is not possible, meaning that the ability to alternate occlusion (obstruction of sight to single eye) with an occluder (or similar filter) is not possible for gaze data purposes. Real-time monitoring of the eye positions is also not possible, meaning the gaze analysis must be processed after the screening phase and not in-situ.

2.3.2 Jazz-novo SN 1060

The Jazz-novo SN 1060 is a head mounted eye-tracking device developed primarily for pilots to collect information of their interaction with the cockpit of the plane. Designed and built by Polish company, Ober Consulting, this device measures vertical and horizontal eye movements (1000 Hz), head rotation and acceleration in both axes (1000 Hz), photoplethysmographic signals (heartbeat and relative changes in blood oxygenation) (500 Hz), and audio signals (8 kHz) [13]. The setup for this requires a BioSemi data acquisition set and the corresponding LabVIEW data acquisition software, ActiveView, which is compatible with Windows, Mac, and Linux machines. The Jazz-novo does not provide individual tracking of the eyes, instead it provides the averaged deviation of the two eyes by illuminating the inner canthi and pupils with low intensity IR light [13]. This leads us to having to come up with another solution to tackle our research problem. To overcome this a pair of coloured dichoptic filters are placed in between the screen and the subject's two eyes to suspend vision of the target point in one eye, this is explained in detail in *Section 2.4*.

2.4 Dichoptic Stimulus Presentation

Dichroic filters can be used to present different stimuli to each eye. They can allow monocular presentation to one eye whilst suppression of an image to the other eye. This was trialled in the paper by Economides et al. [7], where subjects wore specialised glasses containing dichroic filters; red for the right eye and blue for the left eye. The red filter was highpass and blue filter was lowpass, with cutoff frequencies at 600 and 501 nm, respectively. The stimuli shown on screen were either red, blue or purple dots on a greyish-purple textured background. The purple textured background meant that 'cross-talk' between stimuli presented would be minimised, such that complete suppression occurred in the eye with the opposite filter colour as the stimulus colour (i.e. red filter and blue stimulus would be suppressed in the right eye). The trials done in this paper showed whilst strabismic subjects fixated one eye centrally on the screen (at a crosshair) through dichoptic stimulus presentation, they were still able to correctly recognise a stimulus in the peripheral vision majority of the times. A similar technique can also be used in our eye-tracking system to present red and blue stimulus at the nine different fixation points, as well as for the tracking tests. This would help in quantifying fixating and tracking performance of each individual eye given the resultant gaze position from the eye-tracker.

2.5 Conclusion of Literature

Early diagnosis and treatment of visual deficits is vital to prevent adverse physical and psychosocial effects on the patient [1, 2, 5]. Strabismus is an exceedingly common visual deficit [3]. We propose to develop an improved test for strabismus; our set up may also yield basic insight into the characteristics of this visual disorder. An eye-tracking system decreases subjectivity and reduces the manual methodology - as seen in the studies by Chen et al. [5], and Saisara et al. [10]. This brings upon an accurate and cost-/time-efficient solution for visual screening tests for the patient as well as the ophthalmologist. Our proposed method would consist of an adaptation of both methodologies presented, as well as include the dichoptic presentation technique for suppression of visual stimulus to a specified eye. A combination of the fixation and tracking tests would help in the diagnosis of strabismus, and classifications of strabismus in subjects. Potentially, this technology could help open a doorway into faster, more mobile solutions for visual screening in clinical practice.

3. Experimental Design

3.1 Equipment Setup

The eye-tracker used for gaze-point acquisition was the Jazz-novo SN 1060 [13]. Worn on the subject's forehead, the eye-tracker used Direct Infrared Oculography to provide gaze position data in terms of X and Y positions. The sampling rate of the eye-tracker was 1 kHz with eye position readings given in arbitrary units (a.u.), corresponding to relative pupil deviation from the inner canthi. The horizontal measurements and vertical measurements ranged between $\pm 35°$ and $\pm 20°$, respectively. The X and Y positions were the resultant (averaged) horizontal and vertical displacements of both eyes; not a pair of individual eye-tracking measurements. This led to some slight alterations in our experimental design such as introducing the dichroic filters in the test and conducting the fixation and tracking tests twice (with filters swapped). The Jazz-novo also connected to the BioSemi Active Two Data Acquisition unit via an optical cable for data acquisition. Which connected to a second laptop to acquire data using the BioSemi ActiView software [14] as a BDF file.

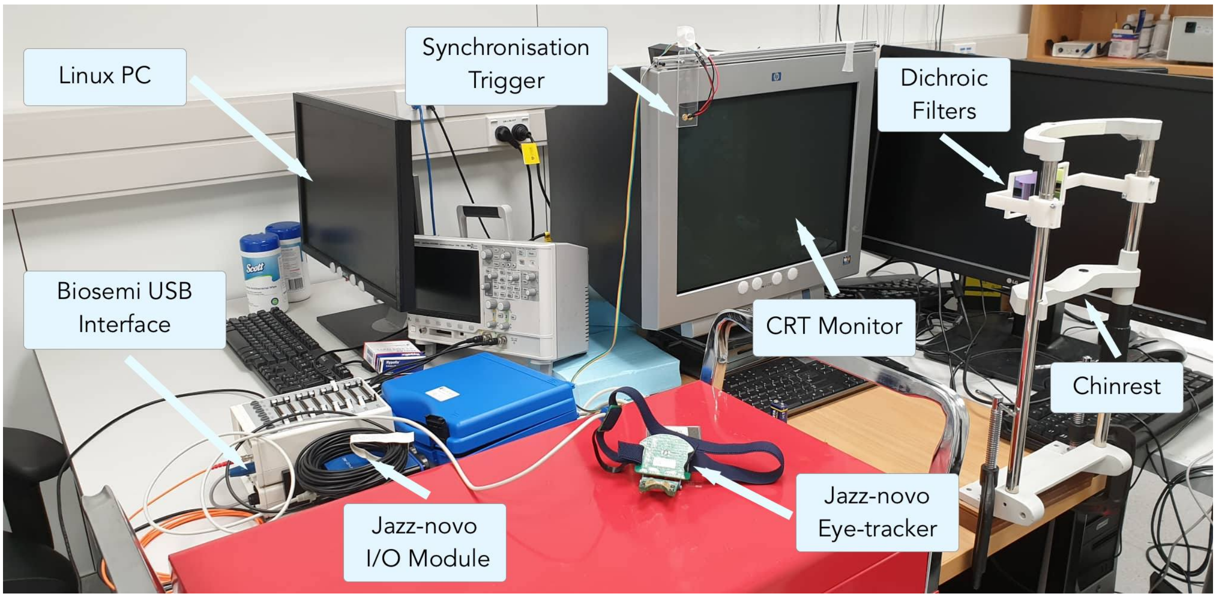
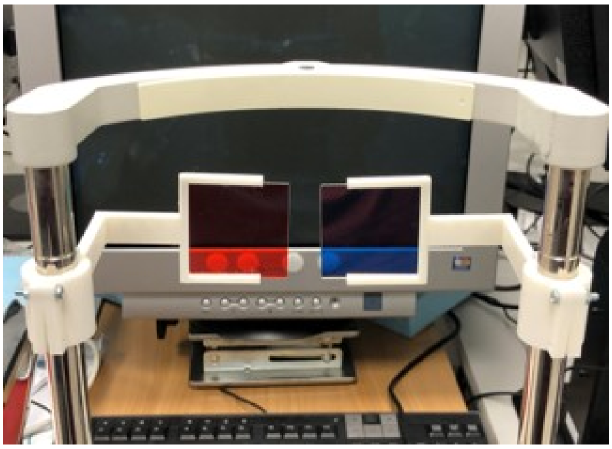


