Quantitative characterisation of eye movements in typical and atypical children

A thesis submitted to Cardiff University for the degree of Doctor of Philosophy

By

Valldeflors Viñuela Navarro

School of Optometry and Vision Sciences
Cardiff University

June 2015

Supervised by Dr J Margaret Woodhouse OBE,
Prof Jonathan T Erichsen and Miss Cathy Williams

Acknowledgements

It seems it was yesterday when my “planned one year adventure” to the UK began. Who would have thought that almost five years later I would be writing a PhD thesis acknowledgements in a rather sunny day in Cardiff? During these years I shared my “adventure” with many people from many different UK locations that deserve a huge thank you. However, I will only acknowledge in here those who shared with me the last three years and possibly the craziest ones of this “adventure”.

I would like to extend my most sincere thanks to my supervisors, Dr Maggie Woodhouse, Professor Jon Erichsen, Miss Cathy Williams and my advisor Dr Fergal Ennis. I am most grateful for their continuous support and guidance throughout my PhD. Thank you all for always finding the time to discuss anything - from experimental results and statistics to professional career difficulties. Although Dr Tony Redmond was not directly involved in this project, I would also like to thank him for his equally important academic, professional and personal advice. I must also acknowledge the College of Optometrists for funding this research and giving me the opportunity to be one of their Postgraduate Scholars.

I take this opportunity to give a special thanks to Maggie for being an exceptional main supervisor that along these three years has become a mentor, a friend and a real source of career inspiration. I sincerely appreciate all the hours you spent with me sharing all your knowledge and experience making me a better researcher, and indeed, a better Optometrist. A special thanks also goes to Jon, my second supervisior, who despite his busy schedule he always finds time (no matter how late in the day!) to discuss with me from eye movement data and results to the use of the “Oxford comma”.

A very special thanks goes to the children and their parents who took part in my studies. This thesis would not have been possible without them. I must also acknowledge all the teachers of White Rose Primary School and Kitchener Primary School, in particular Mr Phillips and Mr Colins. I can only hope that all children, parents and teachers involved in the research have found the experience as enjoyable and rewarding as I have.

During the data collection in the schools I was sometimes assisted by some of my PhD and Optometry colleagues Beth Flynn, Chris Jones and Louise Terry. Their support was invaluable to timely and accurately collect the data for the main studies of this PhD. I must also thank my colleagues from the Research Unit for Nystagmus (RUN), Dr Matt Dunn and Lee McIlreavy for our frequent exchange of knowledge on eye movements and the continuous Matlab support they have given me. Thank you also to Dr Rod Woodhouse and Professor Chris Harris for their invaluable support in computer programming and eye movement data analysis, respectively.

I would also like to thank the residents of Room 1.18 and 1.19 as well as other PhD colleagues. Thank you to Enyam, Lindsay, Louise, Nikki, Steph and Tamsin for your friendship and support. In particular I would like to thank "lovely little Shindy" for our late evening philosophical as well as entertaining chats, exchanges of skills, and unconditional venting of tears and frustrations. In the same way, I would like to thank the lovely ladies in the School of Optometry office and in particular to the super-lovely Sue Hobbs. I thank her for her continuous support and encouragement, and all the faith she has in me (after all!). Thank you Sue for helping this troublemaker in every single trouble! Having said that, I must acknowledge all the staff of the school. Thanks for "adopting me" in this lovely and friendly place!

I could not have completed my thesis without the unconditional "distance-support" received from my family in special my parents, Paco Vinuela and Rosa Navarro as well as my partner in crime and auntie Marta Navarro. Thanks for always being there!

Last, but by no means least, thank you to Ross Wain for being by my side in probably some of the most important decisions of my life such as persuading this PhD and for being my "UK family". There are no words to express how grateful I am…Thanks for being the voice of reason and not letting me give up on this.

Abstract

Children with delayed reading skills and/or poor academic achievement are increasingly being referred to Eye Care Professionals with suspected eye movement/"tracking" difficulties. However, current clinical techniques are highly subjective, poorly controlled, and relatively imprecise. It is therefore reasonable to suggest that Eye Care Professionals face challenges in recognising and diagnosing genuine eye movement disorders, and consequently, fail to support and/or manage these children. The principal aim of the studies described in this thesis was to characterise eye movements in children with learning related difficulties who are frequently considered to be at risk of eye movement disorders.

Using a novel child-friendly method, we have shown that, in general, eye movement characteristics in children with reading/learning related difficulties are not different from those in typically developing age-matched children when compared as a group. The findings also showed that when eye movement characteristics in children with reading/learning related difficulties were compared on an individual basis, some of these children had eye movement parameters outside their age-matched norms. Further, our results suggested that children whose eye movements were outside their age-matched norms, generally corresponded to those who had specific, more complex and global difficulties (e.g. dyspraxia, general developmental delay).

In conclusion, the studies presented in this thesis suggest that there is an association between specific learning difficulties and eye movement disorders, but challenge the view that eye movement disorders can be found in isolation in children with delayed reading/academic performance. Finally, based on the sum of results obtained, simple actionable guidelines are proposed to improve the examination of eye movements in clinical practice in order to recognise genuine eye movement disorders.

Table of contents

Chapter 3 Development of a child-friendly setup for eye movement research

Chapter 4 General methods

Chapter 5 Normative values for eye movements in school age children

Chapter 6 Eye movements in children with an Individual Education Plan (IEP) related to delayed reading skills

Chapter 7 Eye movements in children referred with suspected eye movement difficulties

Chapter 8 Discussion and future work

Appendices

List of figures

Chapter 1 Introduction

Chapter 2 Scoping exercise: What are eye movement/ "tracking" difficulties?

Chapter 3 Development of a child-friendly setup for eye movement research

Chapter 4 General methods

Chapter 5 Normative values for eye movements in school age children

Chapter 6 Eye movements in children with an Individual Education Plan (IEP) related to delayed reading skills

Chapter 7 Eye movements in children referred with suspected eye movement difficulties

Chapter 8 Discussion and future work

List of tables

Chapter 1 Introduction

Chapter 2 Scoping exercise: What are eye movement/ "tracking" difficulties?

Chapter 4 General methods

Chapter 5 Normative values for eye movements in school age children

Chapter 6 Eye movements in children with an Individual Education Plan (IEP) related to delayed reading skills

Chapter 7 Eye movements in children referred with suspected eye movement difficulties

Abbreviations

ABS	Absolute
Acc	Accommodation
ADHD	Attention deficit hyperactivity disorder
ANOVA	Analysis of Variance
BINO	Binocular
CL	Confidence limits
CN	Cranial nerve
CT	Cover test
CYL	cylinder
D	Distance
D.VA	Distance visual acuity
DC	Dioptre cylinder
DS	Dioptre sphere
DEM	Developmental eye movement
DLPL	Dorsolateral pontine nucleus
DS	Dioptre sphere
EOG	Electroculography
FEF	Frontal eye field
I	Intercept
IEP	Individual Education Plan
LE	Left eye
MEP	Mean eye position
Microsacc	Microsaccade
N	Near
N.VA	Near Visual acuity
NPC	Near Point Convergence
NSUCO	Northeastern State University College of Optometry
NYSOA K-D	New York State Optometric Association King Devick
OKN	Optokinetic nystagmus
PIC	Participant Identification Centre

PPRF	Paramedian pontine reticular formation
RE	Right eye
RET	Retinoscopy
RMS	Root-mean-square
S	Slope
SC	Superior colliculus
SCCO	Southern California College of Optometry
SD of MEP	Standard deviation of the mean eye position
SD	Standard deviation
SE	Standard error
SENCO	Special Education Needs Coordinator
SOT	Esotropia
SP	Smooth pursuit
SPEC	Smooth-Precise-Extense-Complete
SPH	Sphere
STEREO	Stereopsis
UC	Ulster-Cardiff
VA	Visual acuity
VI	Visually Impaired
VOR	Vestibulo-ocular reflex
XOP	Exophoria
YO	Year old

Chapter 1 Introduction

1.1. Introduction

A large percentage of learning (80%) is done visually (Garzia 2006), and as a consequence, vision can be considered a vital sensory input for children during their development and learning. Thus, any condition that impairs vision including uncorrected refractive errors, binocular vision and/or accommodative deficits may reduce performance in learning, recreational and/or occupational environments (Flax 2006). In addition to the aforementioned, eye movements are also a potential cause of visual impairment, as they allow us to continuously fixate on an object of interest or words in a text, sequentially shift our gaze to visually explore the surrounding space, involuntarily shift our gaze to new objects that appear in our visual field, and accurately track moving objects (Leigh and Zee 1999). Hence, eye movement difficulties may also have an impact on children's development and learning, due to their potential impact on children's performance in learning, recreational and/or occupational environments.

The prevalence and characteristics of eye movement difficulties in children is unknown. Further, Eye Care Professionals are frequently faced with children considered to be at risk of eye movement difficulties, who are referred by Educational Professionals (e.g. Psychologists) and Health Care Professionals (e.g. Occupational Therapists and General Practitioners) on the grounds of "poor tracking", skipping words and losing their place when reading (Scheiman and Wick 2008a; Barrett 2009). The main aim of the studies described in here is to produce normative values for eye movements in typical children, and ascertain the prevalence and characteristics of genuine eye movement difficulties in children with delayed reading skills, and children referred with suspected eye movement difficulties.

The present chapter provides a general introduction to the characteristics and development of normal eye movements, and an overview of possible associations between eye movements and learning. Finally, the chapter presents and evaluates different methods currently used to assess eye movements in optometric practice, and introduces the technologies nowadays available to record eye movements.

1.2. Eye movements

There are different types of eye movements that account for specific purposes and suit several types of objects, motions and conditions (Dodge 1903; Leigh and Zee 1999). This literature review focuses on those eye movements known as fixational eye movements, which move the eyes and fixate an object of interest in the visual field (Dodge 1903). These include smooth pursuit, saccades and visual fixation.

1.2.1. Smooth pursuits

Smooth pursuit eye movements are responsible for the smooth tracking of slow moving objects and maintaining their image on the fovea. Their main functions are to stabilise the image of the moving target on the fovea minimizing retinal image motion and to cancel optokinetic nystagmus (OKN) resulting from tracking small moving targets against a stationary background (Wong 2008). In general, pursuit is obtained by a combination of smooth pursuit and saccadic eye movements. The latter are responsible for realigning the image of the moving object if it falls outside of the fovea at any time (Barnes 2011).

Smooth pursuit eye movements comprise different phases: the initiation, maintenance and termination (Barnes 2011). During the initiation, also known as the open loop phase, the smooth pursuit begins 100-130 ms after the target starts moving (latency), with a saccade and an initial acceleration of the eyes that is not related to the velocity of the moving target (Figure 1.1). This typically results in a slight overshoot of the eyes with respect to the target in position and velocity, but soon after this, the eyes match the velocity and position of the target (Figure 1.1). After that, the pursuit is sustained and the acceleration of the eyes depends on the target velocity (Barnes 2011). During this period, known as the maintenance or closed loop phase, the motion of the object projected on the retina is reduced to a fraction of the target motion. This is achieved by extraretinal mechanisms coming from the brain that provide velocity and timing information from previous stimulation (Masson et al. 2010). Once the target motion stops, there is an approximately 100 ms deceleration in which the velocity of the eyes progressively decreases (Barnes 2011).

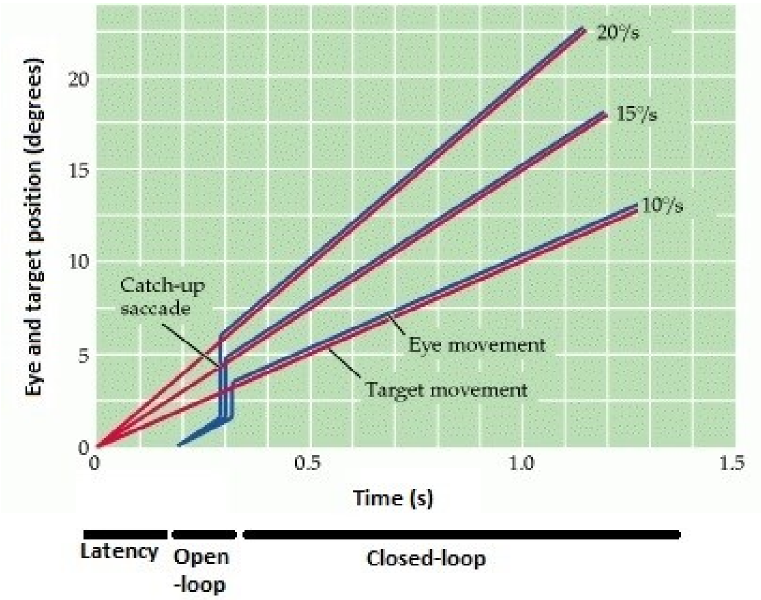


Figure 1.1. Smooth pursuit eye movements.The traces represent the eye position during time (blue lines) while tracking a moving object (red lines) at three different velocities (Purves et al. 2001).

Smooth pursuit paradigms

The characteristics of smooth pursuit described above are obtained as a response to a target that starts moving unexpectedly at a constant velocity, also known as a ramp paradigm (Figure 1.2a). Other common approaches used to assess smooth pursuit performance include step-ramp and sinusoidal motion paradigms (Leigh and Zee 1999). The step-ramp is a modification of the traditional ramp, but in this case, the fixation target suddenly moves (step) to a new position displaced from the original position prior to the constant velocity (ramp) movement of the target (Figure 1.2b). Many researchers have used this step-ramp stimulation in order to avoid the saccade found in the smooth pursuit initiation phase (Barnes 2011). Sinusoidal motion (Figure 1.2c) consists of a target moving with a velocity that continuously changes. These paradigms are the most commonly used, but some studies have used triangular waveforms (Zackon and Sharpe 1987; von Hofsten and Rosander 1997), which involve a constant velocity target that abruptly changes direction at regular intervals.

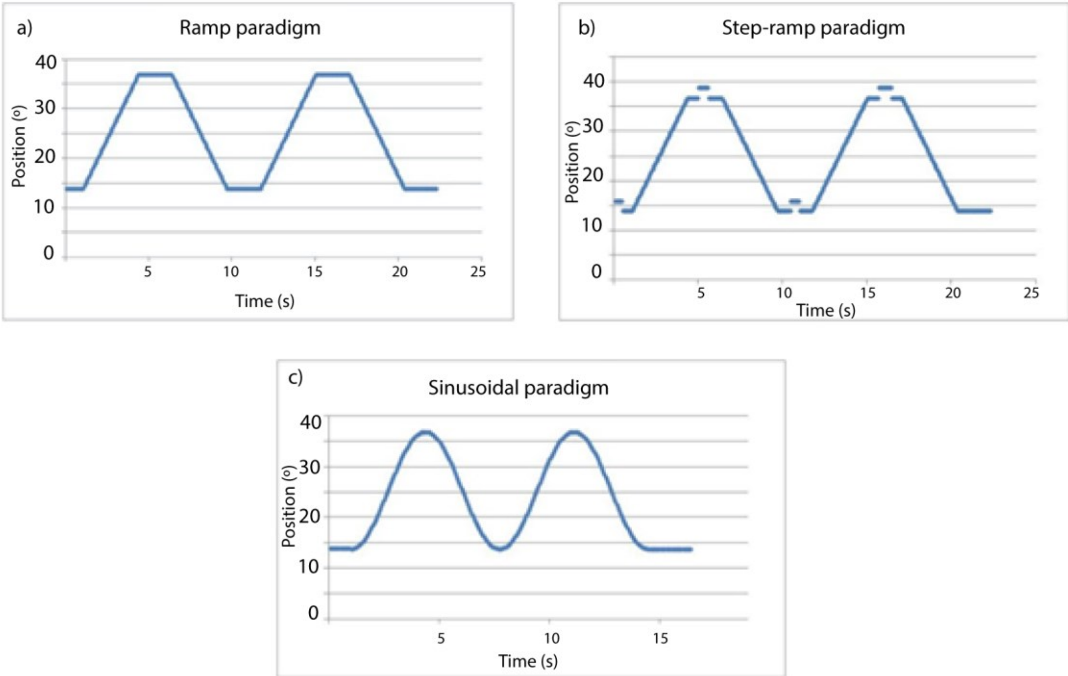


Figure 1.2. Diagram of the three most common motion paradigms used to investigate smooth pursuit eye movements. a) Ramp; b) Step-ramp; c) Sinusoidal.

Smooth pursuit performance parameters

Different parameters can be used to assess smooth pursuit performance, including gains and the number of saccades during the smooth pursuit.

Velocity gain, which is determined by the mean eye velocity divided by the target velocity, is a widely used parameter to assess the quality of smooth pursuit eye movements in response to a moving target (Barnes 2011). Values close to one indicate that the eyes are able to accurately match the velocity of the target presented. Position gain is calculated by dividing the position of the eyes by the position of the target. Hence, position gains close to 1 indicate that eye position matches well the target position, while lower or higher gains suggest that the eye position lags or leads the target position, respectively.

Additional information on smooth pursuit performance can be obtained from the number of saccades produced during a smooth pursuit task (Ross et al. 1996). Moreover, the saccades found in smooth pursuit are suggested to be an essential part of the pursuit system as their purpose is to reduce positional errors during smooth pursuit and realign the target when it falls outside of the fovea (Barnes 2011). Consequently, an increased number of saccades or an increased amplitude of the saccades during the smooth pursuit also indicates difficulties matching the target velocity and position (de Brouwer et al. 2002).

Smooth pursuit neural pathway

Control signals for smooth pursuit continuously specify the motion of the target to be followed by the eyes. The pursuit pathways in the brain stem and cerebellum produce a control signal to generate an appropriate velocity command, and a copy of this velocity signal is also sent to the neural integrator to generate the position component for the motor command (Squire at al. 2008).

For simplicity we will describe the pathway of horizontal smooth pursuit eye movements. Retinal information about the velocity and the location of the moving target are analysed by the lateral, parietal and midtemporal cortices (May and Corbett 1996). The signals in these areas are then transmitted to the cerebellum, specifically to the flocculus and paraflocculus in the vestibular nucleus of the cerebellum via the dorsolateral pontine nucleus (DLPN) (May and Corbett 1996). Pre-motor neurons from these areas project to the brain stem circuit, which in the case of horizontal smooth pursuit will activate the lateral rectus and the contralateral medial rectus via the abducens nucleus (Leigh and Zee 1999). These extra oculomotor muscles, once activated, will move the eyes in order to follow the moving target. This pathway is schematically represented in Figure 1.3. For more information about the cortical control of smooth pursuit eye movements, which will not be discussed here, the reader is directed to the comprehensive text, *The Neurology of Eye Movements* (Leigh and Zee 1999).

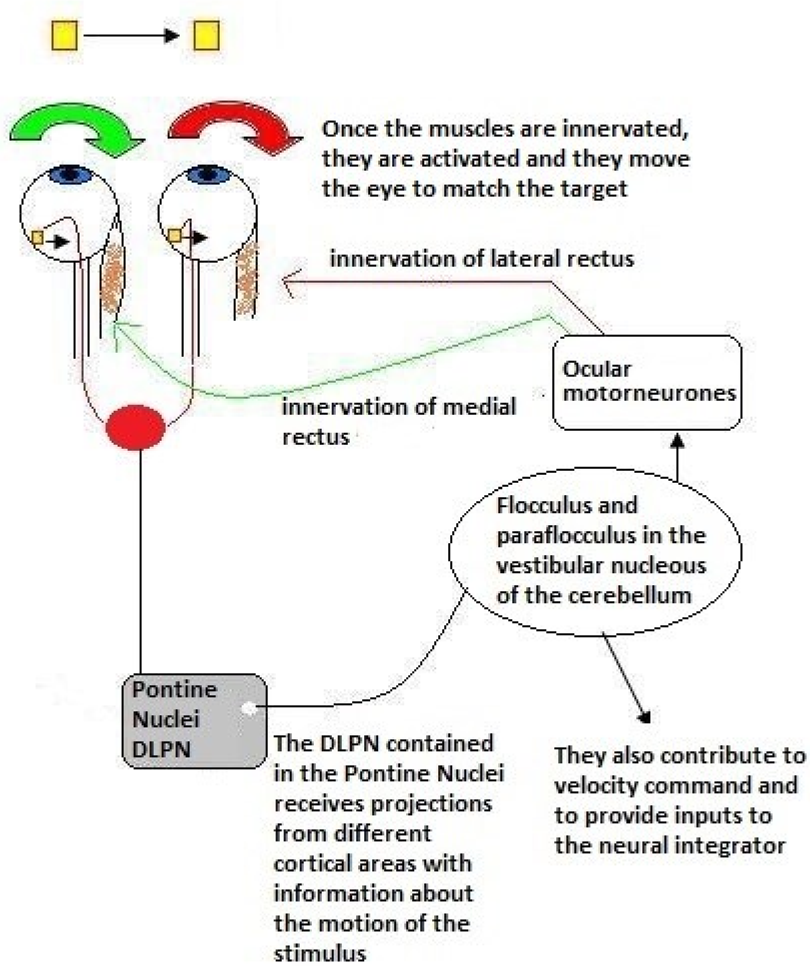


Figure 1.3. Diagram of the horizontal smooth pursuit neural pathway.

Smooth pursuit eye movement development

Smooth pursuit in infancy

Although some early studies suggested that smooth pursuit was absent in young infants (McGinnis 1930; Dayton et al. 1964), it is now generally accepted that young infants are able to pursue moving objects by combining smooth pursuit and saccadic eye movements (Kremenitzer et al. 1979; Phillips et al. 1997; von Hofsten and Rosander 1997; Pieh et al. 2012). In infants, smooth pursuit is mainly achieved by sequences of saccades, but these decrease very early in life at which point pursuit starts to be mainly dominated by smooth pursuit eye movements (von Hofsten and Rosander 1997; Pieh et al. 2012).

Pieh et al. (2012) recently studied smooth pursuit maturation in infants ranging from 1 to 18 months. Their results showed an intensive and profound development of smooth pursuit in the first 6 months of life. In agreement with previous studies (Kremenitzer et al. 1979; von Hofsten and Rosander 1997; Lengyel et al. 1998), the authors claimed that, at the age of 1 month, pursuit is dominated by saccades, but by the age of 6-7 months, the frequencies of saccades have significantly decreased, and by then, smooth pursuit eye movements have achieved important improvements in velocity and position gain values (Rutsche et al. 2006; Pieh et al. 2012).

Although there is significant development in the first months of life, smooth pursuit performance seems to be still below adult levels at the age of 1 year (Rutsche et al. 2006; Pieh et al. 2012). For instance, velocity gains have been reported to be of the order of 0.5 at the age of 1, increasing up until the age of 2-3 years reaching values close to 0.8 (Rutsche et al. 2006; Pieh et al. 2012). In contrast, velocity and position gains of the order of 0.8 have been reported below the age of 1 by some authors (Jacobs et al. 1992; von Hofsten and Rosander 1997), suggesting that adult-like smooth pursuit can be achieved in young infants for short periods of time, however this performance cannot be maintained throughout a long lasting task.

An important fact to take into account is that the stimuli used in these studies evaluating smooth pursuit in infants had very different characteristics, and an infant's ability to smoothly pursue a target is extremely dependent on the target characteristics (Roucoux et al. 1983; Pieh et al. 2012). For instance, studies in newborns using slow, large targets have reported the presence of smooth pursuit eye movements (Kremenitzer et al. 1979; Shea and Aslin 1990; Grönqvist et al. 2006), but studies using small, fast targets have not reported smooth pursuit but sequential saccades to track a moving object (McGinnis 1930; Dayton et al. 1964). Therefore, it can be argued that, in this population, the presence of smooth pursuit or the presence of only saccadic eye movements when following a moving target is highly dependent on the stimulus characteristics, and the results from different studies should be carefully compared. In addition, some authors have suggested that stimuli involving step-ramp motion paradigms are better for assessing smooth pursuit in young infants than the other motion paradigms (Shea and Aslin 1990). This idea was further supported in a later published study that showed that not only the size and the velocity of the stimulus is important but also the motion of the stimulus (von Hofsten and Rosander 1997).

Table 1.1 summarises the most relevant studies on smooth pursuit in infants and provides more details on the stimulus characteristics and the results found in each study.

Author and year	Participants	Stimulus characteristics	Smooth pursuit parameters	Results summary
Kremenitzer (1979)	-28 infants aged 1-3 days	-Solid black circle (12º) -Constant velocity motion (horizontal) -9º/s, 14º/s, 19º/s, 25º/s, 32º/s and 40º/s	-Total time of smooth pursuit -Number of smooth pursuit segments per second -Mean duration of the smooth pursuit segments -Number of saccades per second	Newborns are able to pursue targets with velocities <14º/s by combining saccades and short segments of smooth pursuit. Significant decrease in the duration and frequency of smooth pursuit between <9º/s and <14º/s. Not many infants show segments of smooth pursuit for velocities of >19º/s.
Roucoux (1983)	-6 infants aged from 1 to 12 months	-Mickey mouse face (2º-10º) -Constant velocity motion (horizontal)	-Velocity gain (qualitative data)	Young infants aged 4-5 weeks are able to track moving targets at low velocities (<10º/s)
Shea and Aslin (1990)	- 10 infants aged 1.5 to 2.5 months -2 adults	-White square (2º) -Step-ramp motion paradigm (horizontal) -3º/s, 6º/s and 12º/s	-Velocity gain -Number of saccades	Infants up to 2.5 months of age can smooth pursuit targets of velocities <10º/s. Periods of adult-like smooth pursuit found for low velocities.
Von Hofsten et al. (1997)	-11 infants aged 2, 3, 4 and 5 months	-Yellow happy face (10º) -Sinusoidal motion (horizontal) -Peak velocities 16º/s, 33º/s and 65º/s -Triangular motion (horizontal) -Constant velocities 10º/s, 20º/s and 40º/s	-Velocity and position gains -Number of saccades, and mean saccadic amplitude -Proportion of smooth pursuit -Head - gaze ratio, head gain	Infants as young as 2 months are able to track (even fast velocities) with a combination of movements of head and gaze. There is a significant increase of proportion of smooth pursuit, the frequency of saccades is maintained and the amplitude of the saccades is reduced between 2-3 months.
Phillips et al. (1997)	-20 infants aged 1 to 4 months - 10 adults	-Red light (1.7º) -Constant velocity motion (horizontal) -4º/s, 6º/s, 16º/s, 24º/s, 32º/s	-Proportion of smooth pursuit -Velocity gain -Time devoted to smooth pursuit (with saccades) -Velocity and position gain -Latency -Saccadic frequency	Infants up to 4 months can smooth pursuit targets of velocities <12º/s. Velocity gains increase and frequency of saccades and latency decrease with age (1-4 months). These values are still below adults.

Lengyel et al. (1998)	-95 infants aged 1 day to 114 days	-Square with gratings (9.4º) -Constant velocity motion (horizontal) -7.5º/s	-Velocity gain -Total smooth pursuit time	No differences in the first 4 months of life in velocity gain but a significant increase in the total smooth pursuit time during this period.
Görnqvist et al. (2006)	-10 infants retested at 5, 7 and 9 months	-3D happy face (1º) -Continuous circular motion and sinusoidal (horizontal and vertical) -0.2 Hz (peak vel. 6.9º/s) and 0.4 Hz (peak vel. 13.8º/s)	-Velocity gain -RMS (Root-Mean-Square error -Ratio between the target and the eye position) -Time phase (difference in time between target and eye)	Infants at the age of 5 months are able to track any of the smooth pursuit conditions presented in the study. Increase in velocity gain with age. Gains still below adults.
Görnqvist et al. (2011)	-32 infants retested at 2 and 4 months	-Happy face 8º -Constant velocity and sinusoidal (horizontal)	-Velocity gain -Saccades per second -Proportion of smooth pursuit	Increase in velocity and proportion of smooth pursuit and decrease in the number of saccades between 2 and 4 months.
Pieh et al. (2012)	-89 infants 1-18 months	-Black square (1.2º), black and white chessboard square (4.7º), schematic face and scrambled face -Constant velocity motion (horizontal) -7.5º/s, 15º/s and 30º/s	-Velocity gain -Duration of longest SP segment -Mean eye velocity -Saccadic frequency -Tracking time (with saccades)	Profound development of smooth pursuit in the first 6 months of life with a reduction of the number of saccades and increase in velocity gain. No differences in these parameters between 7 and 18 months. Little effect of target size and type.

Table 1.1. Summary of studies investigating smooth pursuit in infants.

Smooth pursuit in preschool and school-age children

A number of studies have evaluated the development of smooth pursuit in school children (Kowler and Martins 1982; Accardo et al. 1995; Haishi and Kokubun 1995; Tajik-Parvinchi et al. 2003; Rutsche et al. 2006). Although the methods and procedures in these studies were different, their results supported the idea that smooth pursuit is still in development in school age children.

One of the largest studies to date evaluating the development of smooth pursuit in children showed that the proportion of time devoted to smooth pursuit (i.e. without saccades) and velocity gains both significantly increase between 1 and 6 years of age (Figure 1.4) (Rutsche et al. 2006). Unfortunately, this study did not include an adult group, and therefore it cannot be concluded whether or not smooth pursuit eye movements are adult-like at the age of 6 or earlier. However, results from a different study evaluating smooth pursuit in older children and a group of 10 adults, further supported an immaturity of the smooth pursuit system in school age children (Accardo et al. 1995). Although the results indicated that older children have velocity and position gains very similar to those found in adults, their eyes still do not match the position and velocity of the target as accurately as adults do. This study concludes that, even at the age of 12 years, childrens' smooth pursuit eye movements are still immature (Accardo et al. 1995). In contrast, other authors have reported negligible differences in smooth pursuit gains between adults and children aged 7 to 11 years old (Ingster-Moati et al. 2009; Irving et al. 2011). Hence, it is clear that smooth pursuit eye movements are not mature and adult-like for children aged 4 to 8 but the debate still continues about their development and maturation levels after that age.

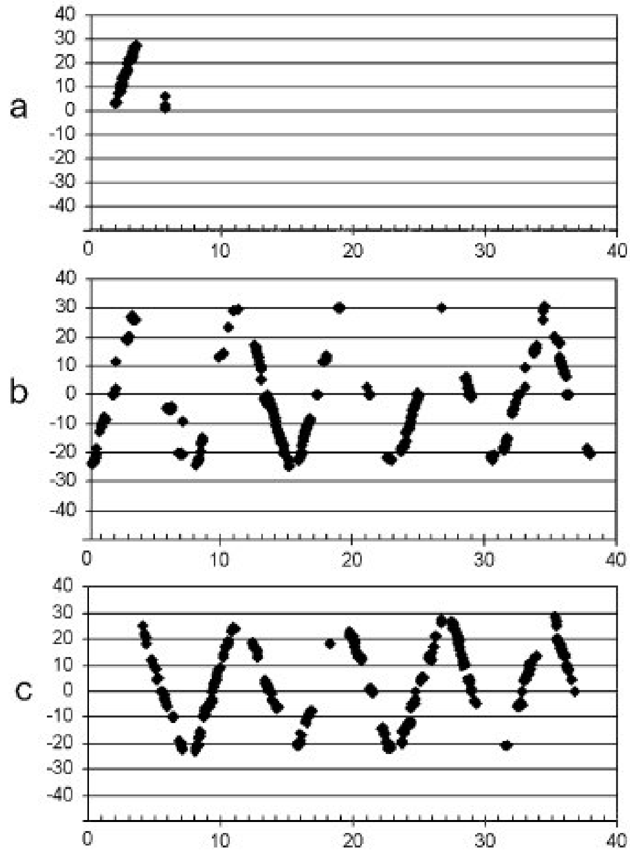


Figure 1.4. Smooth pursuit eye movement recordings from children of different ages (a)1.5 year; b) 3.5 years and c) 6 years) that illustrate an improvement of smooth pursuit performance with age. Adapted from Rutsche et al. (2006).

There are a number of possible arguments that can explain the conflicting results found in the literature. In general, eye movement parameters have been reported to be more variable within a group of children than within a group of adults (Black et al. 1984a; Accardo et al. 1995). This variability might arise from different maturation levels within children of the same age and/or external factors (attention and fatigue) that strongly interfere with smooth pursuit performance (Accardo et al. 1995). In addition, researchers in this field have been using different setups and stimulus characteristics to investigate smooth pursuit development in school age children. This lack of agreement on the methods and procedures might also contribute to the contrasting results obtained by different authors.

Smooth pursuit in preadolescence and adolescence

There have also been few studies describing the development of smooth pursuit in young adolescents. Ross et al. (1993) recorded smooth pursuits in children aged from 7 to 15 years and provided evidence to support further maturation of smooth pursuit eye movements after the age of 7, especially for fast moving targets. The most important limitation is that, again, there was no adult population sample, and therefore we cannot deduce from this study if smooth pursuit achieves adult levels by 15 years of age, earlier, or whether there is further development in mid-late adolescence. However, Katsanis et al. (1998) provided evidence to support the view that smooth pursuit is still not mature in early adolescence (12-13 years). Their results showed no significant differences between the adolescent group (17-18 years old) and the adult group in gains, saccadic amplitudes and saccadic velocities. In contrast, the adolescent and adult groups were found to have significantly better smooth pursuit performance than the preadolescent group (12-13 years old) using the same parameters.

In summary, it can be proposed that smooth pursuit is not fully mature in primary school children. Although smooth pursuit eye movements in this population are very close to those found in adults, these seem not to achieve "full" adult values until late childhood or pre-adolescence (8-12 years). Moreover, some smooth pursuit characteristics could be completely developed in early-mid childhood, but others may take longer to develop. This is supported by the fact that some smooth pursuit characteristics are found to achieve values close to adults earlier than others. For instance, horizontal smooth pursuit gains (position and velocity) have been shown to have values like those in adults around the age of 10 (Ross et al. 1993; Accardo et al. 1995; Rutsche et al. 2006; Ingster-Moati et al. 2009), but other parameters such as saccadic amplitudes or frequencies (Ross et al. 1993; Katsanis et al. 1998) as well as some higher-level smooth pursuit abilities, such as mental tracking abilities and incorporation of visual feedback into smooth pursuit (Haishi and Kokubun 1995; Tajik-Parvinchi et al. 2003), develop further until mid-late adolescence.

Table 1.2 summarises the most relevant studies on smooth pursuit in children and adolescents provides more details on the stimulus characteristics and the results found in each study.

Author and year	Participants	Stimulus characteristics	Smooth pursuit parameters	Results
Kowler and Martins (1982)	-2 children aged 4 and 5 years	-Small bright point -No details on target motion	-Position and velocity gains -Saccades during smooth pursuit (qualitatively assessed)	Smooth pursuit in children is similar to that in adults.
Ross et al. (1993)	-53 children aged 7 to 15 years	-Small black target -Constant velocity motion (horizontal) -6º/s and 12º/s	-Velocity gain -Saccadic frequency -APS (amplitude of saccades per second)	Increase in gain and decrease in the amplitude of saccades with age for the 12º/s smooth pursuit. No differences across ages for the 6º/s velocity.
Accardo et al. (1995)	-10 children aged 7 to 12 years -10 adults	-No details on target -Sinusoidal motion (horizontal)	-Velocity gain -Phase (ratio eye position to target)	Differences in velocity gains and phase between children and adults.
Haishi and Kokubun (1995)	-25 children aged 4, 5 and 6 years -5 adults	-Spot of light (1º) -Sinusoidal motion (horizontal) -0.3Hz, 0.5 Hz, 0.7Hz	-Power ratio (difference between eye and target velocity calculated by Fourier components) -Phase difference (difference between target and eye movement)	No difference in power ratio across the different ages. Differences in phase across the different ages.
Katsanis et al. (1998)	-137 participants aged 11-12 and 17-18 years and adults	-Luminescent dot (0.4º) -Sinusoidal motion (horizontal) -0.4Hz	-Velocity gain -RMS error -Time devoted to pursuit -Saccade rate (number of saccades divided by total task time) -Amplitude and velocity of saccades	All parameters studied were lower in 11-12 year olds compared to 17-18 year olds and adults. Smooth pursuit in 17-18 years old is adult-like. Pre-adolescents aged 11-12 are more variable as a group when compared to adults and 17-18 year olds.
Tajik-Parvinchi et al. (2002)	-40 participants: 10 children aged 4-6 10 children aged 8-10 10 children aged 12-16 10 adults	-Large triangle isosceles constant velocity (horizontal and vertical) - Own/researcher finger following a random pattern	-Velocity gain -Frequency of saccades -Mean saccadic amplitude	Differences in velocity gain and saccades between young children and adults and between young children and teenagers for smooth pursuit. No differences across age groups for vertical smooth pursuit.

Salman et al. (2006a)	-38 children aged 8-19 years	-White square (12min arc) -Sinusoidal motion (horizontal and vertical) -0.25 Hz (peak velocity 15.5º) 0.5 Hz (peak velocity 31º/s)	-Velocity gain -Phase (difference in degree between eye and target position)	Velocity gains increase with age in this child population for the horizontal smooth pursuit.
Rustche et al. (2006)	-358 children aged from 6 weeks to 6 years	-Coloured squares (1.2º) -Constant velocity motion (horizontal) -7.5º/s, 15º/s and 30º/s	-Velocity gain -Attention time (time of pursuit with saccades) -Time of smooth pursuit (without saccades)	Increase across ages for all the parameters.
Ingster-Moati et al. (2009)	-65 children aged 7 to 11	-No details on target -Sinusoidal motion paradigm (horizontal and vertical) -Peak vel. 30º/s	-Velocity gain -Ratio between horizontal and vertical velocity gain	No increase in gain across ages (horizontal and vertical). Horizontal smooth pursuit matures between 7-9 years and vertical smooth pursuit matures between 7-11 years.
Irving et al. (2011)	-53 participants aged 3 to 30 years	-Dots and pictures (0.5º to 1º) -Constant velocity motion (horizontal) -10º/s, 20º/s, 20º/s and 30º/s	-Velocity gain	With pictures, velocity gain only increases with age (in children) for the 30º/s velocity while with dots, velocity gain increases with age for all velocities (in children).

Table 1.2. Summary of studies investigating smooth pursuit in children, preadolescents and adolescents.

1.2.2. <u>Saccades</u>

Saccades are the eye movements responsible for shifts of gaze that bring a peripherally placed object of interest into the foveal region. Saccades can be voluntary as part of a purposeful behaviour, for example on command or memory guided (Wong 2008), but they generally occur reflexively (May and Corbett 1996). Reflexive saccades include movements from the most rudimentary saccades, such as the quick phases of vestibular and optokinetic nystagmus, to reflexive saccades in response to the appearance of a new visual stimulus (Wong 2008).

The basic characteristics of a typical saccade are: an initial extreme acceleration followed by a relatively smaller deceleration with a slight undershoot, and a peak velocity that depends on the amplitude of the saccade (Figure 1.5) (Carpenter 1988).

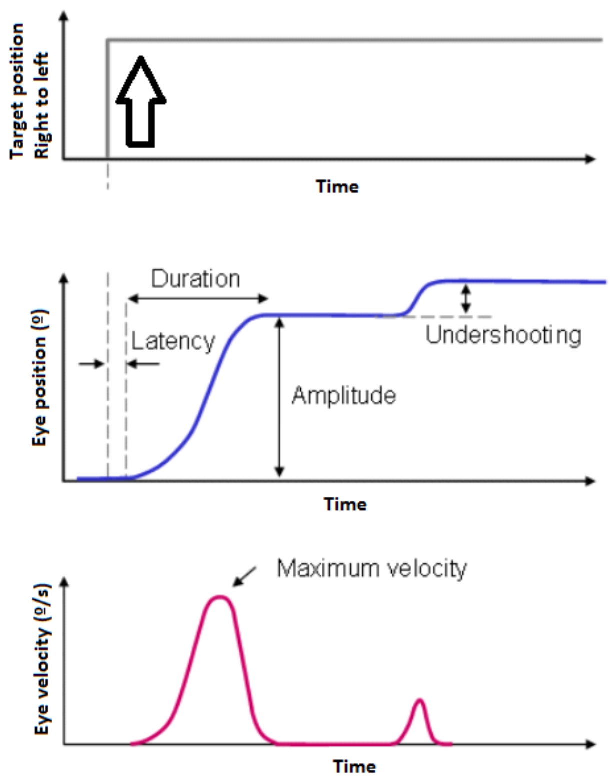


Figure 1.5. Saccadic eye movement in response to a step stimulus (i.e. a target whose horizontal position shifts). After the latency, the eyes rapidly move to the new position, generally undershoot and move one or several times to accurately match the target position. Adapted from Malmivuo and Plonsey (1995).

The initial acceleration appears to be almost the same for all saccades, independently of their amplitude, however peak acceleration and velocity vary with amplitude (Hyde 1959). For example, peak velocity increases with the amplitude of the saccade, meaning that larger saccades have higher peak velocities, and this parameter varies from 30º/s up to 800º/s for amplitudes ranging from 0.5º to 40º (Carpenter 1988). Similarly, the duration of the saccade also increases with saccadic amplitude with duration ranging from 30 ms to 100 ms for saccadic amplitudes of 0.5º to 40º (Carpenter 1988), respectively. This systematic relationship between duration, peak velocity and amplitude for a range of different saccades is known as the main sequence (Bahill 1975).

Saccadic performance parameters

Further studies of the saccadic main sequence showed that, if the duration of all the saccades generated by a typical adult is plotted against their amplitude, a linear relationship is observed between these two features (Bahill 1975) (Figure 1.6a). Moreover, the equation of the line of best fit on that data (linear regression) usually has a slope between 2 and 2.7 and intercepts ranging from 20 to 30 in typical adults (Garbutt et al. 2001).

Although peak velocity also increases with saccadic amplitude, the relationship between these two parameters is not linear (Bahill 1975) (Figure 1.6b). If saccades of different amplitudes are produced and their peak velocities are plotted against their amplitudes, the peak velocities progressively saturate beyond saccadic amplitudes of 15º- 20º, with asymptotic values around 550º/s (Figure 1.6b). These data are more difficult to interpret through equations as different approaches such as power law fit or logarithmic (base 10) plots can be taken (Garbutt et al. 2001). But it is well established that peak velocities should be around 200º/s, 300º/s, 400º/s and 500º/s for saccades of 5º, 10º, 15º and 20º, respectively (Boghen et al. 1974).