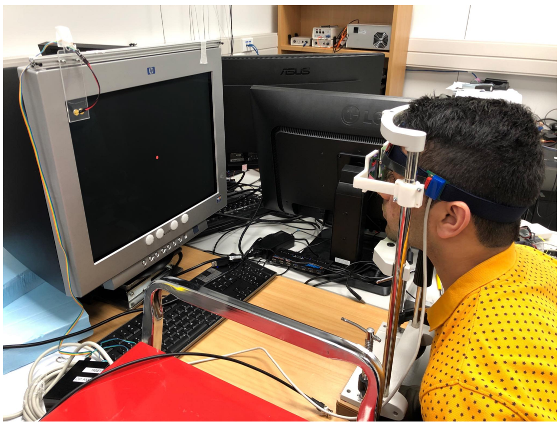
Figure 3 Overview of eye-tracking system setup

The test stimuli were shown on a Cathode Ray Tube (CRT) monitor running on a Linux system - placed 50 cm away from the subject. The screen resolution was fixed at 1152 x 864 pixels and screen refresh rate at 75 Hz. Two photodiodes were fixed at the top left-hand side of the monitor to detect the pulsation of a white square. This white square pulsation was designed as a trigger point for the commencing of different events, such as the start of calibration points, fixation points, and smooth pursuit tasks. The photodiodes connected to an Arduino Uno, which read the ADC value and output a digital 'High' when a white square (ADC $\geq$ 1000) was detected. This allowed for time synchronisation of data points to the test events later during analysis. A chin rest was used to ensure the distance from the monitor was kept constant for all subjects and to prevent head movement during the course of the screening tests.

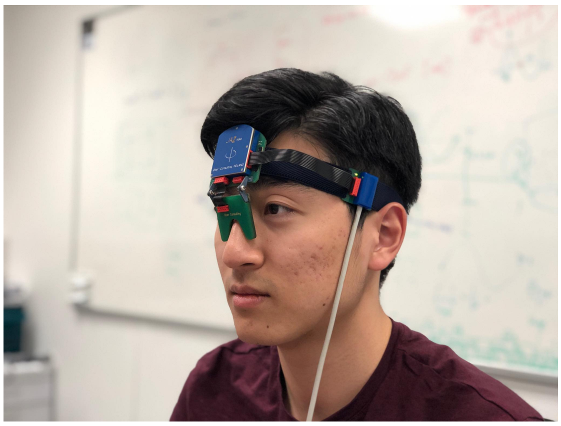
A pair of dichroic filters (blue and red) were also fixed in front of the subject's eyes; slotted within a 3D printed mount. These 50 x 50 mm filters allowed transmission of a narrow wavelength of light to pass through, whilst reflecting others from the visible spectra. The blue filter's transmittable wavelength range was 465-525 nm, whilst the red filter's transmittable wavelength range was 600-680 nm. Due to the high level of reflection from dichroic filters, the lights in the room were switched off during the tests to allow subjects to focus on the stimuli presented. The experimental setups are shown in *Figure 3* and *Figure 4*.



(a)



(b)



(c)

Figure 4 a) Chinrest and dichroic filter setup for subject. b) Subject performing fixation test. c) Subject wearing the Jazz-novo eye-tracker.

3.2 Eye-tracking Tests

Concluding the literature review, having revealed fixation and tracking tests are both great measures of a subject's visual ability - there were two sets of tests planned for the subject to undertake. First, the 9-point fixation test - a grid of nine points equally spaced across the computer monitor. Second, the tracking test - a stimulus moved back and forth along the horizontal meridian, or the vertical meridian. In both cases, the displacement of the stimulus against time was sinusoidal. These tests were created using MATLAB and the Psychtoolbox-3 [15] packages which are available as an open-source resource for vision and neuroscience research. The tests were simple and required minimal effort from subjects allowing them to be effective on all ranges of subjects, including children.

3.2.1 Fixation Test

The fixation test consisted of a set of four calibration points and a set of nine fixation points, both made of 10-pixel wide circles. The calibration points were arranged in a grid formation such that they formed the perimeter of a square. The colour of these calibration points were white so that both eyes were able to perceive the stimuli (past the filters) and the subject would fixate normally using binocular perception. The points were displayed one after another for a period of three seconds each; starting from top right, then bottom right, bottom left, and eventually top left - order is shown in *Figure 5a*. These four segments allowed visualisation of the subject's relative gaze position on the screen as well as calculation of the resolution coefficient, C. The resolution coefficient enabled us to convert measurements from arbitrary units to units of mm, for both horizontal and vertical meridians. These values were acquired by finding the difference between the top and bottom calibration points for vertical, and the difference between left and right calibration points for horizontal. Then, dividing by the physical length of the grid in screen space - 195 mm for both.

The fixation test consisted of nine stimulus locations. At each location, the stimulus alternated between red and blue at a rate of 1 Hz. The order of the stimulus being presented is shown in *Figure 5b* - starting at top left and working around the grid in the shape of the digit '2' such that minimal effort was required between transitions of fixation point locations. The nine points were equally spaced at a distance of 288 pixels ($\approx$ 50 mm) vertically and horizontally from each other, such that the various points were easily distinguishable from each other in the acquired data. The total duration of the test was 111 seconds with a break in between so that the subject's eyes did not incur excess stress which could have led to poorer fixating performance. From the fixation tests we aim to see relatively large oscillations in gaze position for a subject with misalignment in the visual axis when fixating alternation between blue and red stimuli, at 1 Hz.