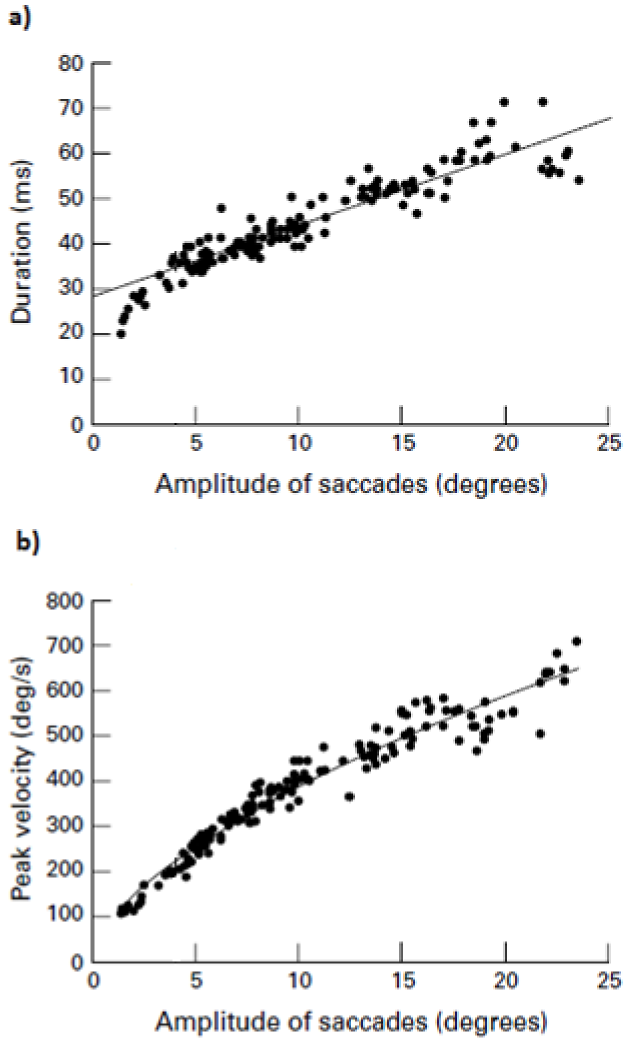


Figure 1.6. Typical saccadic main sequence for duration vs amplitude (a) and peak velocity vs amplitude (b). Adapted from Garbutt et al. (2001).

More recently, saccadic mean and peak velocities have been shown to be highly correlated and exhibit a 1 to 2 ratio in their absolute value (Di Stasi et al. 2013). Moreover, this ratio, which is known as Q ratio, has been suggested to be extremely constant, generally of the order of 1.6-1.7, independently of the amplitude of the saccades (Harwood et al. 1999; Garbutt et al. 2003a). The Q ratio can be easily obtained by multiplying the peak velocity of the saccades by their duration and plotting them against their amplitude. Then, fitting a line through the origin on those data is performed to obtain the value of the Q ratio (Figure 1.7). This parameter can be considered an indicator of the saccadic velocity waveform (Leigh and Zee 1999). Thus, Q ratios above 2 suggest that the saccadic velocity waveform is interrupted at some point by a discrete deceleration (Garbutt et al. 2003a).

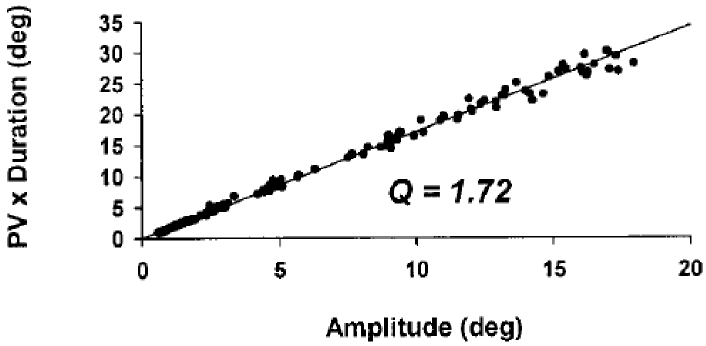


Figure 1.7. Typical saccadic main sequence for peak velocity x duration vs amplitude (Harwood et al. 1999).

Given these stereotypical relationships found in duration, peak velocity and peak velocity x duration with respect to saccadic amplitude in typical saccades, the main sequence has been described as a useful measure of saccadic performance and an invaluable tool to assess the "normalcy" of the saccades in an individual (Ramat et al. 2007).

Saccadic performance can also be measured in terms of accuracy. In general, when our eyes are directed to a new object of interest, these do not land exactly in the precise centre of that object (Leigh and Zee 1999). Hence, the eyes usually show some degree of saccadic inaccuracy (dysmetria) that includes mainly undershoots (hypometria) but also some overshoots (hypermetria) of the eye position with respect to the target position. The degree of dysmetria has been reported to be relatively small in normal conditions, approximately 10% of the saccadic amplitude for non-predictable visual targets (Becker and Fuchs 1969; Leigh and Zee 1999). For large saccadic amplitudes, it is normal to find a hypometria and a consequent corrective saccade to accurately reach the target. In contrast, for small saccadic amplitudes the accuracy is improved, resulting in accurate or slightly hypermetric saccades (Carpenter 1988; Kowler and Blaser 1995).

Finally, latency is another well-studied saccadic characteristic. The latency, also known as reaction time or saccadic initiation time, is the interval between the target presentation and the eye movement onset. The latency for typical saccades ranges from 150 to 250 msec, but this parameter has been suggested to be extremely variable (Gilchrist 2011). A typical adult generates saccades within 200 ms, but latencies can be sometimes as low as 100 ms or as high as 350 ms for the same condition (Gilchrist 2011). Moreover, they can also be increased by factors such the presentation of the saccadic stimuli in overlap with the initial stimuli, the predictability of the target motion, and also by less controllable factors including the motivation and attention of the individual (Leigh and Zee 1999). More recently, saccadic latencies have been considered to be a measure not only of oculomotor control but also of visual processing, decision-making and attention processes (Gilchrist 2011).

Saccadic neural pathway

Horizontal and vertical saccades are controlled by the horizontal gaze centre or paramedian pontine reticular formation (PPRF) and the vertical gaze centre, respectively (May and Corbett 1996). For simplicity, we will describe the pathway of a horizontal saccade in response to a stimulus in the left visual field.

The neurons in the frontal eye fields (FEF) and superior colliculus (SC) receive inputs from the retina containing the information about the amplitude and direction of the saccade required to match a stimulus (Gaymard and Pierrot-Deseilligny 1999). Once the direction and the amplitude of the desired saccade is determined in these supranuclear structures (FEF and SC), the axons of the same structures are projected to the PPRF (in the case of a vertical saccade, these axons are projected to the vertical gaze centre). The PPRF has a direct control of the abducens motor neurons and interneurons and transforms the signal received from the FEF and SC into motor commands. The abducens nucleus motor neurons project their axons in their ipsilateral nerve to the lateral rectus muscle. At the same time, the abducens nucleus interneurons project the axons in their contralateral medial longitudinal fasciculus to the motor neurons controlling the medial rectus (Byrne and Dafny 1997). Hence, different types of motor neurons contribute to generate the final saccade command (Keller 1974) by coordinating the control of the synergist and antagonist muscles. After this, the muscle contractions are maintained by the neural integrator to keep the eye at the required angle of gaze to continue fixating the target after the saccade (Leigh and Zee 1999).

This pathway is schematically represented in Figure 1.8. For more information about the cortical control of saccadic eye movements, which will not be discussed here, the reader is directed to the comprehensive text, The Neurology of Eye Movements (Leigh and Zee 1999).

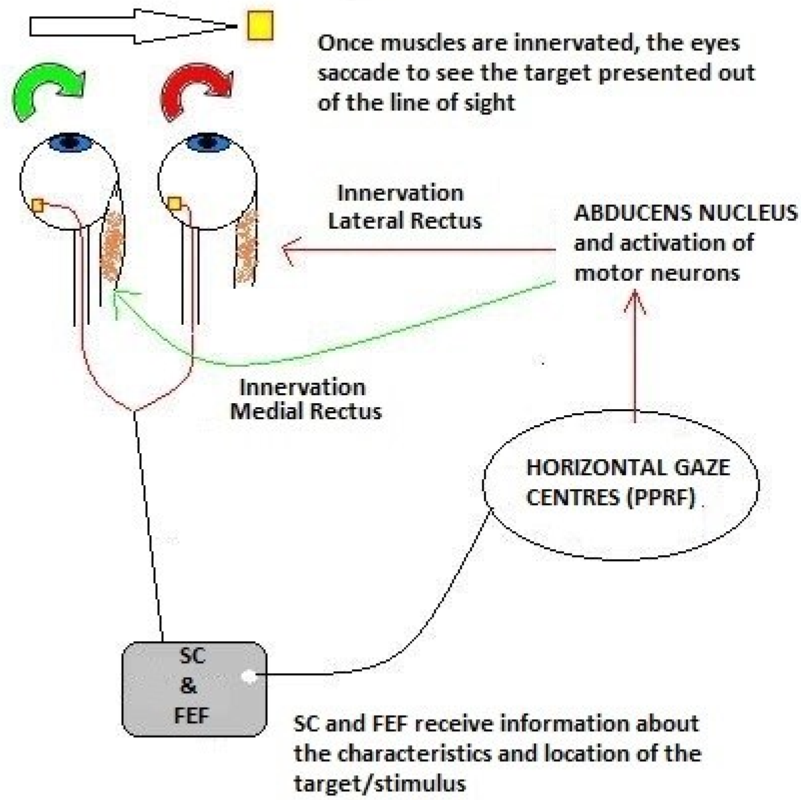


Figure 1.8. Diagram of the horizontal saccadic neural pathway.

Saccadic eye movement development

Saccades in infancy

An early study proposed that saccades in infants aged between 2 weeks and 5 months were accurate but slower than those found in adults (Hainline et al. 1984). Interestingly, the same study showed that slow saccadic velocities in infants were found when presenting a geometric-shaped stimulus while adult typical saccadic velocities were found in the same infants when presenting a texture-based stimulus (Hainline et al. 1984). These findings indicate that infants are able to produce adult-like saccades when presented with an appropriate stimulus. Nevertheless, these results should be approached cautiously because the authors used a very low frequency eye tracker (60Hz) and the eye tracker was not individually calibrated for each participant.

Since it has been shown that the main sequence of saccades and the quick phases of OKN are the same (Garbutt et al. 2001), this could be a better approach to examine saccadic velocity and main sequence in infants. This technique might reduce some attentional issues that can arise when presenting stimulus at different positions as it depends less on patient co-operation. In fact, a more recent study evaluating the saccadic main sequence using OKN did not find any evidence to support slow saccades in infants (Garbutt et al. 2006). In contrast, they found that infant OKN quick phases (saccades) tended to be faster than the quick phases (saccades) in adults. Although these findings do not directly support those obtained by Hainline et al. (1984), both results can be combined to suggest that saccadic eye movements in infants can be as fast as in adults with the appropriate stimulus and setup. In contrast, the saccades may be slower if the stimulus used does not fully engage the infant's attention or the saccadic task requires too much participant cooperation.

Other measurements such as saccadic latencies and amplitudes (gain and accuracy) can offer additional information about the maturation stage of the saccadic system. In the case of saccadic accuracy, it is well established that, to match the position of the target, infants do not produce a single and accurate saccade but a sequence of successive smaller saccades (Salapatek et al. 1980; Garbutt et al. 2006). Not surprisingly, the number of subsequent saccades to reach the target decreases with age resulting in increasingly accurate saccades (Salapatek et al. 1980).

Latency, which is the time between the stimulus presentation and the initiation of the saccade, has been reported to be longer in very young infants than in adults (Aslin and Salapatek 1975). Saccadic latencies lower than those found by Aslin and Salapatek (1975) but still higher than those found in adults are also found in older infants between 4 and 8 months (Gredebäck et al. 2006) supporting the existence of saccadic development that involves a reduction in latencies during the first months of life (Gredebäck et al. 2006).

There is only a limited literature evaluating how saccades develop in infancy. However, a review of the extant literature suggests that some saccadic characteristics can be adult-like in very young infants when using the appropriate stimulus and technique. For example, it can be argued that saccadic velocity and main sequence develop and reach values similar to adults early in life. In contrast, some characteristics, such as latency and accuracy, are not adult-like in very young and also older infants. Unlike the main sequence, these features improve in the first months of life but do not reach adult levels in infancy.

Table 1.3 presents a summary of the most relevant studies on the characteristics of saccades in infants.

Author and year	Participants	Stimulus characteristics	Saccadic parameters	Results
Aslin and Salapatek (1975)	-24 infants aged 1 month -24 infants aged 2 months	-Annular targets (26 mm) -Saccades of 10º, 20º, 30 and 40º to the left and to the right from the central fixation -Saccades of 10º and 20º upward and downward from the central fixation -Saccades of 10º, 20º and 30º diagonally from the central fixation target	-Latency -Amplitude -Direction of the first saccade (correct or not)	Latency decreases from 1 to 2 months of age. Saccades are not accurate. The number of the first saccades made to the correct direction after target presentation does not change between 1 and 2 month infants.
Salapatek et al. (1980)	-8 infants aged 2 months old	-Bright red orange targets (2º) -Saccades of 10º, 20º and 30º to the right of the central fixation -Continuous (target remained on) and interrupted (peripheral target extinguished after first saccade)	-Number of saccades to accurately match the target for both continuous and interrupted tests	The number of successive saccades to accurately match the target is the same between both conditions and depends on eccentricity.
Hainline et al. (1984)	-64 infants aged from 14 days to 151 days -11 adults *eye movement recordings from 39 infants were discarded	-Black and white geometric shapes (circle, square and triangles sizes ranging from 5º to 30º) -Textures consisting of black and white line/stripe patterns -Stimuli presented at the same time in different screen locations and saccades are assessed from infants freely scanning this stimulus	-Peak velocity vs amplitude main sequence	Peak velocity vs amplitude function parameters (slope and intercept) do not change with age. The stimulus had an effect on the peak velocity vs amplitude main sequence. Textures provide main sequence parameters similar to those from adults.
Garbutt et al. (2006)	-20 infants aged 2 to 18 months -7 adults	-Full field brightly coloured patterned curtain used as OKN stimulus -Relative speed of the curtain relative to the infant: 30º/s, 60º/s and 90º/s	-Main sequence duration vs amplitude main sequence -Peak velocity vs amplitude main sequence	Infants have almost significantly shorter saccadic durations (i.e faster saccades) than adults. No differences in peak velocity vs amplitude main sequence between infant and adults. Infants show hypometric saccades.

Table 1.3. Summary of studies investigating saccades in infants.

Saccades in preschool children and school children

There is not a large body of literature on saccadic eye movements in children aged from 1 to 3-4 years old (Fukushima et al. 2000; Yang et al. 2002). Most studies evaluating saccadic eye movements in children study children of 4 years and older (Cohen and Ross 1978; Ross et al. 1994; Salman et al. 2006b).

Despite the knowledge gap between 1 and 4 years old, the results found in the studies evaluating saccades in young (4-5 years) children are consistent with those found in infancy. Hence, findings from young children indicate that latency is still in development and is greater than in adults (Fukushima et al. 2000; Yang et al. 2002) and that saccadic velocities and gains are not significantly different between children and adults (Fukushima et al. 2000). Saccadic latency continue to decrease with age (Cohen and Ross 1978; Muñoz et al. 1998), and although there is some disagreement with regard to the age at which adult-like latency is reached, it can generally be suggested that this parameter reaches adult levels around the age of 10 years (Cohen and Ross 1978; Muñoz et al. 1998; Yang et al. 2002).

Overall, different properties of saccadic eye movements also seem to have different developmental stages. Thus, some saccadic parameters, such as saccadic main sequence (duration and peak velocity), reach adult levels earlier in life (Irving et al. 2006; Salaman et al. 2006b) while accuracy and latency reach maturation in early childhood and in pre-adolescence, respectively (e.g. Cohen and Ross 1978; Accardo et al. 1992; Fischer et al. 1997; Muñoz et al. 1998; Yang et al. 2002; Irving et al. 2006). However, according to the above mentioned studies, saccades reach adult levels much earlier than smooth pursuit eye movements.

Table 1.4 summarises the results of the most relevant studies on saccadic eye movements in children with details about the setup and procedures.

Author and year	Participants	Stimulus characteristics	Saccadic pursuit parameters	Results
Cohen and Ross (1978)	-15 children mean age 8.6 -17 adults	-Small red light -Saccades of 5º and 15º either size of the central fixation target. -The two lights appear simultaneously and one of them disappears leaving a single fixation target	-Latency	Latencies in children are significantly lower than those in adults.
Accardo et al. (1992)	-6 children aged 7 to 11years	-LED light -Stimuli randomly moving (random time and position) between +/- 25º (horizontal)	-Latency -Amplitude -Saccadic peak velocity -Duration -K ratio (mean to peak velocity ratio)	No differences in latency and absolute duration of the saccades between adults and children (aged 7-11). Peak velocities in children are higher than in adults while the K value is lower in children than adults. The results found suggest that there are differences in childrens' saccadic velocity profiles.
Fischer et al. (1997)	-281 participants aged 8 to 70 years	-White target (0.1º) on green Background -Saccades 4º to the right and to the left from central fixation	-Latency -CRT (corrective time for the second corrective saccade) -Saccades	Latency decreases with age until the age of 15-20 years for saccades. Similar results for CRT.
Muñoz et al. (1998)	-168 subjects aged 5 to 79	-RED LED lights -Saccades +/- 20º from the centre (horizontal)	-Latency -Amplitude -Peak Velocity	Latencies are higher in children aged <11 years compared to adults. Significant hypermetria in children aged 5-8 years. Children aged 5-8 years have higher latencies and increased intra-subject variability in most parameters.
Fukushima et al. (2000)	-99 children aged 4-13 years -22 adults	-LED lights -Saccades of 8º, 12º and 24º to the left and to the right from the centre. Stimulus position was random and displayed after 500ms from the previous	-Latency -Amplitude -Peak velocity	Latency decreased with age from 4 to 13 years. Children <12 years have latencies longer than adults. Latencies in children aged 12 and 13 are adult-like. No differences in saccadic peak velocity and amplitudes between adults and children.

Yang et al. (2002)	-15 children aged 4-12 years -15 adults	-LED -Saccades of 20º to the right and left from the centre (horizontal)	-Latency	Saccadic latency is longer in children than in adults. Latency decreases significantly with age reaching adult levels at the age of 10-12 years.
Irving et al. (2006)	-195 participants aged from 3 to 86 years	-White dot on black background -Saccades of amplitudes 1º to 60º (horizontal)	-Latency -Gains -Peak velocity	Children aged <5 have significantly longer latencies than any other age group except for the group >60. Latencies decrease with age and by the age 7 these seem to be very similar to adults. No differences in saccadic gains between children of different ages. Peak velocity increases with age from 5 to 15 years, then they stabilise until the age of 60.
Salman et al. (2006b)	-39 children aged 8 to 19 years	-White square (12 min of arc) -10º & 15º from centre (horizontal) -5º and 10º from centre (vertical)	-Latency -Gains -Peak velocity	No differences in saccadic gains and peak velocity across ages. Latency decreases with age. There is a vertical latency asymmetry. Gains and peak velocities are adult-like.
Iriving et al. (2011)	-53 participants aged 3 to 30 years	-Dots and pictures (0.5º to 1º) -Saccadic stimuli randomly presented from +/-30º in steps of 5º (horizontal)	-Latency -Peak Velocity -Gain -Response and error rate	Latency decreases with age and it is lower in children when using pictures compared to dots. Peak velocity does not change with age but higher peak velocities can be obtained in children if using pictures. Error rates are lower when using pictures.
Bucci and Sessau (2014)	-69 children aged 6-15 years	-Red filled circles (0.5º) -Saccades of 13.2º upwards and downwards from the centre (vertical)	-Latency -Gain -Peak velocity	Latency for upwards and downward saccades decreases with age. Gains do not change with age but upward saccades were more hypermetric than downward saccades.Slower peak velocities for upward saccades and no change with age.

Table 1.4. Summary of studies investigating saccades in children, pre-adolescents and adolescents.

1.2.3. Visual fixation

During visual fixation the image of a stationary object of interest is maintained on the fovea, and this requires attention as well as the inhibition of inappropriate eye movements such as saccades (Luna and Velanova et al. 2011). However, our eyes are never still and some eye movements that are imperceptible to the observer, such as drifts, tremors and microsaccades (Figure 1.9) occur during periods of normal fixation (Martinez-Conde et al. 2004).

Microsaccades are very small saccades of less than 1º of visual angle, drifts are smooth eye movements of slow velocity and tremors are rapid oscillations of the eyes smaller than microsaccades (Pelak 2010). For a comprehensive review on these eye movements occurring during fixation, which will be not discussed here, the reader is directed to the review by Martinez-Conde et al. (2004).

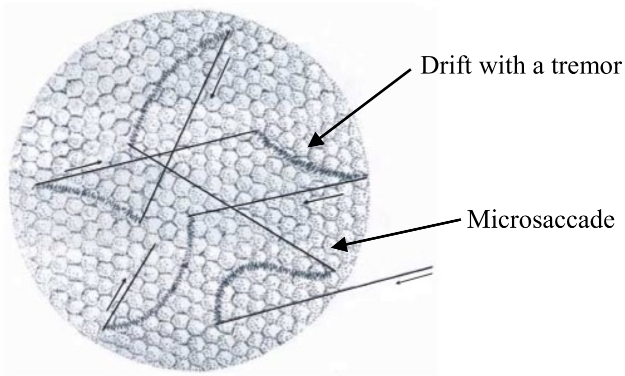


Figure 1.9. Physiological eye movements during visual fixation: drifts, tremors and microsaccades (Martinez-Conde et al. 2004; adapted from Pritchard 1962).

Fixation can be easily studied by asking the participant to "keep looking" at a static target presented for a period of time. Fixation stability is generally quantified by the scatter of eye position with respect to the mean eye position (standard deviation of the mean eye position) (Kosnik et al. 1986; Moller et al. 1996; Hamstra et al. 2001). However, there are other parameters such as the mean eye position (horizontal and vertical) also referred to by some authors as the centre of gravity of the eye position (Ygge et al. 2005). The number of saccadic events including saccades (>1º) and microsaccades (<1º) are also very useful measures to quantify the quality of the fixations.

Visual fixation neural pathway

Similar to the pathways described for smooth pursuit and saccadic eye movements, visual fixation is also achieved by controlling the motor neurons that innervate the extraocular muscles. Hence, after a phasic pulse of innervation that contracts the extraocular muscles to generate a saccade, the level of innervation in these muscles is maintained so the eye is kept in position so that the image of the object of interest is on the fovea (Leigh and Zee 1999).

The firing rates of the motor neurons are controlled by the brainstem circuit that receives the signals with regard to the object of interest and determine whether the eyes move or are held in place (Fuchs and Luschei 1970). When the eyes are stationary and fixating an object after a saccade or smooth pursuit, the firing rate of oculomotor neurons is proportional to the eccentricity of the eye position and the balance of the forces exerted by the different muscles at a given orientation (Squire et al. 2008) .

Visual fixation development

Despite the fact there are not many available studies assessing visual fixation in infants and children, visual fixation is evident early in life (Luna and Velanova 2011) and its control and stability improves with age during childhood (Luna et al. 2008; Luna and Velanova 2011).

It is generally accepted that, in typically developing children, the number of intrusive saccades (Ygge et al. 2005; Aring et al. 2007) as well as the number of saccades towards distractors (Paus et al. 1990) significantly decrease from 5 to 10-15 years of age. At the same time, the mean standard deviation of the mean eye position also decreases and stabilises with age (Ygge et al. 2005; Aring et al. 2007). Although none of these studies evaluating visual fixation in children had an adult sample for comparison, the results seem to indicate that most fixation parameters stabilise between the ages of 8-10 years. After the age of 10, no significant differences are found between children aged from 10 to 15 years (Ygge et al. 2005), and this suggests that adult values have been achieved by that age.

1.3. Eye movements and learning

An efficient and coordinated oculomotor control is vital in the classroom environment as it allows pupils to perform rapid, accurate saccades during reading and/or scanning the images in a text book and perform accurate smooth pursuit eye movements as the teacher progresses through a variety of teaching routines (Rouse 2006). Moreover, eye movements are also vital for recreational activities such as sports and social interactions, which can be suggested to also have a significant impact on children's development and learning.

1.3.1. Eye movements and reading

Saccades and fixations are very important components of reading as they provide the first step to extracting the visual information from the text. For that reason, there is an extensive literature assessing saccadic eye movements and fixations in individuals with reading difficulties (Lefton et al. 1979; Black et al. 1984b; Solan 1985a; Solan 1985b; Powers et al. 2008; Bucci et al. 2012). The following section summarises and discusses previous research on eye movements in individuals with reading difficulties, with emphasis on saccadic eye movements and fixations.

Saccades, fixations and reading difficulties

Typically, during reading, our eyes move along the lines of text by performing a series of saccades of different amplitude and directions, interspaced with fixations of variable duration (Figure 1.10). Generally, the saccades are forward saccades so the eyes move and fixate from one word to the next, but they occasionally move backwards (back-up saccades and regressions) to re-fixate a previous word.

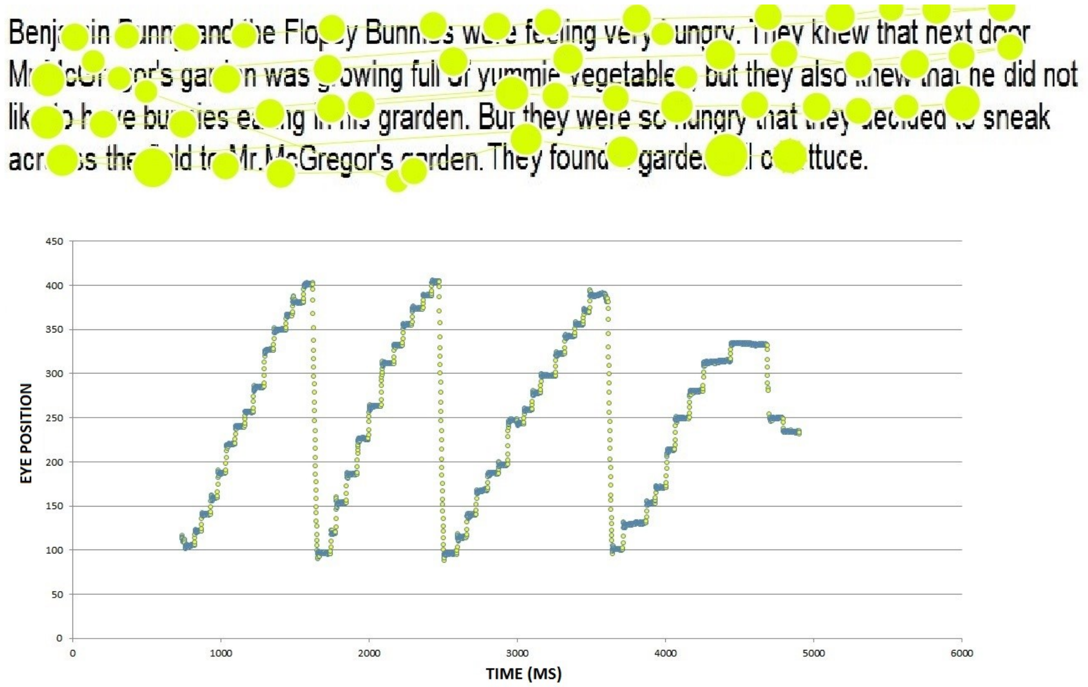


Figure 1.10. Typical pattern of saccades (lines in the top figure) and fixations (dots in the top figure) during reading.

It is accepted that eye movement behaviour during reading differs between good and poor readers. Several early studies found that, during reading, non-skilled readers show more fixations, longer fixation durations and more regressions (back to previous words) than skilled readers (Griffin et al. 1974; Lefton et al. 1979; Poynter et al. 1982; Solan 1985b). The increase in the number of fixations and regressions inevitably indicates an increased number of saccades. Lefton et al. (1979) further reported an increased variability in the number of saccades, number of fixations and the duration of the fixation within a group poor readers compared to good readers of the same age. Perhaps the most interesting finding was that, while good/average readers showed a very similar eye movement strategy for each line of text (similar number of saccades and fixations and duration of fixations), poor readers performed very differently in each line of text and paragraph. Consequently, poor readers showed a relatively unstructured and unorganised eye movement strategy during reading (Lefton et al. 1979).

Twenty-five years ago, the dominant view was that eye movements during reading were independent of the linguistic and lexical characteristics of the text (Rayner and Liversedge 2011). Therefore, eye movement disorders were often proposed to be the cause of delayed reading skills. Later research has changed this view, and it is now clear that parameters such as fixation time and the amplitude of saccades during reading are strongly influenced by the text characteristics (Rayner and Liversedge 2011) as well as the linguistic skills of the reader (Kuperman and Van Dyke 2011). Hence, it can be argued that the differences found in eye movements during reading in poor readers, can arise from the text linguistic, syntactic and lexical characteristics or even from text difficulty rather than from poor eye movement control or even from both. This argument might be key in a child population, as children, especially those learning to read, are less experienced with texts, are less familiar with the common words that adults tend to skip when reading, and have a less varied and elaborated vocabulary than adults.

Surprisingly, there are not many published studies evaluating saccades and fixations in individuals with delayed or poor reading skills during non-reading tasks. The early results from Pavlidis (1981) showing eye movement differences in children with dyslexia and controls in a sequential eye movement task (non-reading task) have been difficult to replicate. Thus, contrary findings have shown no differences in eye movements during non-reading tasks in individuals with dyslexia (Brown et al. 1983; Olson et al. 1983; Stanley et al. 1983) and poor readers (Black et al. 1984b) compared to age-matched controls.

Overall, the relationship between saccades, fixations and reading performance remains unclear (Poynter et al. 1982; Black et al. 1984a; Kiely et al. 2001). First, it has already been proposed that oculomotor ability is not the principal cause of reading difficulties, and the multifactorial nature of reading difficulties implies that saccadic control could be one, but not the only, factor hampering reading in a population of poor readers (Taylor 1965; Poynter et al. 1982; Kiely et al. 2001). Consistent with this, most studies assessing saccadic eye movements in poor readers have often not obtained any other optometric or vision measure other than the eye movement recordings. Visual aspects such as accommodation, refractive error and vergence may interfere with reading performance (Grisham et al. 2007). If these are not assessed, it cannot be determined if they are also contributing to the reading problem in an individual. Second, as most studies evaluating saccades and fixations in poor readers have focussed on assessing these type of eye movements during reading tasks, it is difficult to differentiate an atypical eye movement behaviour arising from oculomotor control difficulties from one arising from the inherent text characteristics. As described above, studies in which eye movements in poor readers were recorded in non-reading tasks have found conflicting results and conclusions cannot be drawn yet.

However, studies investigating the relationship between eye movements and reading/learning related difficulties should be carefully compared and interpreted, as the cause-and-effect relationship between these two might be better determined with a longitudinal study. In general, the studies investigating the association between eye movements and learning related difficulties (e.g. Poynter et al. 1982; Black et al. 1984a; Kiely et al. 2001) are cross sectional studies so that they can not provide a definite answer to this debate. In contrast, a longitudinal study may detect developments or changes in the characteristics of the target population (children with reading/learning related difficulties) over time so that sequences of events could be established to provide a clearer cause-and-effect relationship. Notwithstanding, cross-sectional studies are quicker and will provide evidence for whether or not there are links/associations between reading/learning related difficulties and eye movement deficits. Consequently, cross-sectional studies are the first step to inform longitudinal studies.

Smooth pursuits and reading difficulties

Smooth pursuit eye movements have not been widely investigated in individuals with delayed reading skills. A study qualitatively assessing smooth pursuit eye movements without an eye tracker found an association between “failing” the smooth pursuit test and obtaining low scores in other tests, including letter recognition and phonological awareness (Callue et al. 2005). These tests are related to certain reading abilities and are strongly associated with reading performance (Catts et al. 2000; Callu et al. 2005). Because smooth pursuit eye movements and reading abilities share some cognitive components and involve the activation of common brain areas (Callu et al. 2005), it can be suggested that these eye movements might also be relevant and important to assess in individuals with reading difficulties.

1.3.2. Eye movements and learning difficulties

In UK education services, the term "learning difficulty" refers to individuals with specific learning difficulties of different severities and origins (Holland 2011). This umbrella term includes a number of conditions such as dyslexia and dyscalculia that do not occur as a result of an intelligence impairment, and also other conditions including autism that involve a more general impairment (Holland 2011).

It has been suggested that eye movement difficulties might be frequently found in children with learning difficulties (Sherman 1973; Fukushima et al. 2005) as a result of a different developmental trajectory or brain dysfunction (Fukushima et al. 2005; Luna et al. 2008; Rommelse et al. 2008). In general, children with different learning difficulties show low smooth pursuit gains and longer latencies in antisaccades (saccades to the opposite direction to the target presented) than age-matched controls (Fukushima et al. 2005), but no significant differences in the dynamics of saccades (prosaccades). Therefore, the main deficit found in those with learning difficulties appears to be in voluntary (antisaccades and smooth pursuit) rather than in involuntary control of eye movements (saccades). Nevertheless, eye movement control in different learning difficulties should be studied separately to further understand the specific deficits in each population. To elaborate this point, the following paragraphs briefly present the eye movement characteristics observed in the most prevalent learning difficulties (Prior 1996). For a comprehensive review on eye movement deficits in these learning difficulties the reader is directed to the review by Rommelse et al. (2008).

Dyslexia

Dyslexia is described by the British Dyslexia Association as a "learning difficulty that primarily affects the skills involved in accurate and fluent reading and spelling" (Rose 2009). Although the terms reading difficulty and dyslexia are commonly used interchangeably (e.g. Black et al. 1984; Solan 1985a; Solan 1985b; Prior 1996), not all children with reading difficulties have dyslexia. In this thesis the term "reading difficulty" describes difficulties in reading that the school considers sufficient to need further support. Within the group there may have been children with difficulties in phonological and language skills such as in dyslexia and also non specific reading difficulties that might be due, for example, to low intelligence and lack of interest. We did not specify or measure the cause of the reading difficulty in our subjects.

A question of intense debate in recent decades, the answer to which still remains unclear, is whether there are any eye movement differences between children with dyslexia and typical developing children of the same age. A large number of studies have suggested that saccades and fixations during reading in children with dyslexia differ from those in typical children (Pavlidis 1981; Rayner 1985). However, this is still unproven as studies evaluating eye movement during non-reading tasks have not found any differences in saccadic performance between children with and without dyslexia (Brown et al. 1983; Olson et al. 1983; Stanley et al. 1983). Despite the fact that individuals with dyslexia might have different eye movements to typical age-matched controls, these are more likely to be the a result of poor decoding abilities (e.g. Eden et al. 1994; Hutzler et al. 2006; Prado et al. 2007; Bucci et al. 2012) or the comorbidity of other learning difficulties (Callu et al. 2005) that are likely to impact on oculomotor control. Overall, it would appear that poor eye movement control is probably not the cause of dyslexia but may be one of several symptoms of the condition (Eden et al. 1994).

Attention deficit/hyperactivity disorder (ADHD)

ADHD is a neurobehavioural disorder characterised by inattention, hyperactivity and impulsivity (American Psychiatric Association 2013). These features are associated with dysfunctions of the frontostrial circuitry (Tannock 1998; Castellanos 2001).

Eye movement studies have been extensively used to characterise the inhibition and impulsivity disorders found in individuals with ADHD. While it is not clear whether there is a smooth pursuit deficit in individuals with ADHD, it is quite well established that there is a deficit in saccadic control in this population (Rommelse et al. 2008). In general, children with ADHD exhibit longer saccadic latencies and an increased number of errors in antisaccades (saccades opposite to the target presentation) when compared to age-matched controls (Muñoz et al. 2003; Muñoz and Everling 2004; O'Driscoll et al. 2005; Mahone et al. 2009). However, ADHD is frequently presented along with other learning difficulties (Rommelse et al. 2008) and therefore the eye movement deficits could occur as a result of these comorbid difficulties.

Autism

Autism is a neurodevelopmental disorder characterised by difficulties in social interactions and communication (Takarae et al. 2004). These difficulties arise from maturation abnormalities in several areas of the brain (Casanova et al. 2002; Cody et al. 2002).

Most studies investigating eye movements in autism have focussed on eye movement patterns when exposed to social scenes (Klin et al. 2002; Riby and Hancock 2008) and face images (Pelphrey et al. 2002; Rutherford and Towns 2008; Wilson et al. 2012) rather than on "pure" oculomotor control tasks. With the exception of one study that found slower saccades in children with autism (Goldberg et al. 2002), saccadic dynamics in this population have repeatedly been shown to be as fast and as accurate as those in typical controls (van der Geest et al. 2001; Luna et al. 2007).

In contrast, smooth pursuit in children with autism has been shown to be impaired with lower gains and inaccurate catch-up saccades (Scharre and Creedon 1992; Takarae et al. 2004). These results have been shown to be highly correlated with poor motor and coordination abilities. Consequently, the smooth pursuit deficits in autism are likely to be a manifestation of a more general sensorial and motor deficit rather than an isolated oculomotor deficit.

While a great deal of research has been conducted on eye movements and dyslexia (Pavlidis 1981; Rayner 1985; Biscaldi et al. 1994; Prado et al. 2007; Bucci et al. 2012), there is a growing body of literature that characterises eye movement control in other common specific learning difficulties (Fukushima et al. 2005; Ingster-Moati et al. 2009; Oh et al. 2013). Moreover, there is also a growing interest in further investigating eye movement characteristics in children with non-specific learning difficulties (Scheiman and Rouse 2006), which are currently undetected, undiagnosed and consequently unsupported.

1.4. The clinical examination of eye movements

The clinical examination of eye movements is important to detect anomalies that could cause difficulties or impair vision in both adults and children. Moreover, the previous section has shown that eye movements can be different in children with learning difficulties as compared to typical developing children. This further supports the importance of examining eye movements in atypical children and children with apparent difficulties in eye care practice. The following section introduces the tests and procedures used to examine eye movements in clinical practice.

1.4.1. Simple observational tests

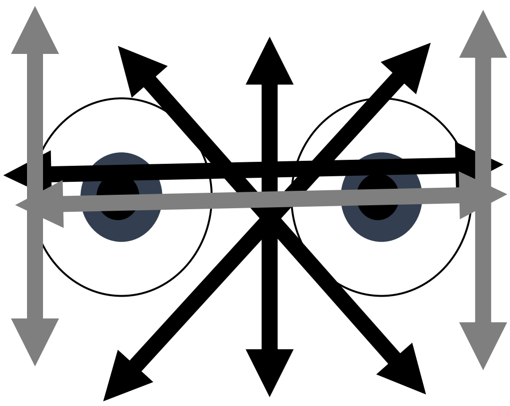
Smooth pursuit

For the clinical examination of smooth pursuits, Leigh and Zee (1999) suggest holding a pencil at 1 metre from the patient's eyes and ask the patient to track the pencil tip that should be moved slowly back and forth at a uniform speed. The examiner should assess smooth pursuit eye movements in horizontal, vertical and diagonal directions (Figure 1.11a), and look for corrective saccades that will indicate inappropriate gains. For instance, catch-up saccades indicate low gains and back-up saccades indicate high gains.

Another subjective technique to examine smooth pursuit in clinical practice is called the "diagnostic H" (Scott 1995). This procedure allows the practitioner to evaluate horizontal and vertical eye movements, as well as extraocular muscle functions. To perform the procedure, a pen torch is held about 50-60 cm away and moved following an "H" shape pattern (Figure 1.11a). The examiner can evaluate horizontal and vertical smooth pursuit eye movements during the target motion. To evaluate the muscle actions and functions, the examiner should monitor the corneal reflex from the pen torch during the whole test, and particularly in the extreme "H" positions. If the corneal reflex is not centred in the patient's pupils in the extreme positions, the eye with the off-centred reflex may have a paretic or paralysed muscle (Scott et al. 1995).

The examination of reflexive slow phases in the OKN drum (Figure 1.11b) may also be useful to examine smooth pursuit in young individuals (young children or infants) or individuals in whom cooperation is reduced (Wong 2008).

a)



b)

Figure 1.11. Examination of smooth pursuit eye movements in optometric practice using a moving target across different meridians (a black lines) and moving a pen torch following a "H" shape (a grey lines); and an OKN drum (b (Brandt et al. 2005)).

Saccadic eye movements

Leigh and Zee (1999) suggest that the best approach to examining saccades is to use two targets and instruct the patient to alternate their fixation on the targets. Saccades can be examined in both, horizontal and vertical directions. Leigh and Zee (1999) also propose a protocol for saccadic examination in which the examiner should observe spontaneous saccades, saccades responding to visual or auditory targets and also saccades to command. During this test, the examiner should make judgements about latency, velocity, trajectory, accuracy and conjugacy of the saccades performed based on simple observation. When there is a suspected saccadic deficit, the examiner should further assess the saccadic system and try to localise the basis of the abnormality. To do this, involuntary quick phases should first be evaluated using an OKN drum (Figure 1.11b), followed by visually guided saccades and finally voluntary saccades (Leigh and Zee 1999). The saccadic task affected indicates the type of saccadic deficit. For example, acquired ocular motor apraxia is characterised by a loss of visually-guided saccades (reflexives) or difficulties in voluntary saccadic tasks, but normal function of the OKN quick phases (saccades) (Wong 2008).

Visual fixation

Fixation tests are aimed at examining the ability of the patient to maintain steady fixation on an object (Scheiman and Rouse 2006). The targets commonly used for this in adults are geometric shapes and lights (Kosnik et al. 1986; Moller et al. 2006; Subramanian et al. 2013). In children, targets such as patterns, pictures and changing stimuli are recommended (Paus et al. 1990). The examiner should observe the binocular fixation of a patient for a period of 10 seconds (Scheiman and Wick 2008b). All patients except very young, inattentive, hyperactive or anxious patients should be able to maintain stable fixation with no observable movement of the eyes for this period of time (Scheiman and Wick 2008b). During this test, the examiner should make judgements on how stable the eyes are and look for the presence of intrusive saccades.

1.4.2. <u>Observational tests with standardised rating systems</u>

The Southern California College of Optometry (SCCO) oculomotor test

The SCCO test offers two quick and simple routines for testing saccades and smooth pursuit. The saccadic routine proposes the evaluation of these eye movements only in the horizontal meridian. The targets to be used should have a letter printed on them whose size corresponds to a visual acuity of approximately 6/24. The targets are situated approximately 40 cm away from the patient's eyes, separated approximately 20 cm from each other and placed equidistantly to the patient's left and right. The test is performed in monocular and binocular conditions. The examiner instructs the patient to move his/her eyes from one target to another 10 times while keeping the head steady (Barber 1995; Griffin and Grisham 2002a). During the test, the clinicians should look for inaccuracies in the eye movements. The test score is mainly based on the accuracy (undershooting) of saccades. The ratings are made from 1+ to 4+, as follows: 4+ if saccades are accurate, 3+ if there is some undershooting in the saccades, 2+ if there is significant saccadic undershooting, 1+ if the patient cannot perform the task or if latency is abnormally increased (Griffin and Grisham 2002a). 2+ is the cutoff for failing or passing the test. Any head movements that cannot be controlled by the patient are also a recorded as a test failure, because the patients are asked to keep their heads steady during the task. Griffin and Grisham (2002a) cited an early study (Hoffman and Rouse 1980) that proposed that failure in this test may indicate a saccadic dysfunction and a need for referral.

The SCCO approach for testing smooth pursuit eye movements follows the same rating scale and target characteristics. The protocol involves placing the target 40 cm away from the patient's eyes and moving it left-right-left, up-down-up and following the same pattern in the two diagonal orientations with the head steady. The target should be moved a total of 20 cm in a smooth manner (20 cm in 2 seconds) from the patient's mid line or the primary gaze (Scheiman and Rouse 2006). A score of 4+ is given if smooth pursuit eye movements and fixations are accurate during the whole test, 3+ if the smooth pursuit is accurate but one fixation loss is observed, 2+ when there are two fixation losses, and 1+ if there are more than two fixation losses. The failure cutoff is again 2+ and the presence of head movement is also considered as failing the test. Smooth pursuit is recommended to be examined in monocular and binocular conditions.

Overall, the SCCO presents a very limited qualitative approach to testing saccades and smooth pursuit. The ratings are only made from a few observations of the eye movements and concentrate on saccadic undershooting and smooth pursuit accuracy. Moreover, due to the development of eye movements, children of different ages may perform differently. Hence, younger children may present more difficulties in the smooth pursuit task, not only because of oculomotor deficits, but simply due to normal age developmental differences.

The Northeastern State University College of Optometry (NSUCO) oculomotor test.

The NSUCO test was developed in 1990, but it was not until 1992 that the same authors introduced the NSUCO oculomotor norms and the NSUCO complete battery of tests. The NSCUO oculomotor test assesses both saccades and smooth pursuit in terms of ability, accuracy, head movement and body movement (Scott et al. 1995; Scheiman and Wick 2008b). The test gives complete directions on the administration and procedure of the test, including a description of the target to be used and a standardised scoring system and normative data by ages (Maples and Flicklin 1990). Basically, the patient stands in front of the examiner and is presented with one moving target for testing smooth pursuit or two stationary targets for testing saccades. The targets consist of coloured, reflective "hat pins inserted into small dowel sticks", but for children, the use of Disney character targets on pencils are recommended (Maples and Ficklin 1988; Maples and Flicklin 1990). Both tests are only done binocularly, and no instructions are given about whether the head needs to remain still during the test.

Saccades are only performed in the horizontal meridian, and the targets should be placed no more than 40 cm away from the patient's face and no more than 10 cm either side of the patient's midline (20 cm in total). The patient has to look at each target and change from one to the other on command (Scheiman and Wick 2008b). For smooth pursuit, a rotational motion is performed in both clockwise and anticlockwise directions, and the path should not be more than 20 cm in diameter (Maples and Flicklin 1990). The examiner instructs the patient to keep looking at the target as it moves.

The examiner has to evaluate, by direct observation, the eye movement performance in both tasks, but following the scoring criteria showed in Table 1.5 and 1.6. The results can be compared with the normative age values provided (Maples and Flicklin 1990).

NSUCO SCORING CRITERIA (SACCADES)	
Ability Points	Observation
1	Completes less than two round trips
2	Completes two round trips
3	Completes three round trips
4	Completes fours round trips
5	Completes five round trips
Accuracy Points	(Can the patient accurately and consistently fixate so that no noticeable correction is needed?)
1	Large over or undershooting is noted 1 or more times
2	Moderate over or undershooting noted one or more times
3	Constant slight over or undershooting noted (>50% of the time)
4	Intermittent slight over or undershooting noted (<50% of the time)
5	No over or undershooting
Head and body movements	(Can the patient accomplish the saccade without moving his or her head?)
1	Large movements of the head or body at any time
2	Moderate movement of the head or body at any time
3	Slight movement of the head or body (>50% of time)
4	Slight movement of the head or body (<50% of time)
5	No movement of head or body

Table 1.5. NSUCO scoring criteria for the examination of saccades (Scheiman and Wick 2008b).

NSUCO SCORING CRITERIA (SMOOTH PURSUITS)	
Ability Points	Observation
1	Cannot complete half rotation in either clockwise or counter clockwise direction
2	Completes half rotation in either direction
3	Completes one rotation in either direction but not two rotations
4	Completes two rotations in one direction but less than two rotations in the other direction
5	Completes two rotations in each direction
Accuracy Points	(Can the patient accurately and consistently fixate so that no noticeable refixation in needed when doing pursuits?)
1	No attempt to follow the target or requires greater than 10 refixations
2	Refixations five to ten times
3	Refixations three to four times
4	Refixations teo times or less
5	No refixations
Head and body movements	(Can the patient accomplish the pursuit without moving his or her head?)
1	Large movements of the head or body at nay time
2	Moderate movement of the head or body at any time
3	Slight movement of the head or body (>50% of time)
4	Slight movements of the head or body (<50% of time)
5	No movement of the head or body

Table 1.6. NSUCO scoring criteria for the examination of smooth pursuits eye movements (Scheiman and Wick 2008b).

A group of studies performed by the authors, in which they demonstrated the potential of the test to detect eye movement differences between above and below average child readers, further supported the usefulness of the test (Maples and Flicklin 1990). Although recognising that more evidence is needed to accurately establish the relationship between failing this test and reading performance, the NSUCO authors suggest that poor readers are twice as likely to have below average scores for their age in most of the NSUCO skills graded (Maples and Flicklin 1990). In addition, the same test has been reported to have high inter-rater and test-retest reliability (Maples and Ficklin 1988).

The standardised procedures and scoring, the existence of normative values for different ages and the acceptable inter and intra-rater reliability propose the NSCUO as a consistent, reliable and accurate approach to examine eye movements in clinical practice.

1.4.3. <u>Visual-verbal tests</u>

Visual-verbal tests provide an objective and quantitative examination of eye movements during a simulated reading task that involves reading a series of numbers (Richman et al. 1983). Saccades, which are the only type of eye movement that can be examined with these tests, are assessed indirectly in terms of the speed at which numbers can be seen, recognised and verbalised accurately (Scheiman and Wick 2008b).

The Pierce Saccadic test and the New York State Optometric Association King-Devick (NYSOA K-D) test

The Pierce Saccadic test (Figure 1.12) is the original visual-verbal test designed to examine saccadic function (Rouse 2006). It consists of three parts, each part using a card that displays two separate rows of printed numbers. The patient is instructed to hold the card at their normal reading distance in a well-illuminated environment and read the numbers aloud as fast as possible (Scheiman and Wick 2008b). The cards gradually increase in difficulty from the first to the forth one by reducing the vertical space between the numbers. However, the saccades evaluated in this test do not represent well those performed during reading conditions, as during reading, we perform horizontal saccades of different amplitudes that involve a more precise word to word eye movement (Oride et al. 1986; Scheiman and Wick 2008b).

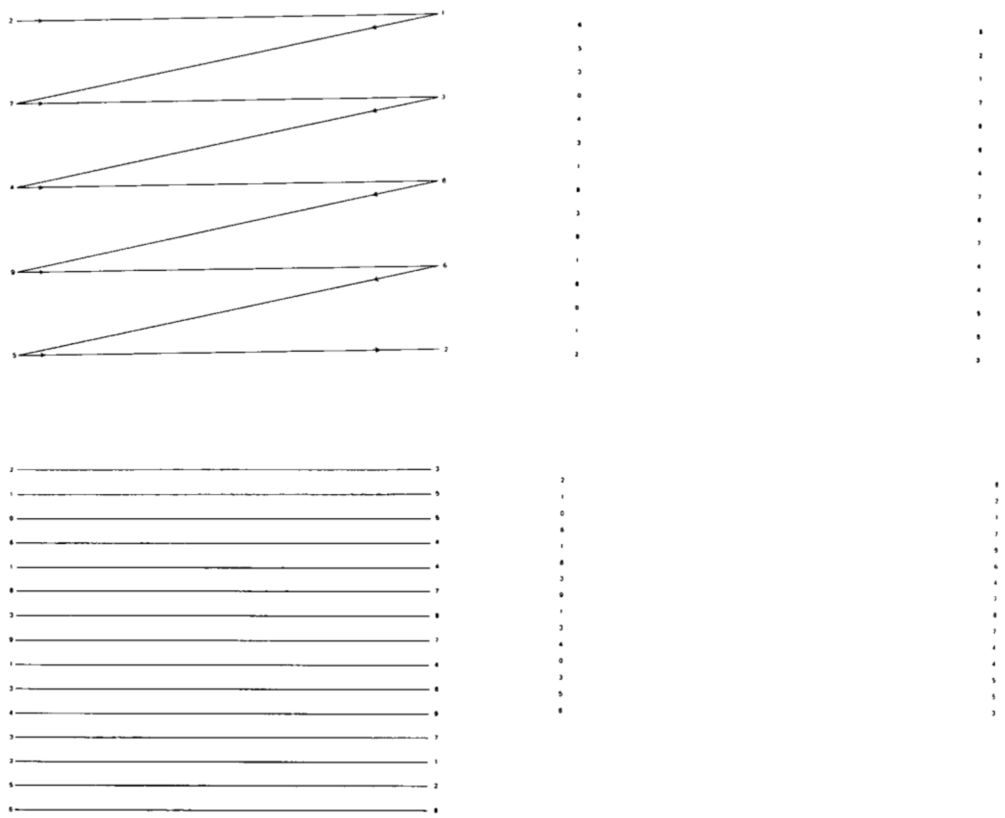


Figure 1.12. The Pierce saccadic test (Oride et al. 1986).

To address the limitations found in the Pierce Saccadic test, the NYSOA K-D test (Figure 1.13) was developed at the Illinois College of Optometry in 1976 (Barber 1995). The modifications were aimed to better represent the characteristics of the saccades produced during reading, and therefore assess for precise horizontal saccades of different amplitudes (Lieberman et al. 1983). The NYSOA K-D test consists of a demonstration card and three other cards with increasing difficulty (Figure 1.13). Each card (except the demonstration card) consists of 8 rows with numbers with a Snellen equivalent of 20/100 at 40 cm. Card I consists of randomly horizontal spaced numbers connected by horizontal lines, while cards II and III do not have connecting horizontal lines. Finally, card III has a reduced vertical separation between the columns of numbers in addition to a random horizontal separation between numbers in each line. Again, the instructions given are to call out the numbers as fast as possible, and the examiner records the time and errors made (Lieberman et al. 1983). Because the horizontal spacing between numbers is random in cards II and III, this test has been suggested to be more appropriate for examining reading eye movements (Lieberman et al. 1983).

Normative values for different age groups were also produced by the authors using a sample size of 137 subjects. These norms were further corroborated by an independent study using a larger sample of children (n=1202) aged from 6 to 14 years of age (Lieberman et al. 1983).

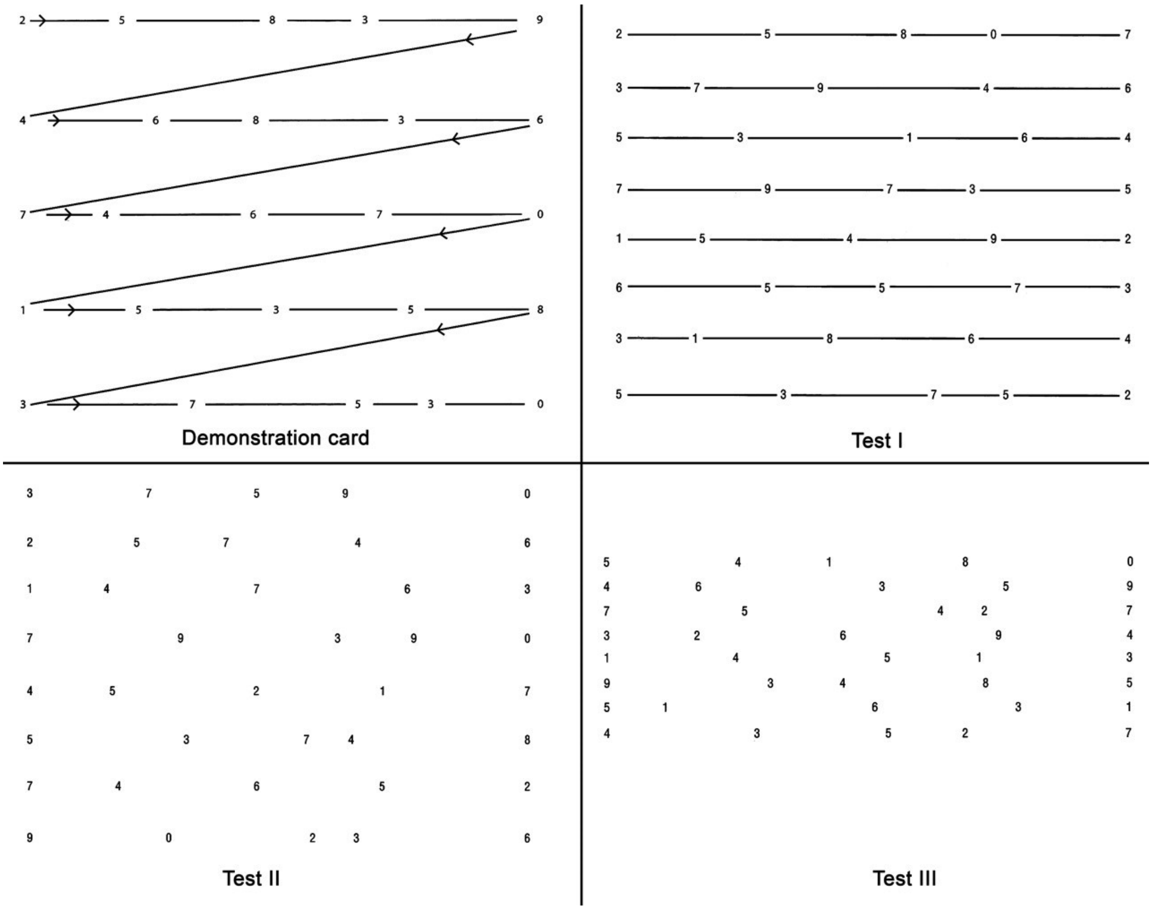


Figure 1.13. The NYSOA K-D test.

Initially, the NYSOA K-D test produced advantageous returns, however after these initial successes, a number of disadvantages become apparent. Several studies have questioned its use because clear improvements in time (reduced time) and errors (fewer errors) have repeatedly been found on retest (Oride et al. 1986; Kulp and Schmidt 1997). In addition, the relationship between the test results and real reading performance has been questioned (Cohen et al. 1983; Oride et al. 1986; Kulp and Schmidt 1997). Consequently, a differential diagnosis cannot be made with this test between children with number recognition, verbal integration or numeracy difficulties and children with saccadic difficulties.

The Developmental Eye Movement test (DEM)

The aim of the the Developmental Eye Movement test (DEM) (Figure 1.14), which was introduced in 1987 (Richman and Grazia 1987), was to solve the problem found with the NYSOA K-D test by differentiating saccadic deficits from a poorly-developed automaticity in number naming (Richman et al. 1983).

The test consists of two sections: horizontal and vertical. The vertical subset, which is performed first, contains two tests with 40 (80 in total) numbers arranged vertically (Figure 1.14a). The horizontal section also has 80 numbers horizontally arranged in a random spatial array (Figure 1.14b). Corrections of misnamed numbers are allowed when they are made in 12 seconds or less, and the examiner should explain that to the child (Scheiman and Wick 2008b). Similar to NYSOA K-D and Pierce Saccadic tests, the child is instructed to read the numbers aloud as quickly as possible, trying to keep the head steady and without finger pointing. The practitioner records the time and errors during the test (Richman and Grazia 1987). At the end, the total time is transformed to the adjusted time by taking into account the number of addition (added numbers) and omission (skipped numbers) errors (Richman and Grazia 1987). Finally, ratios are calculated by dividing the horizontal time by the vertical time (Richman and Grazia 1987; Garzia et al. 1990). Ratios are the measure that allows the practitioner to differentiate between automaticity of naming the numbers and saccadic dysfunction (Richman et al. 1983). High ratios with high horizontal time but normal vertical time point to difficulties in the horizontal subtest and consequently suggest a horizontal saccadic deficiency (Richman and Grazia 1987). However, if both times (the horizontal adjusted and the vertical) are increased it can be concluded that there is a problem in the automaticity of naming numbers (Richman and Grazia 1987). The test provides tables with normative values for children aged 6-13 years of age. The ratios and times of any child examined can be then compared with the normative values to decide if there is a saccadic deficit or not (Richman and Grazia 1987; Garzia et al. 1990).

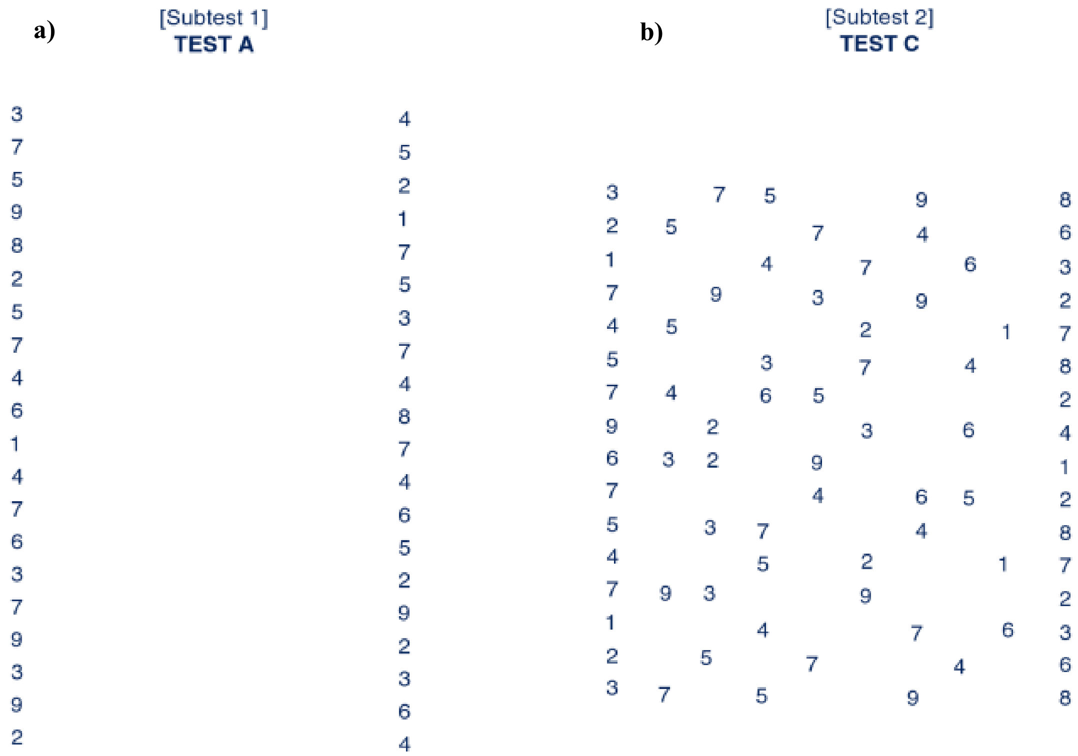


Figure 1.14. The Developmental Eye Movement test (DEM) (Taub et al. 2012).

Of particular concern is again the issue of the test-retest variability and the possible learning effect found in the DEM test. The designers of the test suggested that DEM test has good intra-subject test-retest reliability (Garzia et al. 1990). However, not all values obtained from the DEM have been found to be consistently repeatable, and the final ratio, calculated to make the eye movement diagnosis, has been shown to be the least repeatable value (Rouse et al. 2004; Tassinari and DeLand 2005). These findings are of significant relevance as the ratio scores might have a direct impact on the clinician's decision, diagnostic and possible management.

Finally, the validity of the DEM test for effectively identifying saccadic difficulties has recently been questioned (Ayton et al. 2009; Medland et al. 2010, Webber et al. 2011). First, the DEM scores and ratios seem to be poorly correlated with saccadic measurements obtained from eye movement recordings (Ayton et al. 2009). Further, British, Arabic and Indian individuals (adults and children) have also been assessed with the DEM test in both directions, from right to left and from left to right (Medland et al. 2010). Interestingly, Arabic and Indian individuals who were habitual left to right readers (reading English texts) but also often read right to left (reading their own language texts) were found to be good at DEM in both directions. In contrast, British individuals (habitual left to right readers only) appeared to have reduced DEM scores when performing the test from right to left. The authors concluded that poor readers may have low DEM scores because they have not yet trained their eye movements to read. Thus, they suggested that young children who have not yet learnt to read fluently are likely to have low DEM scores, which are not the result of an eye movement dysfunction or deficit (Medland et al. 2010).

Overall, these studies propose that the DEM test does not test saccadic eye movements when reading, but do suggest that the DEM test results may be related to visual processing and verbalization skills. Thus, despite the test being useful for distinguishing children at risk of reading problems or academic delays, the evidence suggests that DEM is probably not appropriate for assessing saccadic function.

This section has given an overview of the different procedures and tests currently available to Eye Care Professionals to assess eye movements in clinical practice. First, the procedures widely used by practitioners described in section 1.4.1 are based on gross observations of the eye movements. These procedures make it almost impossible to diagnose eye movement difficulties but some developed quantitative and standardised methods provide an improved and more reliable approach for the examination of eye movements in clinical practice. However, it is important to point out that standardised procedures and grading schemes for saccadic and smooth pursuit eye movements described in section 1.4.2 are only commonly used in the USA, but have not been widely adopted in the UK and mainland Europe. Finally, the visual-verbal tests designed to assess saccadic eye movements during reading (section 1.4.3) are not entirely robust, and practitioners have questioned their utility.

1.5. Eye movement recording methods

Eye movement recording systems are the only tools that allow us to objectively and quantitatively assess eye movements. The first eye movement recordings dated from the 18th century, but it was not until the 19th century that the first quantitative eye movement measures were obtained (Eggert 2007).

Besides the steady subsequent improvement reached in terms of spatial and temporal resolution and accuracy, the most relevant advance is perhaps the recent achievement of highly accurate non-invasive techniques. The first eye movement recording attempts were highly invasive and required the attachment of objects to the eyeball in order to track its movements (Karatekin 2007). These early antecedents resulted in the four most common eye trackers types used today: the scleral search coil, electro-oculography (EOG) and photo-oculography (Eggert 2007). These devices are briefly described in the next sections.

1.5.1. Scleral Search Coil

The scleral search coil is a method for recording eye movements that measures the voltages in one or two coils induced by a magnetic field (Robinson 1963) (Figure 1.15). The coils are embedded in soft contact lenses that are fitted on the eye (Figure 1.15b). The magnetic fields are then generated by three pairs of large coils mounted in a cubic frame in which the subject's head is placed at the centre (Robinson 1963) (Figure 1.15a). The search coil spatial resolution is 0.01º, and the temporal resolution is 1000Hz (Hertle and Dell'Osso 2013). Thus, it has been described as the most reliable and versatile eye movement recording method (Robinson 1963), capable of measuring eye movements around the three axes (Leigh and Zee 1999). For these reasons, the search coil is considered the gold standard in eye movement recordings (Traisk et al. 2005; Houben et al. 2006). However, the introduction a contact lens containing a search coil on the participant eye and the use of local anaesthetic make this method the least comfortable and tolerable for patients (Leigh and Zee 1999). Moreover, the search coil is unsuitable for recording periods longer than 30 minutes (van der Geest and Frens 2002), and for obvious reasons it is also unsuitable for children.

a) b)

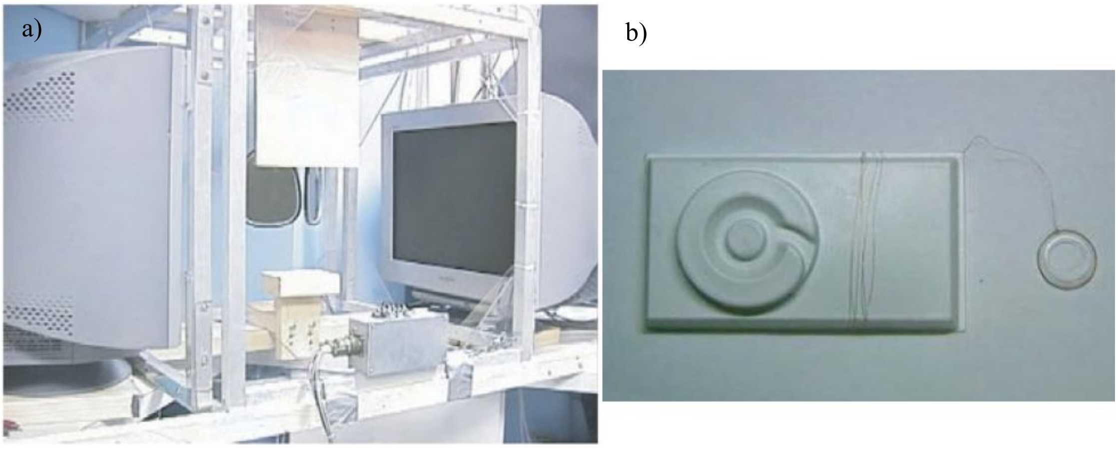


Figure 1.15. Search coil magnetic system set up for an experiment with dichoptic stimuli (screen mirrors and monitors) (a). An electric magnetic field will be generated around the head of the participant and an alternating voltage will be induced in the scleral contact lens with the embedded coil (b) (Hertle and Dell'Osso 2013).

Some pilot studies have compared results obtained with the search coil, EOG (Lappe-Osthege et al. 2010) and photo-oculography (van der Geest and Frens 2002; Houben et al. 2006). The findings suggest that some eye movement measures are dependent on the recording method (e.g. saccadic duration) whereas others are not (e.g. peak velocity) (Houben et al. 2006; Lappe-Osthege et al. 2010). These results corroborate the view that the search coil is the best approach to precisely and accurately evaluate three-dimensional eye movements, but that less invasive EOG and photo-oculography methods are an excellent alternative that offer a compromise between accuracy, precision and patient comfort.

1.5.2. Electrooculography (EOG)

Electroculography (EOG) is based in the principle that the human eye is an electrical dipole (Duchowski 2007) and uses a series of external electrodes attached to the skin around the eye to measure changes in the potential (voltage) when the eyes rotate. Thus, a rightward eye movement will produce an increased potential on the temporal side of the right eye and on the nasal side of the left eye. The EOG is still widely used, but some limitations have been described, such as reduced temporal and spatial resolution (Hertle and Dell'Osso 2013) or difficulties during vertical eye movement recordings (Leigh and Zee 1999; Eggert 2007). More importantly, changes in potential (voltage) can arise from photoreceptor activity (e.g. during changes in luminance in the retina) resulting in inaccurate measurements of the eye position (Carpenter 1988; Berg and Scherg 1991).

1.5.3. Photo-oculography

Photo-oculography is based on tracking the position of eye markers in a 2-D image (Hertle and Dell'Osso 2013). It comprises a wide variety of techniques that measure different visible features of the eye under rotation/translation. For example, the apparent shape of the pupil, the position of the limbus, the Purkinje images and the pupil margin (Duchowski 2007).

These eye movement systems come as head-mounted or remote (Hölmqvist et al. 2011). Head-mounted includes those that have the eye movement recording system together with a camera, mounted on a type of helmet or head band, so that eye movements can be easily distinguishable from head movements (Hertle and Dell'Osso 2013). The Skalar IRIS (Figure 1.16) is an example of this type of photo-oculography system. The IRIS uses infrared light and its nasal and temporal detectors detect changes in the amount of the infrared light reflected from the limbus, which produces a variable voltage that is used to establish the eye position of each eye (Russo 1975). This system has a spatial resolution of 0.05º and a guaranteed sampling frequency of 250Hz with no dropped frames (Cambridge Research Systems 2015).

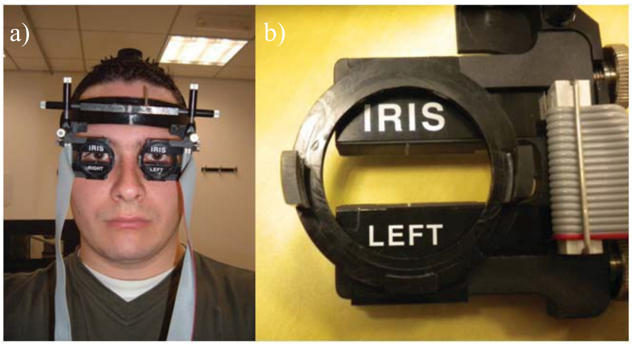


Figure 1.16. Skalar IRIS headset. a) Head band and oculars. b) Right close up of the left eye ocular. Figure reproduced from Jones (2011) with consent.

Remote eye movement recording systems use the same eye-fixed markers (limbus, pupil margin, Purkinje image) to calculate head position as well as eye position (Hertle and Dell'Osso 2013). This is generally achieved by obtaining 3 dimensional angular eye positions from the image coordinates of the eye markers (Howard and Evans 1963). Two examples of remote infrared photo-oculography systems are the EyeLink 1000 and Tobii TX300. The EyeLink 1000 has a monocular and a binocular sampling rate of 1000Hz and 500Hz, respectively, and a spatial resolution of 0.1º (SR Research 2015). The Tobii TX300 (Figure 1.17) records eye movements binocularly at a sampling rate of 300Hz and a spatial resolution of 0.5º (Tobii Technology 2015a) . Both remote eye movement recording systems calculate the position of the eyes from the combined reflection of the infrared light from the pupil margin and from the Purkinje images.

Figure 1.17. Tobii TX300 eye tracker unit (Tobii Technology 2015a).

1.6. Summary and thesis structure

This first chapter has introduced the background and literature relevant to this research. This included the development of eye movements from infancy to adulthood, the possible associations between eye movements and learning difficulties, and the conventional methods to assess eye movements in clinical settings. Finally, the chapter presented the latest technologies currently available to measure eye movements objectively.

Chapter 2 presents the results from a scoping exercise performed to obtain a better understanding of the research field, incuding the gaps and the potential issues that this study should address. Based on these findings and the literature, the objectives and aims of this research are presented at the end of chapter 2.

Chapter 3 presents the pilot studies undertaken to develop the methods used in the main studies of this thesis. The findings from the pilot studies are discussed to justify the experimental setup and procedures chosen to conduct the research. Then, chapter 4 presents a complete description of the methods and includes the details of the optometric test and eye movement recording procedures performed in later chapters.

Chapters 5 and 6 present the findings from the main studies. Chapter 5 provides normative eye movement values (smooth pursuit, saccades and visual fixation) for primary school age children, while chapter 6 compares the eye movement results from children with delayed reading skills to the normative values presented in chapter 5. Finally, chapter 7 presents the findings from a group of children who have been referred with suspected eye movement difficulties.

The final chapter summarises the results of all the studies undertaken in this thesis, considering the main limitations and discussing the implications of the findings for further research.

Chapter 2 Scoping exercise: what are eye movement/ "tracking" difficulties?

2.1. Introduction

Children are increasingly being referred mainly by Educational Professionals (e.g. Educational Psychologists) to Eye Care Professionals (e.g. Optometrists and Orthoptists) with suspected eye movement difficulties, on the grounds of "tracking difficulties", skipping words, and losing the place when reading (Scheiman and Wick 2008a; Barrett 2009). Given the current clinical techniques to examine eye movements, which range from gross observation, through standardised observational procedures/ratings (e.g. NSUCO) to indirect visual-verbal tests (e.g. DEM test) (see chapter 1, section 1.4), it is reasonable to suggest that Eye Care Professionals face challenges in their decision-making, diagnosis and management when it comes to these referrals.

For example, this problem is frequently encountered in the Special Assessment Clinic at Cardiff University, and personal communications with other Eye Care Professionals further support the view that this is a larger scale problem. Consequently, the research group considered that the best starting point of this research should be to discuss the characteristics, diagnosis, and management of eye movement difficulties with both Eye Care and Educational Professionals.

2.2. Aims

- Ascertain current opinion with regard to eye movements and "tracking" difficulties in children amongst Eye Care and Educational Professionals

- Discuss with Eye Care and Educational Professionals their methods for examining, diagnosing and managing eye movement difficulties

2.3. Methods

2.3.1. Participants

Structured interviews (face-to-face) were held with 11 professionals involved in children's eye care (n=7), children's educational care (n=3) and children's health care (n=1) (Table 2.1). The only Health Care Professional who took part in this scoping exercise was an Occupational Therapist. For simplicity and convenience, the results from this Health Care Professional were grouped with those from the Educational Professionals (Table 2.1). The professionals interviewed worked in the Bristol, Glamorgan, and Gloucestershire areas. The areas were chosen for their easy accessibility and transport facilities from the main research location.

Number of participants	Profession
4 Educational Professionals	2 Teachers of the Visually Impaired (VI)
	1 Educational Psychologist
	1 Occupational Therapist
7 Eye Care Professionals	4 Orthoptists
	3 Optometrists

Table 2.1. Number and professional details of the participants.

Each participant was contacted individually by the researcher (e-mail or phone) and was invited to take part in the scoping exercise. No previous information about the nature of the questions was provided, but the participants were told that the research project aimed to investigate eye movement difficulties in children. Once the participants agreed to take part, an appointment for the interview was made at their convenience. In all cases except one, the participants were visited in their usual place of work (hospital, school or university). Only one participant preferred to come to the School of Optometry and Vision Sciences, Cardiff University to meet the researcher for the interview.

2.3.2. The Interview

The interviews were performed face-to-face and the same structure was adopted in respect of the questions and their order for each participant. The open-ended questions were previously designed to focus on the participant's thoughts, experiences and views of the following areas (see Appendix A for a copy of the interview sheets):

- Characteristics of eye movement/"tracking" difficulties and their association with learning related problems

- Eye movement difficulties referrals

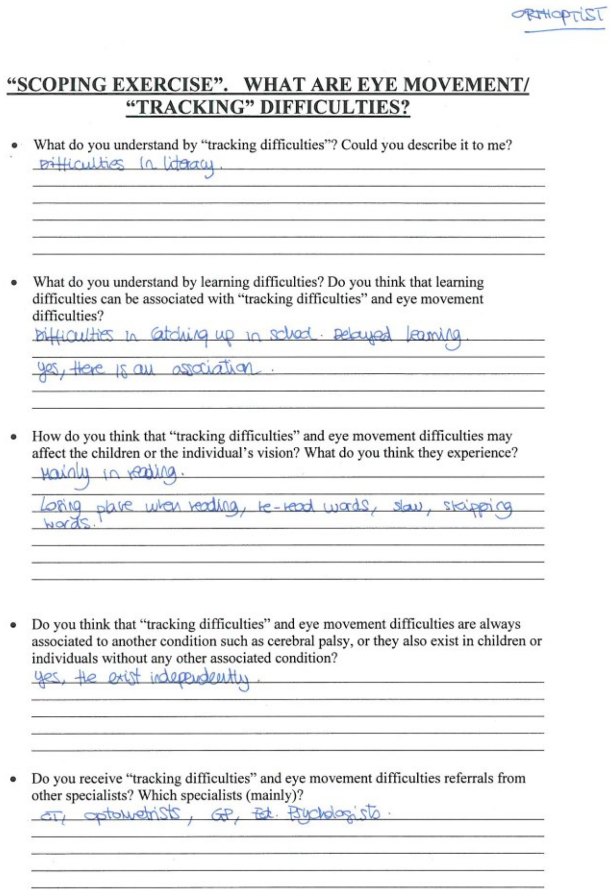
- Eye movement examination

- Management and treatment of eye movement/"tracking" difficulties

2.3.3. Qualitative analysis of the participant's responses

During the interview, the researcher took detailed notes of the answers given in an interview sheet (Figure 2.1). No names or contact details were kept on the interview sheet, only the profession of the participant was written at the top of that sheet (Figure 2.1).

After each interview, the researcher reviewed the notes made and created a report summarising and listing the statements and major issues found in the answers. Finally, a content analysis was performed by counting the frequency of different statements and identifying the major issues raised that were common amongst the participants.


ORTHOPTIST

"SCOPING EXERCISE". WHAT ARE EYE MOVEMENT/ "TRACKING" DIFFICULTIES?

- What do you understand by "tracking difficulties"? Could you describe it to me?
  Difficulties in literacy.
- What do you understand by learning difficulties? Do you think that learning difficulties can be associated with "tracking difficulties" and eye movement difficulties?
  Difficulties in catching up in school. Delayed learning.
  Yes, there is an association.
- How do you think that "tracking difficulties" and eye movement difficulties may affect the children or the individual's vision? What do you think they experience?
  Mainly in reading.
  Losing place when reading, re-read words, slow, skipping words.
- Do you think that "tracking difficulties" and eye movement difficulties are always associated to another condition such as cerebral palsy, or they also exist in children or individuals without any other associated condition?
  Yes, the exist independently.
- Do you receive "tracking difficulties" and eye movement difficulties referrals from other specialists? Which specialists (mainly)?
  OT, optometrists, GP, Ed. Psychologists.

Figure 2.1. Interview sheet with the notes taken for one of the participants.

2.4. Results

2.4.1. <u>Eye movement/"tracking" difficulties: characteristics, signs and symptoms</u>

Of the 11 professionals interviewed, 4 described the term "tracking difficulties" as reading and literacy difficulties, 5 as experiencing difficulties in following moving objects, and 2 as poor oculomotor control (Figure 2.2). Figure 2.3 expands on the answer to this question and shows the responses given by the two groups of professionals separately. The most interesting finding is that more than half (4 out of 7) of the Eye Care Professionals interviewed described "tracking" difficulties as difficulties in "following moving objects", while only 1 Educational Professional (out of 4) shared this view. Half of the Educational professionals (2 out of 4) described "tracking" difficulties as "reading and literacy" difficulties.

When the participants were asked about the association between eye movement/ “tracking” difficulties and learning difficulties, most stated that they understood there to be a link between learning difficulties and eye movement/“tracking” difficulties. Despite agreeing with this general statement, 2 participants also mentioned that learning difficulties are not always associated with eye movement problems and that these are more associated with intellectual and processing difficulties. However, both expressed the belief that eye movements can have a role in learning difficulties because they add an extra barrier to the learning process.

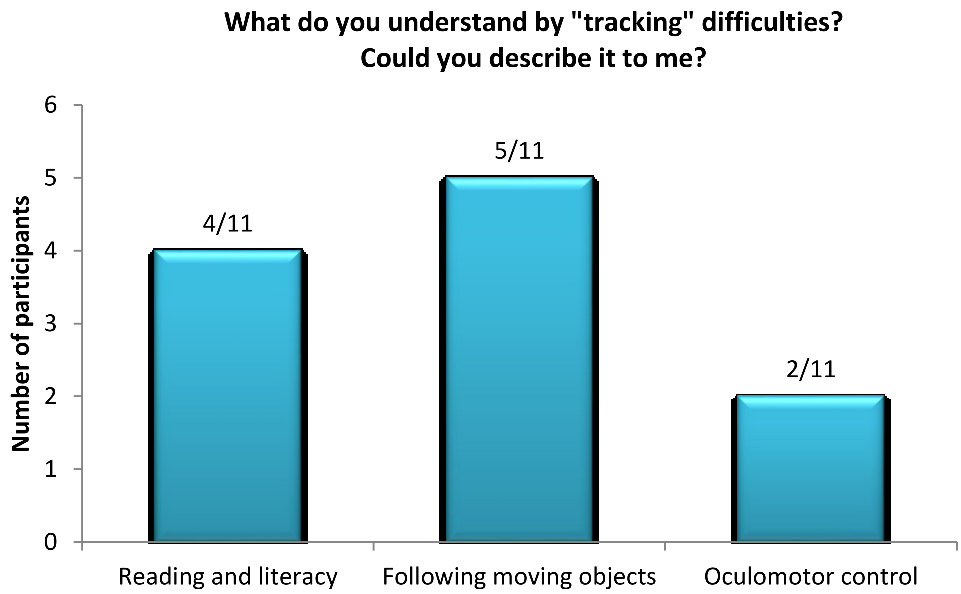


Figure 2.2. Bar chart showing the response of the participants to the question "What do you understand by "tracking” difficulties?

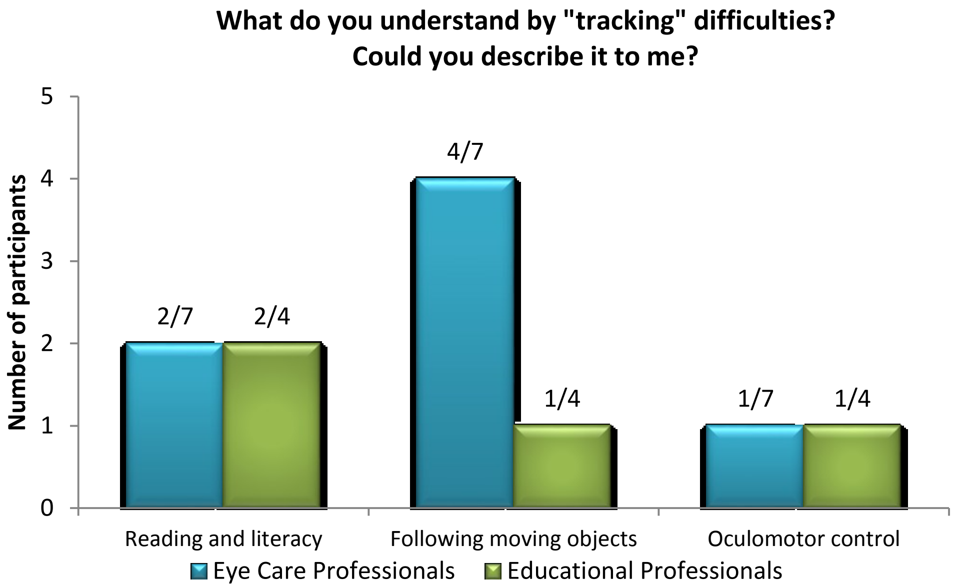


Figure 2.3. Bar chart showing the response of the participants (by profession) to the question "What do you understand by "tracking" difficulties?