3.2.2 Tracking Test

Tracking tests consisted of two sets of horizontal and two sets of vertical smooth pursuit tasks; each with blue or red stimuli. The tracking tests also required calibration points before commencing the smooth pursuit tasks to quantify relative screen gaze positions. The first set of calibration points were displayed at the left and right locations on the screen (indicated by the points labelled '1' in *Figure 5c*). Then the tracking of a blue stimulus began which travelled from left to right twice, followed by a red stimulus with an identical path; as shown in *Figure 5d*. Models of these paths were created using a phase shifted sin function,

$$X_{position} = a\sin(2\pi f + \phi) \tag{1}$$

where a is the amplitude or distance from centre to the point horizontally (in pixels), f the frequency or speed of the moving target, and ϕ the phase shift to start the target tracking from the left position.

Similarly, the second set of calibration points were displayed at the top and bottom locations on screen (indicated by the points labelled ‘2’ in *Figure 5c*) before commencing the vertical smooth pursuit. These calibration points were followed by a set of blue then red vertically moving targets between the top and bottom grid points. The path modelled for the blue and red stimuli were similar in nature to *Equation 1* but with output as Y pixel position for vertical motion, rather than X.

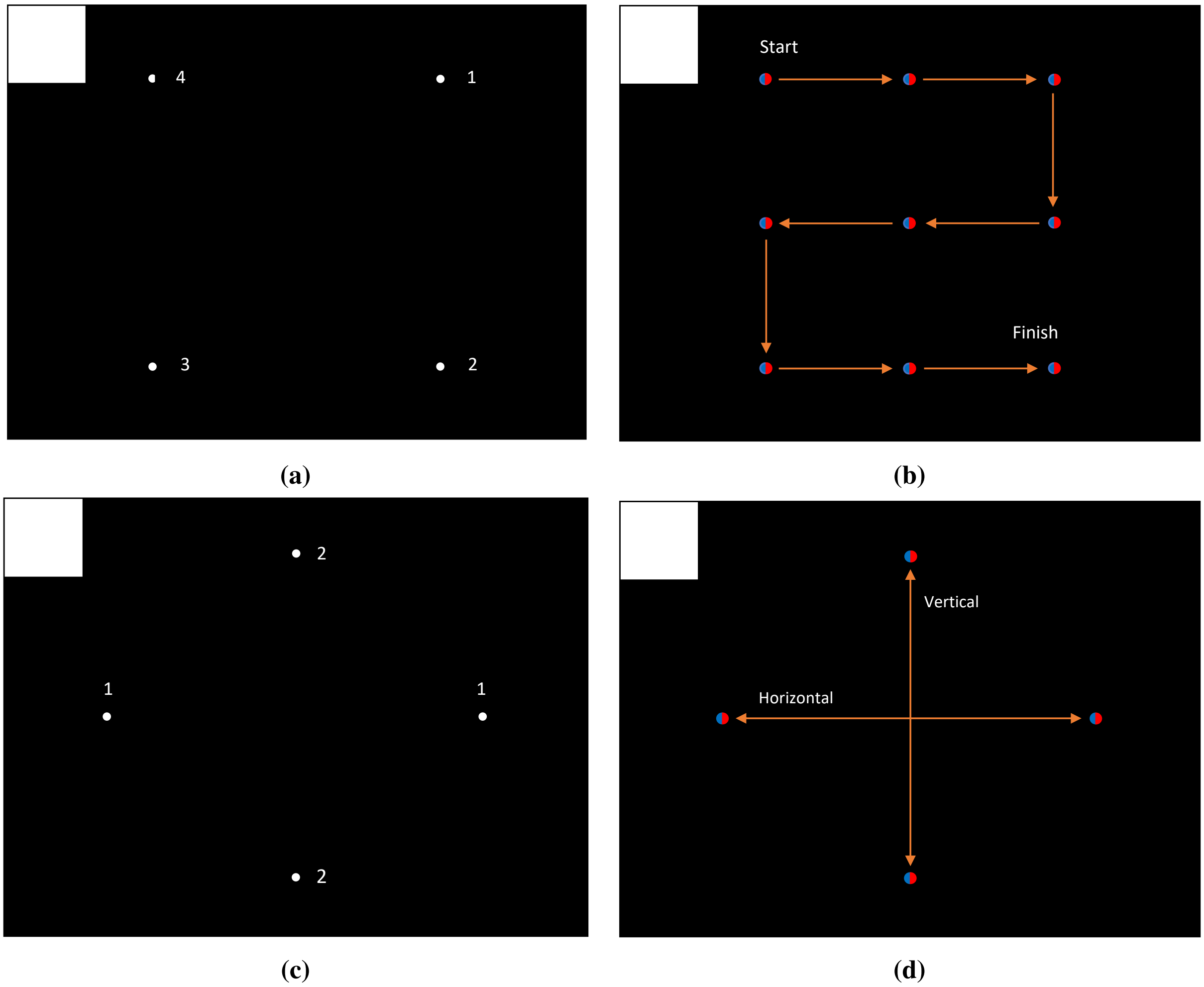


Figure 5 Fixation and tracking test stimuli layout. a) 4-point calibration for fixation test. b) Fixation test layout. c) Two 2-point calibration for tracking test. d) Tracking test layout

The frequency of the modelled sine wave was constant at 0.12 Hz, meaning the total duration of two cycles was 16.67 seconds for each smooth pursuit task. The total duration for the tracking tests was $\approx$ 105 seconds - combining smooth pursuit segments and the breaks in between these segments. The speed of the smooth pursuit segment was designed such that saccadic eye movements would not occur - velocity of stimuli less than 30°/s. The actual speed was less than 10°/s at max velocity (in the centre).

Due to the nature of the Jazz-novo eye-tracker, acquiring individual eye gaze points was not possible, hence, a workaround solution using the dichroic filters was implemented. Applying the phenomenon of dichoptic presentation, the filters were used such that only a single eye was being engaged at a time. The stimulus colour was adjusted to the correct intensity such that it was perceivable by the subject by the corresponding filter (i.e. red colour - red filter), and completely occluded by the opposite. This enabled us to simulate individual eye-tracking by allowing only one eye to fixate and correctly assume the resultant X and Y positions corresponded to that single fixating eye.

3.3 Subject Testing

3.3.1 Testing Procedure

Multiple volunteers took part in initial testing of the system and eight subjects participated in the formal trials for analysis. All volunteers reported they were visually normal - in the sense that they did not have known strabismus. Some subjects were regular users of prescription glasses but weren't able to wear them on top of the Jazz-novo. However, the subjects reported they could clearly distinguish the red and blue presented stimuli hence their fixating/tracking performance was not biased.