In terms of the association between eye movement/"tracking" difficulties and other conditions such as cerebral palsy, schizophrenia or autism, 9 participants stated that eye movements/"tracking" difficulties can be found isolated from any other condition. However, 5 of these 9 professionals mentioned that eye movement and "tracking" difficulties are more common in children with underlying conditions. One of the 11 participants pointed out that she has never come across an isolated eye movement difficulty, but suggested that they may exist. One participant completely disagreed with the general view, stating that eye movement and "tracking" difficulties can only be found in children with underlying conditions.

When asked to report on the signs and symptoms of children with eye movement/ "tracking" difficulties, the participants responded with a large variety of signs and symptoms. As a consequence, we classified the signs and symptoms into two main groups: (a) reading problems, and (b) outdoors and/or general daily activity problems. The results are illustrated in Figure 2.4 and show that 3 out of 11 professionals stated that eye movement /"tracking" difficulties affect only reading abilities. In general, the signs and symptoms described included poor and slow reading, missing words in a sentence and losing the page when reading. Only 1 participant stated that children with eye movement /"tracking" difficulties have problems in outdoor and general daily life activities. For instance, the participant reported that these children may have difficulties in following moving objects, finding items in clustered environments, and locating people in crowded places. Six out of 11 (54.54%) participants (3 Eye Care Professionals (42.85%) and 3 Educational Professionals (75%)) stated that children with eye movement and "tracking" difficulties show signs and symptoms of both, reading problems and outdoors and/or general daily activity problems. These six professionals stated that these result in reading and learning difficulties in addition to more general difficulties such as poor sport performance, poor gross motor skills and poor coordination. One of the eleven participants did not know and preferred not to answer the question.

Overall, these findings suggest that most professionals, independently of their profession, believe that children with eye movement and "tracking" difficulties have reading problems but also more general and less specific difficulties in daily life activities.

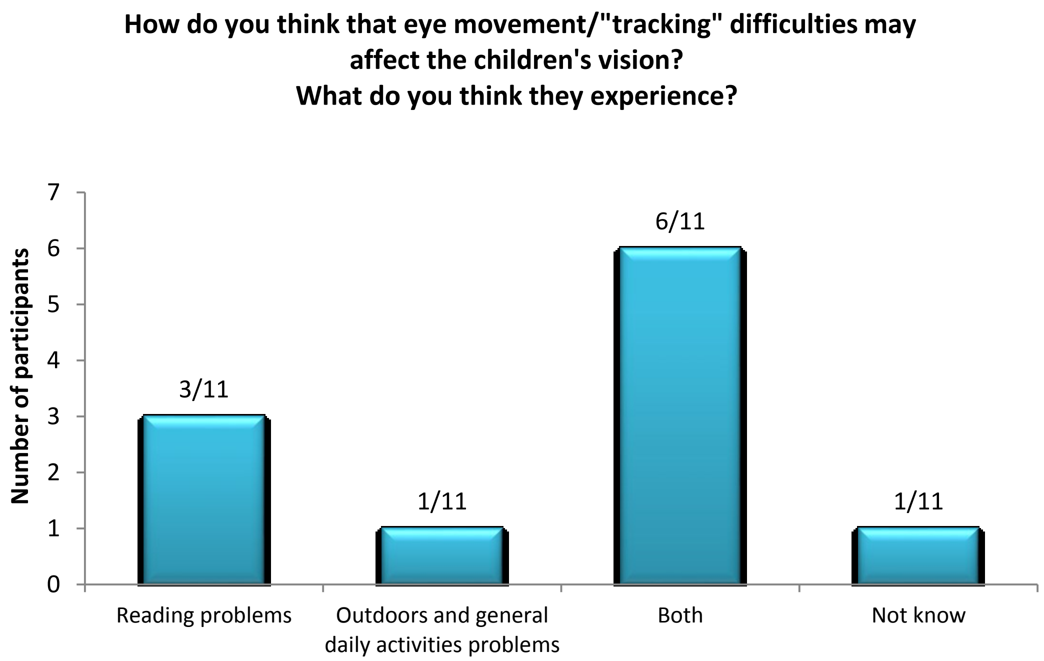


Figure 2.4. Bar chart showing the response of the participants to the question "How do you think that eye movement/"tracking" difficulties may affect the children's vision? What do you think they experience?

2.4.2. Eye movement/"tracking" difficulties referrals

Not surprisingly, most Educational Professionals stated that they mainly receive referrals related to eye movement and "tracking" difficulties from other Educational Professionals and from schools. Only the two Teachers of the Visually Impaired (VI) confirmed that they sometimes get referrals from Eye Care Professionals. However, they pointed out that those particular referrals are usually because these children have other visually impairing conditions (e.g. nystagmus).

Figure 2.5 shows the answers of the Eye Care Professionals (Optometrists and Orthoptists separately) to the question about the eye movement difficulties referrals. The figure shows that Eye Care Professionals participants (n=7) mainly receive referrals related to eye movement difficulties from Educational Professionals but some of them state that they also get referrals from Eye Care and Health Care Professionals (e.g. GPs). Interestingly, Orthoptists are the only Eye Care Professionals that seem to get referrals regarding eye movement difficulties from Educational as well as Eye or Health Care Professionals (mainly GPs). In contrast, all the Optometrists that participated reported that they most commonly get these referrals from Educational Professionals.

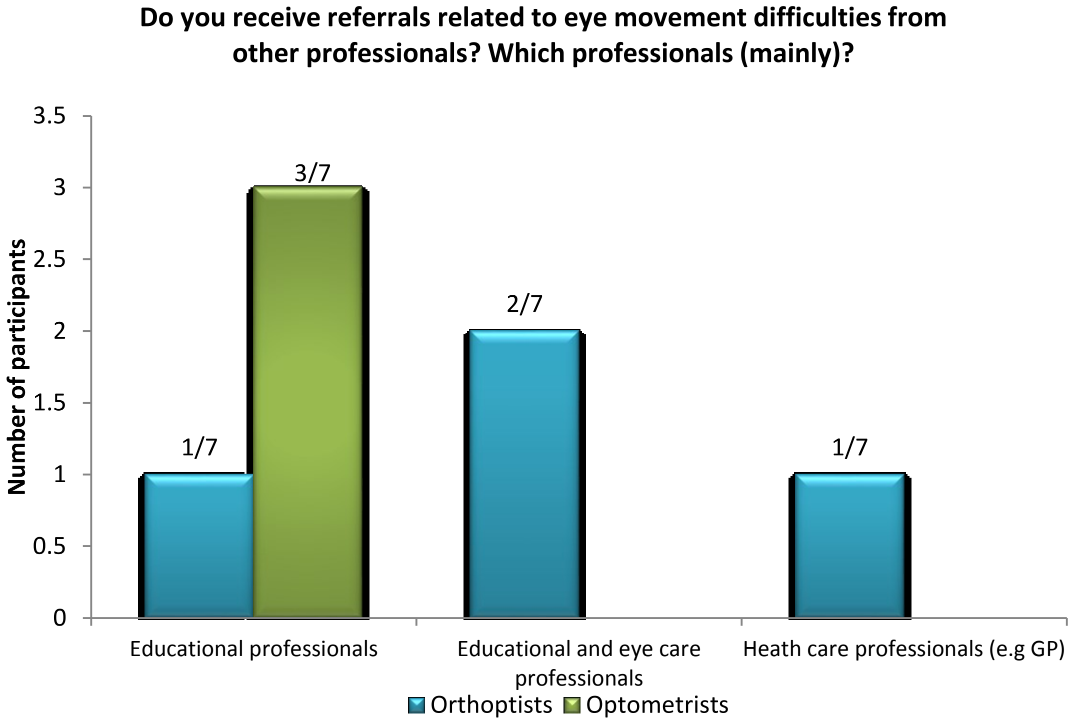


Figure 2.5. Bar chart showing the response of the participants (Eye Care Professionals only) to the question "Do you receive referrals related to eye movement difficulties from other professionals? Which professionals (mainly)?

2.4.3. <u>Eye movement examination</u>

Eye movement examination by Eye Care Professionals

Seven of the 11 participants were Eye Care Professionals (3 Optometrists and 4 Orthoptists) and all of the questions related to the assessment of eye movements were put to them. They were asked if they examine eye movements routinely in all patients, and in response, 3 Orthoptists (3 our of 4) stated that they examine smooth pursuit and saccadic eye movements in all patients. Two participants (1 Optometrist and 1 Orthoptist) stated that they examine smooth pursuit in all patients and saccades only in patients referred with reading problems, suspected saccadic problems and patients that have been diagnosed with a condition that may affect the saccadic function (e.g. stroke). Finally, two Eye Care Professionals, both of whom were Optometrists, responded that they do not examine eye movements routinely but that they do examine smooth pursuit in most children and in adults with signs and symptoms related to muscle restrictions and/or extra oculomotor palsies. The same two participants further stated that they never assess saccadic eye movements. When the participants were asked about visual fixation, the majority commented that they do not specifically test it, however they indirectly assess fixation stability when performing a cover test.

Smooth pursuit examination

With regard to smooth pursuit examination, quite different methods and procedures were found amongst the 7 Eye Care Professionals. The responses given were as follows:

- 3 out of 7 examine smooth pursuit in all meridians (horizontal, vertical and obliques).
- 2 out of 7 examine smooth pursuit in the horizontal and vertical meridians.
- 1 out of 7 examines all meridians looking for muscle restrictions and then only checks for smooth pursuit in the horizontal meridian at two different speeds (first slow and then fast).
- 1 out of 7 examines horizontal, vertical and oblique smooth pursuits. For the horizontal meridian, the movement is very slow and the patient's head is held still.

For the examination of smooth pursuit, most Eye Care Professionals use a pen torch, but some use a pen or a pencil and ask the patient to look at the tip. In addition, most of them stated that, when assessing smooth pursuit in children, they substitute the pen torch or the pencil with a toy or a coloured light.

Saccades examination

Interestingly, four different methods to examine saccades were used by the 5 practitioners, who stated that they test saccadic eye movements either routinely (n=3) or only when clinically relevant (n=2). The answers provided are as follows:

- 2 pens separated 30-40 cm in horizontal and vertical meridian.
- Pen-nose only in horizontal.
- 2 pens in horizontal with 2 different amplitudes (short distance between pens and longer distance between pens).
- 2 pens with 2 amplitudes in horizontal and vertical.

With regard to the target, all the Eye Care Professionals used two pens.

Eye movement examination by Educational Professionals

Of the 4 Educational Professionals participating, only 1 of them examines eye movements. However, this is not performed in all children but only in those with poor coordination, learning problems, or with suspected eye movement problems. This Educational Professional tests smooth pursuit for the horizontal and vertical meridians, followed by fixation stability and convergence using a pen or a toy. In some situations, this Educational Professional tests for OKN and vestibular ocular reflex (VOR). OKN is tested by presenting the OKN drum, and when testing for VOR, a unique technique is used in which children are placed on a platform that hangs from the ceiling and they are asked to perform different tasks while spinning or moving on the platform.

2.4.4. <u>Management and treatment of eye movement/"tracking" difficulties</u>

Three of the participants (1 Occupational Therapist and 2 Orthoptists) offer exercises or "visual therapy" to improve eye movements in children whose results are abnormal. The exercises they mentioned included word searches, follow paths, circle letters in a text, etc. One of these professionals gives the children reading exercises and occasionally these are combined with full body movement and coordination exercises.

Six participants do not offer exercises when results are abnormal (3 Optometrists, 2 Orthoptists, and 1 Educational Psychologist), but they generally refer to other professionals for an evaluation of treatment and/or management. Finally, the two Teachers of the VI do not provide exercises or treatment but they do provide help and assistance for children with eye movement problems so they can compensate for their visual deficits and maximise their visual abilities.

2.5. Discussion

This scoping exercise is important to the research as the results provide a better understanding of the field, the gaps and key issues which this research should address.

The results confirm that most referrals related to eye movement difficulties received by Eye Care Professionals (Optometrists and Orthoptists) are made by Educational Professionals. However, the same results show that eye movement and "tracking" difficulties have very different meanings to Eye Care and Educational Professionals. Moreover, within each of these professional groups, there are still different views with regard to the definition of eye movement/"tracking" difficulties, as well as their signs, symptoms and impact. The participants (independently of their profession) only clearly agreed on the idea that there is a link between eye movements and learning difficulties.

The findings on the questions related to the eye movement examination in clinical practice show a crucial lack of agreement within even this small sample of Eye Care Professionals. Although the basic testing approach is maintained, the procedures used substantially differ between practitioners. The current scoping exercise also shows that smooth pursuit is more routinely assessed in eye care practice, compared to saccades which are only assessed if it is considered clinically relevant by the practitioner.

Most of the participants taking part in this scoping exercise do not provide treatments to children with eye movement difficulties. However, they tend to refer these children to other professionals to be considered for treatment/appropriate management. Although the results of this scoping exercise are insufficient to define the management trends in children with eye movement difficulties, our results agree with views described in a review by Barrett (2009) that suggest that most treatments/therapies made available to these children are, in general, not evidence-based, standardised or commercialised.

These interesting and previously unreported results encourage the view that there is a significant miscommunication and misunderstanding between groups of professionals (Eye Care Professionals and Educational Professionals) involved in the health care of children with learning related difficulties. Furthermore, because Eye Care Professionals examine eye movements in some but not all children with learning related difficulties and use often quite subjective different procedures for this examination, there is evidence to suggest that this misunderstanding and miscommunication also exists within Eye Care Professionals (e.g. Optometrists and Orthoptists).

Finally, with this misunderstanding and miscommunication, there is a risk that some children with specific, functionally important eye movement disorders are unrecognised, undiagnosed and consequently unsupported. Similarly, children whose eye movements are within the normal range for their age, may be misdiagnosed with eye movement difficulties, when in fact their deficits are not primarily caused by their oculomotor system but by other visual or non-visual factors.

2.6. Aims and objectives of the current thesis

Based on the conclusions reached in the literature review (chapter 1) and scoping exercise (chapter 2), the principal aim of this thesis is to examine eye movements in children with learning related difficulties, whom Educational Professionals and some Optometrists frequently consider at risk of eye movement difficulties.

As current eye movement examination approaches are highly subjective, poorly controlled and relatively imprecise, the use of an eye tracker in this study provides the opportunity to quantitatively establish eye movement normative values for typical developing school age children. Although there are extant studies that have investigated eye movements in typical children using eye trackers, it can be argued that these studies do not result in an optimal measure of eye movement characteristics in this population, as a significant number of the studies failed to adjust their setup and procedures to the child population (see chapter 1, Tables 1.2 and 1.4). For that reason, we produce in this thesis normative eye movement values for children using a child-friendly setup.

Some studies have provided evidence suggesting that eye movements are different between typical children and children with learning difficulties (e.g. Biscaldi et al. 1994; Fukushima et al. 2005; Prado et al. 2007; Oh et al. 2013). However, these studies have mainly investigated eye movements during reading related tasks. These studies fail to identify whether the differences found in eye movements between these groups of children during reading are a result of eye movement difficulties or other visual or non-visual factors, including processing, language, or decoding difficulties. Thus, by comparing the eye movement results obtained from typically developing school age children, children with reading related difficulties, and children referred with suspected eye movement difficulties during non-reading related tasks with our child-friendly setup, the expected outcome of this study is to better understand the prevalence of genuine eye movement difficulties, and to the extent to which they exist. Moreover, the study expects to achieve a better understanding of the exact nature of eye movement performance in atypical children and children with apparent learning related difficulties in terms of their quantitative dynamic characteristics.

Finally, collating all of the results from each of the studies completed as part of this PhD, the researcher aims to produce actionable insight in the form of simple guidelines to improve the examination of eye movements in clinical practice. These guidelines will be designed to support the efficiency with which Optometrists recognise genuine eye movement disorders in children, and thus ensure that these children are diagnosed and receive the support they need in good time.

Chapter 3 Development of a child-friendly setup for eye movement research

3.1. Introduction

The type of stimulus and its features have an impact on eye movement performance in children and infants (Rustche et al. 2006; Irving et al. 2011; Pieh et al. 2012). As shown in the summary tables presented in chapter 1 (Tables 1.2 and 1.4) small dots, squares or LED lights on a white/black background have been the visual stimuli used for most eye movement research in children. Recent evidence (Irving et ak. 2011) has increased the need for more appropriate stimuli to investigate oculomotor control in children as this population is strongly affected by the nature of the stimulus, and improvements can be found in eye movement performance if a cartoon or a picture is used.

A similar issue exists with the motion of the target for smooth pursuit, as there is also no established standard paradigm for use with children. Therefore, the findings from different studies evaluating smooth pursuit in infants and children cannot be extrapolated to a full characterization of smooth pursuit development, as different setups, stimuli, velocities, and/or motion types have been used to investigate this (see chapter 1, Tables 1.1 and 1.2).

This chapter describes the setup and stimuli designed to investigate eye movements in typically developing school age children (chapter 5), children with reading related difficulties (chapter 6), and children referred with suspected eye movement difficulties (chapter 7). This chapter also includes three pilot studies carried out to evaluate the effects of stimulus type, size and motion paradigm on smooth pursuit performance. Finally, collating the results from each of the pilot studies (stimulus type, stimulus size and stimulus motion paradigm), the optimal configuration of the stimulus to be used in the following studies is determined.

3.2. Specific aims

- Design a child-friendly setup and stimuli to evaluate eye movements in children

- Determine the appropriateness of the designed child-friendly stimulus to assess smooth pursuit eye movements

- Determine the optimum size and motion paradigm characteristics of the stimulus to be used in the assessment of smooth pursuit eye movements in children

3.3. Tobii TX300

The Tobii TX300 (Tobii Technology, Stockholm, Sweden) was the eye tracker used in this project and was used in all the experiments and studies described in this thesis. This eye tracker was chosen for several reasons. First, it is a completely non-invasive infrared remote eye tracker that collects gaze data at a sampling rate of 300Hz. Second, this system has large volume for head position that allows the recording of eye movements, including fast eye movements such as saccades, without the need for a chin-rest. The system comprises an eye tracker unit and a removable widescreen monitor (23”) with a resolution of 1920x1080 (Figure 3.1).

Figure 3.1. Tobii TX300 infrared eye tracker unit attached to the widescreen monitor (Tobii Technology 2015a).

The Tobii TX300 eye tracker is based on the principle of reflections of infrared light from the optical surfaces of each eye, whose relative positions are used to establish the orientation of the eyes. The infrared source illuminates the eyes and produces the Purkinje I image (light reflection from the anterior cornea). Sensors contained within the same eye tracker unit capture these reflection images that allow the position and orientation of the eyes to be established. According to the manufacturers, the reflection patterns obtained from the subjects' corneas are not the only measures used to establish eye position. These reflection patterns are combined with other visual data about the subject. Then, image processing algorithms and complex mathematics are used to calculate the 3D position and orientation of each eyeball and the relative position (i.e. gaze) with respect to the screen. However, the manufacturers do not give any more detailed information regarding the instrument and/or its algorithms for confidentiality reasons. Gaze accuracy, which is described as the (average) angular distance from the actual gaze position to the one measured by the eye tracker, reported by the manufacturer for this system, is 0.4º and 0.3º for gaze angles <25º in monocular and binocular conditions, respectively (Tobii Technology 2015b). Gaze precision is described as the spatial variation between individual gaze samples and is calculated by the instrument manufacturer as the root-mean-square (RMS) of successive samples. Gaze precision for this system is reported by the manufacturer to be 0.09º and 0.07º monoculary and binocularly, respectively. In addition, repeatability studies were performed in a small sample of adult subjects (n=11) and showed that the eye movement parameters obtained for a smooth pursuit task with the Tobii TX300 with our setup and analysis were highly repeatable. For instance, the mean test-retest difference for velocity and position gain was of the order of 0.02 and 0.07, respectively. Similarly, the mean test-retest difference for the number of saccades and microsaccades was 1 and 0.7, respectively (Appendix B). Finally, the manufacturer's specification document claims that binocular gaze accuracy as well as binocular and monocular gaze precision are maintained when the distance from the eye tracker to the subject is between 50 cm and 80 cm (Tobii Technology 2015b).

The eye tracker can be controlled using Matlab or its customised software, Tobii Studio™ (Tobii Technology, Stockholm, Sweden). This latter software provides a comprehensive user-friendly platform to generate stimuli and calibrate, record and analyse eye movements.

3.4. Child-friendly stimuli

The child-friendly stimuli designed and proposed in this project are a customised animated stimulus for smooth pursuit and fixation stability tests and animal cartoon characters for the saccadic tests. The stimuli were created using the software Flash® CS5 Professional (Adobe Systems Incorporated, San Jose, USA). The movement and morphing for the smooth pursuit and fixation stimuli were incorporated using the programming language Actionscript® 3.0 (Adobe Systems Incorporated, San Jose, USA) for the Adobe® Flash® Platform.

3.4.1. Smooth pursuit stimulus

The stimulus designed to assess smooth pursuit in children can be described as a customised animated stimulus. This comprises an animal cartoon image generated within a 2º x 2º square (Figure 3.2) that moves horizontally or vertically, while continuously changing shape and colour as it morphs into different animals (Figure 3.3). The eyes and a small dot situated within the animal cartoon are maintained constant (no changes of shape and colour) in order to provide a fixation point throughout the test. The animal theme was chosen because it is not gender dependent and should be sufficiently interesting for children of different ages.

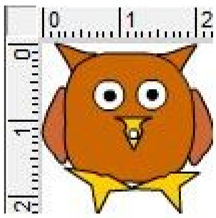


Figure 3.2. Animal cartoon character generated within 2º x 2º square (at 65 cm).

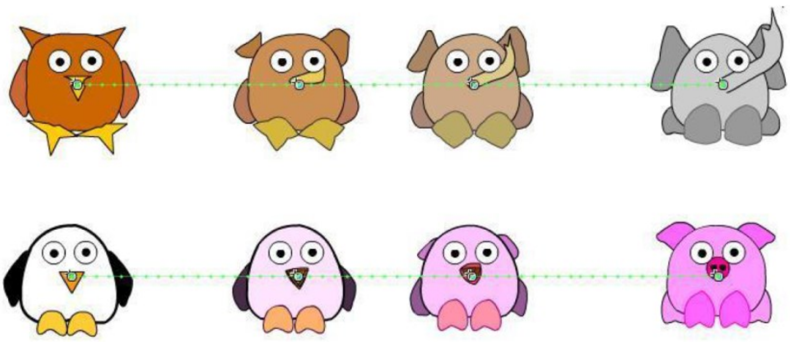


Figure 3.3. Customised animated stimulus. Illustration of the changes of shape and colour of the stimulus as it morphs into different animal cartoons and moves horizontally.

Traditional stimuli (e.g. black dots or light spots) used for eye movement research tend to be smaller than the stimulus that we propose here (2º). However, this stimulus has more details than those used traditionally, and it might be that a smaller size would result in a very crowded and confusing stimulus. In addition, it has been suggested that the perception of a more complex image such as a face can be influenced by its size, and this might potentially impact on children and their attention (Lundy et al. 2001). Moreover, Lundy et al. (2001) proposed that children's attention can be manipulated by modifying the stimulus size. They further suggested that size manipulation does not have an effect on children aged 10 or above, but that larger angular size may improve recognition and performance in children aged 7 or younger (Lundy et al. 2001). In accordance with this, the size chosen for our smooth pursuit stimulus aimed to optimise the cartoon recognition and children's attention.

3.4.2. Saccadic stimulus

Similar to smooth pursuit eye movements, saccades have also been assessed traditionally using small dots and light spots. However, a recent study in children showed improvements in saccadic parameters, such as peak velocity, when using a cartoon as a saccadic target rather than a dot (Irving et al. 2011). The difference in performance between the cartoon and the dot was significant in young children up to the age of 7; after that age, the difference decreased, and in adult subjects, the saccadic performance appeared independent of the stimulus type. There are some studies evaluating the accuracy and precision of saccades using different stimulus sizes and shapes. Kowler and Blaser (1995) compared saccadic latency, precision and accuracy between the traditional single-point targets, circles and diamond shapes of sizes up to 4º. Their results reported no differences in the saccadic parameters between the single point stimuli and circles or diamond shaped stimuli up to 3º of visual angle (Kowler and Blaser 1995). Similarly, Dick et al. (2004) found that latency and accuracy were significantly different between saccadic stimuli sizes 1º and 10º but not between stimuli sizes of 1º and 5º. These results suggest that there is an effect of stimulus size on saccadic performance only for stimuli sizes of 5º or more (Dick et al. 2004). With regards to stimulus shape, saccadic performance has been shown to be maintained for geometric shapes (Kowler and Blaser 1995; McGowan et al. 1998) and also for random dot stimuli (McGowan et al. 1998). The results obtained from a study using random dot stimuli suggested that neither the size of the patterns or their unusual shape interfered with saccadic performance. In addition, the same authors pointed out that, when participants were asked "to look at the new appearing stimulus as a whole" with no specific instructions on where to look, most saccades landed at precise locations that coincided with the stimulus geometric centre (McGowan et al. 1998). In accordance with all this as well as the possible perception and attention issues described in the previous section (section 3.4.1), the stimuli chosen to test saccades were animal cartoons also of 2º in size. These stimuli had very similar characteristics to the customised animated stimulus designed for the smooth pursuit task.

3.4.3. Visual fixation stimulus

The stimulus designed for smooth pursuit was adapted to be used in the visual fixation task. The 2º customised animated stimulus was positioned in the geometric centre of the widescreen monitor and no horizontal or vertical movement was applied. The position of the stimulus did not change, but as previously described in section 3.4.1, the stimulus continuously changed shape and colour while morphing into different animal cartoons.

3.5. Child-friendly head stabiliser

Remote eye trackers allow us to perform eye movement recordings with relatively little head restriction. Hence, this type of eye tracker is the most feasible for eye movement research in infants and young children. However, it has been suggested that data quality with remote eye trackers is compromised with too much head movement but can be improved by restricting the participant's head (Hölmqvist et al. 2011). Tobii manufacturers claim that their eye trackers can successfully record eye movements at an operating distance (eye tracker to subject) of 50-80 cm (Tobii Technology 2015b). Interestingly, all their published precision and accuracy tests are performed at an operating distance of 65 cm. An unpublished study carried out by our research group recorded eye movements from 5 subjects positioned at 50, 60 and 70 cm from a Tobii remote eye tracker (Shaimin 2012). The quality of the eye movement recording was assessed through the validity index provided by Tobii Studio^{TM} Software. These validity values represent the percentage of eye movement samples correctly identified from both eyes during the recording. For example, if data from both eyes are obtained throughout the recording, the validity value would be 100%, but if some data points are missing from one or both eyes a decreased validity index would be obtained. The results from this pilot study are presented in Figure 3.4 and clearly show that 60 cm has the highest percentage of sampled data. In contrast, this value is clearly compromised when eye movement recordings are obtained at an operating distance of 70 cm from the eye tracker. In accordance with these results and the published tests by the eye tracker manufacturers, the eye tracker to subject distance chosen for all the studies was 65 cm.

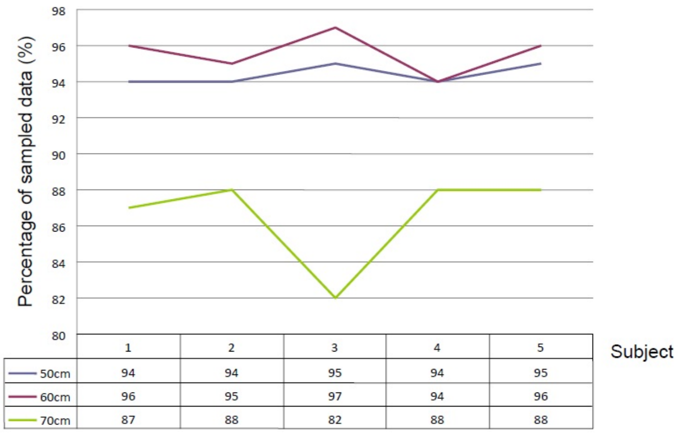


Figure 3.4. Validity percentages for eye movements sampled by the Tobii X120 at 3 different distances. Figure reproduced from Shaimin, 2012 with consent.

The operating distance between the eye tracker and the subject is not only important to obtain the best possible data quality but also to maintain the same test characteristics amongst participants. Changes in this distance would result in different amplitudes presented in saccadic testing as well as different stimulus velocities for the smooth pursuit test. In contrast, the use of a full chin and a forehead rest is not feasible for children, especially for young children and children with special needs. In addition, a full head restriction is far from a normal situation, as we do not have our heads restricted in real world conditions. Therefore, a customised head stabiliser that allowed some horizontal and vertical head movement but maintained a fixed eye tracker to subject distance was designed.

The head stabiliser, which was built into a mobile table in order to make it easily transportable (Figure 3.5 and 3.6), consists of an articulated arm and a customised forehead rest. The metallic articulated arm was covered by a patterned foam and allowed an easy adjustment of the forehead rest in order to suit the child's height and position. The customised forehead rest was attached to the end of the articulated arm and features an adjustable plastic toy crown (Figure 3.5 and 3.6).

Figure 3.5. Customised child-friendly head stabiliser.

Figure 3.6. Child with Down's syndrome using the child-friendly stabiliser during an eye movement recording.

3.6. Pilot study 1: Evaluation of the effect of stimulus type on smooth pursuit performance parameters (adults)

The stimulus described in detail in section 3.4.1 has very different characteristics to the stimuli frequently used to assess smooth pursuit in adults and children. This first pilot study aims to investigate any differences in smooth pursuit performance parameters between the newly-designed animated stimulus and a more standard visual stimulus in an adult group.

3.6.1. Methods

Participants

Twenty adult volunteers (7 females and 13 males, mean age 24 (SD±1.42)) were recruited from the School of Optometry and Vision Sciences at Cardiff University (staff and students). Inclusion criteria for participation in the study were a spherical equivalent refractive error between +8D and -8D, best corrected visual acuity logMAR 0.0 or better in each eye at distance and near, and no ocular pathology. Individuals lacking such criteria or having strabismus, photosensitive epilepsy or unwillingness to give consent were excluded.

The study obtained ethical approval from the School of Optometry and Vision Sciences Research and Audit Ethics Committee, and procedures were in accordance with the guidelines of the Declaration of Helsinki. Written consents were obtained from all the participants. A copy of the information sheets, consent forms and a copy of the ethical approval obtained from the above mentioned ethics committee are included in Appendices B and C.

Preliminary tests

Monocular distance visual acuity with prescription, if any, was obtained from all adult participants. Visual acuity was measured with a Keeler LogMAR test situated at 3 metres from the participant. Each participant was required to hold the occluder in front of the left eye first as the researcher asked him/her to identify the first letter of each row. If the participant was able to correctly identify the first letter of the last row, then they were asked to read out all the letters from that final row. Alternatively, if the participant incorrectly named the first letter of a row, they were asked to read out all the letters in the previous row. If two or more letters from that row were correctly named that was considered the visual acuity threshold. The occluder was then placed in front of the right eye and the same procedure was repeated to obtain visual acuity for the left eye. Finally, binocular visual acuity was obtained by asking the participant to read out the letters of the smallest line achieved in monocular conditions. If all letters from that row were correctly named, the participant was asked to read out the letters in the next row. Similarly, the threshold was set as the row in which the participant could correctly identify 2 or more letters. Near visual acuity was assessed in all participants with the near version of the Keeler LogMAR test at 40 cm and the procedure to obtain visual acuity was identical to that described above for distance visual acuity.

Eye movement recording

Simultaneous binocular eye movement recordings were obtained using the Tobii TX300, described in section 3.3 of this chapter. All participants were seated 65 cm from the eye tracker with their eyes in primary position facing the centre of the monitor and the eye tracker. Participants' heads were held in position with the customised child-friendly head stabiliser described in section 3.5. Prior to eye movement recording, the eye tracker was calibrated for each participant using the Tobii 5 point calibration at 5 target positions on the widescreen monitor. The moving stimuli presented were contained within the calibrated area. Calibration was accepted only when the eye positions were successfully calibrated for all the points presented (for more details on calibration, see chapter 4, section 4.3.1 and chapter 4, Figure 4.6).

The customised 2º animated stimulus (details in section 3.4.1) was presented on a white background moving horizontally following a 6º/s ramp paradigm. The stimulus appeared for one second at 10º to the left of the participant's straight ahead position. After this initial fixation period, the stimulus moved horizontally (left to right) following a constant velocity motion (6º/s) that lasted 3.33 seconds. The stimulus stopped when it was at 10º to the right of the participant's straight ahead position (Figure 3.7). Two second fixation periods were presented between each ramp (left to right or right to left with constant velocity stimulus movement) before the stimulus moved again to the left or to the right. A total of four smooth pursuit ramps were presented, so the stimulus moved left to right and right to left twice. The stimulus presentation lasted for 22.33 seconds.

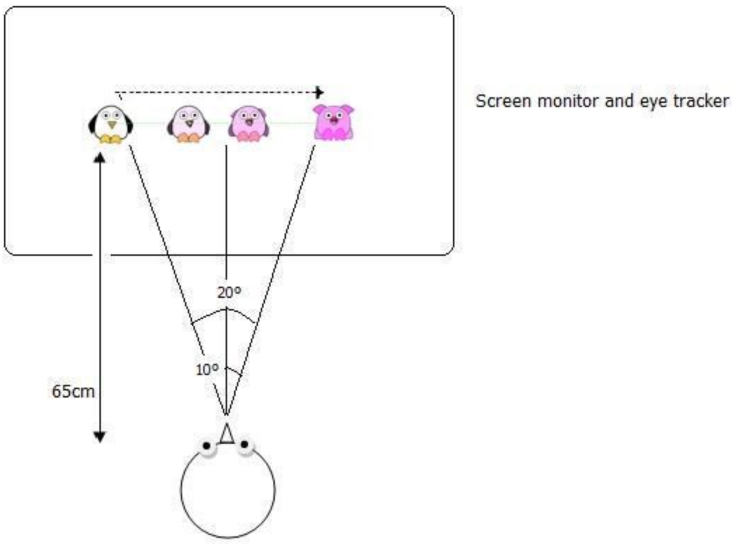


Figure 3.7. Diagram of the setup illustrating the distance of the eye-tracker from subject and the amplitude of the stimulus movement.

Consistent with previous studies (Kowler and Martins 1982; Accardo et al. 1995; Irving et al. 2011; Ego et al. 2013; Lions et al. 2013) a standard visual stimulus that was a black filled circle (i.e. dot) was presented following the same procedures. The standard visual stimulus, referred to as *"standard dot"* subtended 1º of visual angle and contained a small white dot in the centre (Figure 3.8) that provided a fixation point.

Figure 3.8. Standard visual stimulus referred as "1º standard dot".

Data analysis

Data containing timestamp and horizontal and vertical eye positions were obtained from the Tobii Studio TM software and analysed using custom software written in Matlab (The Mathworks, INC, Natick, MA, USA). Eye velocity was obtained from the data by differentiating the eye position over time, and these data were smoothed using a low pass filter (Behrens et al. 2010).

Saccades were automatically detected with the adaptive threshold algorithm described by Behrens et al. (2010). This algorithm calculates the acceleration profile and compares single acceleration data points to the preceding 200 points in order to detect changes in the acceleration profile. This algorithm was also used to analyse the data from the main study and it is further discussed and described in detail in the methods section of this thesis (chapter 4, section 4.3.3).

The eye traces marking the detected saccades were plotted and displayed on the screen monitor for visual inspection as shown in Figure 3.9. Saccades were then removed and the intervals of smooth pursuit were further analysed (Figure 3.10).

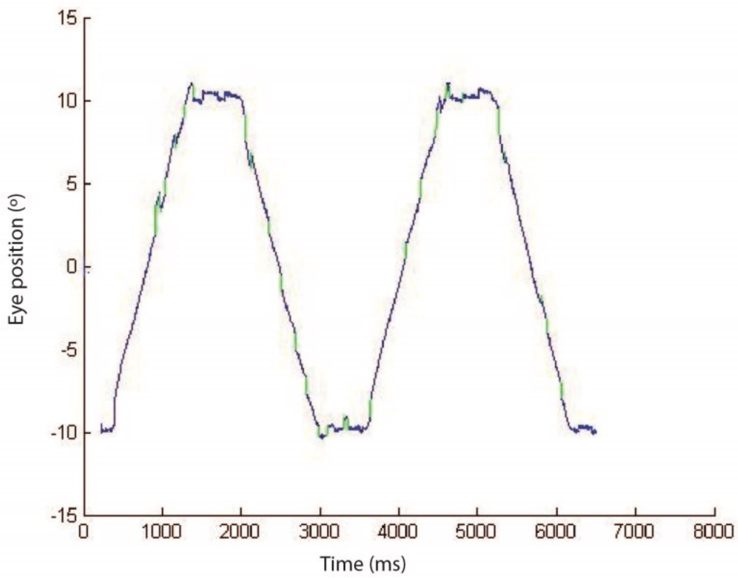


Figure 3.9. Smooth pursuit eye traces (marked in blue) automatically obtained after using and adaptive threshold algorithm to detect saccades (marked in green).

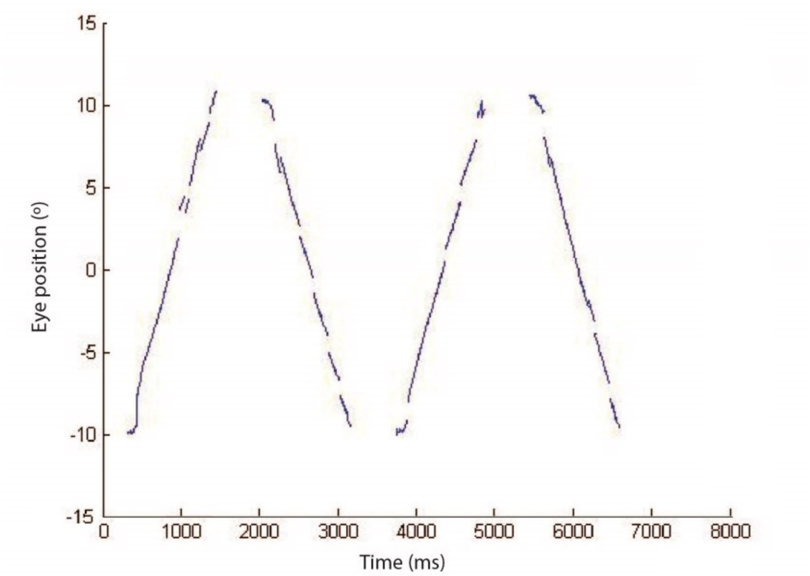


Figure 3.10. Smooth pursuit eye traces after removing the saccadic events detected.

For calculating velocity and position gains, some authors exclude periods of possible slowed smooth pursuit from their analysis (Lisberger and Pavelko 1989; Behrens et al. 2010). In contrast, other authors include all smooth pursuit segments suggesting this may offer a better measurement for global smooth pursuit function (Radant and Hommer 1992; Ross et al. 1997). In any case, the difference in gain scores across these two measures has been reported to be less than 2% with a greater than 0.95 correlation (Ross et al. 1997). Because smooth pursuit in children has been reported to be slower than in adults (e.g. Ross et al. 1993; Rutsche et al. 2006; Irving et al. 2011), the researcher considered that excluding periods of slowed smooth pursuit from the analysis could mask a genuine slower smooth pursuit. Therefore, all smooth pursuit segments were included in the analysis to obtain a more realistic measure of smooth pursuit global performance.

A linear regression was performed on each segment of smooth pursuit data (i.e. without saccades). The slope of the fitted equation was defined as the eye velocity for that segment. The velocity of each segment was then weighted for the duration, and these time-weighted velocities were averaged together to obtain the mean velocity for that full smooth pursuit task. Velocity gain was then calculated by dividing the time-weighted mean eye velocity by the stimulus velocity.

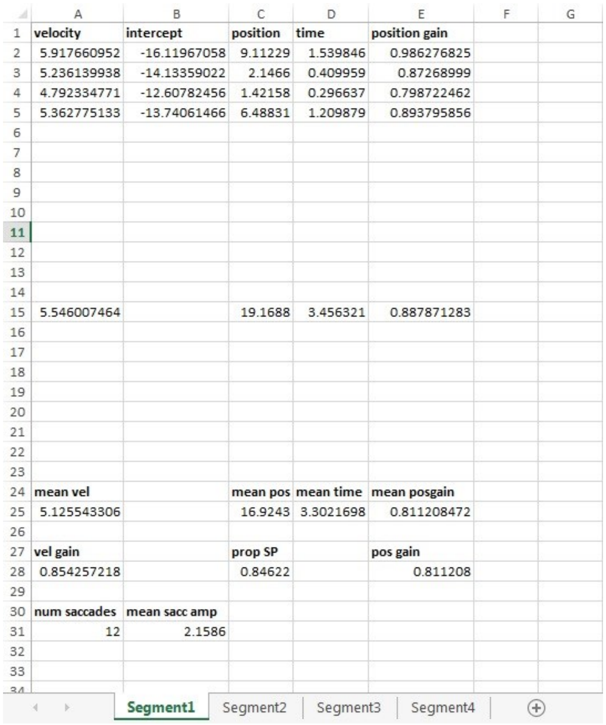
Position gain was defined as the mean ratio between eye position and stimulus position for every smooth pursuit segment. This parameter was calculated by dividing the eye position at the end of each segment by the position of the stimulus at that exact moment. The position gains obtained from all smooth pursuit segments were averaged to obtain the mean position gain.

The total proportion of smooth pursuit (proportion of SP) was defined as the total eye movement involving slow phase (i.e. without saccades) divided by the total stimulus movement (20º for each smooth pursuit presentation). This measure was calculated in order to obtain complementary information about the participants' level of attention and/or the difficulty of the task relative to each participant. A low proportion of SP would correspond with an increased number of saccades, and therefore it would be an indicator of poor smooth pursuit performance. Alternatively, a low proportion of SP with not many saccades and high gains may potentially suggest that the participant smooth pursuit is good. However, the participant did not pay enough attention to fully perform the smooth pursuit task.