Subjects were tested in the Brain-Computer Interface (BCI) Lab at the University of Auckland with the experimental setup described previously. Subjects provided written, informed consent to the acquisition of their eye-tracking data, and for their results to be published in this report (and other media). Each subject was required to do four sets of eye-tracking tests with filters swapped - two fixation tests and two tracking tests. Subjects were told instructions prior to testing the process of each test; including the calibration points and rest breaks. The first test was the fixation test with the red filter on the left and blue filter on the right (filter placement RB). After finishing, the filters were swapped (filter placement BR), and the same fixation test carried out again in order to reduce any bias relating to a single eye - from having greater colour perception (i.e. can see red brighter). Then, the tracking test was carried out with the same filter placement, BR. Finally, the filters were swapped back to their original RB placement and the tracking test was carried out again. The process diagram is shown below in *Figure 6*.

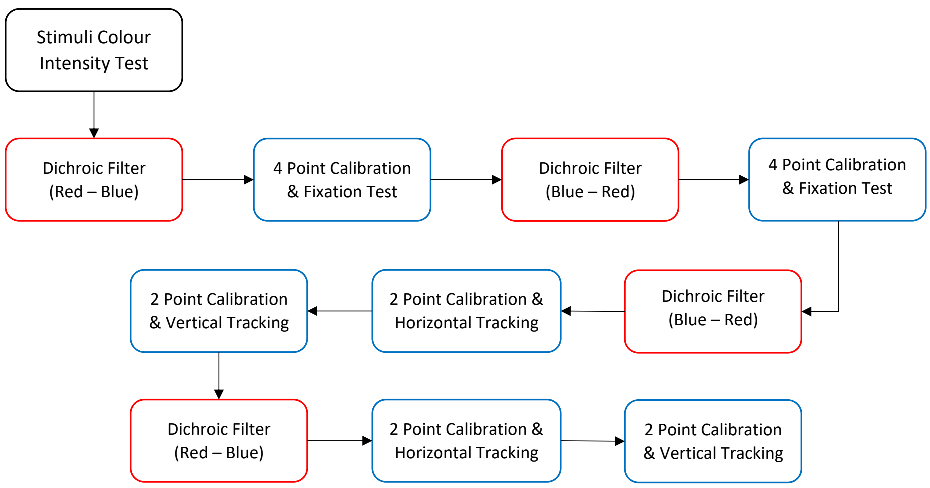


Figure 6 Subject testing procedure flow diagram

During testing, caution had to be taken to get the appropriate luminosity of the stimuli for each subject as the red generally had some 'cross-talk' through the blue filter. This meant a faint shadow of the red stimuli was perceived through the blue filter if the stimulus was too bright. To overcome this, before formal testing, a red and blue stimuli were presented at the centre of the screen and subjects were asked to observe both colours through each filter to determine if any transmission was observed in the incorrect filter. If so, the intensity (0 - 255) was decreased until the 'cross-talk' was unnoticeable. Most subjects required an intensity of 40% for the red stimulus, and 50% for the blue stimulus.

4. Data Processing

4.1 Data Acquisition

Acquiring data from the Jazz-novo eye-tracker required substantial software setup. Three different sets of software and toolboxes were required to acquire and display the gaze point data; BioSemi ActiView, FieldTrip Toolbox, and MATLAB.

The Jazz-novo was connected to the BioSemi Active Two Data Acquisition unit which exclusively worked with the BioSemi ActiView software. This proprietary software, also developed by BioSemi, was used to generate the '.BDF' file type, which was not a common software file type. Hence, a MATLAB toolbox - the Fieldtrip toolbox [16] - was installed to decipher the saved '.BDF' file. The toolbox contains a range of functions for the acquired data by reading the 'BDF header' and the specified signal channels in the file. For this study, only the 'EyeX' (X Position), 'EyeY' (Y Position), and the 'Status' (Trigger) channels were of importance. These were saved to MATLAB variables - 'rawX', 'rawY', and 'trig' - to be accessed during data analysis. The data flow diagram is shown below in *Figure 7*.

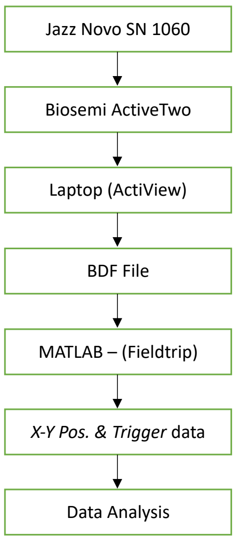


Figure 7 Data acquisition methodology

4.2 Data Filtering and Segmentation

The BioSemi Active Two sampled at a frequency (2048 Hz) more than double that of the Jazz-novo eye-tracker (1000 Hz). This meant that the Nyquist criterion was met and subsequently, every even indexed value was an exact replica of the previous value. Hence, the acquired raw data was filtered such that these copies were deleted. Once filtered, the data were segmented into the respective 3 second long calibration segments, and fixation or tracking segments. Fixation segments comprised of 8 seconds worth of data at each of the nine points. Although the fixation at each point lasted 10 seconds, the beginning and ending one second worth of data points were deleted to eliminate any early anticipation the subject may have performed from switching too soon. Tracking data were left at their entire 16.7 seconds long segments because anticipation could be ruled out; the subject simply had to follow the stimuli.

5. Results and Discussion

Data from fixation and tracking tests were analysed and reviewed independently for each subject. This analysis was done by applying the Fast Fourier Transform (FFT) method to individual subject's segmented data. The analyses revealed the amplitudes at 1 Hz frequency for the different fixation points, and the gain and phase of tracking performance from the tracking tests. Relevant information of each of the eight subjects in the formal trials are presented below in *TABLE 1*.

Table 1 Subject information

Subject	Sex	Known Presence of Strabismus	Dominant Eye	Eye Colour
A	Male	No	Right	Blue
B	Female	No	Right	Brown
C	Male	No	Right	Blue
D	Male	No	Right	Green
E	Male	No	Left	Brown
F	Male	No	Right	Brown
G	Female	No	Right	Brown
H	Female	No	Right	Brown

5.1 Fixation Test

5.1.1 Subject A Results

The 9-point fixation test was the first screening test to be performed. Amongst the group, Subject A had interesting results overall in their fixation data so their respective plots are presented in *Figure 8*. The top-left plot, *Figure 8a*, shows all nine fixation points for Subject A with filter placement RB (red filter on left, blue filter on right). This plot shows the X against Y position for the eight second long segmented fixation data. As can be seen, the clusters on the left and right side have greater spread than those in the centre, indicating that the subject had higher magnitude in oscillations and deviated their eyes further to re-fixate on the points at the sides, compared to the centre section.