The amplitudes of all the detected saccades were calculated by subtracting the eye position at the end of the saccade from the eye position at the beginning of the saccade. The amplitudes were calculated, and saccades below 1º were classified as microsaccades (Martinez-Conde et al. 2004; Martinez-Conde et al. 2009). The amplitude of all the saccades (>1º) detected and removed from the smooth pursuit traces were averaged to obtain the mean saccadic amplitude.

The software produced a Microsoft Excel file for each participant and stimulus condition with the data of each smooth pursuit ramp in separate sheets. In each sheet, each row corresponded to the calculated values of the different smooth pursuit intervals on each ramp. An Excel Macro was computed to calculate the averages of these parameters for each segment and the final average was displayed on the first sheet (Figure 3.11).

The gains (velocity and position), proportion of SP, number of saccades (saccades of amplitudes >1º), mean amplitude of the saccades and number of microsaccades (saccades of amplitudes <1º) obtained from all participants were averaged to obtain the mean values of the parameters for each stimulus and type (customised 2º animated stimulus and 1º standard dot).



	A	B	C	D	E	F	G
1	velocity	intercept	position	time	position gain		
2	5.917660952	-16.11967058	9.11229	1.539846	0.986276825		
3	5.236139938	-14.13359022	2.1466	0.409959	0.87268999		
4	4.792334771	-12.60782456	1.42158	0.296637	0.798722462		
5	5.362775133	-13.74061466	6.48831	1.209879	0.893795856		
6							
7							
8							
9							
10							
11							
12							
13							
14							
15	5.546007464		19.1688	3.456321	0.887871283		
16							
17							
18							
19							
20							
21							
22							
23							
24	mean vel		mean pos	mean time	mean posgain		
25	5.125543306		16.9243	3.3021698	0.811208472		
26							
27	vel gain		prop SP		pos gain		
28	0.854257218		0.84622		0.811208		
29							
30	num saccades	mean sacc amp					
31	12	2.1586					
32							
33							

Segment1 | Segment2 | Segment3 | Segment4

Figure 3.11. Excel file output obtained for each participant. Each Excel sheet contained the data for each smooth pursuit ramp (in the picture named as "Segement1", "Segment2", "Segment3" and "Segement4").

Statistical analysis

The purpose of the analysis in this section is to determine any effect of stimulus type on the parameters of smooth pursuit in a group of 20 adults. Paired t-tests were the most appropriate tests for this.

In this project, IBM SPSS software package version 18.0 (IMB SPSS INC, Chicago, IL, USA) was used for all statistical analysis. The distribution of the data was evaluated using histograms and Shapiro-Wilk tests. All parameters except the mean amplitude of the saccades ($p<0.001$) and the number of microsaccades ($p<0.001$) were normally distributed. Therefore, to compare smooth pursuit performance between the

2º animated and the 1º standard dot stimuli, a non-parametric Wilcoxon test was used for the mean amplitude of saccades and the number of microsaccades, and parametric paired t-tests were used for the other parameters. For statistical purposes, a p value lower than 0.05 was considered to be statistically significant.

3.6.2. Results

All subjects had monocular visual acuity for distance and near of at least logMAR 0.0, no participants had binocular anomalies (absence of strabismus tested with the CT and normal stereopsis tested with the Frisby Stereotest) or ocular pathology.

The smooth pursuit performance parameters obtained from all participants with the 2º animated and the 1º standard dot stimulus were averaged to obtain the mean value for each stimulus type. The mean smooth pursuit parameters (±SE) are plotted in Figures 3.12 and 3.13.

It can be observed that on average the 2º customised animated stimulus produces higher velocity and position gains (Figure 3.12a and 3.12b), as well as higher total proportion of SP (Figure 3.12c). These differences in performance are further corroborated with statistical tests. Paired t-tests revealed significant differences in position gain ($p=0.025$), velocity gain ($p=0.014$) and the total proportion of SP ($p=0.002$) between the 2º animated and the 1º standard dot stimulus.

With regard to the number of saccades, Figure 3.13 illustrates very similar results. The mean number of saccades (>1º) are lower with the animated than with the standard dot stimulus (Figure 3.13a), and this difference in the number of saccades was significant ($p=0.008$). In contrast, paired t-test and Wilcoxon tests revealed that stimulus type had no effect on the number of microsaccades ($p=0.582$) or the mean amplitude of the saccades ($p=0.732$) (Figure 3.13c and 3.13b), respectively.

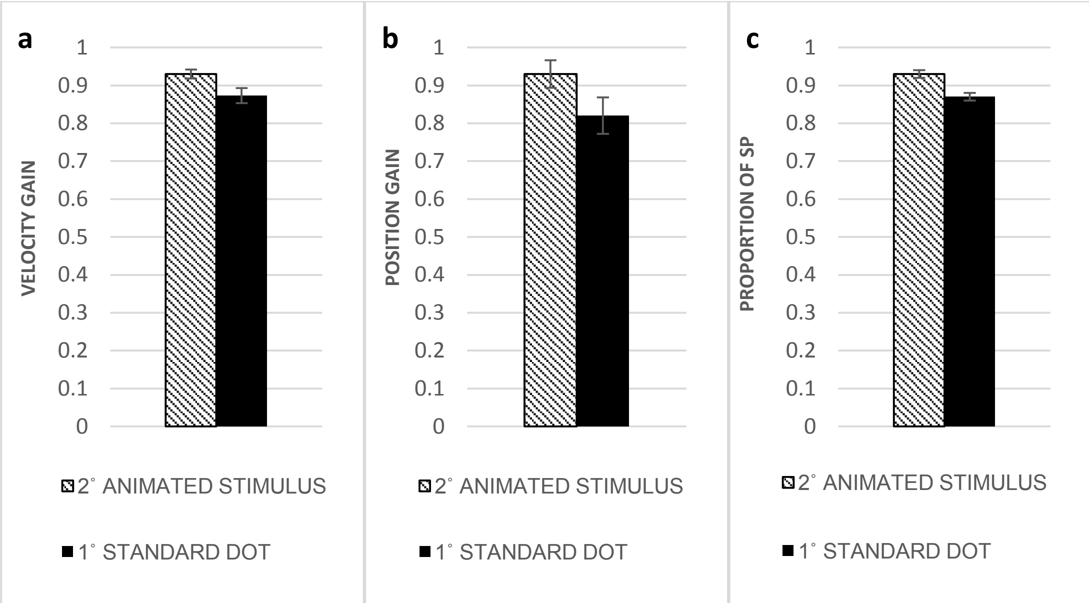


Figure 3.12. Mean (±SE) velocity gain (a), position gain (b) and proportion of SP (c) for the 2º animated stimulus (striped bars) and for the 1º standard dot (solid bars).

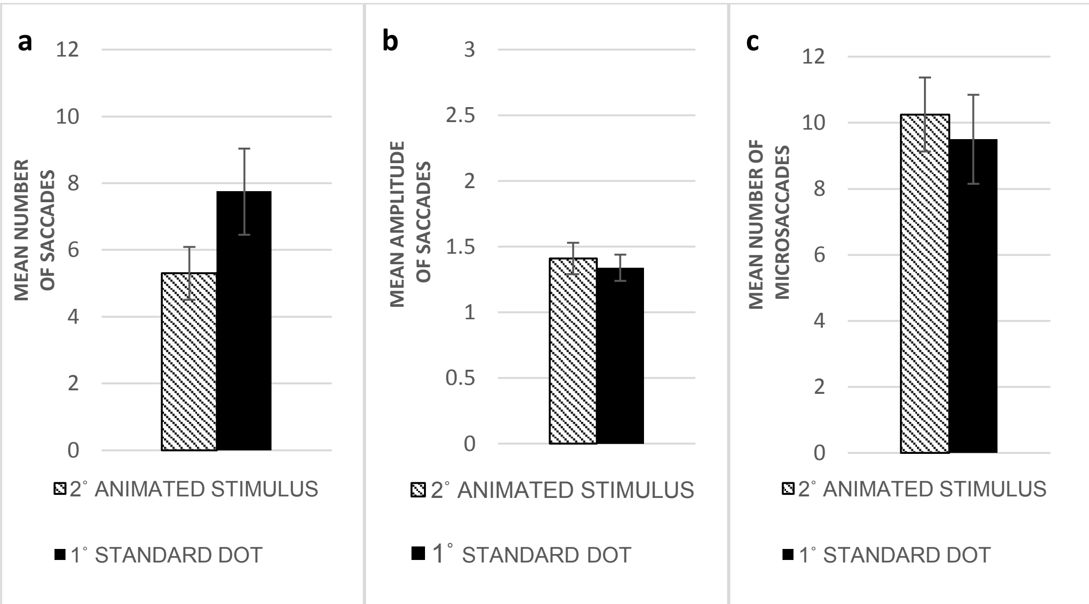


Figure 3.13. Mean (±SE) number of saccades (a), amplitude of saccades (b) and number of microsaccades (c) for the 2º animated stimulus (striped bars) and the 1º standard dot (solid bars).

3.7. Pilot study 2: Evaluation of the effect of stimulus size on smooth pursuit performance parameters (adults)

In the above pilot study, significant differences were found in smooth pursuit performance between the two types of stimuli presented. However, the two stimuli had different sizes (2º animated and 1º standard dot), and therefore the results found could be attributed to this difference in size rather than to the type of stimuli. Hence, the following pilot study aims to investigate any differences in smooth pursuit performance parameters between the two stimuli sizes previously presented.

3.7.1. Methods

Participants

Ten adult volunteers (5 females and 5 males) with mean age of 21.50 (SD±2.12) were recruited from the School of Optometry and Vision Sciences at Cardiff University (staff and students). Inclusion criteria for participation in the study were a spherical equivalent refractive error between +8D and -8D, best corrected monocular VA logMAR 0.0 or better at distance or near, and no ocular pathology. Participants lacking such criteria, having strabismus, any ocular pathology, photosensitive epilepsy or unwillingness to give consent were excluded.

The study obtained ethical approval from the School of Optometry and Vision Sciences Research and Audit Ethics Committee, and procedures were in accordance with the guidelines of the Declaration of Helsinki. The ethical approval and the information sheets and consent forms approved by the above mentioned ethics committee are in Appendices B and C.

Preliminary tests

Distance and near visual acuity (monocular and binocular) were obtained for each participant following the same procedures described in section 3.6.1 of this chapter.

Eye movements recording

Each adult participant who took part in this pilot study was seated, and their head restricted following the same procedures described in the previous pilot study (section 3.6.1). Before the eye movement recording, the eye position was calibrated for 5 target positions on the windscreen monitor (Tobii 5 point calibration). Calibration was accepted only when the eye position was successfully calibrated for all the 5 points presented.

After the calibration, a 1º or a 2º standard dot stimulus was randomly presented on a white background following a 6º/s ramp paradigm identical to that described in pilot study 1 (section 3.6.1). Then, the stimulus size was changed to the other remaining size (1º or 2º) and measures were repeated following the same motion paradigm and velocity.

Data analysis

The smooth pursuit eye movement traces were analysed following the same procedures described for pilot study 1 (section 3.6.1). The mean velocity gain, position gain and proportion of SP were calculated for each participant. Similarly, the saccades (>1º and <1º) during the smooth pursuit were detected using the same adaptive threshold algorithm (Behrens et al. 2010). These saccadic parameters were also obtained for each participant in accordance with the procedures described in section 3.6.1 of this chapter.

The smooth pursuit parameters obtained from all the participants were averaged to obtain the mean values of the parameters for each standard dot stimulus size.

Statistical analysis

The purpose of the analysis in this section is to determine the effect of stimulus size (1º vs 2º) on the parameters of smooth pursuit in a group of 10 adults. Paired t-tests were the most appropriate tests for this.

The distribution of the data was assessed using histograms and Shapiro-Wilk tests. All parameters except velocity gain (p=0.004) were normally distributed. Therefore, non-parametric Wilcoxon test was used for velocity gain, and parametric t-tests were used for the other parameters. For statistical purposes, a p value lower than 0.05 was considered to be statistically significant.

3.7.2. Results

Although 10 adult subjects took part in this study, only data from 9 participants are presented here as one subject had an alternating strabismus. His data were therefore excluded from the analysis. The nine participants had monocular distance and near visual acuities of at least logMAR 0.0, no binocular anomalies and no ocular pathology.

Figures 3.14 and 3.15 illustrate the mean values (±SE) of the studied smooth pursuit parameters for the 1º and 2º standard dot stimulus. Figure 3.14a and 3.14b suggest that velocity and position gains are independent of the stimulus size, as the mean values of both stimuli presented appear very similar. The mean values obtained for these velocity and position gains are approximately of 0.9 for both stimuli. Non-parametric Wilcoxon and parametric paired t-tests did not show significant differences in velocity gain (p=0.176) or position gain (p=0.829). The Figure 3.14c shows that the mean proportion of SP is slightly higher with the 1º than with the 2º standard dot. However, this difference was not significant (p=0.334).

The mean number of saccades and microsaccades detected during the smooth pursuit task for each stimulus size is illustrated in Figure 3.15a and 3.15c. In general, the number of saccadic events, either saccades (amplitudes >1º) or microsaccades (amplitudes <1º), appear to be slightly lower for the 1º standard dot than for the larger size presented (2º). However, parametric paired t-tests revealed no differences in the number of saccades above 1º amplitude (p=0.211), the mean amplitude of the saccades (p=0.605) and the number of microsaccades (p=0.858) between the two sizes studied.

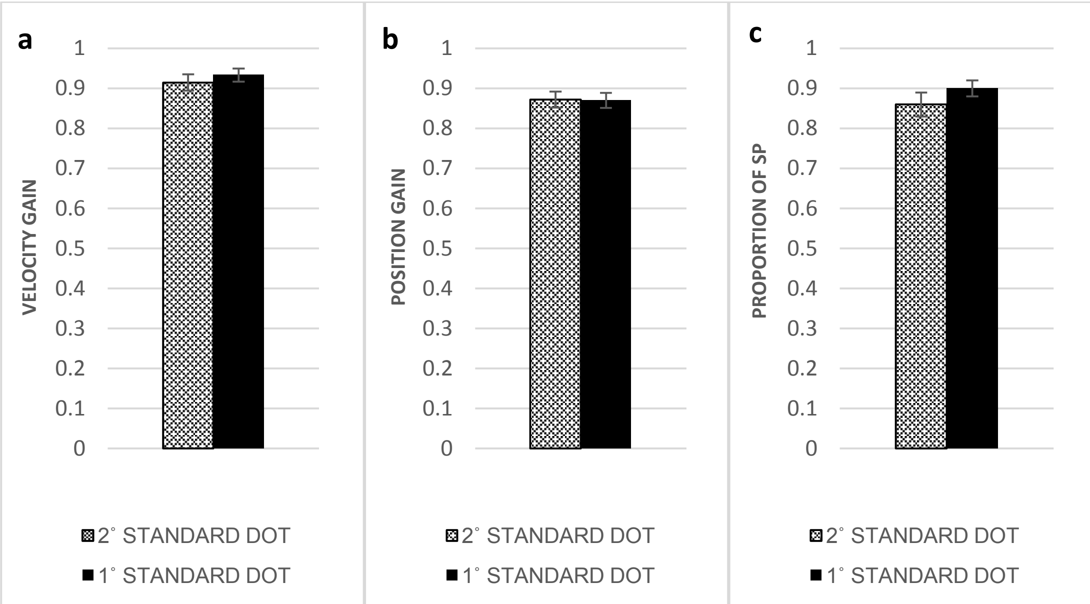


Figure 3.14. Mean (±SE) velocity gain (a), position gain (b) and proportion of SP(c) for the 2º dot (patterned bar) and for the 1º dot stimulus (solid bar).

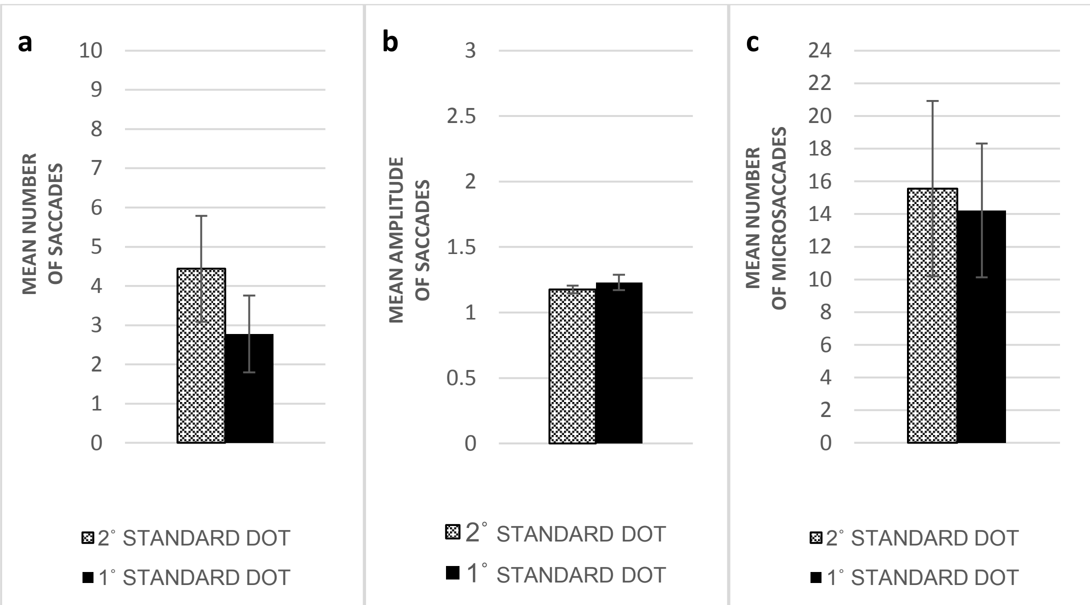


Figure 3.15. Mean (±SE) number of saccades (a), amplitude of saccades (b) and number of microsaccades (c) for the 2º standard dot (patterned bar) and for the 1º standard dot stimulus (solid bar).

3.8. Pilot study 3: Evaluation of the effect of motion paradigm on smooth pursuit performance (children)

There are different motion paradigms available to evaluate smooth pursuit eye movements. These have been described in detail in chapter 1 section 1.2.1. In summary, the three main motion paradigms are the ramp, the step-ramp and the sinusoidal motion paradigms. The ramp motion paradigm, which was used in the previous two pilot studies, consists of a target that starts moving suddenly at a constant velocity for a certain period of time (Barnes 2011). In the step-ramp paradigm the target has an initial displacement (step) from the original position prior to the constant velocity movement of the target (ramp). Finally, the eye movements can also be studied in response to a stimulus for which velocity continuously changes in a sinusoidal manner (more details in chapter 1, section 1.2.1 and chapter 1, Figure 1.2).

These different motion paradigms (see chapter 1, Tables 1.1 and 1.2) have been used to study smooth pursuit eye movements in infants and children. Although an early study suggested that the step-ramp paradigm should be used in infants and young children in order to increase their attention (Rashbass 1961), not many authors have discussed the reasons for choosing a particular motion type over another in their studies. Therefore, there is not an established motion paradigm to study eye movements in children, and it is not clear if the motion paradigm has an effect on smooth pursuit performance. This pilot study aims to investigate the effects of different motion paradigms on smooth pursuit performance in children in order to determine the best motion paradigm to be used in our main study.

3.8.1. Methods

Participants

Twelve children (5 females and 7 males) with mean age 6.33 (SD±3.62) were recruited for this last pilot study. The child volunteers were recruited by posting an advert in the Cardiff University Eye Clinic, the Cardiff University Notice Board, and by sending an e-mail to all Cardiff University staff members.

All parents who contacted the researcher regarding the advert were provided with a parent information sheet, a child information sheet and a consent form (copies of these documents are included in Appendix D). The parents had the opportunity to ask questions and discuss the study with the researcher by e-mail and/or telephone. Child participants were required to come for a single visit in which the researcher explained the study procedures, and time was given to ask questions before they agreed to take part and sign the consent form. The procedures of this pilot study as well as the information sheets and consent forms were approved by the School of Optometry and Vision Sciences Research and Audit Ethics Committee, and were in accordance with the guidelines of the Declaration of Helsinki (documents in Appendix C and D).

Inclusion criteria for this pilot study were best corrected near and distance visual acuity of logMAR <0.3, mean spherical refractive error between +8D and -8D, no binocular anomalies and no ocular pathology. Child participants who did not meet these criteria, with photosensitive epilepsy or whose parents were not willing to give signed consent were excluded from the study.

Optometric screening test

A preliminary screening optometric test was performed in all child participants in order to ensure that they met the inclusion criteria. For this, the researcher performed visual acuity, a cover test and Mohindra retinoscopy.

<u>Visual acuity</u>

Two different logMAR tests were used to assess visual acuity: the Keeler logMAR and the Crowded Kay Pictures test. The children were given the choice of test (Jones et al. 2003). The chosen test was then placed at 3 m and visual acuities were obtained monocularly using a pair of occluder glasses, starting with the right eye first. The procedure was the same as that described for adults in section 3.6.1 of this chapter. Then, the occluder glasses were changed and visual acuity for the left eye was obtained. The child could verbally identify the pictures or match them on a card. Finally, near visual acuities for the right and left eye, respectively, were obtained using the near version of the child's preferred test. The visual acuity threshold was determined by the last row in which the child participant could verbally identify or match two or more of the pictures or letters (more details on this procedure in chapter 4, section 4.2.1).

Cover test

A cover test was performed in all child participants in order to check the alignment of visual axes and any strabismus. The child was required to fixate at a distance target, which was a picture placed on the wall 3 m away. The researcher placed an occluder in front of the left eye first to assess any strabismus of the right eye and then the occluder was placed in front of the right eye to assess the presence of strabismus in the left eye. The same procedure was performed with a near target to assess ocular alignment at near (more details on this procedure in chapter 4, section 4.2.1).

Retinoscopy

The available retinoscopic techniques to objectively determine refractive error in children are: static distance retinoscopy, cycloplegic retinoscopy and Mohindra retinoscopy.

In this pilot study, we used the Mohindra technique for obvious reasons: it is much more child-friendly, no waiting time for the drops to take effect is required and because cycloplegic refraction would not allow us to perform the eye movement recording. As this technique takes place in complete darkness, children were sat next to parents and with a continuous physical contact to ensure the child did not jump or slide from the chair in the dark. Retinoscopy was performed on each eye by neutralizing the retinal reflex in the two primary meridians of each eye by hand holding trial lenses in front of the eye tested while simultaneously occluding the other eye. The most powerful meridian was neutralized first with a spherical lens. If a cylindrical component was observed, then a cylindrical lens was also placed in front of the eye with its axis aligned with that meridian direction. After retinoscopy, +1.00D was subtracted from the result (Saunders and Westall 1992) and recorded in sphero-cylinder form.

Eye movement recording

The eye movement recordings in children followed the same procedure as the previous pilot study involving adult participants.

Children were seated 65 cm from the widescreen monitor and the eye tracker, and their heads were restricted using the head stabiliser previously described. Before the eye movement recording, a Tobii standard 5-point calibration was performed.

The 2º animated stimulus was presented on a white background following three different motion paradigms. First, the 2º animated stimulus was presented following a 6º/s ramp paradigm which was identical to that presented in the previous pilot studies (for details see section 3.6.1). Then, the same stimulus was presented using a step-ramp motion paradigm. The stimulus appeared initially for ten seconds at 10° to the left of the participant's straight-ahead position. Then, the stimulus was horizontally displaced 1º and remained one second in that new horizontal position before returning to the original position to start its movement following a 6º/s ramp motion. The stimulus moved a total amplitude of 20º and stopped when it was located at 10º to the right of the participant's straight-ahead position. The stimulus displacement (step) was repeated before every smooth pursuit ramp. The step-ramp motion stimulus presentation lasted for 23.33 seconds. For the sinusoidal motion, the animated stimulus moved with a velocity that was continuously changing in a sinusoidal manner; so that the velocity of the stimulus increased from the beginning of the movement to the middle of the movement, where velocity achieved its maximum value, and then velocity was sinusoidally decreased reaching zero at the end of the movement. For this final motion paradigm, the fixation periods between ramps were deleted and the task lasted for 14.33 seconds.

Data analysis

The number of saccades, including saccades above 1º of amplitude and microsaccades, were detected following the same procedure as in pilot studies 1 and 2 (for details see section 3.6.1 of this chapter). Similarly, the amplitude of the saccades was obtained by subtracting the eye position at the end of the saccade from the eye position at the beginning of the saccade. Position gain, velocity gain and proportion of SP for the ramp and the step-ramp paradigm were calculated following the same procedures as in the two previous pilot studies (described in section 3.6 of this chapter).

In contrast, velocity gain for the sinusoidal motion was not calculated with linear regression as described for the constant velocity motions. This type of movement requires a different type of fitting to adjust to the sinusoidal velocity changes. Hence, a polynomial fitting was performed along the eye position data without the saccades. The velocity gain was then defined as the coefficient of determination, R^2, between the smooth pursuit data and the polynomial fit. This value is a test of goodness of fit and applies to matching the real eye movement data to an ideal equation. This procedure can be considered to be similar to linear regression performed for the constant velocity motions.

Statistical analysis

The same statistical software as that used in the previous pilot studies (section 3.6 and 3.7 of this chapter) and the main studies (chapter 5 and 6) was used. All data except the number of microsaccades were normally distributed according to Shapiro-Wilk tests and histograms. Although one parameter (proportion of SP) was not normally distributed, parametric analysis of variance (within subject repeated measures ANOVA) was still used for statistical purposes as this test has been suggested to be robust to moderate deviations from normality (Glass et al. 1972; Lix et al. 1996). For statistical purposes, a p value lower than 0.05 was considered to be statistically significant.

3.8.2. Results

The mean monocular visual acuity of all the children who took part in this pilot study was logMAR 0.036 ranging from logMAR 0.20 to logMAR 0.00 and no child had strabismus. Refractive error (mean sphere in the most ametropic eye) ranged from -0.25D to +1.25D, and no child wore spectacles.

Figures 3.16 and 3.17 show the mean values for smooth pursuit parameters with the different motion paradigms. Velocity and position gains appear to be very similar for the ramp and the sinusoidal motion paradigms, while gains obtained with the step-ramp appeared to be slightly lower than for the other motion paradigms (Figure 3.16a and 3.16b). For instance, velocity gain is 0.91, 0.88 and 0.92 and position gain is 0.90, 0.86 and 0.93 for the ramp, the step-ramp and the sinusoidal motion, respectively. However, none of these differences were statistically significant. Parametric repeated measures ANOVA with a Greenhouse-Geisser correction determined that velocity gain (F=1.689; p=0.222) or position gain (F=3.254; p=0.093) were not significantly different between the motion paradigms testes. Similarly, a repeated measures ANOVA (no Greenhouse-Geisser correction needed as sphericity was not violated) revealed no statistically significant differences in proportion of SP between the ramp, the step-ramp or the sinusoidal motion (F=3.213; p=0.062).

Figure 3.17a, 3.17b and 3.17c illustrate the mean number of saccades with amplitudes >1º, the mean saccadic amplitude for these saccades and the mean number of microsaccades. It can be noted from the Figure 3.17a that the number of saccades (>1º) is very close to 4 independently of the motion paradigm and that the mean amplitude of the saccades is close to 2 for all conditions. The mean number of microsaccades is slightly higher in the ramp paradigm (Figure 3.17c), but this parameter is below 10 for any motion paradigm. Repeated measures ANOVA did not reveal significant differences in the mean number of saccades (>1º) (F=1.420; p=0.265), the mean amplitude of the saccades (F=1.137; p=0.341) and mean number of microsaccades (F=2.824; 0.083).

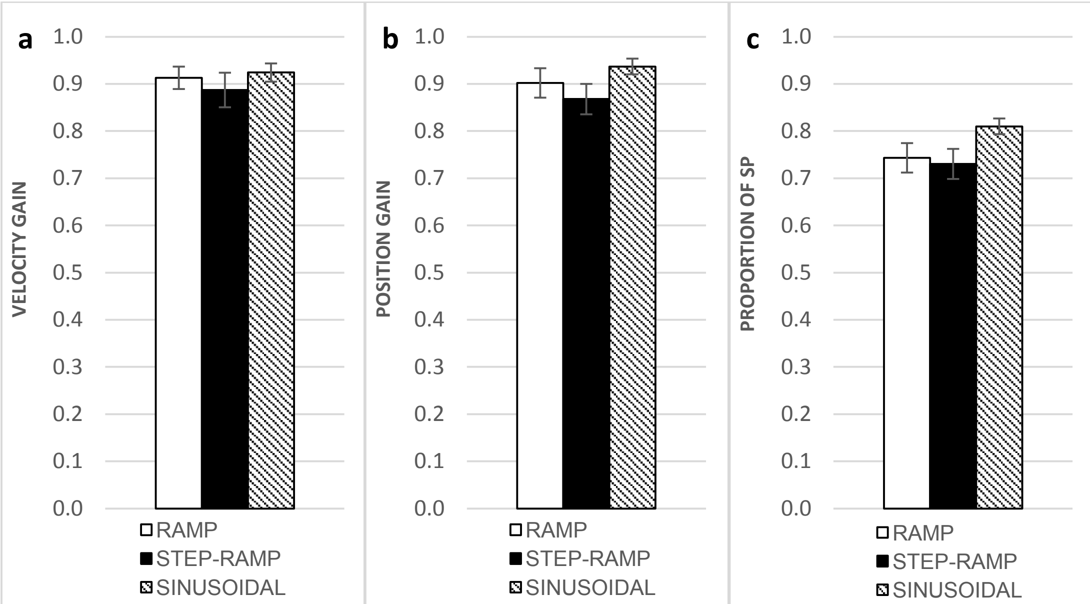


Figure 3.16. Mean (±SE) velocity gain (a), position gain (b) and proportion of SP (c) for the ramp (solid white bars), step ramp (solid black bars) and sinusoidal motion paradigm (striped bars).

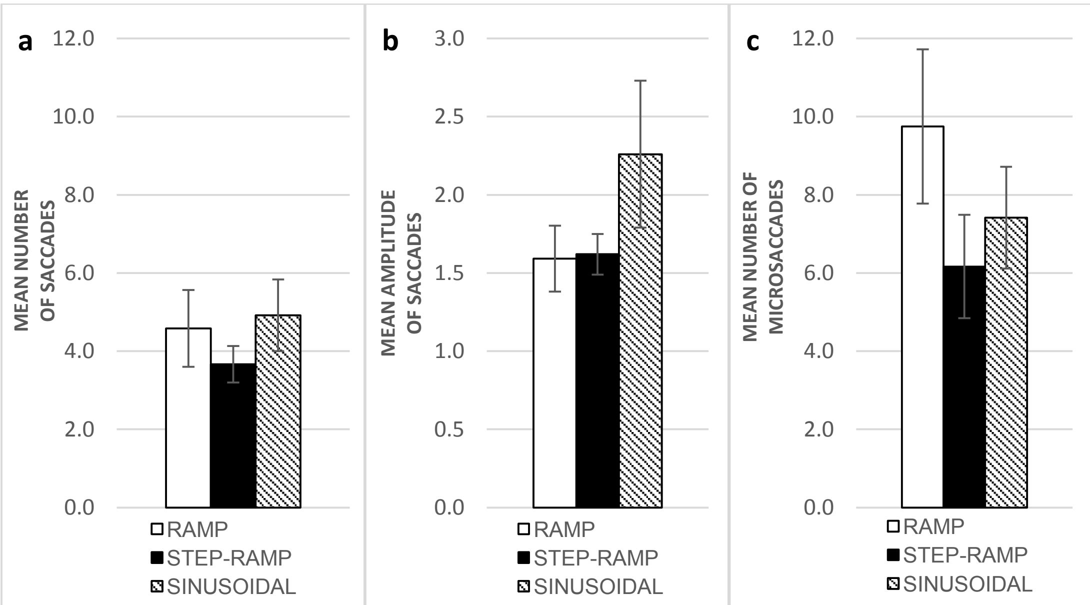


Figure 3.17. Mean (SE) number of saccades (a), amplitude of the saccades (b) and number of microsaccades (c) for the ramp (solid white bars), step-ramp (solid black bars) and sinusoidal motion paradigm (striped bars).

3.9. Discussion

Different stimuli can be used to study eye movements, but changes in some of their characteristics may affect the subjects' overall eye movement performance. This chapter describes the stimuli and setup designed to study eye movements in this project. In addition, the effects of different stimulus characteristics on smooth pursuit performance parameters were evaluated in order to establish the best stimuli to be used in children to assess this particular eye movement.

3.9.1. Effect of stimulus type on smooth pursuit performance in adults.

Saccades and smooth pursuit eye movements have been assessed traditionally using dots and light spots in both adults (Flechtner et al. 2002; Yang et al. 2002; Ettinger et al. 2003; Judge et al. 2006) and children (Kowler and Martins 1982; Accardo et al. 1995; Yang et al. 2002; Salman et al. 2006a; Lions et al. 2013). However, a recent study demonstrated that children up to 12 years of age respond better to pictures than to dots, and that improvements in oculomotor response can be obtained with these targets (Irving et al. 2011). In accordance with this, animal cartoon characters and an animated morphing stimulus of 2° of visual angle are proposed for this project to assess saccades and smooth pursuit, respectively.

There is a very close relationship between attention and smooth pursuit, such that higher attention engagement improves smooth pursuit performance (Shagass et al. 1976; Sweeney et al. 1994). We postulated that, in adults, an animated stimulus would provide similar results to those found for picture-based/standard stimuli, but our results show significant improvements on smooth pursuit performance parameters in adults using an animated target compared to a standard non-animated (i.e standard dot) target. The smooth pursuit gains obtained for the dot stimuli were similar to those reported in the literature for dots or similar stimuli and velocities (Tajik-Parvinchi et al. 2003; Irving et al. 2011; Ke et al. 2013). These results suggest that our adult population was not different from previously studied samples, and furthermore, an improvement in this group of adults was found when using our novel stimulus.

3.9.2. The effect of size on smooth pursuit perfromance in adults

The size of the customised stimuli we propose in this chapter is larger than the average size of the traditional stimuli used for eye movement research. The size of the stimulus has been shown to have little effect on saccades up to sizes of 5º (Kowler and Blaser 1995; Dick et al. 2004). In contrast, there is relatively little information on the effect of target size on smooth pursuit performance, but for example, the use of a large stimulus for smooth pursuit may elicit an OKN response instead (Pola and Wyatt 1985). Hence, it could be argued that the differences in smooth pursuit performance parameters in adults between the 2º animated stimulus and the 1º standard dot found in the first pilot study (chapter 3, section 3.6) were an effect of stimulus size rather than an effect of stimulus type. For that reason, the second pilot study was designed to assess any possible effects on smooth pursuit performance parameter arising from using a larger stimulus size. The results showed no differences in any of the smooth pursuit parameters between the two dot sizes (1º and 2º) in an adult group and this suggests that these stimuli sizes are potentially interchangeable. Additionally, as no differences were observed between a 1º and 2º dot stimulus in our adult population, it would appear that the differences in the smooth pursuit performance parameters observed between the 2º animated stimulus and the 1º dot are more likely to be due to the stimulus type rather than to stimulus size.

3.9.3. Effect of motion paradigm on smooth pursuit performance in children

Finally, studies quantitatively evaluating eye movements in adults and children have used different motion paradigms, however few authors have presented their rationale for choosing one paradigm over another. Hence, in the third pilot study described in this chapter, we studied the effect of three different motion paradigms on smooth pursuit performance in children using the novel animated stimulus. All of the parameters studied were similar across the different motions presented suggesting that, when using the animated stimulus, the same values should be obtained independently of the motion paradigm used.

The results obtained confirm that eye movement performance, in particular smooth pursuit performance, can be improved with a more interesting or interactive stimulus in an adult population. The stimuli proposed in this chapter are unique and innovative, especially the animated morphing stimuli proposed for the assessment of smooth pursuit and fixation eye movements. In addition, it is the first time that an animated stimulus has been utilised in the study of eye movements, and since this stimulus was shown to improve smooth pursuit performance in adults, we expect this improvement to be even more evident in children. Although this was not directly investigated in this chapter, we believe that these stimuli will be of particular value when assessing eye movements in children with diagnosed or suspected Attention Deficit Disorder or short attention spans, especially as the children can be encouraged to name the animal as it changes, thus hopefully maintaining and confirming their interest and attention.

3.10. Summary

The aims of this chapter were to assess the effect of different stimulus characteristics on smooth pursuit performance parameters in order to establish the best stimuli to be used in the assessment of smooth pursuit in children and inform the design of a child-friendly stimuli and setup to study eye movements. Overall, the results presented support the use of attention-grabbing stimuli (i.e animated stimulus) to obtain optimal eye movement recordings in children.

Chapter 4 General methods

4.1. Introduction

Clinically, there are a number of unanswered questions relating to eye movement anomalies and their characteristics in school-age children, as well as the association between such eye movement anomalies and reading and/or learning difficulties. In order to provide optimal normative values for eye movements in school-age children and evaluate the possible relationship between learning difficulties and eye movement anomalies, a case control study was conducted.

This chapter includes a complete description of the clinical procedures used to assess vision and binocularity in the study participants and the established eye movement recording design and protocol. Finally, this chapter describes the eye movement data analysis performed to obtain the results presented in the following chapters of this thesis (chapters 5, 6 and 7).

4.2. Optometric test

An optometric test was performed prior to the eye movement recording to ensure that all child participants had good visual acuity and no binocular vision or accommodative problems.

An informative letter was posted to the parents of the children tested in the school premises (children recruited for the study presented in chapters 5 and 6) who were found to have an uncorrected refractive error and/or any binocular deficit. In the letter, the researcher explained that, during the optometric examination, she detected a potential deficit in their child's vision and recommended the parents to take their child for a full eye examination. It also indicated that the researcher could be contacted for more information regarding this as well as offering to provide a full eye test at Cardiff University, if they wished.

The parents of the children who came to the School of Optometry and Vision Sciences to participate in the research (children recruited for the study presented in chapter 7) were verbally informed of the results and whether their children needed a full eye examination immediately after the optometric test.

4.2.1. *Visual acuity*

There are different methods and tests to evaluate visual acuity in children. The method chosen depends on the child's age, level of attention, comprehension and communication. Visual acuity tests may be divided into three categories: resolution, detection and recognition (Leat et al. 1999; Saunders 2010). Recognition acuity tests involve the ability to detect, resolve and recognise a target such as a letter or a picture. These visual acuity tests are more sensitive than resolution and detection tests and optometrists are recommended to use them whenever appropriate in children after the age of 2.5 years (Saunders 2010). In accordance with this, two recognition logMAR tests were used to assess visual acuity in the study participants: the Kay Picture Crowded and the Keeler logMAR tests (Figure 4.1). The tests were both in crowded format as it is well established that the sensitivity of these tests is increased when they are used in this format (Stuart and Burian 1962). Each child was allowed to choose which of the two tests he/she preferred (Jones et al. 2003). Visual acuity was measured in all the participants with their spectacle correction, if any.

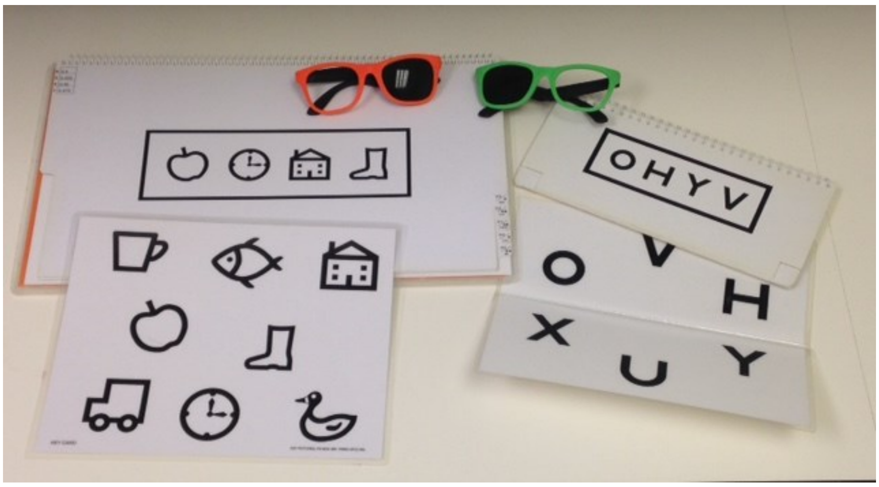


Figure 4.1. Kay Picture Crowded and Keeler LogMAR tests with occluder glasses.

Distance visual acuity

Distance visual acuity was measured by presenting the child's preferred test from a distance of 3 m. Children could verbally identify the letters or pictures in the chart or match them on a card. For those children who decided to verbally identify the letters or the pictures, the examiner first asked them to verbally name all the letters or pictures of the matching card.

The examiner occluded the left eye of the participant first with a pair of occluding glasses (Figure 4.1), positioned herself 3 m away from the child, and presented the first page of the test. The child was asked to name or alternatively match the first picture of the row of four. This procedure was repeated for smaller sizes of pictures or letters. When a child failed to recognise the first picture or letter from a row of four, the examiner checked the other pictures or letters in the same row. The visual acuity threshold recorded corresponded with the smallest line in which the child could identify 2 or more pictures. The procedure was repeated occluding the right eye with the occluding glasses. After that, the examiner presented the last line of pictures or letters that the child was able to see monocularly. The examiner asked the child to name or match all the pictures on that row. If two or more pictures or letters from that row were correctly named or matched, the examiner presented the next smaller size and the procedure was repeated until reaching the child's threshold in binocular conditions. The threshold recorded corresponded with the smallest line in which the child could identify 2 or more pictures/letters.

Near visual acuity

Near Visual acuity was measured by presenting the near version of the child's preferred test at 40 cm. Monocular and binocular visual acuities at near were measured in each participant using the same procedure described for measuring distance visual acuity.

4.2.2. Ocular alignment

Ocular alignment can be evaluated using the cover test, Hirchberg test or Krimsky test (Griffin and Grisham 2002b). The Hirchberg and Krimky tests use the corneal reflex as a way to evaluate ocular alignment. These tests are extremely useful in very young children as little cooperation is required, and they provide a good estimate of ocular alignment. However, they are not sensitive enough to detect large phorias or small tropias (Griffin and Grisham 2002b). The cover test has been described as a more precise and an easy enough procedure to evaluate ocular alignment in children, but it requires more cooperation from the subject in order to maintain fixation on the target while the examiner is performing the test. In the following studies, we used the cover test to evaluate the presence of phorias and tropias as it is more precise than the other tests described and because it is appropriate for the age range of the participants.

Distance cover test

For the distance cover test, the participant was asked to fixate on a cartoon picture placed in the wall 3 m away. To maintain the participant's attention, the examiner asked questions regarding the picture. While the participant was fixating on the picture, the examiner covered the left eye with an occluder and assessed the movement of the right eye (uncovered eye). A movement of the unoccluded eye in this situation suggested a tropia, and if observed, the direction and an approximation of the magnitude (small, medium or large) were recorded. When the occluder was removed from the left eye, the examiner watched for any movement of the left eye (previously occluded eye). A movement of the occluded eye just after removing the occluder suggested heterophoria, and if observed, the direction and the magnitude (small, medium or large) were recorded. This procedure was then repeated for the right eye to evaluate the presence of strabismus in the left eye. Finally, each eye was covered and the occluder alternated between the two eyes several times (alternating cover test). The examiner watched both eyes for movement to detect heterophoria in case it was missed during the unilateral cover test.

Near cover test

The above procedure was repeated using a fixation stick as a near target in order to assess near ocular alignment. The fixation stick, which was placed 40 cm away from the participant's eyes, had a picture printed on it (Figure 4.2). In order to maintain the participant's attention, the examiner kept on asking questions regarding the picture presented on the fixation target.

4.2.3. <u>Convergence</u>

Near Point Convergence (NPC)

To assess convergence ability, the same near target was used (Figure 4.2). Immediately after performing the near cover test, the participant was asked to keep looking at the picture printed on the fixation stick placed at 40 cm. The participant's attention was attracted by asking him/her to look at a small detail from the picture (e.g. "the monkey's nose") and name what color this feature was. At the same time, the examiner slowly moved the fixation stick towards the participant, while observing the participant's vergence movement. Objective NPC was performed so that the children were not asked to report double vision, and when the examiner observed a break of the convergence (divergence and monocular fixation), that was considered as the NPC. The examiner recorded NPC was <5 cm and if NPC >5 cm, the distance from the convergence break up point to the nose was measured with a tape measure or ruler.

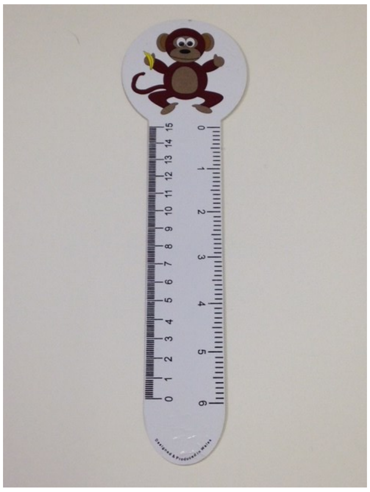


Figure 4.2. Near fixation target.

4.2.4. Stereopsis

Tests designed to measure stereopsis present slightly different images to each eye, creating a retinal disparity so 3D and depth can be perceived. Some tests, including the Titmus test and the Randot test, use spectacles (with polarized or coloured filters) to present a slightly different image to each eye. Alternatively, other tests such as the Frisby and the Lang stereotests accomplish the same with no glasses by using real depth stereopsis or prism separation.

The Frisby stereotest

A slightly modified version of the Frisby stereotest was used in our studies. A demonstration plate was introduced in order to differentiate children who have a genuine binocular deficit from those who do not understand the test (Saunders et al. 1996). The demonstration plate has the same shape and size as the traditional Frisby plates but it contains 3 empty squares and a square that contains a random-dot circle. This circle can be seen by participants with and without any binocular anomaly and is used to check the participant's comprehension of the test. Each participant was asked to find the "blue ball" and was encouraged to touch the circle. Younger children (4 to 7 year old) were asked to find "the blue ball", and when "pressing the blue ball", they were rewarded with a sound produced from a toy hidden behind the test and between the examiner knees (Saunders et al. 1996). After presenting the demonstration plate, the examiner presented the traditional Frisby plates beginning with the largest disparity plate. Each plate was presented twice, and after each presentation, the examiner hid the plate behind her back and rotated the plate, so the orientation of the random-dot circle was changed and the same plate was presented. If the participant located the target on two consecutive trials, the next plate (with decreasing disparity) was presented. The end point was reached when the patient failed to locate the target or located the target from the last plate. The testing distance used was 40 cm so the disparities recorded by the examiner were 340 sec arc, 170 sec arc or 85 sec arc for the first, second and third plate, respectively.

4.2.5. Ocular motility assessment

The examiner assessed ocular motility using a pen torch with a toy target (Figure 4.3) that was initially positioned in the participant's vision midline about 40 cm away. The examiner asked the participant to keep on looking at the illuminated target while she moved the target from the participant's vision midline to the left (patient's right), then returning to the centre and finally to the right (patient's left). The procedure was repeated in the vertical meridian along the participant medial plane to assess vertical smooth pursuit. The velocity of the target was slow, and the examiner tried to maintain it constant throughout the test. The examiner objectively judged on the quality of the eye movements during the task. If no difficulties or eye movement deficits were observed the examiner recorded "SPEC" that stands for "smooth, precise, extense and complete" eye movements. Alternatively, if these features were not observed the examiner recorded the characteristics of the eye movements observed (jerky, saccadic intrusions, restricted at certain positions, etc.)

Figure 4.3. Motility fixation targets.

4.2.6. Refractive error

In general, the standard procedures of static retinoscopy followed by a subjective exam are not feasible in all children. The available retinoscopy techniques to obtain refractive error from children are: (1) static distance retinoscopy, (2) distance cycloplegic retinocopy, and (3) Mohindra retinoscopy. As already described in chapter 3, section 3.8.1 Mohindra retinoscopy is the best approach for our studies for obvious reasons: it is much more child-friendly, no waiting time for drops to take effect is required, and cycloplegic refraction would not allow us to perform the eye movement recording on the same occasion. This retinoscopic technique takes place in complete darkness and is performed while the participant fixates at the examiner's retinoscope light, placed 50 cm away from the patient.

Unfortunately, Mohindra retinoscopy could not be performed in two of our studies as complete darkeness could not be achieved in the rooms that the schools made available for the study. Therefore, Mohindra retinoscopy as described in chapter 3, (section 3.8.1) was used to obtain the refractive error from child participants in the studies involving atypical children and children referred with suspected eye movement disorders (chapter 7). In contrast, static distance retinoscopy was used in the studies performed in the schools (chapters 5 and 6) with the aim of screening for evident refractive errors (Basra-Badh et al. 2013). For the static distance retinoscopy, the examiner asked the participant to fixate at a target placed on the wall 3 m away. In order to keep the participants' attention, the examiner constantly asked questions regarding the target. The examiner positioned herself and held the retinoscope at arm's length away from the participant. Retinoscopy was performed on each eye by neutralizing the retinal reflex in the most powerful meridian first. Once this meridian was neutralized using spherical lenses, the perpendicular meridian was assessed. If the examiner noticed a large retinal reflex in this meridian suggesting a cylinder of more than 1.00D, the examiner neutralized it with cylindrical trial lenses. If the observed retinal reflex in this meridian was very bright and had a very fast movement (suggesting it was close to neutralization), the examiner did not fully neutralize the reflex. After retinoscopy, the examiner working distance (+1.75D) was subtracted from the result and recorded in the sphero-cylinder form. If the cylinder was not neutralized (for low cylinders) the examiner recorded the spherical refractive error result and noted that a cylinder lower than 1.00DC was observed.

4.2.7. Accommodation

Amplitude of accommodation is measured in adults using the approximation and the "push up" methods. These are very subjective and require a lot of cooperation and understanding of the test as the participant has to report when the presented target is clear and when it becomes blurred. Although these methods are widely used to assess accommodation, they have been described to be challenging to accurately determine accommodative function in children aged 4-11 (Adler et al. 2013). For that reason, dynamic retinoscopy was used as an alternative and objective method to assess accommodative function.

The examiner objectively assessed accommodation accuracy using dynamic retinoscopy with the Ulster-Cardiff (UC) cube (Figure 4.4). The target in this UC Cube is an illuminated Perspex cube with a picture on each face. The UC cube was placed on the near point ruler at 25 cm. Questions about the illuminated picture presented were asked during the task to stimulate accommodation and maintain the participant's attention. The examiner placed the retinoscope alongside the target and evaluated the retinoscopic reflex while the participant was looking at the target. If the child was not accommodating accurately and a retinal reflex was observed, the retinoscope was moved further away from (with reflex - underaccommodating) or closer to (against reflex - overaccommodating) the child. The dioptric difference between the target and the neutral reflex were recorded if there was a lag or a lead of more than +1.00D (i.e. outside of the normative range). If accommodation was within the norms (+/-1.00D from the UC Cube position), the examiner recorded "within the norms".

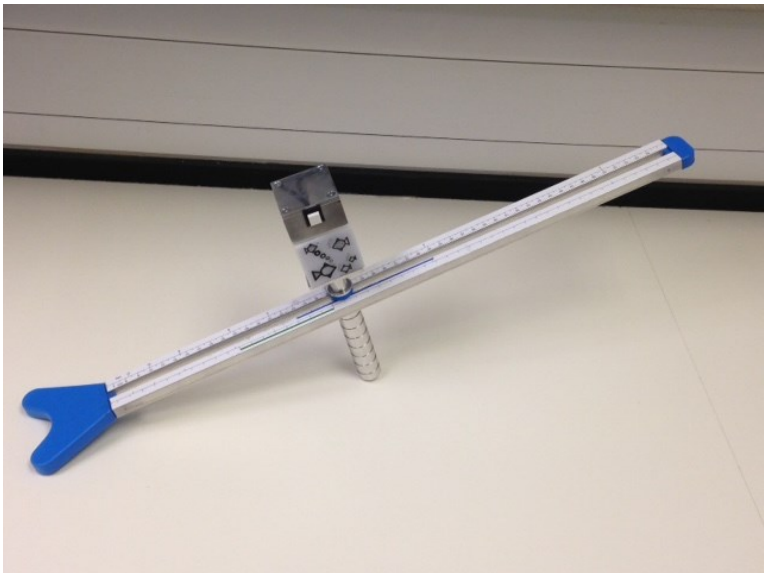


Figure 4.4. UC Cube.

4.3. Eye movement recording

Eye movement recordings were obtained in binocular conditions using the Tobii TX300 eye tracker. Children were seated 65 cm away from the computer monitor and the eye tracker with their eyes in primary position and facing the centre of the computer monitor. The child-friendly head stabiliser was intended to be used in all children to maintain their head at the same distance from the eye tracker and the screen throughout the test. However, some children aged ten and eleven preferred not to use the head stabiliser. In this situation, the researcher explained to the child the importance of keeping the head still at the same distance from the screen throughout the test.

Before the calibration and the eye movement recording, the height of the participant's chair and/or eye tracker desk was adjusted to ensure that the subject's eyes were positioned in front of the geometrical centre of the screen and also the central calibration point. This was ensured by carefully assessing the eye position in the pre-calibration window screen (Figure 4.5). If needed, the participant or the eye tracker horizontal position was also adjusted.

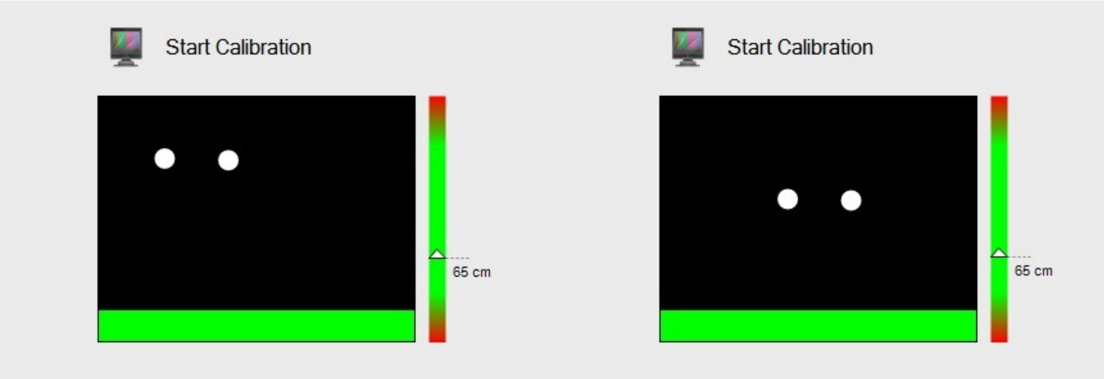


Figure 4.5. Pre-calibration window showing a non-aligned participant (left) and an optimally aligned participant (right).

4.3.1. Calibration

Prior to the eye movement recording, the eye tracker was calibrated for each participant using the standard Tobii 5 point calibration. During the calibration procedure, Tobii Studio™ presented a target (red dot) that randomly moved to 5 points on the screen, including the geometric centre and the 4 corners of the screen. All stimuli presented later were contained within the calibrated area, which corresponded with the widescreen dimensions. Once the calibration was finished, Tobii Studio™ presented the quality of the calibration (Figure 4.6). If the post calibration screen showed no calibration, bad calibration or poor eye movement detection for one or more of the calibration points (Figure 4.6 right), calibration was repeated, and it was only accepted when the eye movement positions were calibrated for all 5 points presented (Figure 4.6 left).

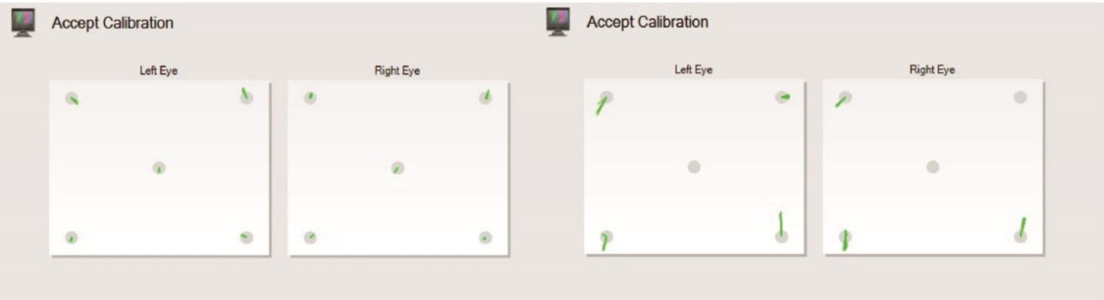


Figure 4.6. Calibration window showing a desired calibration (left) and an offset and incomplete calibration (right).

4.3.2. Eye movement recordings tasks

Eye movements were recorded while the participants performed a set of visual tasks. Three different visual tasks were presented so that three different eye movements could be studied: smooth pursuits, saccades and visual fixation. The three eye movement tasks were performed in the same order by all the participants.

Smooth pursuit

The first task performed was the smooth pursuit eye movement. This task was chosen as the first one because it requires more attention engagement than the saccadic task.

Smooth pursuit motion paradigms do not have a significant effect on smooth pursuit performance, as previously assessed and discussed in chapter 3. The results presented in the pilot studies from chapter 3 imply that any motion paradigm can be used to assess smooth pursuit in school-age children, as the eye movement performance, would not be affected by the paradigm used. Hence, the customised animated stimulus described in chapter 3, section 3.4.1 was presented following a ramp motion paradigm. In addition, two velocities were tested, so the smooth pursuit system could be studied at a slow, easy condition and also at a more challenging level at which the smooth pursuit system was pushed to higher limits of performance.

An initial start button was displayed in the center of the screen before the test began (Figure 4.7). When the participant was ready, the researcher clicked the start button and the smooth pursuit test started by presenting the customised animated stimulus moving horizontally at a constant velocity of 6º/s and then followed by a 12º/s stimulus velocity. This stimulus presentation was identical to that described in the pilot studies with adult participants in chapter 3, section 3.6.1. Then, the same stimulus was presented moving vertically following the same motion paradigm and velocities. The amplitude of the target movement was 20º, ±10º from the geometric centre of the screen (see diagram in chapter 3, Figure 3.7).

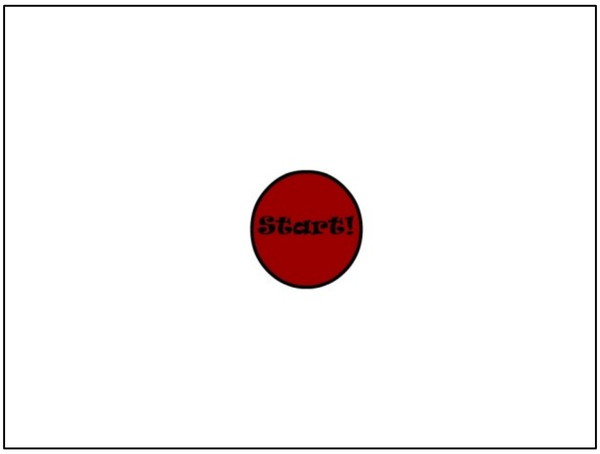


Figure 4.7. Start screen.

Saccades

After the smooth pursuit task, the eye movements were recorded while the participants were performing a saccadic test. The stimuli used for eliciting saccades consisted of animal cartoons of 2º of visual angle (see details of stimulus in chapter 3, section 3.4.2) at a viewing distance of 65 cm. Saccades were first assessed in the horizontal plane followed by the assessment of saccades in the vertical plane.

<u>Horizontal Saccades</u>

Traditionally, saccadic main sequences are studied by repeatedly presenting stimuli at different amplitudes from a central fixation point so that each saccade starts from the same central position. To obtain the saccadic main sequence with this method it would be necessary to present a large number of stimuli and the testing time would be approximately 10 minutes. We presumed that this method would be challenging for the children in our case group (atypical children and children with delayed reading skills) as it requires continuous effort and concentration for a long period of time. Hence, we proposed a modification of the traditional saccadic main sequence method in which the target does not return to the centre after each presentation, and therefore, each saccade is started from the previous position. This modification was implemented to decrease the overall testing time and make the test more appropriate for all children to be tested. In addition, typical school-age children might also benefit from this modification, as possible fatigue effects would be minimised, and they would spend less time away from their classrooms.

Saccades of 5º, 10º, 15º and 20º amplitude to the left and to the right without gaps or overlaps were elicited so that, after each saccadic stimulus presentation, the previous one disappeared simultaneously. The order of the saccadic amplitude was randomised, and a total of 64 saccades were elicited, 8 saccades for each amplitude and direction (with traditional method 128 saccadic presentations would be needed). Gellerman Fellow sequences were combined (Fellows 1967) to avoid eliciting more than three consecutive saccades in the same direction and the time of the target presentation for each saccade was randomised, ranging between 0.5 and 2 seconds. These approaches were taken to avoid children being able to predict when and where the next saccadic stimulus would be presented. All children were tested using the same sequence and order of stimuli presentations, so they all did exactly the same saccadic test.

An initial star-shaped fixation target was displayed in the centre of the screen before the test started. When the participant was ready to start, the researcher clicked the mouse and the first target was presented.

<u>Vertical saccades</u>

Saccades of 5º, 10º and 15º of amplitude upward and downward were elicited. A total of 48 vertical saccades were elicited, 8 for each amplitude and direction. The characteristics of the vertical saccadic test were the same as the ones established for the horizontal saccadic test. Saccades of 20º could not be elicited for the vertical main sequence because the amplitude was limited by the height of the widescreen monitor. Saccadic amplitudes and duration of stimulus presentation were randomised, and no more than three saccades were elicited towards the same direction. The same sequence and order of the target presentation was presented to each participant, so all participants did exactly the same vertical saccadic test.

Visual fixation

The saccadic test was followed by the visual fixation test. An initial start button was displayed in the centre of the screen before the test started. When the participant was ready, the researcher clicked the start button and the fixation presentation began. The customised 2º animated stimulus was also used in this test (see details of stimulus in chapter 3, section 3.4.3). The stimulus was placed in the centre of the screen on a white background. In this case, the stimulus did not move or change its location on the screen but continuously changed shape and colour, morphing into different animal cartoons throughout the test. The stimulus was presented for 8 seconds.

4.3.3. Data Analysis

The raw eye position data for each eye movement test was obtained from the eye tracker software. These data were generated in the form of .tsv files and included the timestamp, horizontal eye position and vertical eye position. The files were exported to Microsoft Excel and finally saved as .xlms files.

The eye position traces were analysed offline using custom software written in Matlab (The Mathworks, Inc., Natick, Massachussets, United States). An automatic program was written to initially convert the eye position data from millimetres (eye position in the screen) to degrees of visual angle. Then, eye velocity was obtained by differentiating the eye position over time and smoothed with a 3 window moving average filter, to reduce the additional noise arose from the differentiation process (Behrens and Weiss 1992). After this, an .xlms file that contained the timestamp, the eye position in degrees and the velocity in degrees per second was generated so that it could be directly input into the saccadic detector algorithm.

Saccadic detector

The adaptive threshold algorithm described by Behrens et al. (2010) was used to automatically detect saccades in the smooth pursuits, saccades in the saccadic task and saccades during the visual fixation task. This algorithm calculates the acceleration signal (differentiating eye velocity over time) and analyses this signal in relation to the preceding acceleration data. The basic principle of this algorithm is that the acceleration signal during a fixation or a smooth pursuit eye movement is 0, and therefore, changes in that signal, which are related to saccades, would be easily detected (acceleration signal values different from 0). However, noise is always present, and consequently, acceleration values constantly vary and are rarely 0. The adaptive threshold algorithm uses the standard deviation of the 200 preceding acceleration data points and the factor N which was determined experimentally by the authors (N=3.4) to define and set the acceleration thresholds. Most of the acceleration signal with its noise will fall in the interval between +3.4*SD and -3.4*SD and a saccade would be detected only when the acceleration signal is out of these calculated limits. Furthermore, this threshold is modified and re-established (in accordance with the preceding acceleration values) after the saccade has ended and the acceleration has decreased. Figure 4.8 illustrates how the algorithm works.

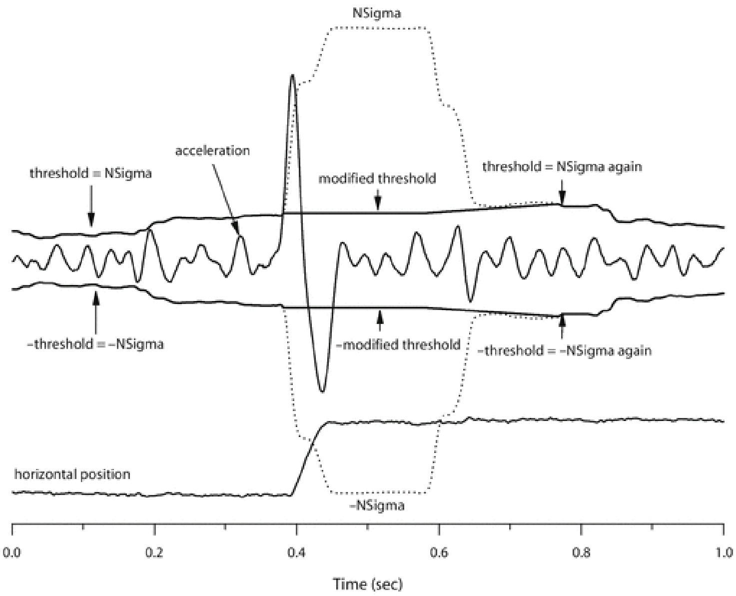


Figure 4.8. Adaptive Threshold Algorithm (Behrens et al. 2010).

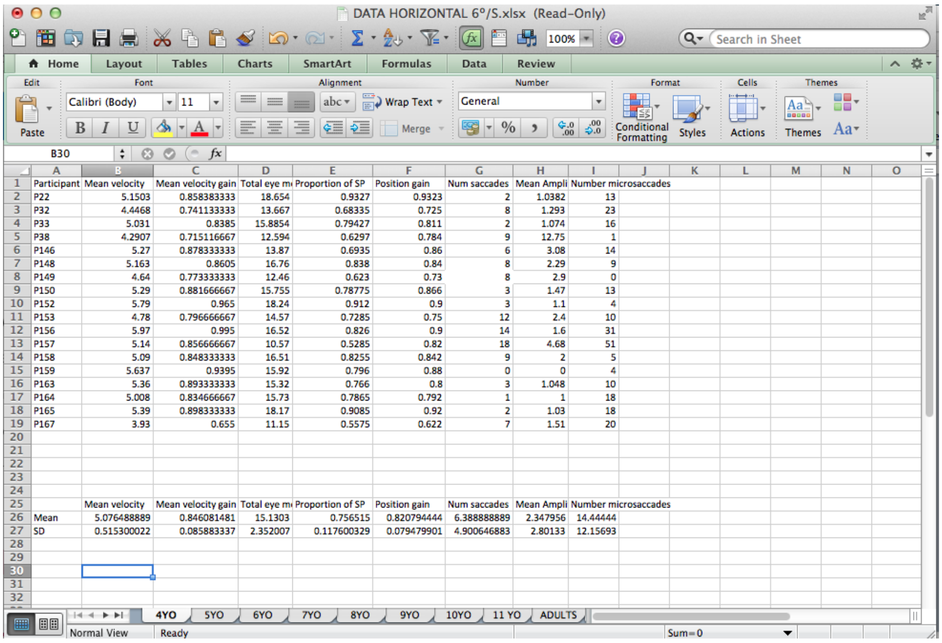
Smooth pursuit

The adaptive threshold algorithm described above was used to detect saccades during the smooth pursuit task. The eye movement traces for the smooth pursuit task and the saccades detected with the algorithm were plotted and displayed on the computer monitor. Periods of smooth pursuit that were free of saccades were further analysed as described in the previous smooth pursuit analysis (see chapter 3, section 3.6.1) to obtain velocity gain, position gain and the total proportion of SP.

Position gain is defined as the ratio between the eye position and the target position, and it indicates how accurately the eyes match the position of the stimulus during its movement. Position gains below 1 indicate that the position of the eyes lags behind the position of the stimulus, and position gains above 1 imply that the position of the eyes leads the position of the stimulus, i.e. the eyes are ahead of the stimulus. Similarly, velocity gain indicates in the same manner how accurate the velocity of the eyes is with respect to the velocity of the stimulus. Both gain measurements provide information about ability of the eyes to match the moving stimulus. The proportion of SP is defined as the total smooth pursuit (i.e. without saccades) divided by the total stimulus movement (20º). This measure shows the proportion or ratio of the smooth pursuit produced by the participant out of the total smooth pursuit demanded by the target movement amplitude. The number of saccades detected by the algorithm and their amplitude (eye position end of saccade subtracted by the eye position at the beginning of the saccade) were also obtained and used to further evaluate the quality of the smooth pursuit.

A customised Matlab program generated an Excel file for each participant and smooth pursuit task (6º/s and 12º/s, horizontal and vertical) that contained mean velocity gain, mean position gain, number of saccades (≥1º amplitude), mean amplitude of saccades (≥1º amplitude) and the number of microsaccades (≤1º amplitude) (details in chapter 3, section 3.6.1 and chapter 3, Figure 3.11).

Finally, a new Excel file was created for each smooth pursuit task (6º/s horizontal, 12º/s horizontal, 6º/s vertical, 12º/s vertical) that contained the smooth pursuit performance parameters for all the study participants. In this file, data from the participants were entered into separate Excel sheets according to their age and the values obtained from all participants in each age group were averaged to obtain the mean value for each age group (Figure 4.9). Excel files like that shown in Figure 4.9 were created for each study and group of participants (chapter 5: typical developing school age children, chapter 6: children with reading related difficulties and chapter 7: children referred with eye movement difficulties).



Participant	Mean velocity	Mean velocity gain	Total eye m	Proportion of SP	Position gain	Num saccades	Mean Ampli	Number microsaccades
P22	5.1503	0.858383333	18.654	0.9327	0.9323	2	1.0382	13
P32	4.4468	0.741133333	13.667	0.68335	0.725	8	1.293	23
P33	5.031	0.8385	15.8854	0.79427	0.811	2	1.074	16
P38	4.2907	0.715116667	12.594	0.6297	0.784	9	12.75	1
P146	5.27	0.878333333	13.87	0.6935	0.86	6	3.08	14
P148	5.163	0.8605	16.76	0.838	0.84	8	2.29	9
P149	4.64	0.773333333	12.46	0.623	0.73	8	2.9	0
P150	5.29	0.881666667	15.755	0.78775	0.866	3	1.47	13
P152	5.79	0.965	18.24	0.912	0.9	3	1.1	4
P153	4.78	0.796666667	14.57	0.7285	0.75	12	2.4	10
P156	5.97	0.995	16.52	0.826	0.9	14	1.6	31
P157	5.14	0.856666667	10.57	0.5285	0.82	18	4.68	51
P158	5.09	0.848333333	16.51	0.8255	0.842	9	2	5
P159	5.637	0.9395	15.92	0.796	0.88	0	0	4
P163	5.36	0.893333333	15.32	0.766	0.8	3	1.048	10
P164	5.008	0.834666667	15.73	0.7865	0.792	1	1	18
P165	5.39	0.898333333	18.17	0.9085	0.92	2	1.03	18
P167	3.93	0.655	11.15	0.5575	0.622	7	1.51	20

	Mean velocity	Mean velocity gain	Total eye m	Proportion of SP	Position gain	Num saccades	Mean Ampli	Number microsaccades
Mean	5.076488889	0.846081481	15.1303	0.756515	0.820794444	6.388888889	2.347956	14.44444
SD	0.515300022	0.085883337	2.352007	0.117600329	0.079479901	4.900646883	2.80133	12.15693

Figure 4.9. Final Excel file for 6º/s horizontal smooth pursuit obtained for the study presented in chapter 5.

Saccades

Saccades were automatically detected with the adaptive threshold algorithm described by Behrens et al. (2010), which was also used in the smooth pursuit analysis. After detecting the saccades, data were plotted marking the saccades and displayed on the computer monitor (Figure 4.10).

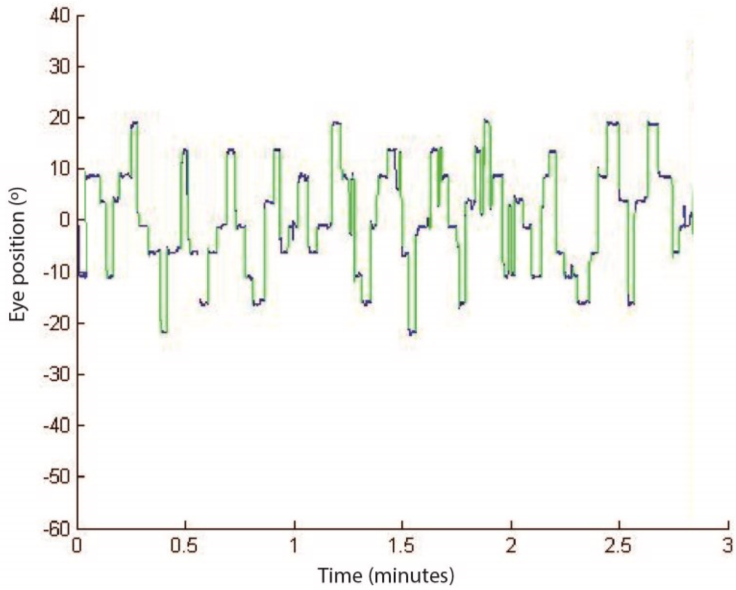


Figure 4.10. Eye movement traces for the saccadic task with the detected saccades (green) marked using the adaptive threshold algorithm described by Behrens et al. 2010.

The amplitude, duration and peak velocity of all the saccades detected were calculated with a custom program written in Matlab. The amplitude and the duration of the saccades were obtained by subtracting the time and position at the end of each saccade from the time and position of the start of each saccade detected. The peak velocity was defined as the maximum velocity during the saccade. The program obtained this parameter automatically by using an inbuilt Matlab function (Max) that returns the largest/maximum value from a vector or matrix. Hence, this function detected the maximum velocity value of each one of the saccades detected with the adaptive threshold algorithm.

Only saccades with amplitudes above 4º were used for regression and statistical analysis (Garbutt et al. 2001). Typical peak velocities for saccades of 20º of amplitude range between 450º/s and 600º/s (Boghen et al. 1974). Detected saccades with velocities higher than 700º/s indicated a large amplitude saccade (larger than 20º) and suggested that the child may have looked away from the screen. Thus, saccades with peak velocities above 700º/s were considered an artefact and were removed from further analysis.

Saccades show a unique feature, which is that they have a consistent relationship between their peak velocity and their amplitude as well as between their duration and their amplitude (Bahill 1975). These relationships, known as saccadic main sequences, have been used to characterise normal saccades, and they provide invaluable information regarding the saccadic dynamics of an individual. The main sequence has been further reported to be a very powerful tool to study saccadic eye movements, their neurophysiological control and to define "normalcy" of saccades (Bahill 1975). For that reason, main sequence duration vs amplitude, peak velocity vs amplitude and peak velocity x duration vs amplitude were studied (for more details on the saccadic main sequence relationship see chapter 1, section 1.2.2) . Additionally, saccadic gains for the different saccadic amplitudes tested were also studied.

Main sequence

Six plots were obtained for the horizontal and vertical saccadic task from each child participant. The main sequence plots for the horizontal saccadic test obtained from one of the participants in our study (P01) are presented below to illustrate in detail the saccadic analysis performed. Duration vs amplitude main sequence was obtained by plotting the amplitude (º) and the duration (ms) of each saccade detected in the X and Y axis, respectively. Two plots were obtained so the first one showed the duration vs amplitude main sequence separating the saccades to the left and to the right (or downward and upward saccades in the case of vertical saccades) (Figure 4.11), and the second one combined the saccades made towards both directions (Figure 4.12). A linear regression, as shown in Figure 4.12 was obtained for the saccades to the left, to the right and also for the saccades towards both directions combined (Figure 4.12). The slope (S) and intercept (I) obtained were displayed in the plot as shown in Figure 4.12 and were used for statistical purposes.

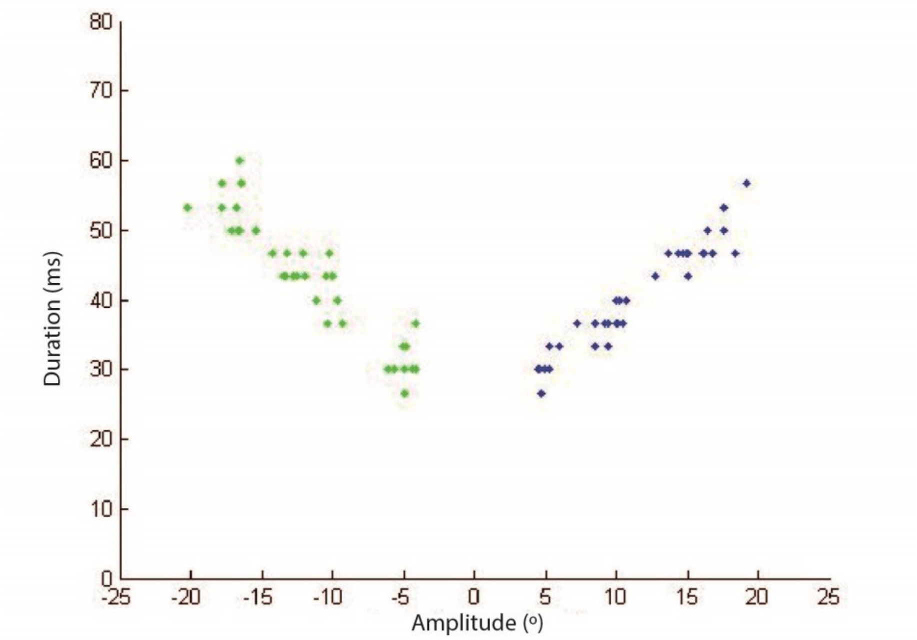


Figure 4.11. Duration vs amplitude main sequence obtained for participant P01 separating the left (green) and right (blue) saccades. The amplitude (º) and the duration of the saccades are plotted on the X and Y axis, respectively.

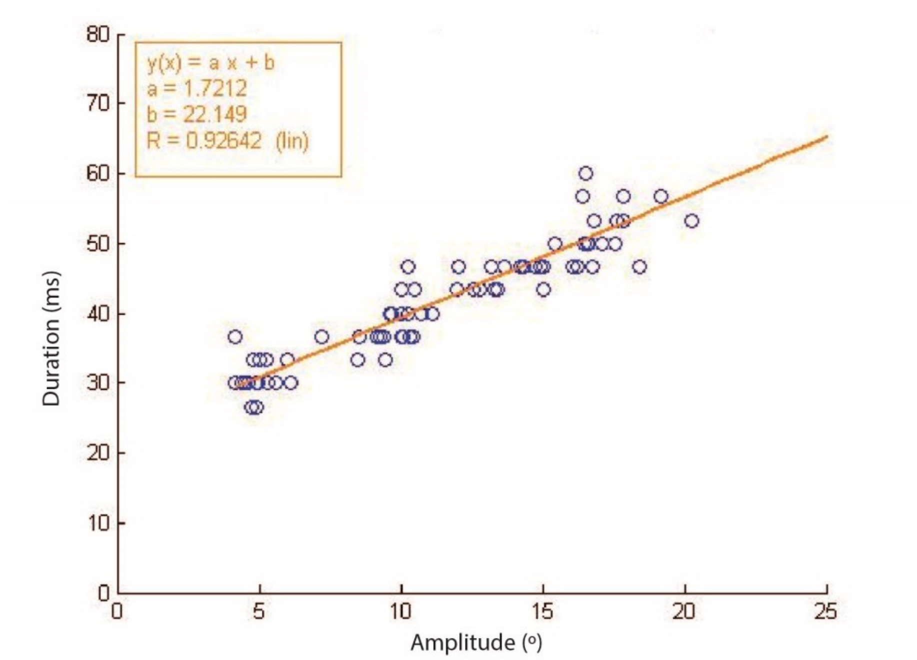


Figure 4.12. Duration vs amplitude main sequence and the corresponding linear regression for saccades to the left and to the right combined for participant P01.

For the peak velocity vs amplitude main sequence, the amplitude and the peak velocity of the saccades detected were plotted in the X and Y axis, respectively. Figure 4.13 shows peak velocity vs amplitude main sequence separating the saccades to the left and to the right obtained in the analysis from participant P01. The relationship between peak velocity and amplitude is not linear. Therefore, a power fit was performed ($y=Ax^n$) for this main sequence for each subject (Figure 4.14). This process has been described as being equivalent to a logarithmic (base 10) plot and curve fitting (Garbutt et al. 2001). Similarly, a power fit was obtained for the saccades to the left, to the right and for the all the saccades (both directions combined) (Figure 4.14). The parameters A and ^{n} were used for statistical purposes.

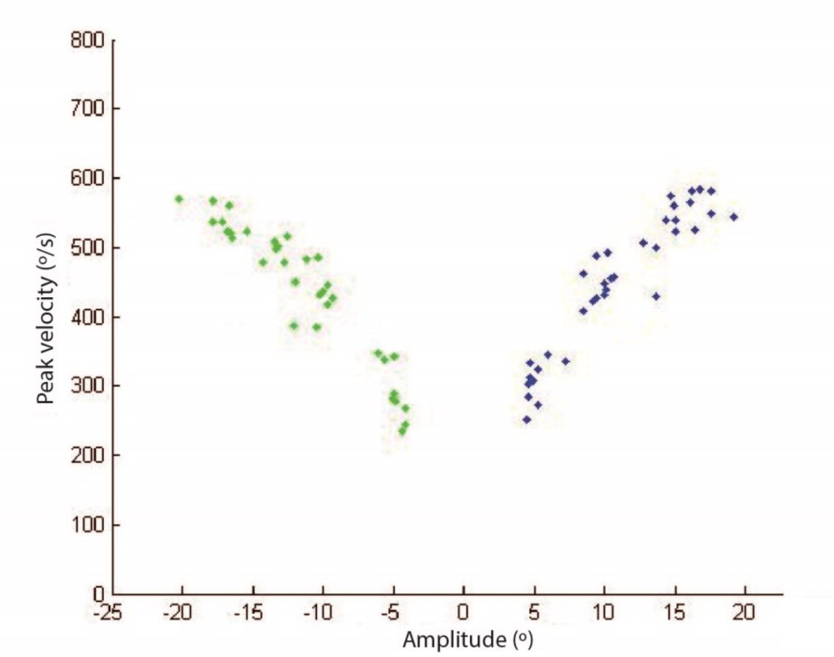


Figure 4.13. Peak velocity vs amplitude main sequence obtained for participant P01 separating the left (green) and right (blue) saccades. The amplitude (º) and the peak velocity (º/s) of the saccades are plotted in the X and Y axis, respectively.

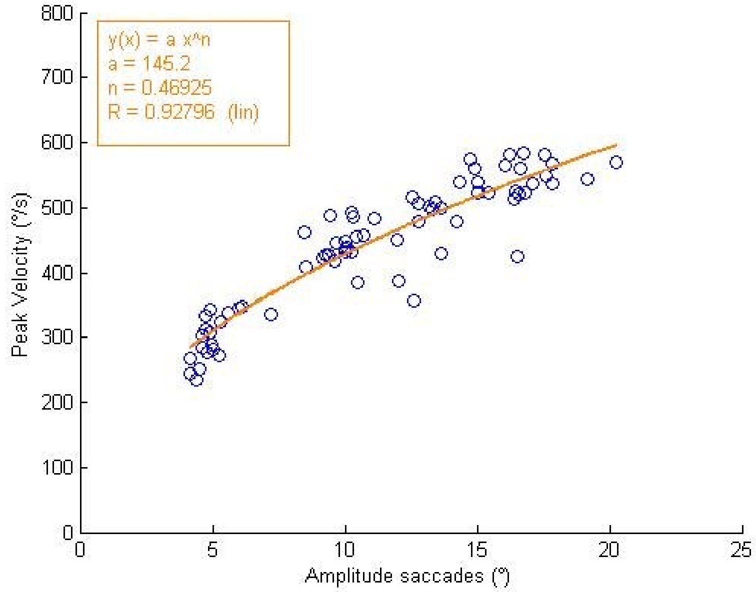


Figure 4.14. Peak velocity vs amplitude main sequence and the corresponding power fit for saccades to the left and to the right combined for participant P01.