These oscillations can be seen distinctly in *Figure 8b*. The plot of X and Y displacement against time expresses fixation point 6 (middle-left point of grid) as there were significant amounts of horizontal and vertical oscillations present. Using FFT, this fixation point was analysed to retrieve the oscillation amplitude at the 1 Hz component - the frequency at which the blue and red stimuli were oscillating. These FFT plots are shown in *Figure 8c* for X oscillation and in *Figure 8d* for Y oscillation, for both filter placements RB and BR.

The 1 Hz component of the FFT revealed that Subject A was alternating fixation. Subject A is a visually normal subject but the pattern of results suggests they may show signs of incomitant strabismus - signs of visual paralysis in different gaze directions [6]. Comparing Subject A's amplitudes of X and Y oscillations; the two 1 Hz component peaks for X with

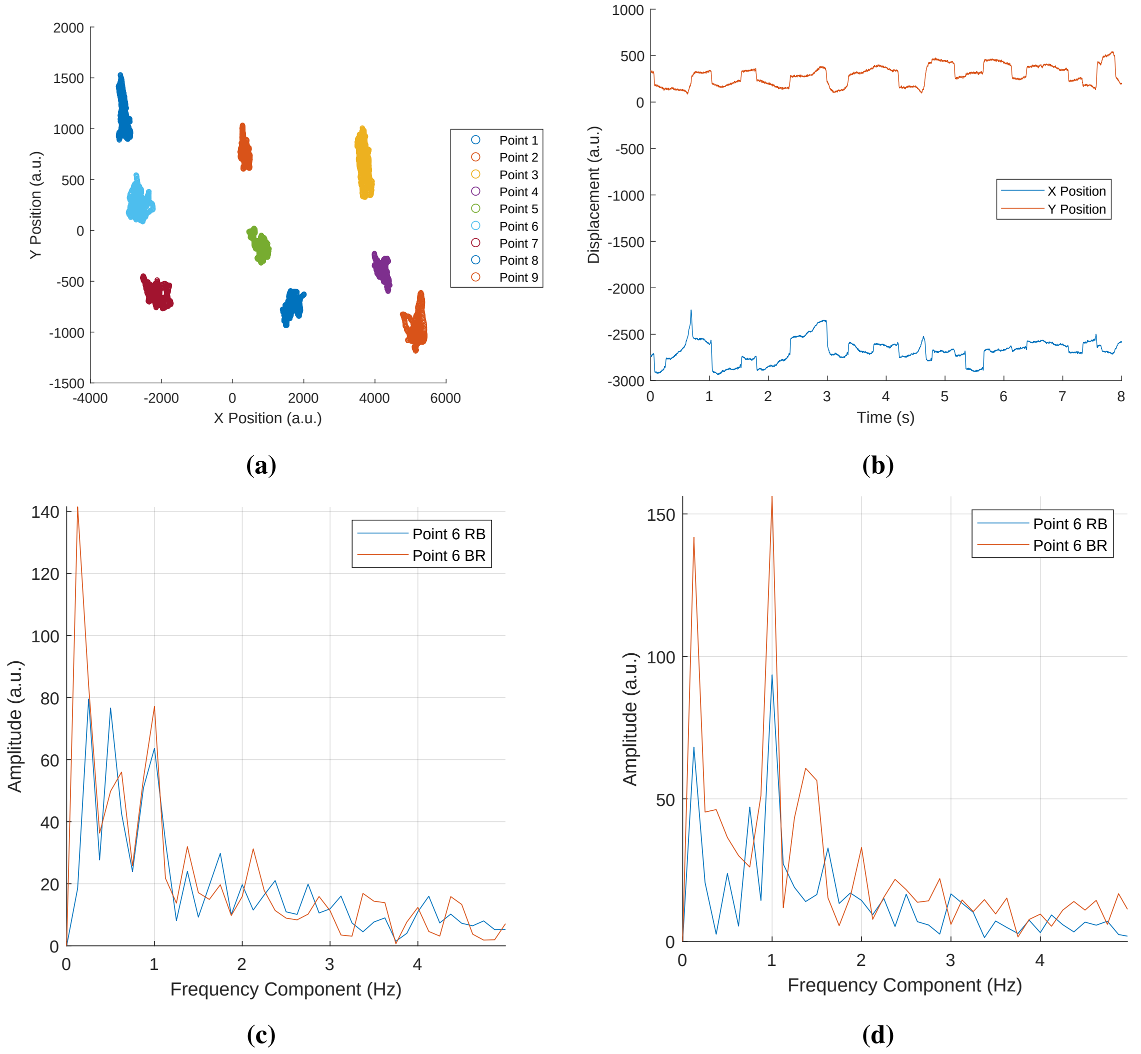


Figure 8 Subject A fixation test with filter placement RB. a) XY plot of the 9-point fixation test. b) X and Y displacement against time for fixation point 6. c) FFT analysis of X position at fixation point 6. d) FFT analysis of Y position at fixation point 6.

filter placement RB (62 a.u.) and BR (78 a.u.), are relatively lower than those for Y with filter placement RB (92 a.u.) and BR (158 a.u.). This suggests that whilst gazing towards the left, Subject A had greater magnitude of deviation vertically in their visual axes. This could also indicate the subject had a greater level of hypo/hyper-tropic strabismus rather than eso/exo-tropic.

The amount of deviation of the eye could also be quantified using the amplitude of these 1 Hz peaks. The deviation is equivalent to the amplitude of the oscillation during fixation, in units of millimetres. Realising the deviation required computing the difference between the fixation and calibration amplitudes at 1 Hz, with respect to the resolution coefficient, as described in the following equation

$$Deviation = \frac{A_1}{C} - \frac{A_0}{C} \tag{2}$$

where A_1 = *fixation point amplitude at 1 Hz*, A_0 = *calibration point amplitude at 1 Hz*, C = *resolution coefficient (a.u./mm)*, and $Deviation$ = *deviation noticed on screen (mm)*. The deviation could be considered for both horizontal and vertical deviations. For Subject A it was approximated that the horizontal deviation was 1.00 mm, and the vertical deviation was 6.12 mm. These were the average values from both RB and BR filter placements.

Plausibility of these deviations need to be confirmed. To confirm the accuracy and precision of these deviation values, multiple trials on the same subject could be conducted to observe if there is minimal variability within trials, in the future. Averaged deviation values across all nine points could also be taken into consideration. Nonetheless, this analysis does acknowledge the fact that these vertical (or horizontal) oscillations can potentially be used to classify the type, and quantify the severity of strabismus a subject may have.