It has been proposed that the ratio of peak velocity to mean velocity for the main sequence, Q, is between 1 and 2 (Di Stasi et al. 2013), and adult typical values mainly range from 1.54 and 1.80 (Harwood al. 1999; Garbutt et al. 2003a). To obtain this ratio, first the peak velocity*duration vs amplitude main sequence relationship is plotted. Figure 4.15 shows an example of this main sequence plotted for one of our participants (P01). Then, a regression line constrained though the origin (Figure 4.16) is fitted to obtain the ratio Q from the slope of the fitted line (Harwood et al. 1999). This parameter was obtained for each saccadic direction and also for both directions combined, and was also used for the statistical tests.

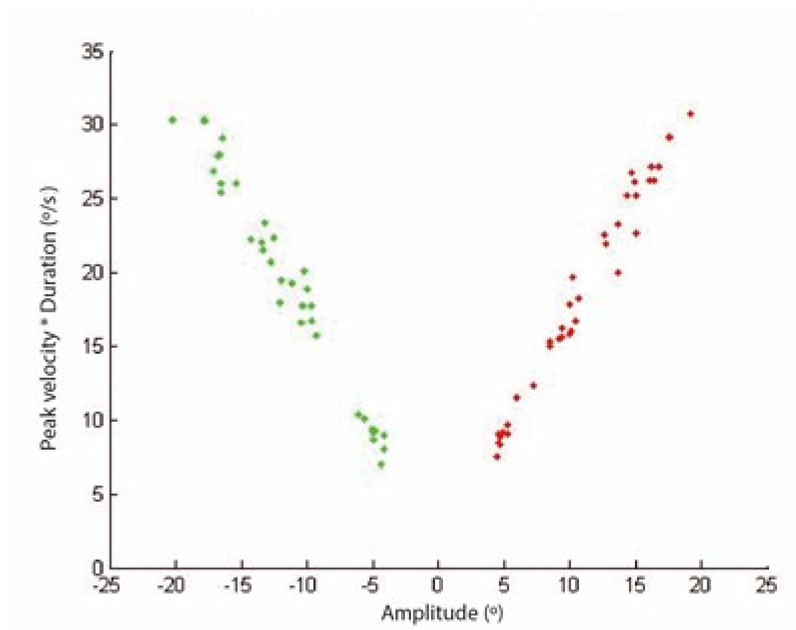


Figure 4.15. Peak velocity x duration vs amplitude main sequence obtained for participant P01 separating the left (green) and right (red) saccades. The amplitude (º) and the peak velocity x duration (º/s) of the saccades are plotted in the X and Y axis, respectively.

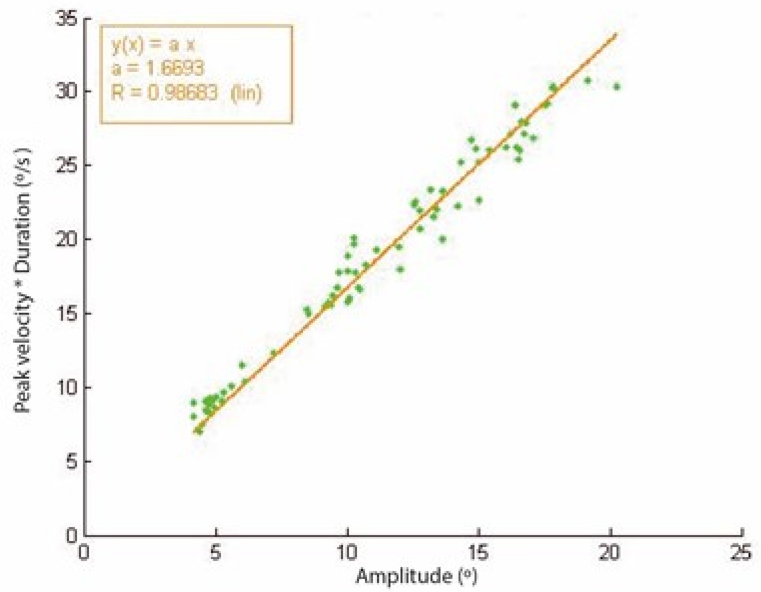


Figure 4.16. Peak velocity x duration vs amplitude main sequence and the corresponding linear regression through the origin for saccades to the left and to the right combined for participant P01.

Finally, an Excel file was created for each saccadic task (horizontal and vertical) that contained the main sequence parameters (S, I, A, n, Q) for all the study participants. The parameters S and I were obtained from the slope and the intercept of the duration vs amplitude main sequence, respectively and describe to the average velocity and duration of the saccades. The parameters A and n were obtained from the power fit function fitted on the peak velocity vs duration main sequence and describe the typical velocity profile of the saccade. The Q ratio which is obtained from the regression line through the origin on the peak velocity x duration vs amplitude main sequence and descrive the reatio mean to peak velocity. Excel files similar to that shown in Figure 4.9 were created for each study and group of participants (chapter 5: typical developing school age children; chapter 6: children with reading difficulties; chapter 7: children referred with eye movement difficulties) and contained the mean values for each saccadic parameter and age group.

<u>Gains</u>

The gain of a saccade is defined as the ratio of the amplitude of the saccade performed divided by the desired saccadic amplitude which is determined by the size of the target step. Hence, this parameter provides information about the accuracy of the saccades.

Saccadic gains of 1 indicate that after the saccade the eye position perfectly matched that of the target and therefore the saccade was accurate. Saccadic gains above or below 1 indicate less accurate saccades with hypermetria and hypometria, respectively.

The gain for each saccade performed was obtained dividing the amplitude of the first saccade after the stimulus presentation by the amplitude of the desired saccade determined by the amplitude of the stimulus step. The mean gain for each saccadic amplitude tested to the right, to the left and for both directions (for horizontal 5°, 10°, 15°, 20° and for vertical 5°, 10°, 15°) was obtained for each participant. Finally, all the gains obtained (to the right, to the left and for both direction) were organised in an Excel file that contained the mean saccadic gains for each amplitude and direction tested in each participant. The data were organised according to the age of the participants in a similar way as showed in Figure 4.9. Excel files containing these data were created for each study and group of participants (Chapter 5: typical developing school age children, Chapter 6: children with reading related difficulties and Chapter 7: children referred with eye movement difficulties).

Visual fixation

The parameters analysed for the visual fixation task were the total number of saccades during fixation (horizontal and vertical saccades), the mean amplitude of these saccades, the mean eye position (MEP) (horizontal and vertical) and the mean standard deviation of the eye position (SD of MEP) (horizontal and vertical). With these parameters, we aimed to investigate how stable fixation was throughout the 8 seconds that the fixation stimulus was presented. A large number of saccades as well as a large standard deviation would suggest that the eyes were not kept steady and, therefore, that visual fixation repeatedly drifted away from the target. Figure 4.17 has been added for illustration purposes and shows the eye position (º) relative to the screen (saccades not removed) of participant P01 during the entire visual fixation task. The central point of this graph and coordinates (0,0) in the graph correspond with the centre of the screen monitor. The mean eye position (MEP) (horizontal and vertical) and the standard deviations (SD) are also shown in the same figure.

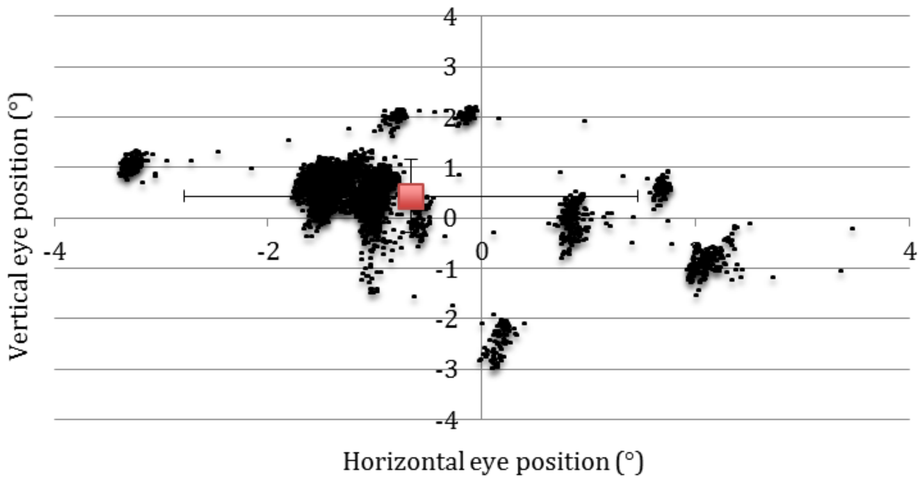


Figure 4.17. Eye position (º) relative to the centre of the screen during the fixation task obtained from participant (P01). The red square indicates the horizontal and vertical MEP.

The saccades during the fixation task were detected using the algorithm described in Figure 4.8. A custom written Matlab program counted the number of saccades, calculated the mean amplitude of the saccades as well as calculated the MEP and the mean SD of MEP. These calculated parameters were displayed in the Matlab command window. The values obtained for all the participants were organised by age and were transferred to an Excel file. The values for each visual fixation parameter obtained from all participants in each age group were averaged to obtain the mean value for each age group. An Excel file was created for study and group of participants (chapter 5: typical developing school age children, chapter 6: children with reading related difficulties and chapter 7: children referred with eye movement difficulties).

4.4. Summary

This chapter has described the methods and procedures for the following studies presented in this thesis. The chapter included detail descriptions of the procedures and tests used to assess the participants' vision and binocularity to ensure that the participants met the inclusion and exclusion criteria. In addition, it has detailed the technical aspects of the tasks presented to record eye movements and also the analysis performed on the data obtained.

The tables below (Tables 4.1 to 4.4) summarise the optometric and eye movement parameters obtained for each participant, age group (mean of each parameter for each age group) and group of children (mean of each parameter for typical developing children, children with reading related eye movement difficulties and children referred with eye movement difficulties).

For a comprehensive review on pathological conditions that have characteristically abnormal values for one or more of the components that emerge from the eye movement analysis described in this chapter, the reader is directed to the reviews by Karatekin et al. 2007, and Anderson and MacAskill 2013.

OPTOMETRIC TEST						
Distance and near VA (monocular and binocular)	Distance and near cover test	NPC	Stereopsis	Ocular motility	Refractive error	Accomodation (Acc)

Table 4.1. Table summarising the optometric parameters obtained for each participant.

SMOOTH PURSUIT (HORIZONTAL AND VERTICAL)					
Velocity gain	Position gain	Proportion of SP	Number of saccades	Mean amplitude of saccades	Number of microsaccades

Table 4.2. Table summarising the smooth pursuit parameters obtained for each participant.

SACCADES (HORIZONTAL AND VERTICAL)					
Slope (S)	Intercept (I)	Q ratio	A coefficient	n coefficient	Saccadic gains

Table 4.3. Table summarising the saccadic parameters obtained for each participant.

VISUAL FIXATION						
Horizontal mean eye position (MEP)	Vertical mean eye position (MEP)	Mean SD of horizontal MEP	Mean SD of vertical MEP	Number of saccades	Mean amplitude of saccades	Number of microsaccades

Table 4.4. Table summarising the visual fixation parameters obtained for each participant

Chapter 5 Normative values for eye movements in school age children

5.1. Introduction

Eye movement research to date has tended to focus on infant and adult populations rather than on school-age children. The development of eye movements has been reviewed in chapter 1, section 1.2, but in general, evidence from previous published studies suggests that saccades achieve adult values in infancy (von Hofsten and Rosander 1997; Lengyel et al. 1998; Grönqvist et al. 2006; Rutsche et al. 2006; Pieh et al. 2012), while smooth pursuit is still in development until early or mid adolescence (Ross et al. 1993; Katsanis et al. 1998; Salman et al. 2006a; Ingster-Moati et al. 2009).

In this thesis, we describe novel stimuli that are quite different from the conventional and standard stimuli used for eye movement research (chapter 3, section 3.4). We are not aware of any study using an *animated stimulus* to assess smooth pursuit or visual fixation, and we are only aware of one study in which cartoons were used to assess saccadic eye movements in children (Irving et al. 2011). For that reason, normative values for eye movements in school age children using the setup and procedures described in chapters 3 and 4 are needed, in order to compare these results with those obtained from children with delayed reading skills and/or learning difficulties, using the same setup and procedures. As will be apparent in the following chapters, all children were tested using the identical methods, procedures and setup, in order to ensure the ability to identify genuine differences in eye movements between children with and without learning related difficulties.

5.2. Aim

- To provide a full characterization of eye movements in school age children and normative values using the novel child-friendly stimuli, setup and procedures described in chapters 3 and 4

5.3. Primary schools participation

Letters were posted to ten primary schools located in the city of Cardiff. This area was chosen for its easy accessibility and transport facilities from the main research site. The letters, which were addressed to the heads of the schools, contained a brief explanation of the research and an invitation to participate in the study. A copy of the patient information sheet, the child information sheet and the consent form (Appendix E) were attached to the letter. If no answer from the school was obtained by two weeks after posting the invitation letter, the researcher phoned to personally invite the school to take part and further discuss the research. Only one school (Kitchener Primary School) agreed to take part in the study. Therefore, in order to obtain a higher response rate, the research team considered expanding the schools recruitment to areas in the outskirts of Cardiff. One of the project supervisors, Dr Maggie Woodhouse, suggested contacting her local school, White Rose Primary School, as this school had previously participated in her research. Dr Maggie Woodhouse personally contacted the head teacher of White Rose Primary School, and a meeting was arranged to meet the researcher and further discuss the study. After the meeting, the head teacher agreed to get the school involved in the study. Therefore, the schools and demographic areas included in the study were determined by the schools' interest and their willingness to participate.

Each school provided a room where the researcher could set up the eye tracker and conduct the study (Figure 5.1).

Figure 5.1. Eye tracker and optometric tests set up in White Rose Primary School.

5.3.1. Participants

One hundred sixty nine children were recruited from the two schools (75 females and 94 males) ranging in age from 4 to 11 years. The data of the children were divided according to their real age. Figure 5.2 shows the number of children and their gender per each age group.

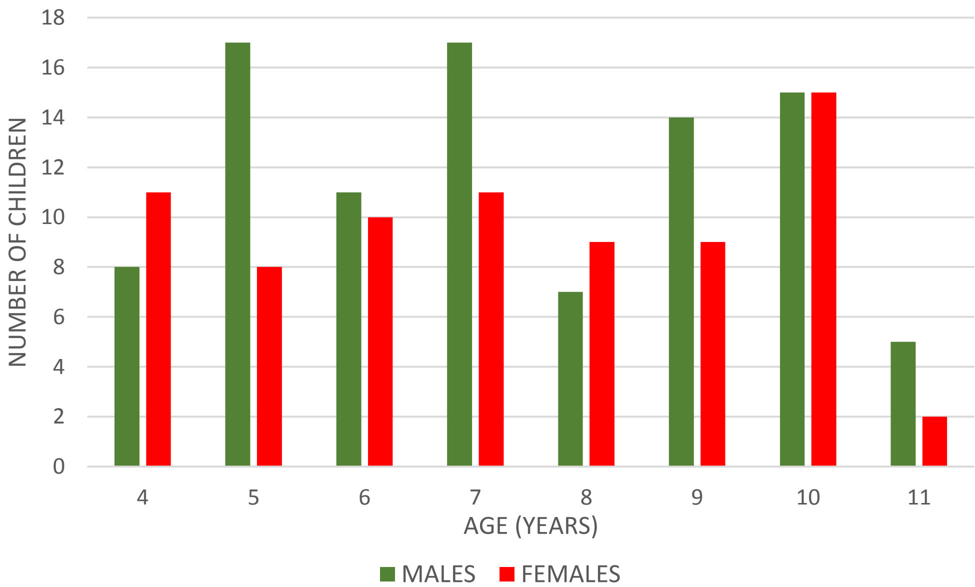


Figure 5.2. Histogram showing the age and gender distribution of all participants.

The data could have been combined to form broader “bins” containing children of certain age groups. For instance, children could have been grouped as: children between 4-6, 7-9 and 10-11 years. Combining data in such a way would result in a decrease in variability and an improvement in the population estimates. However, the disadvantage of grouping together children of different ages would be that each group would contain children with more widely different reading abilities as well as different education levels. Moreover, the approach taken in this thesis matches that found in most studies investigating oculomotor development (e.g. Salman et al. (2006a); Salman et al. 2006b; Ingster-Moat et al. 2009).

In Kitchener Primary School, the teachers and the school Special Education Needs Coordinator (SENCO) randomly selected thirty-four children (17 females and 17 males) from different age groups to take part in the study. This selection was performed as the school had a room available for the study for one week only, and therefore, the number of children that could take part was limited. The parents of the selected children were invited to a meeting to further discuss the study with the researcher and the school SENCO. After the meeting, the parents had time to read the information sheet and sign the consent form. Additionally, if they wished, they could take the consent form and the information sheets and have time to decide whether they wanted their child to take part or not.

The other hundred and thirty-five children (58 females and 77 males) were recruited from White Rose Primary School in Caerphilly County. This school has two classes per year group, and the researcher randomly chose, together with the school, a class per year group (one of the two classes). As requested by the head teacher to facilitate the logistics of the recruitment, the researcher provided the school with copies of the complete parent information sheet, a short version of this document, the child information sheet and an opting out form (Appendix E). The short version of the parent information sheet contained the researcher contact details and it stated that the complete version of the document could be obtained from her (by e-mail or post) or the school head teacher. The teachers enclosed the short version of the parent information sheet, the child information sheet and the opting out form in the bags of all the children from the randomly chosen classes. The school texted the parents of those children to inform them about the study and the documents provided. All children participated except those whose parents returned the opting out form and those who did not attend school during the days that the study was carried out.

Ten adult subjects (5 females and 5 males) with a mean age of 21.50 (SD±2.12), who were undergraduates at the School of Optometry and Vision Sciences at Cardiff University, were also recruited. Eye movement recordings were obtained from these adult subjects while they performed the smooth pursuit task, as this is the only type of eye movement that has been reported to still be in development in childhood and up to mid adolescence (Ross et al. 1993; Katsanis et al. 1998; Tajik-Parvinchi et al. 2003). Therefore, data from an adult group using our setup are also needed to establish when smooth pursuit has achieved adult-like values in children.

The protocol for the school study was approved by the School of Optometry and Vision Sciences Ethics and Audit Committee (Appendix C) and was designed in accordance with the Declaration of Helsinki. The information sheets, consent and opting out form used in the study were approved by the above-mentioned Ethics Committee (Appendix E).

5.4. Study design

A preliminary optometric test (details from the optometric test in chapter 4, section 4.2) was performed prior to the eye movement recording. This was to ensure that all child participants met the inclusion criteria. Children with visually impairing conditions and/or a logMAR visual acuity ≥0.3 were excluded from the study. According to the literature, uncorrected refractive errors can be found in 10-20% of children in European schools (O'Donoghue et al. 2010; Lanca et al. 2014), and these visual acuity criteria were set in order to include children with only low uncorrected refractive errors, mainly myopia (Luo et al. 2006). As a further exclusion criterion, children with a strabismus or refractive errors of more than 8D in the most powerful meridian were not recruited for the study.

Eye movements were recorded in all children in the following order: smooth pursuit (horizontal followed by vertical), saccades (horizontal followed by vertical) and finally fixation eye movements. The calibration, eye movement recording procedures and eye movement data analysis have been described previously in chapter 4, section 4.3.

Most of the children had the preliminary optometric test before the eye movement recording, as the researcher was responsible for both tasks. However, an optometrist occasionally helped so that two children could be seen at a time. In this situation, the optometrist tested the children while the researcher recorded their eye movements, and therefore a small number of children had their eye movements recorded first.

5.5. Children with IEP related to delayed reading skills

Some school-aged children benefit from an Individual Education Plan or IEP, which is a programme designed for children with learning and/or behavioural problems, disabilities, medical issues, etc. IEPs are aimed at describing areas in which a child is experiencing some difficulties and additional support is then provided. In agreement with this, children experiencing reading difficulties and whose reading skills are delayed compared to their peers have an *IEP related to delayed reading skills*. These children are provided with additional reading support in their school.

According to the Kitchener Primary School SENCO and the White Rose Primary School head teacher, in order to decide whether or not a child should hold an IEP related to delayed reading skills, the teachers use their own judgement as well as a list of assessments that include phonic knowledge, phonic skills, recognition of familiar words, sentence reading ability, vocabulary knowledge and text understanding/comprehension. The child's teacher, together with the school SENCO, judges whether or not the results of these tests and the teacher's assessment/observation are appropriate for the general educational curriculum at that age. Although the tests used and the teacher's assessments/observations might differ between schools, most schools would follow a similar process.

The researcher and the optometrists that occasionally helped in the data collection were masked regarding the learning difficulties and/or the Individualized Education Plans (IEP) of the child participants. During the study, the researcher and the optometrists only knew the name, age, school year and class of each child. After the data analysis was complete, the researcher contacted the SENCO and/or the head teacher of each school to obtain the information regarding which children from the sample had an IEP related to delayed reading skills.

The procedure to unmask the children who had an IEP with regard to reading difficulties and/or delayed reading skills was anonymised. The researcher gave the schools a list with the names of all the children from that school who took part in the study with their allocated participant numbers. The schools kept the lists and provided the researcher the participant numbers from those children who had an IEP related to delayed reading skills.

Forty-three children (25.44%) out of the 169 recruited children had an IEP related to delayed reading skills (Figure 5.3). The analysis described in this chapter evaluates the effect of age on eye movements in children without an IEP related to delayed reading skills (n=126). The data from the children with an IEP related to delayed reading skills (n=43) will be studied in detail in chapter 6. For the rest of this chapter, the simple term IEP will refer only to IEP related to delayed reading skills.

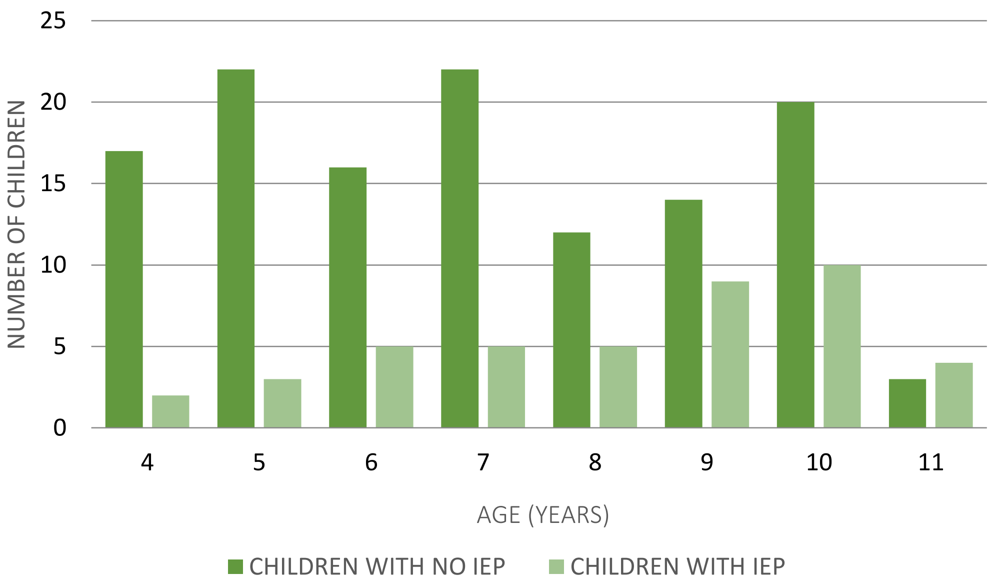


Figure 5.3. Histogram showing the age distribution of the children with and without IEP related to delayed reading skills.

5.6. Results

5.6.1. Optometric test

Data from 4 children who did not meet the inclusion criteria (2 children with nystagmus and 2 children with strabismus) and from 2 children in which the eye tracker was unable to calibrate (for unknown reasons their eyes were not accurately detected) were discarded from the eye movement analysis. Hence, data from a total of 120 participants were analysed and presented in the following results.

The mean absolute spherical refractive error in the children without an IEP was 0.67DS (SD±0.95) for the RE and 0.71DS (SD±1.09) for the LE. A significant cylinder (more than 1DC) was found in 3 children (2.5%). The maximum cylinder found was of -1.50DC.

The distance and near visual acuity from all children whose eye movement recordings were analysed (procedures described in chapter 4, section 4.3.3) and presented in this chapter ranged between logMAR +0.3 and logMAR -0.1 (Distance: mean RE VA logMAR +0.02 (SD±0.08), mean LE VA logMAR +0.03 (SD±0.09), mean binocular VA logMAR +0.01 (SD±0.08); Near: mean RE VA logMAR +0.01 (SD±0.05), mean

LE VA logMAR +0.01 (SD±0.05), mean binocular VA logMAR 0.00 (SD±0.05)). Figure 5.4 illustrates in detail the frequency distribution for distance and near visual acuity of the 120 children without IEP.

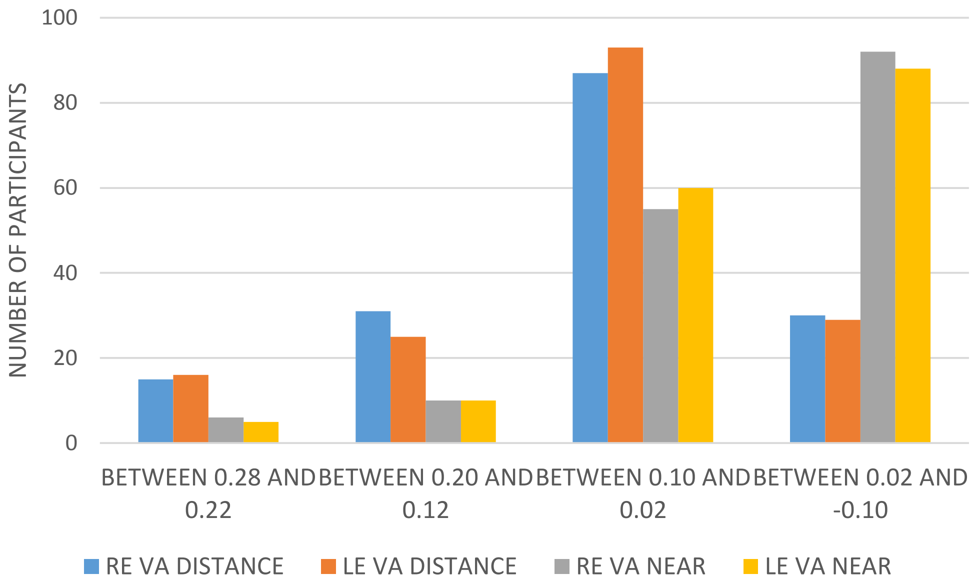


Figure 5.4. Histogram showing the logMAR visual acuity frequency distribution for the children with successful eye movement recordings.

The cover test results showed that one child (0.83%) had a high exophoria at distance, while the other 119 (99.16%) children were orthophoric at distance. At near, 86 (71.66%) children were orthophoric and 34 (28.33%) had phorias (Figure 5.5). Figure 5.6 illustrates the results obtained from the stereopsis test. Most of the children were able to see the third plate of the Frisby stereotest (85"). Two children were only able to see the first plate: both of them were aged 4.

With regards to the NPC, 111 (92.50%) children out of the 120 had their NPC at 5 cm or less. Nine children (7.50%) had NPC more than 5 cm with a maximum value of 8 cm.

The accommodation measurements taken with the UC cube placed at 25 cm showed that only 3 (2.50%) children were outside the norms, with a lag or lead of more than 1D (McClelland and Saunders 2004). Of these, two had a lag between 1D and 2D and one child had a 1.5D lead.

Finally, typical eye movements were found in 113 (94.16%) children with the motility test (recorded as SPEC (Smooth, Precise, Extense and Complete)). Seven children (5.8%) were recorded to have large head movements during the motility test.

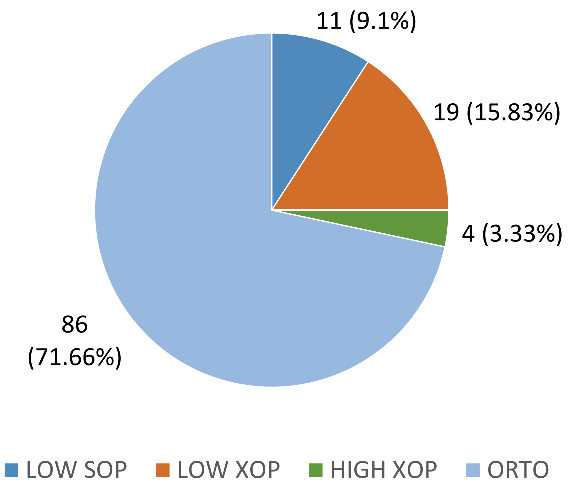


Figure 5.5. Pie chart showing the cover test frequency distribution for the child participants. ORTHO –orthophoria, SOP – esophoria, XOP –exophoria.

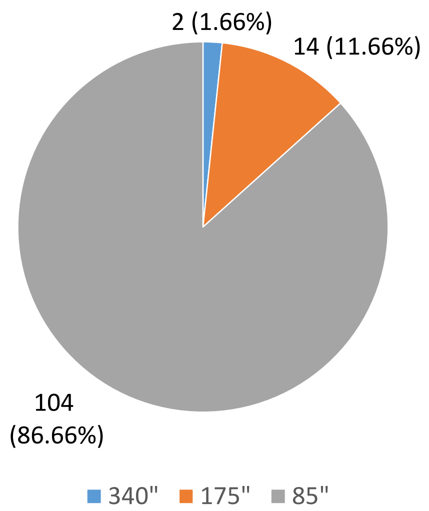


Figure 5.6. Pie chart showing the stereopsis frequency distribution for the children participants.

5.6.2. Eye movement recording success rate

During data analysis, the researcher discarded trials in which the eye movement trace was poor. For example, if in one of the smooth pursuit tasks the participant produced two or fewer ramps of smooth pursuit, this data set was discarded from the analysis (Figure 5.7). Successful smooth pursuit data from 119 (99.16%) and 118 (98.33%) children were obtained for the 6º/s and 12º/s horizontal smooth pursuit, respectively. For the vertical condition, data from 118 (98.33%) and 117 (97.5%) children were obtained for 6º/s and 12º/s, respectively.

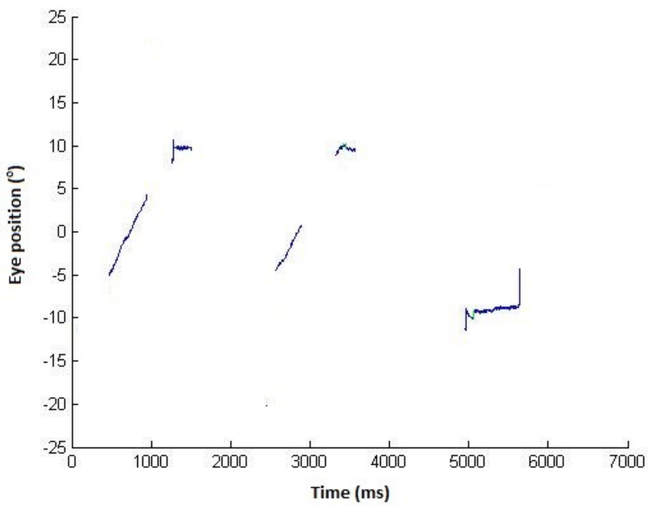


Figure 5.7. Data obtained from a participant aged 6 years that were discarded because only two small segments of smooth pursuit were produced.

Poor eye traces were also obtained from some participants while performing the saccadic task. Figure 5.8 shows a trace in which the eyes were not detected by the tracker during parts of the task, and therefore, data quality is compromised. Traces with similar characteristics to the one shown in Figure 5.8 were considered artefactual, as on all occasions good eye movement data were obtained from the same children for the other eye movement tasks. Of the 120 participants, successful eye movement recordings were obtained from 113 (94.16%) and 103 (85.83%) children for the horizontal and vertical saccade tasks, respectively.

Eye movement recordings in which the eye position was missing during the fixation task (e.g. Figure 5.9) were discarded, leaving a total of 115 (95.83%) eye movement recordings to be included in the analysis for this type of eye movement.

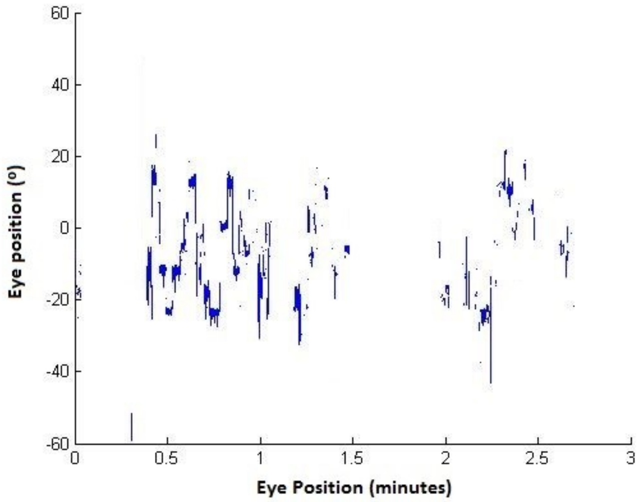


Figure 5.8. Data obtained from a participant aged 6 years that were discarded because the eyes were not detected throughout the saccadic test.

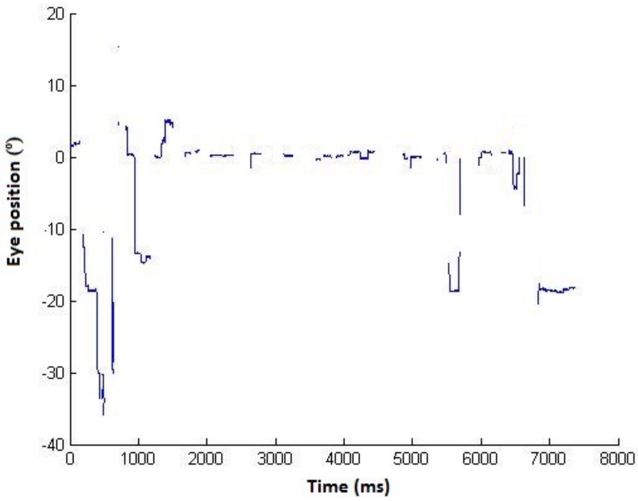


Figure 5.9. Data obtained from a participant aged 9 years that were discarded because the eyes were not detected throughout the fixation test.

It can be proposed that success rates in our study were very high in all the tasks as successful eye movement recordings were obtained from more than 85% of children in all tasks. Table 5.1 shows the percentage of successful eye movement recordings for each eye movement task. It can be observed in that table that the success percentages were very similar for all eye movement tasks (more than 94% percentage of successful recordings) except for vertical saccades. This task was the second longest task and it immediately followed the longest task (horizontal saccades). The long duration of the vertical saccadic task and its similarity with the previous task performed could have resulted in a lack of interest/attention of the participants and consequently lower successful rates.

Eye movement task	Percentage of successful recordings
6º/s horizontal smooth pursuit	99.16%
12º/s horizontal smooth pursuit	98.33%
6º/s vertical smooth pursuit	98.33%
12º/s vertical smooth pursuit	97.5%
Horizontal saccades	94.16%
Vertical saccades	85.83%
Visual fixation	95.83%

Table 5.1. Percentage of successful eye movement recordings for each eye movement task.

5.6.3. Smooth pursuit

Statistical tests

The purpose of the analysis in this section is to determine any effect of age on the parameters of smooth pursuit and evaluate when smooth pursuit achieves adult values. Thus, the smooth pursuit performance parameters obtained from all the participants in each age group were averaged to obtain the mean values for each age group. Then, ANOVA One-Way was used to assess differences in these parameters across ages.

Normality tests including histograms and Shapiro-Wilk tests were performed on all data. Parametric ANOVA has been suggested to be robust to moderate deviations of normality. Simulation studies using non-normally distributed data have shown that a violation of the normal distribution in ANOVA has little effect on statistical results. Moreover, it has been suggested that an increase in false positives due to this violation of normality is unlikely (Glass et al. 1972; Lix et al. 1996). For that reason, parametric ANOVA was used when most of the data (>50%) were normally distributed and only a few parameters were non-normally distributed and non-parametric ANOVA (Kruskal-Wallis test) was used when most of the data were not normally distributed.

Velocity gain, position gain and proportion of SP were normally distributed (Shapiro-Wilk tests $p>0.05$). In contrast, the number of saccades, the mean amplitude of the saccades and the number of microsaccades were not normally distributed (Shapiro-

Wilk test p<0.05). Hence, parametric ANOVA was used for gains and proportion of SP whereas non-parametric ANOVA was used for the saccadic parameters of the smooth pursuit task.

For parametric ANOVA, the homogeneity of variances was assessed with Levene's test for equality of variances. A Welch test was used instead of ANOVA for parameters whose variances were not homogeneously distributed. Post Hoc tests were performed only when ANOVA or Welch tests were significant. Tukey and Games-Howell Post Hoc tests were chosen for parameters with their variances homogeneously distributed and those that were not, respectively. A p value <0.05 was considered significant.

Mann-Whitney paired tests were used to evaluate the differences between age groups when non-parametric ANOVA (Kruskal-Wallis) was significant. Unlike the parametric ANOVA Post Hoc tests (e.g. Tukey and Games-Howell), the non-parametric approach that involves multiple comparisons with Mann-Whitney tests, does not correct for Type I error. For that reason, in order to avoid an increase in Type I error when multiple tests are performed simultaneously (multiple comparisons across age groups), a Bonferroni correction on the p value was performed (Ludbrook 1998). Following the Bonferroni correction, the significance level for the Mann-Whitney tests results was set to p values <0.001.

Horizontal smooth pursuit

The results of the ANOVA for the effect of age on horizontal smooth pursuit are shown in Table 5.1. These results are discussed in detail below.

SMOOTH PURSUIT	6°/s HORIZONTAL		12°/s HORIZONTAL	
	F	p	F	p
VELOCITY GAIN	3.164	**0.003**	2.209	**0.031**
POSITION GAIN	3.715	**0.003**	1.036	0.413
PROPORTION OF SP	1.874	0.093	1.103	0.366
	X^2	p	X^2	p
NUMBER OF SACCADES	12.549	0.128	16.480	**0.036**
AMPLTIUDE SACCADES	7.929	0.450	18.813	**0.016**
MICROSACCADES	24.272	**0.002**	3.170	0.923

Table 5.2. ANOVA results for the effect of age on horizontal smooth pursuit parameters.

<u>Horizontal velocity gain (Figure 5.10)</u>

Mean velocity gains for the horizontal smooth pursuit at 6º/s ranged from 0.84 to 0.94. Figure 5.10 shows a trend towards an increase in the mean velocity gain between 4 and 8 years of age, and this is confirmed by the significant results found in the ANOVA (Table 5.1). Games-Howell Post Hoc test showed that mean velocity gain was different in adults and children aged 4 (p=0.010), 5 (p=0.007), and 6 (p=0.029) years old. Velocity gains in children aged 7 or older than 8 were not significantly different from adults (p>0.05).

Velocity gains for the 12º/s condition were significantly lower than for the 6º/s condition (Paired t-test: t=2.710; p=0.008). The difference in the mean velocity gain between the two velocities is less visible in the younger than in the older age groups. Figure 5.10 shows that the mean velocity gain for the 12º/s condition also tends to increase with age until the age of 8-9 years. ANOVA further confirmed the presence of significant differences in this parameter across the age groups (Table 5.1). Pos Hoc tests revealed differences in mean velocity gain between children aged 5 and 9 years old (p=0.042).

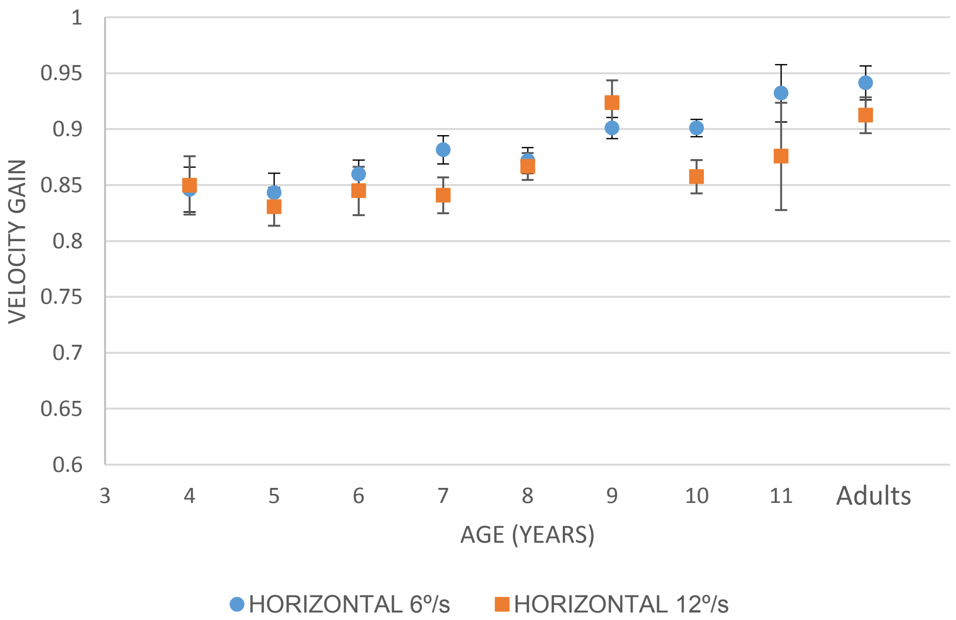


Figure 5.10. Mean (±SE) velocity gain for each age group for 6º/s (blue circles) and 12º/s (orange squares) horizontal smooth pursuit.

<u>Horizontal position gain (Figure 5.11)</u>

Position gain for 6°/s also increases until the age of 7-8, and after this, no differences can be discerned between the older children and the adult group (Figure 5.11). ANOVA results confirmed a significant effect of age on mean position gain for the 6°/s horizontal smooth pursuit (Table 5.1). Post Hoc tests revealed significant differences between adults and children aged 4 ($p=0.047$) and 6 ($p=0.002$) year olds.

Paired t-tests showed that position gains for the 12°/s were, in general, significantly lower than for the 6°/s ($t=4.70$; $p<0.001$). Figure 5.11 shows that the difference in this parameter between the two velocities is small for young children but increases with age. Mean position gain for this velocity is lower across all ages and also in adults. In addition, no trends across ages are observed. ANOVA confirmed that mean position gain does not change with age for the 12°/s condition (Table 5.1).