Similar analyses were carried out with the other test subjects who did not show significant peaks at the 1 Hz component, as subject A did in the Y direction. Subject B had a few distinct peaks whilst most other subjects showed relatively weaker peaks in the X FFT analysis. Peaks observed at the 0.125 Hz component throughout all FFT plots were disregarded, as these were introduced when processing the data into the eight second segments. They were not a true reflection of the subject's fixation performance.

Observing the phase difference between the eyes with both filter placements enables us to check the subject is consistent in their performance and was not unduly biased due to having greater colour perception in one eye. The phase difference plot is illustrated in *Figure 9* - for fixation point 6 with both filter placements RB and BR. In the plot, it appears that the peaks for BR predominantly align with the troughs for RB, and vice versa. This indicates they may be 180° out of phase. Analysis from FFT confirms that at the 1 Hz component, the phase difference is 202°. This indicates that the subject alternated fixation by moving their eyes up for one set, and down at the exact same time stamp with the other filter placement. Thus their performance can be concluded to be unbiased due to effects of the colours. This is consistent with the results of dichoptic presentation (and occlusion) realised through the filters trialled in [7].

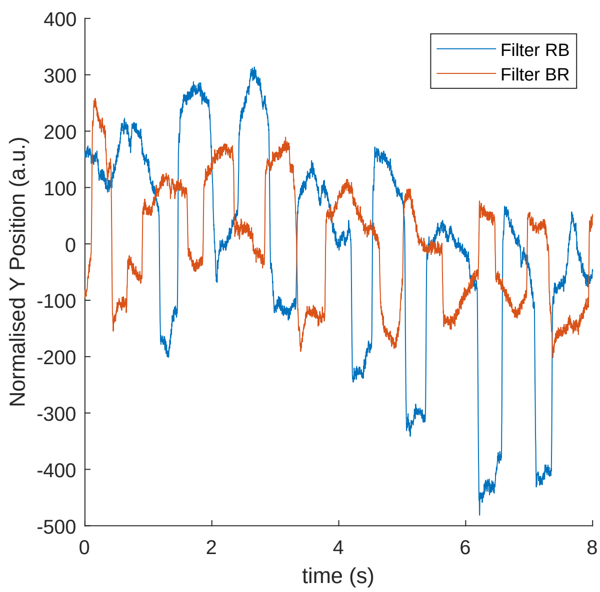


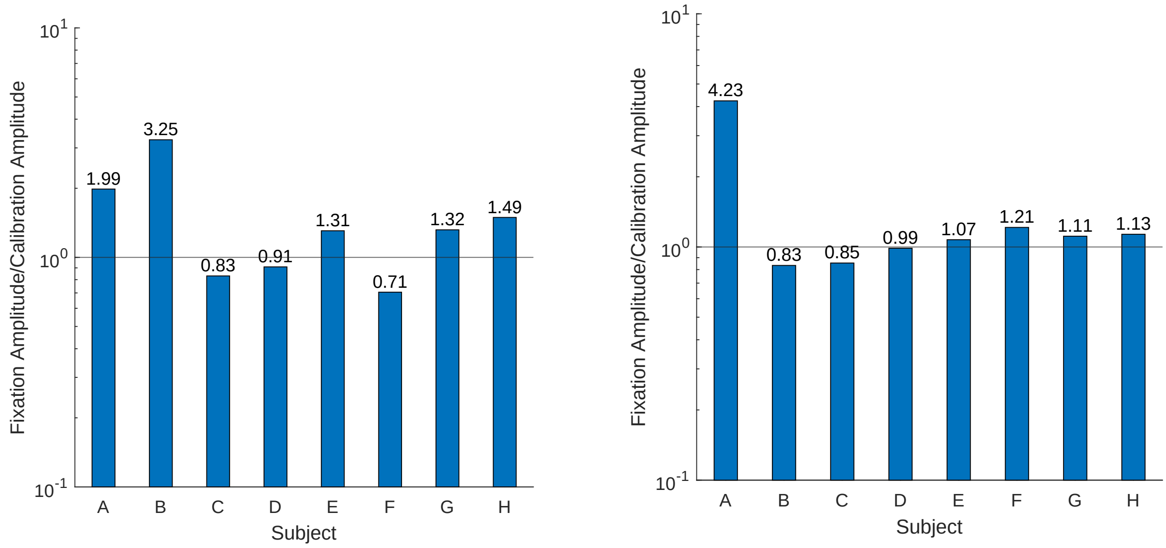
Figure 9 Overlay of normalised Y position for filter placements RB and BR at fixation point 6

5.1.2 Group Results

Vertical or horizontal oscillation may be observed in strabismic patients when occlusion of a single eye is alternated [6]. This is the basis of the manual method of cover test and the adapted, eye-tracking fixation test in our study. The X and Y displacement oscillations are plotted for all eight subjects in *Figure 10* which show the magnitudes of oscillation at fixation point 6 relative to the subject's nearest non-oscillating calibration point, point 3.

As expected a visually normal subject would see little to no oscillations, thus, most subjects' gains are spread around 1. The significantly high gain of Subject B in *Figure 10a* represents high magnitudes of X oscillation at this location which could be expressing symptoms of eso/exo-tropic strabismus. Similarly, the vertical oscillations in Y were only apparent in Subject A, which explains their higher gain amongst the group of test subjects. However, the short segment of calibration (three seconds) with large frequency bins could have an affect on the accuracy of the true 1 Hz amplitude for calibration points. A larger segment of data could have been acquired to help improve this issue.

A gain of lower than 1 is not expected, and implausible, as this signifies the subject was oscillating more during the calibration segment compared to the fixation segment. The error may be explained due to noisy measurements and observed drift in the readings as the test progressed. However, the testing process can still be considered reasonable and valid as it revealed subjects with distinctly high gains - those who could potentially be strabismic.



(a) **(b)**

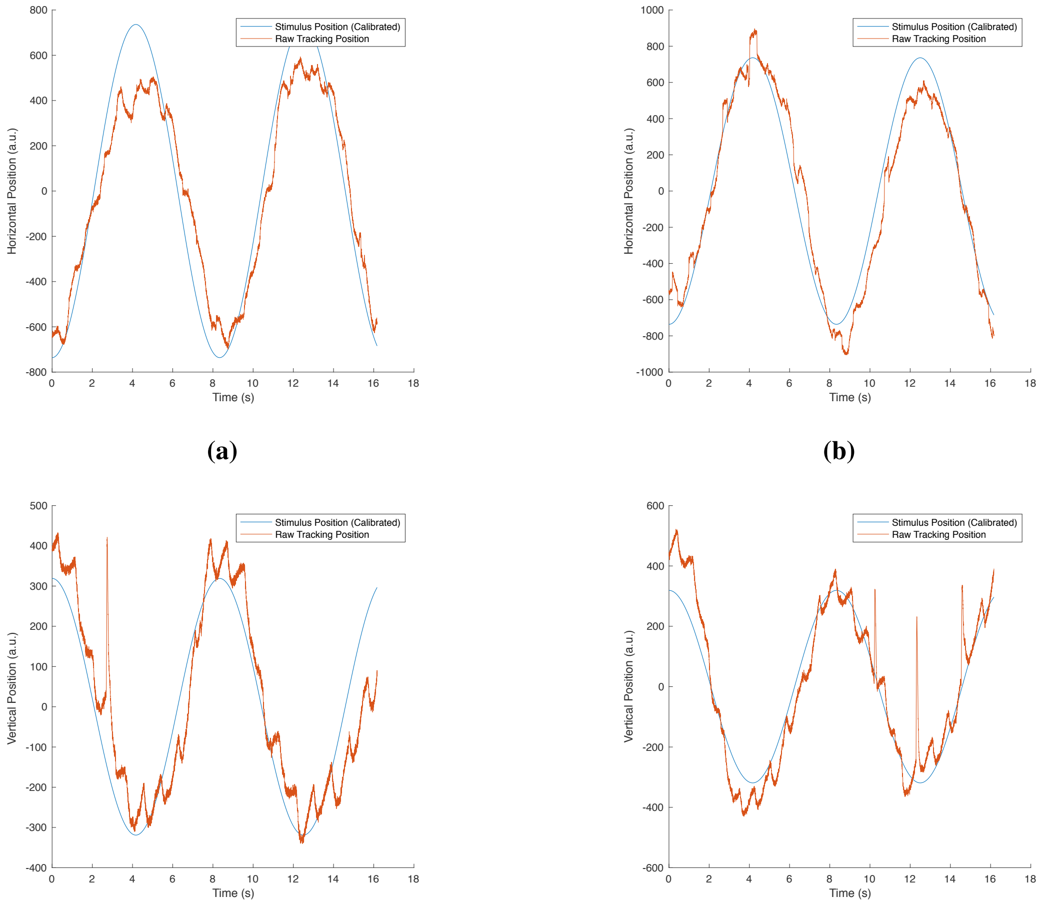
Figure 10 Fixation amplitude at 1 Hz over calibration amplitude at 1 Hz at the bottom-left corner of 9-point grid. a) Relative horizontal gain for all 8 subjects. b) Relative vertical gain for all 8 subjects.

5.2 Tracking Test

5.2.1 Subject B Results

The second section of the experiments included the tracking tests. These tracking tests would enable us to analyse the subject's gain and phase at the 0.12 Hz (frequency of stimulus) in order to determine their tracking performance and whether there are measurable differences between the eyes of subjects to predict strabismus. Similar tracking tests were conducted by Saisara et al. [10], however, they computed the Euclidean distance of the two eyes to predict strabismus rather than conclude the gain and phase in the two eyes.

Subject B, another visually normal subject, was chosen to report on for the individual tracking test analyses. The patterns of Subject B's results suggests that they may have performance differences between the two eyes. In *Figure 11*, the responses of horizontal and vertical smooth pursuit tasks are shown. For each of these, there is one red filter and one blue filter plot, corresponding to the monocular left and right eye-tracking, respectively.



(a) **(b)** **(c)** **(d)**

Figure 11 Subject B tracking test response with filter placement RB. a) Horizontal tracking with left eye. b) Horizontal tracking with right eye. c) Vertical tracking with left eye. d) Vertical tracking with right eye.

Table 2 Subject B Gain and Phase at 0.12 Hz component

	Horizontal		Vertical	
	Left Eye	Right Eye	Left Eye	Right Eye
Gain	0.7695	0.9392	0.9486	1.1004
Phase (rads)	0.4101	0.3353	0.5533	0.2444

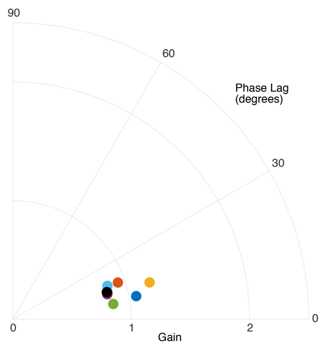
It can be observed from the plots and table above, *Table 2*, that the 0.12 Hz gain is generally larger for the right eye (blue) compared to the left eye. This suggests that when tracking with the right eye, Subject B may have better tracking performance with the right eye than the left. Tracking with the left eye may result in an undershoot. These undershoots (or overshoots) illustrate while the subject was tracking monocularly, the resultant gaze position of both eyes were further in (or further out) than where the stimulus was presented.

The phase from the tracking analyses reveal the lag (in radians) behind the stimulus. Although all quantities have some lag, the plot allows us to see if there have been any anticipation or ‘forward thinking’ by the subject throughout the test. For example, this is apparent in *Figure 11d*, as Subject B was reaching the first trough. In general, Subject B’s right eye had a gain closer to 1 and showed lower phase lag which indicate the ocular dominance of right eye over left eye. We expect to see similar or greater ocular dominance in strabismic patients, via their differences in gain and phase between the two eyes.

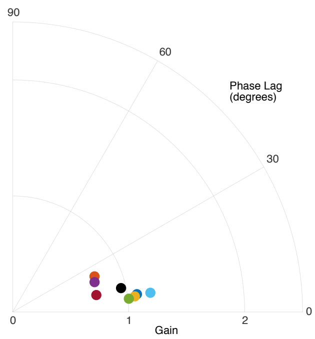
5.2.2 Group Results

Strabismic subjects often suppress images from the deviated eye when viewing binocularly. Due to their seldom use of the deviated eye, tracking performance is significantly poorer in the deviated eye [17]. This tracking test enables the use of both eyes monocularly so the performance of dominant eye (DE) and non-dominant eye (NDE) can be visualised. *Figures 12* and *13* display both DE, NDE, and the difference between the two, for horizontal and vertical tracking. The difference between DE and NDE is represented as the absolute difference in gain and phase - as it was not possible to show a negative gain in a polar coordinate system. Only the first quadrant is shown in the figures because all test subjects had minimal phase lag. If a strabismic (or other) subject were to show large phase lag (or had phase lead), the quadrant could be extended to the full 360° plot.

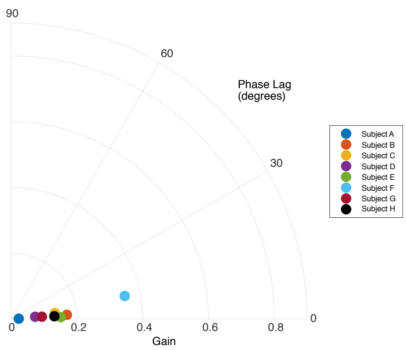
Displayed below are all 8 subjects from the formal trials and their respective DE or NDE plots. In horizontal tracking, *Figure 12*, all but one were fairly consistent between both their tracking tests. Subject F had a larger gain with their NDE and larger phase with their DE hence, the third plot shows this as an outlier. Similar cases were seen in the vertical tracking, *Figure 13*, where Subjects G and H had vastly larger gains from their NDE. These larger gains observed in the NDE may express the fact that the eye is under-utilised, and could be potential characteristics of strabismus.



(a)



(b)



(c)

Figure 12 Polar plot of gain and phase for horizontal tracking. a) Dominant eye tracking. b) Non-dominant eye tracking. c) Difference between dominant and non-dominant eye.

5.3 Accuracy of Results

Of the series of tests explained formerly, a major setback for the results displayed in this section is the lack of comparison with a known strabismic subject. Both the fixation and tracking test are able to distinguish common characteristics exhibited by a strabismic patient - such as large magnitude oscillations, large relative gain between oscillation and

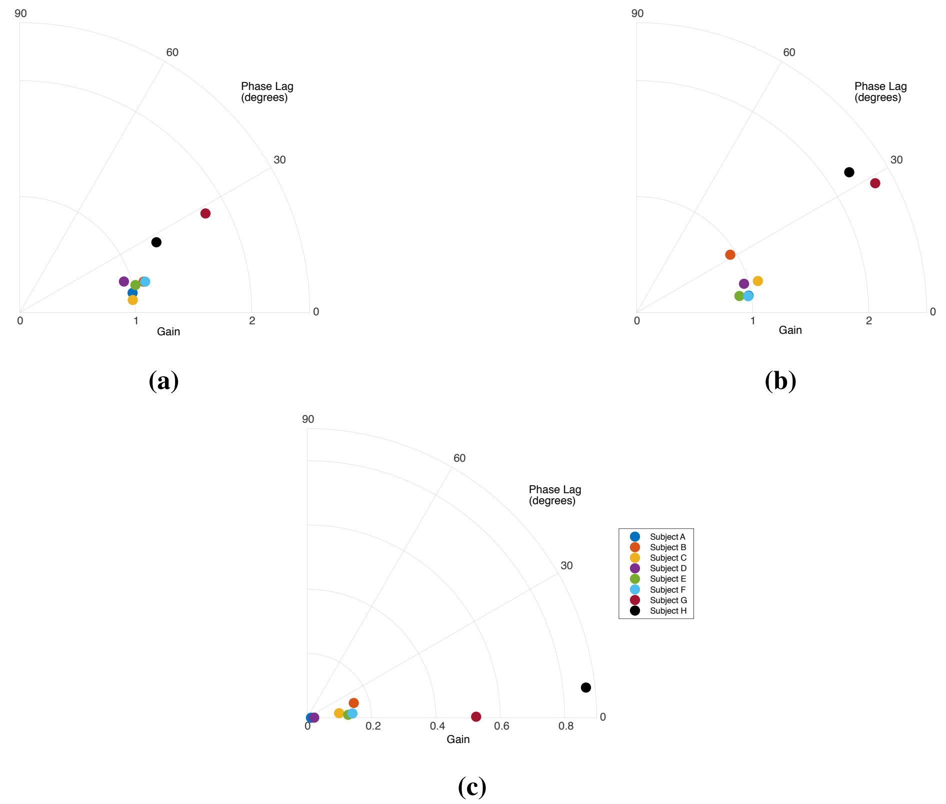


Figure 13 Polar plot of gain and phase for vertical tracking. a) Dominant eye tracking. b) Non-dominant eye tracking. c) Difference between dominant and non-dominant eye.

non-oscillation, under/over-shoot in resultant gaze position, and large gain/phase in NDEs. Another point to note is that the Jazz-novo eye-tracker data was quite easily affected by noise, and had varying drift (especially in vertical axis) if not worn precisely, hence a slight skew in Figure 8a could be noticed. Therefore, not all data shown may be as accurate as analysed, however, control actions were taken to disregard outliers and anomalies as much as possible. Multiple test trials with one subject could be tried in the future to validate the measurements and analyses presented here. Despite the setbacks, the tests presented valid hypotheses in diagnosing a strabismic subject, so the concept of the tests remain valid. A more accurate, and possibly less invasive, eye-tracker could have provided with cleaner results and findings.

6. Conclusion

In this research, we aimed to design, build and test an eye-tracking system for the diagnosis of visual deficits. The central theme revolved around strabismic patients who may require early intervention to prevent further visual deficits, as well as psychosocial issues.

The designed system implemented two forms of testing procedures; the fixation test and the tracking test. The fixation test enabled the analysis of a subject's gaze point in the nine different directions of the grid. The tracking test enabled the analysis and smooth pursuit performance of the two individual eyes. The testing was possible due to the phenomenon of dichoptic presentation with the use of red & blue dichroic filters and coloured stimuli.

The results from the set of trials, with the eight volunteer subjects, revealed the following characteristics from the test, most likely required for diagnosing strabismus:

- Magnitude of oscillations at the 1 Hz frequency component in all 9 gaze directions
- Amount of deviation in individual eye when fixating compared to alternating
- Identifying the deviated eye via under/over-shoots in gaze response in smooth pursuit
- Using difference between DE and NDE gains and phase to illustrate tracking performance

Currently, the results are based off visually normal subjects but further testing with a strabismic patient group could see validation of these results and confirmation of successful diagnosis of strabismus.

7. Future Work

Following the conclusion of this project, some key areas of the research as well as the experimental trials were identified for further development. These are outlined below.

Further testing of subjects. As the principal goal for this research, testing of strabismic patients would be required to conclude the validity of our eye-tracking system as a diagnostic tool for strabismus. Similarly, further testing of visually normal subjects would also be key into recognising patterns such as those observed in this group of subjects.

Automated analysis via Machine Learning. With enough subject data, pattern recognition could be utilised for learning algorithms. These algorithms would help further automate the entire process making it faster and more efficient, and would also allow more accurate, and objective classifications of subjects.

Less invasive methods. Early intervention of strabismus in children and infants is vital. However, the current eye-tracking method may be unsuitable for many children to use. A more accurate and non-invasive eye-tracking device would be required for use on young children such that the device would not introduce any bias during testing from experiencing discomfort.

Mobile system. Utilising the high resolution cameras in tablet and other devices can allow for a mobile system. Having a mobile system would enable a non-invasive screening process and enable high throughput in clinical environments for both patients and clinicians.

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