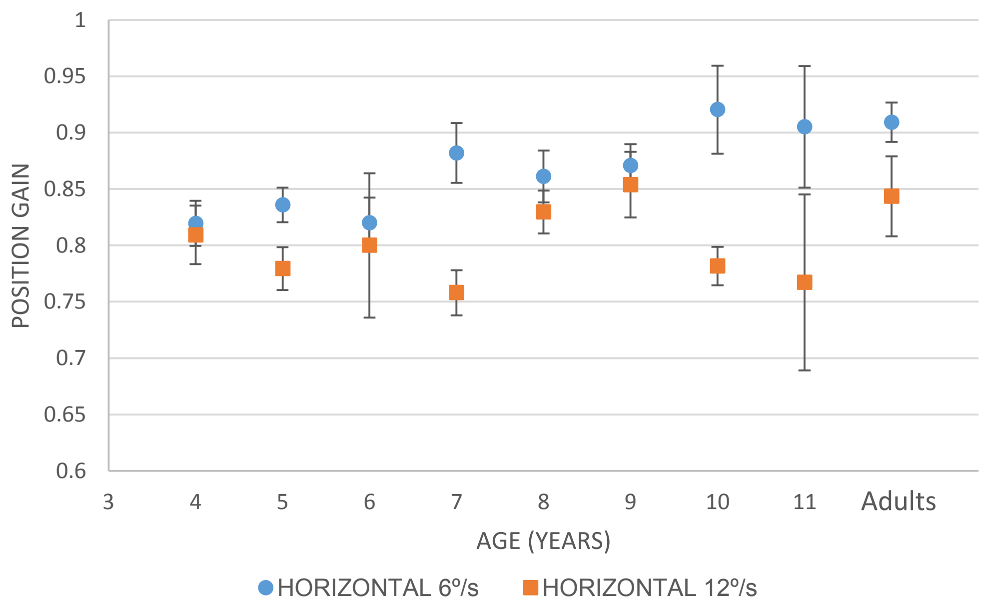


Figure 5.11. Mean (±SE) position gain for each age group for 6°/s (blue circles) and 12°/s (orange squares) horizontal smooth pursuit.

Horizontal proportion of SP (Figure 5.12)

Figure 5.12 shows that the proportion of SP for the 6º/s condition is close to 0.8 for most age groups. Maximum values are found at the age of 8, 9 (0.83 and 0.84, respectively) and in adults (0.85). The proportion of SP in younger children is just below 0.8. ANOVA did not find significant differences across ages for this parameter and condition (Table 5.1).

No significant differences were found between the proportion of SP for 6º/s and 12º/s (t=-1.080; p=0.06). Figure 5.12 shows that the mean proportion of SP does not appear to change with age, as confirmed by ANOVA (Table 5.1).

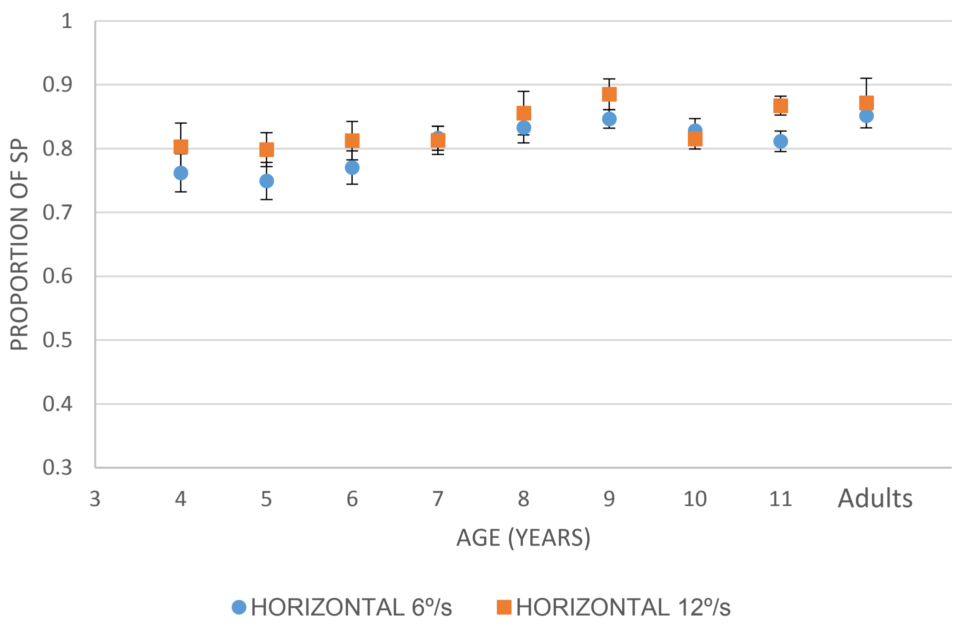


Figure 5.12. Mean (±SE) proportion of SP for each age group for 6º/s (blue circles) and 12º/s (orange squares) horizontal smooth pursuit.

Number of saccades during horizontal smooth pursuit (Figure 5.13)

Figure 5.13 shows that the mean number of saccades at 6º/s ranges between 2 and 8. In addition, the mean number of saccades in most age groups is close to 6 for young children (4-7 years) and just below 6 for older children (8 -11 years). Adults have the lowest mean number of saccades, however the value obtained for this parameter at 9 and 11 years is very similar to adults. The ANOVA result (Table 5.1) confirmed no significant differences across ages.

For the 12º/s smooth pursuit, the number of saccades is significantly higher than that found for the 6º/s condition ($t=-3.350$; $p<0.001$). Children aged 5 have a higher mean number of saccades than the other ages studied, but in the other age groups, the mean number of saccades is around 8, until the age of 10 (Figure 5.13). ANOVA revealed significant differences in the mean number of saccades across ages for the 12º/s condition (Table 5.1). Post Hoc tests revealed that the mean number of saccades in children aged 5 ($p<0.001$) as well as in children aged 7 ($p<0.001$) were significantly different from adults.

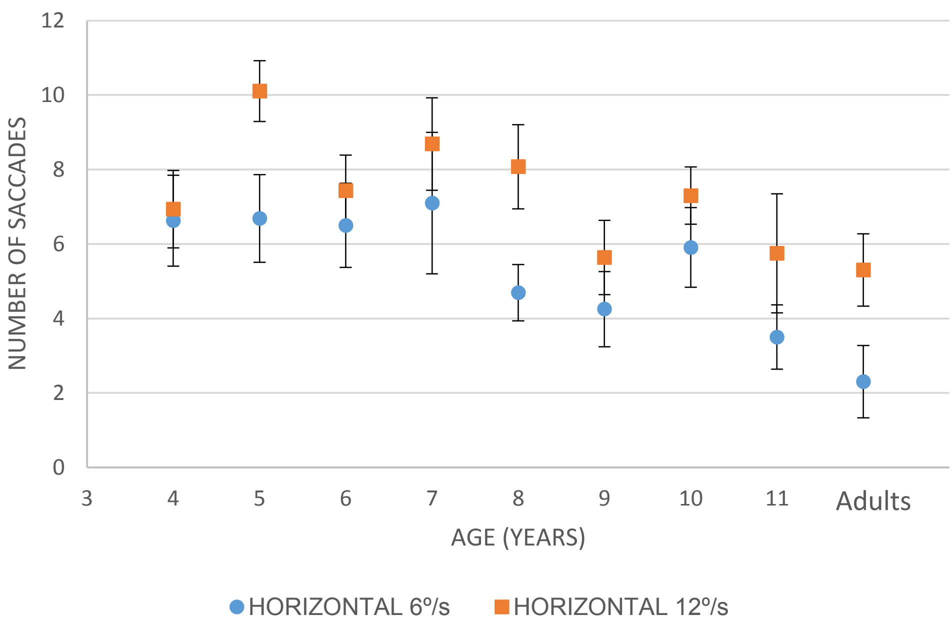


Figure 5.13. Mean (±SE) number of saccades each age group for 6º/s (blue circles) and 12º/s (orange squares) horizontal smooth pursuit.

Mean amplitude of the saccades during horizontal smooth pursuit (Figure 5.14)

The amplitude of the saccades produced during the 6º/s smooth pursuit seems to be higher for children aged 5 and 6 years than for the other age groups (Figure 5.14). In children aged 4 and older than 6 years, the mean amplitude of the saccades is close to 2º. This parameter does not vary significantly across the different age groups, as confirmed by ANOVA (Table 5.1).

For the 12º/s condition, the mean amplitude of the saccades is very similar to that obtained for the 6º/s. Paired t-test did not show differences in this parameter between the two velocities tested ($t=0.127$; $p=0.899$). A similar trend is observed for this condition, suggesting that children aged 5 and 6 have slightly higher saccadic amplitudes (Figure 5.14). The other age groups have very similar saccadic amplitudes to those found in adults. In this case, ANOVA revealed significant differences across ages (Table 5.1) and Post Hoc tests showed that the mean number of saccades was significantly lower in adults than in children aged 5 ($p<0.001$) and 6 ($p<0.001$) years.

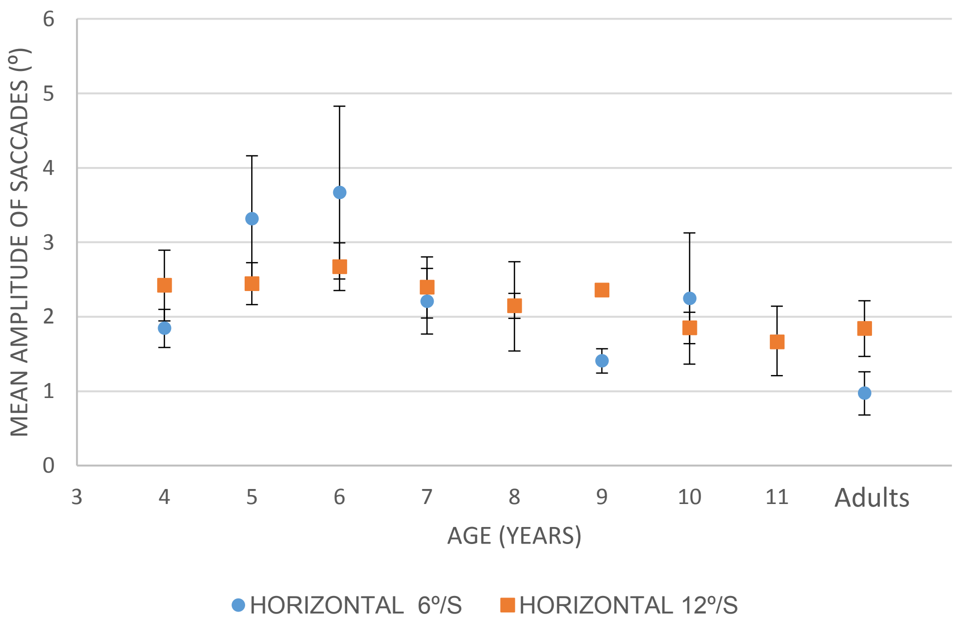


Figure 5.14. Mean (±SE) amplitude of saccades for each age group for 6º/s (blue circles) and 12º/s (orange squares) horizontal smooth pursuit.

Number of microsaccades during horizontal smooth pursuit (Figure 5.15)

Figure 5.15 shows a clear trend towards an increase in the mean number of microsaccades between 5 and 8 years old for the 6º/s horizontal pursuit condition. Thus, the number of microsaccades increases from 8 at the age of 5 to 13 at the age of 8. After that age, the mean number of microsaccades remains between 12 and 16. This increase in the number of microsaccades with age is confirmed by the ANOVA results shown in Table 5.1. Furthermore, Post Hoc tests revealed significant differences between 5 ($p<0.001$) and adults and also between 6 year olds ($p<0.001$) and adults.

For the 12º/s horizontal condition, the mean number of microsaccades is significantly lower than for 6º/s ($t=11.252$; $p<0.001$). The mean number of microsaccades for this condition is below 10 in all age groups, and no differences can be seen between children of any age and adults (Figure 5.15). Kruskal-Wallis confirmed these observations and did not show significant differences across groups in the mean number of microsaccades for the 12º/s horizontal pursuit (Table 5.1).

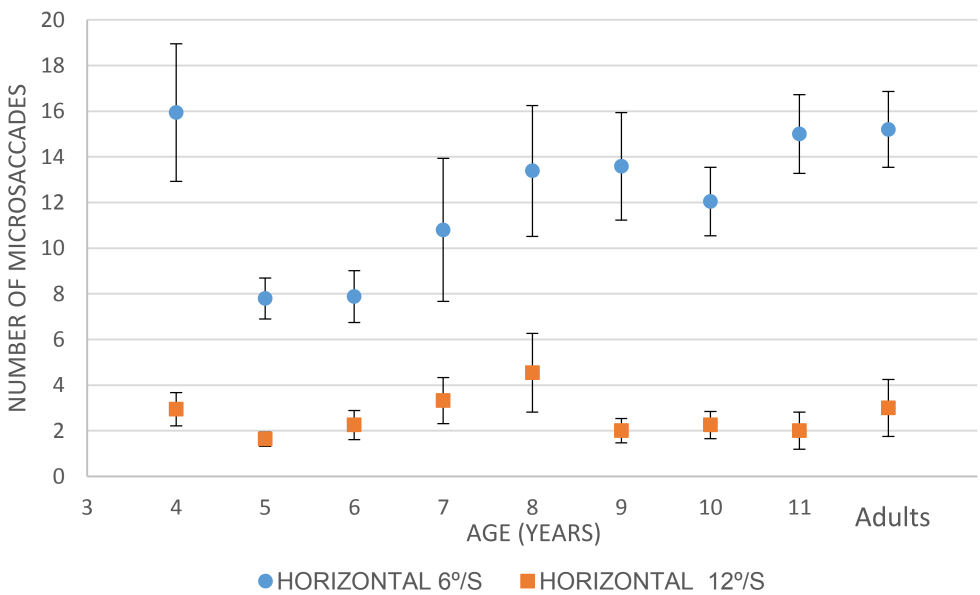


Figure 5.15. Mean (±SE) number of microsaccades for each age group for 6º/s (blue circles) and 12º/s (orange squares) horizontal smooth pursuit.

Vertical smooth pursuit

The results of the ANOVA for the effect of age on vertical smooth pursuit are shown in Table 5.2. These results are discussed in detail below.

SMOOTH PURSUIT	**6º/s VERTICAL**		**12º/s VERTICAL**	
	F	**p**	**F**	**p**
VELOCITY GAIN	1.101	0.368	1.150	0.336
POSITION GAIN	2.152	**0.036**	0.995	0.444
PROPORTION OF SP	2.431	**0.029**	1.948	0.084
	X^2	**p**	**X^2**	**p**
NUMBER OF SACCADES	6.417	0.492	6.487	0.593
AMPLITUDE OF SACCADES	7.950	0.337	7.444	0.490
MICROSACCADES	11.626	0.144	7.632	0.437

Table 5.3. ANOVA results for the effect of age on vertical smooth pursuit parameters.

<u>Vertical velocity gain (Figure 5.16)</u>

Velocity gains for the 6º/s vertical smooth pursuit range between 0.75 and 0.82. Most age groups have mean velocity gains of 0.8, and it can be observed that, even in adults, this parameter is low and below 0.8. No particular trend across ages is observed so it can be suggested that this parameter only changes minimally across age (Figure 5.16) as confirmed by the non-significant ANOVA result (Table 5.2).

Similar to the results found for the horizontal smooth pursuit, an increase in stimulus velocity results in significantly lower gains ($t=4.111$; $p<0.001$). Figure 5.16 shows that the difference in velocity gain between the two velocities tested does not change across ages. Mean velocity gain for the 12º/s vertical smooth pursuit ranges between 0.68 and 0.77, but there were no significant differences in velocity gain for this condition across ages (Table 5.2).

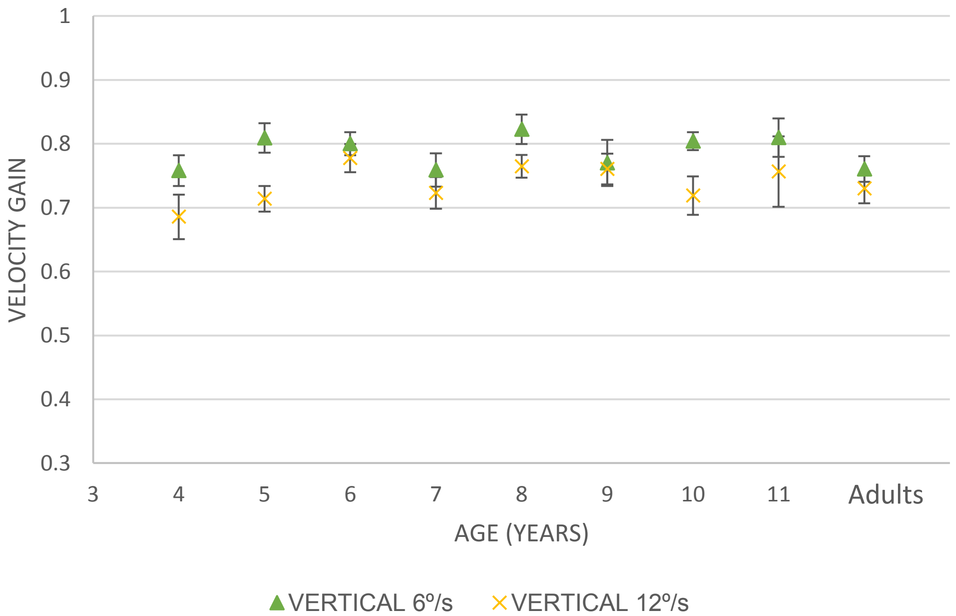


Figure 5.16. Mean (±SE) velocity gain for each age group for 6º/s (green triangles) and 12º/s (yellow crosses) vertical smooth pursuit.

Vertical position gain (Figure 5.17)

Children between the ages of 4 and 7 show mean position gains closer to 0.8 while older children show mean position gains closer to 0.9 (Figure 5.17). ANOVA corroborated that there is an effect of age on the mean position gain for the 6º/s vertical smooth pursuit (Table 5.2). Interestingly, Post Hoc tests did not find significant differences for any age paired comparison, suggesting that there is a trend towards an increase in this parameter but that differences between age groups are not large enough to reach significance in paired comparisons.

For the 12º/s condition, position gains are significantly lower than for 6º/s (t=6.968; $p<0.001$). Figure 5.17 shows that the mean position gain is close to 0.7 for any age group, and the maximum mean position gain observed is 0.77. This parameter does not appear to change with age, and statistical analysis confirms this observation (Table 5.2).

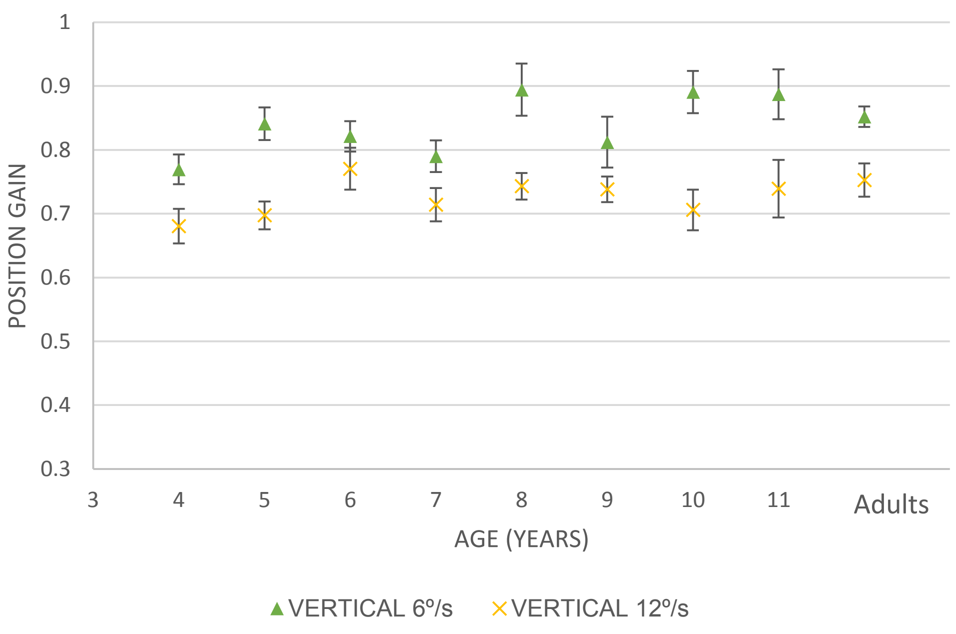


Figure 5.17. Mean (±SE) position gain for each age group for 6º/s (green triangles) and 12º/s (yellow crosses) vertical smooth pursuit.

<u>Vertical proportion of SP (Figure 5.18)</u>

The mean proportion of SP rapidly increases with age for the 6º/s condition until the age of 7. Older than this age, no differences can be observed between older children and adults, and the mean proportion of SP is very close to 0.7 in most age groups (Figure 5.18). ANOVA confirmed an effect of age on the proportion of SP for this condition (Table 5.2). However, similar to the results found for position gain, Post Hoc tests did not find significant differences between any age groups.

For the 12º/s condition, the mean proportion of SP seems to be very similar to that found for the 6º/s smooth pursuit. Paired t-tests did not show differences in the mean proportion of SP between 6º/s and 12º/s (t=0.269; p=0.788). Very small differences can be observed across age groups (Figure 5.18) as confirmed by the non-significant ANOVA results (Table 5.2).

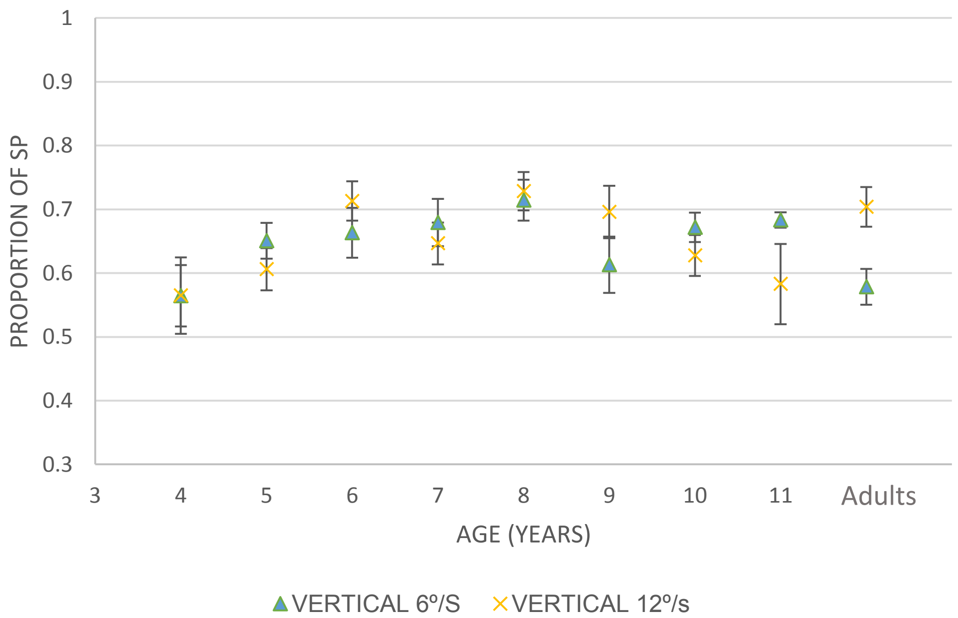


Figure 5.18. Mean (±SE) proportion of SP for each age group for 6º/s (green triangles) and 12º/s (yellow crosses) vertical smooth pursuit.

<u>Number of saccades during vertical smooth pursuit (Figure 5.19)</u>

For 6º/s pursuit, some variations across ages can be observed in the mean number of saccades, but these do not follow a particular trend. Figure 5.19 shows that the mean number of saccades appears to be higher for adults and older children than for younger children, but no significant differences were found in the mean number of saccades across ages (Table 5.2).

Paired t-tests found that the mean number of saccades is significantly lower for 12º/s than for 6º/s (t=-2.332; p=0.022). For 12º/s, the mean number of saccades seems to remain the same across ages (Figure 5.19). Although the lowest mean number of saccades is found in the adults group, this value is remarkably similar to that found in children, and ANOVA did not reveal differences across ages (Table 5.2).

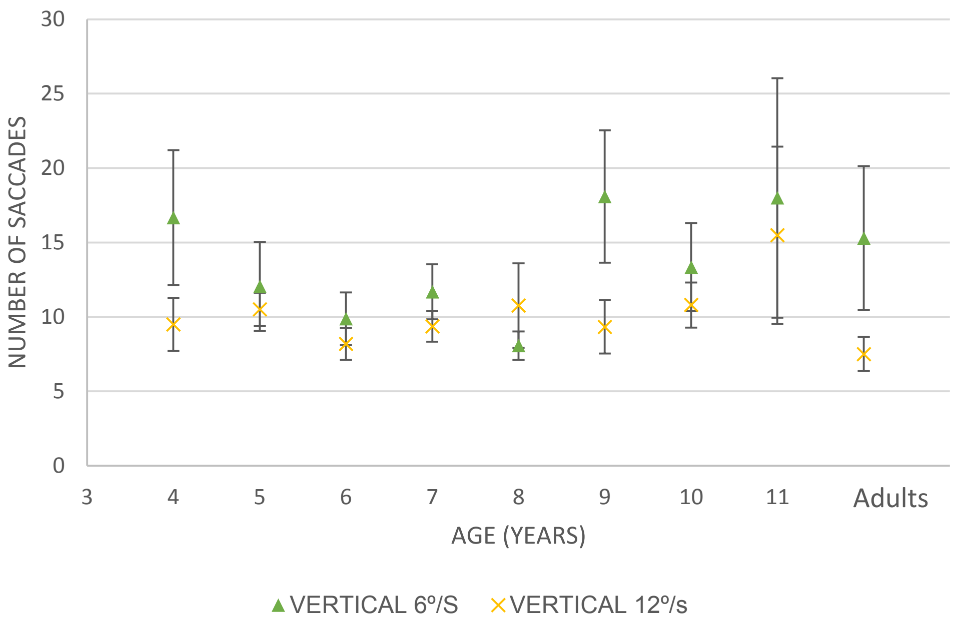


Figure 5.19. Mean (±SE) number of saccades for each age group for 6º/s (green triangles) and 12º/s (yellow crosses) vertical smooth pursuit.

<u>Mean amplitude of saccades during vertical smooth pursuit (Figure 5.20)</u>

The mean amplitude of the saccades decreased from 3º to 2º from 5 to 11 years of age (Figure 5.20). ANOVA showed that there is no change in the mean amplitude of the saccades for this condition across the age groups (Table 5.2).

The mean amplitude of saccades for 12º/s is very similar to that found for 6º/s ($t=-2.332$; $p=0.056$). The mean amplitude of the saccades appears to be slightly lower in 11 year old children and adults than in children aged 5, 6 or 7. However, Figure 5.20 does not show a clear trend for a decrease in the mean amplitude of saccades with age. Indeed, there were no significant differences in the mean amplitude of the saccades across the age groups (Table 5.2).

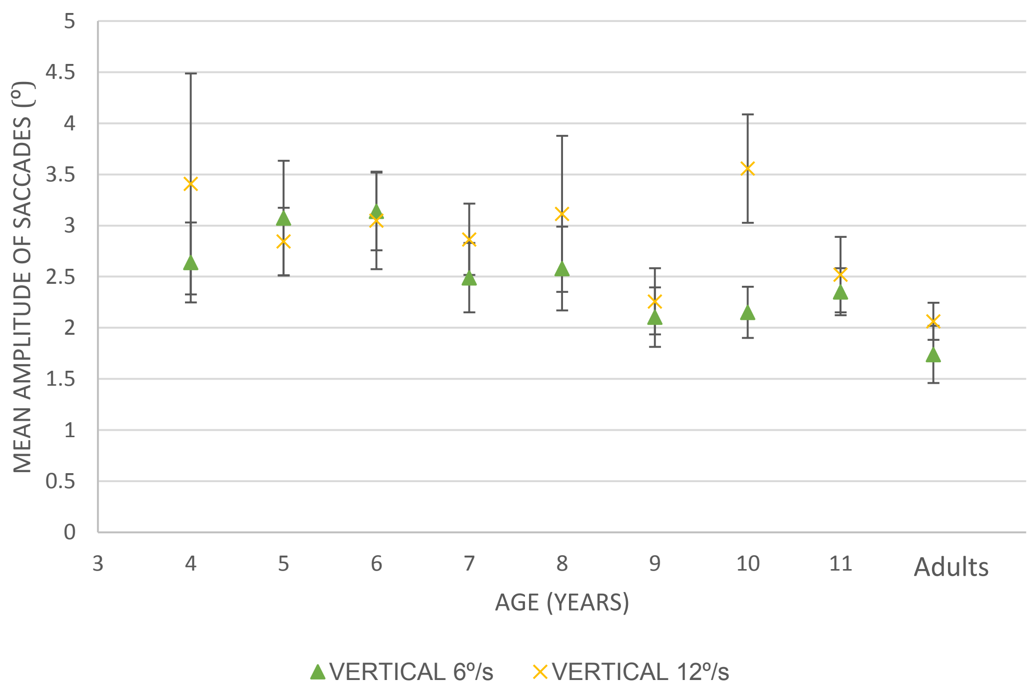


Figure 5.20. Mean (±SE) amplitude of saccades for each age group for 6º/s (green triangles) and 12º/s (yellow crosses) vertical smooth pursuit.

<u>Number of microsaccades during vertical smooth pursuit (Figure 5.21)</u>

Finally, Figure 5.21 shows that the highest number of microsaccades was found in adults. A lower mean number of microsaccades is observed in some children groups. However, it should be noted that this parameter is much more variable than previous parameters and non-parametric ANOVA did not find significant differences across groups.

The number of microssaccades is found to be lower for 12º/s than for 6º/s, and this difference was found to be significant ($t=7.724$; $p<0.001$). For 12º/s, the mean number of microsaccades is below 10 for children younger than 6. In contrast, for ages ranging from 7 to 11 and adults, the number of microsaccades is between 10 and 15 (Figure 5.21). However, ANOVA indicates that age has no effect on the number of microsaccades for the 12º/s vertical smooth pursuit (Table 5.2).

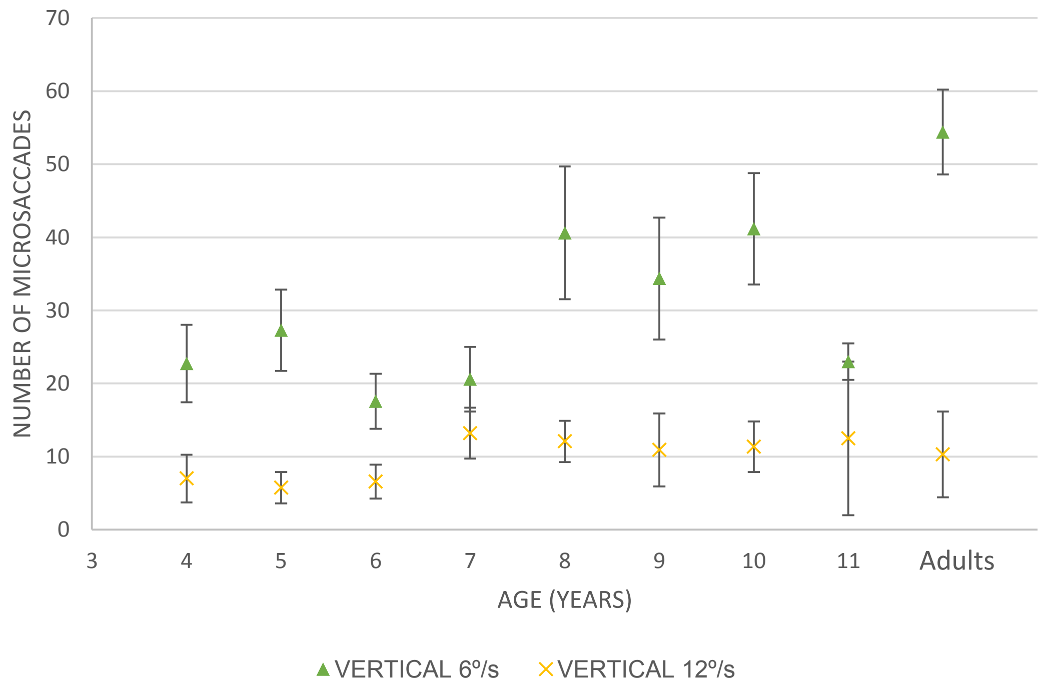


Figure 5.21. Mean (±SE) number of microsaccades for each age group for 6º/s (green triangles) and 12º/s (yellow crosses) vertical smooth pursuit.

Summary

In general, the results obtained from the smooth pursuit tasks suggest that there is some development of smooth pursuit eye movements in school age children, mainly for horizontal smooth pursuit. Indeed, significant differences were found across age groups for horizontal smooth pursuit (gains and saccadic parameters), whereas relatively few differences were found for vertical smooth pursuit (only position gain and proportion of SP at 6°/s). That said, the results obtained from the vertical smooth pursuit demonstrate that smooth pursuit performance is much lower in this direction than in the horizontal direction. This is found for children of all age groups as well as in adults. In addition, error bars seem to also be different between the horizontal and vertical smooth pursuit eye movements. For horizontal smooth pursuit, large error bars are generally only observed for the 11 year old group (e.g. Figure 5.11), which corresponds to the age group with the smallest sample size (n=4). In contrast, large error bars are more frequently observed for the vertical smooth pursuit (Figures 5.19 – 5.21). The large error bars found in the vertical smooth pursuit can be explained by an increased dispersion in the smooth pursuit values in this direction. This is particularly evident for the saccadic events during the smooth pursuit. For instance, large differences in the number of saccadic events are found within children of the same age group while performing the same vertical smooth pursuit task.

Finally, the results demonstrate that, after the age of 7-8 years, smooth pursuit is not different from that found in adults, in either the horizontal or vertical direction.

5.6.4. Saccades

Statistical tests

The purpose of the analysis in this section is to determine the effect of age on the parameters of saccadic eye movements. The most appropriate statistical test for this was ANOVA One-Way.

As previously described in chapter 4, section 4.3.3 regression lines were fitted for each subject for duration vs amplitude and for peak velocity x duration vs amplitude main sequences (see chapter 4, Figures 4.12 and 4.16). Finally, a power fit was performed for the peak velocity vs amplitude main sequence (see chapter 4, Figure 4.14). The slope (S) and intercept (I) obtained from the duration vs amplitude regression line function, the Q ratio obtained from the slope of the regression line through the origin from the peak velocity x duration vs amplitude function, and the power fit function parameters A and n (from the peak velocity vs amplitude main sequences) were analysed statistically.

The main sequence parameters (horizontal and vertical) were obtained from all children and were averaged to obtain the mean values for each age group. Figure 5.22 illustrates the duration vs amplitude main sequence obtained from each one of the 4 year old participants before the parameters were averaged to obtain the mean values for that age group. The main sequence for the horizontal saccadic task was obtained from the saccades to the right and the saccades to the left separately, as well as from both directions combined. Similarly, the main sequence parameters for the vertical saccadic test were obtained from the upward saccades, downward saccades and from both directions combined.

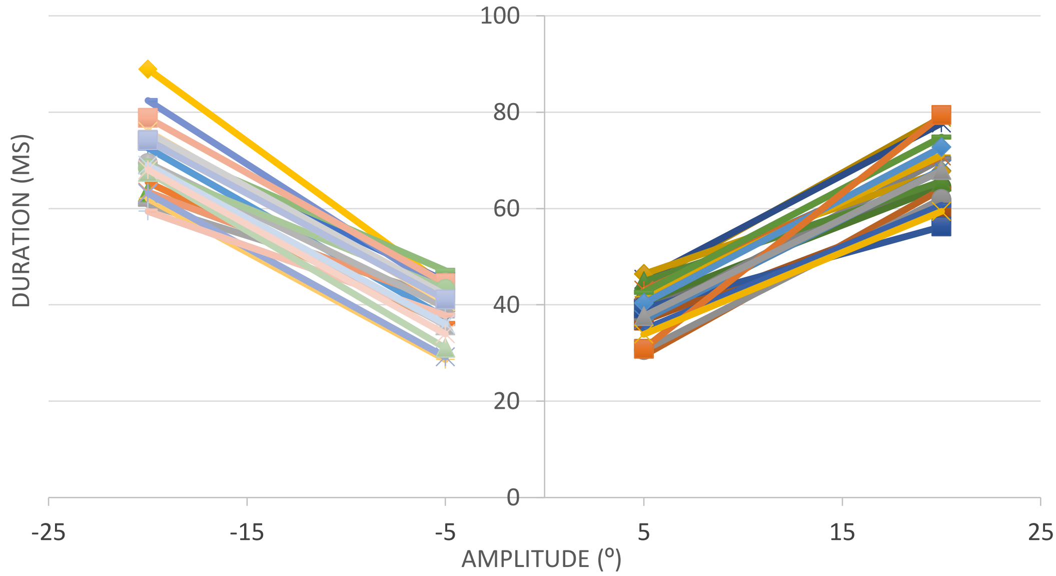


Figure 5.22. Duration vs amplitude main sequence (saccades to the right (positive amplitudes) and saccades to the left (negative values) separately) obtained from all the 4 year old participants.

The distribution of the main sequence parameters (S, I, Q, A, n) (for details on these main sequence parameters see chapter 1 section 1.2.2) for both rightward and leftward saccades was approximately normally distributed as only a small number of parameters did not satisfy normality. The parameter, A, was non-normally distributed for 4 ($p=0.0017$), 8 ($p=0.04$) and 9 year olds ($p=0.035$). The parameters, n, and Q, were also non-normally distributed for 9 year olds ($p=0.035$ and $p=0.005$, respectively). Similarly, the distribution of the upward and downward main sequence parameters was also approximately normally distributed and only a few of the parameters did not satisfy normality (Q ratio not normally distributed for 8 ($p=0.021$), 9 ($p=0.005$) and 11 year olds ($p=0.007$); A not normally distributed for 4 year olds ($p=0.007$) and n not normally distributed at the age of 9 ($p=0.003$)). These findings translate into a small violation of the normality tests that are unlikely to have an effect on the statistical results of the t-tests (Ludbrook 1998). Hence, differences in saccadic dynamics between right and left and between up and down were evaluated using parametric paired t-tests.

The accuracy of the saccades was also assessed by calculating the saccadic gain (amplitude of the first saccade towards the new target divided by the real size of the saccade required as determined by the size of the new target step. For more details on this parameter see chapter 4 section 4.3.3). Saccadic gains were studied in the same way. Hence, directional asymmetries were first assessed by comparing the gains obtained separately for saccades to the right and to the left and upward and downward saccades. The gain towards both horizontal and vertical directions were then combined.

According to Shapiro-Wilk tests, gains for horizontal saccades of 5º, 10º and 15º were normally distributed for all age groups. In contrast, gains for horizontal saccades of 20º of amplitude were not normally distributed for all ages. Saccadic gains were normally distributed for all ages and amplitudes for the vertical saccades. Differences in gains between right and left for saccades of 20º were evaluated using non-parametric paired t-tests. Differences in gains between right and left for the other amplitudes and between up and down saccades were all evaluated using parametric paired t-tests.

Following the same procedure used to assess the effect of age on the smooth pursuit parameters, any changes in the main sequence parameters and saccadic gains with age were analysed statistically by means of ANOVA (see section 5.6.3 in this chapter). An adult group was not required on this occasion as normative values for saccades in adults are known and well established, in particular for the horizontal direction (Boghen et al. 1974; Garbutt et al. 2001).

Horizontal saccades

<u>Main sequence</u>

Table 5.3 shows the duration vs amplitude main sequence parameters, S and I, and the paired t-tests p values obtained from each age group for the saccades to the right and to the left. It can be observed in Table 5.3 that the values, S and I, are similar when the saccades are performed to the right and to the left. Paired t-tests corroborated the absence of horizontal asymmetries for the duration vs amplitude main sequence parameters (S and I).

The mean Q ratio obtained from the peak velocity x duration vs amplitude relationship and the mean power fit function parameters (A and n) obtained from the peak velocity vs amplitude relationship are presented in Tables 5.4 and 5.5. Again, the direction of the saccades does not seem to have an effect on these parameters. The p values obtained from the paired t-tests, which confirm no significant differences between right and left saccades for these parameters, are also presented in these tables.

DURATION – AMPLITUDE MAIN SEQUENCE										
AGE	RIGHT DIRECTION				LEFT DIRECTION				p	
GROUP	S	SD	I	SD	S	SD	I	SD	S	I
4 YO	2.05	0.31	27.18	6.90	2.09	0.67	27.70	8.29	0.809	0.783
5 YO	1.97	0.42	28.06	5.50	2.03	0.58	27.96	6.22	0.591	0.902
6 YO	1.90	0.54	28.75	7.05	2.06	0.44	26.27	4.80	0.452	0.322
7 YO	1.93	0.54	28.75	7.05	2.06	0.28	28.03	3.87	0.279	0.410
8 YO	2.00	0.27	28.25	5.04	2.05	0.31	26.91	4.83	0.785	0.095
9 YO	2.04	0.32	29.91	3.06	2.05	0.30	29.43	4.21	0.738	0.638
10 YO	1.89	0.32	28.52	6.42	1.99	0.43	28.67	5.99	0.260	0.867
11 YO	1.51	0.76	34.55	12.54	1.66	0.06	32.20	3.23	0.749	0.625

Table 5.4. Mean slope (S) and mean intercept (I) parameters with their standard deviation (SD) obtained from the duration vs amplitude main sequence for each age group and direction. Paired t-test p values indicate significant or non-significant differences between right and left parameters.

PEAK VELOCITY X DURATION – AMPLITUDE MAIN SEQUENCE					
AGE	RIGHT DIRECTION		LEFT DIRECTION		
GROUP	Q	SD	Q	SD	p
4 YO	1.62	0.11	1.64	0.10	0.099
5 YO	1.68	0.15	1.67	0.17	0.922
6 YO	1.65	0.08	1.61	0.14	0.783
7 YO	1.66	0.09	1.64	0.08	0.676
8 YO	1.63	0.07	1.59	0.07	0.056
9 YO	1.65	0.09	1.65	0.11	0.419
10 YO	1.63	0.09	1.62	0.08	0.229
11 YO	1.63	0.12	1.66	0.11	0.286

Table 5.5. Mean Q ratio with its standard deviation (SD) obtained from the peak velocity x duration vs amplitude main sequence for each age group and direction. Paired t-test p values indicate significant or non-significant differences between right and left parameters.

PEAK VELOCITY – AMPLITUDE MAIN SEQUENCE										
AGE	RIGHT DIRECTION				LEFT DIRECTION				p	
GROUP	A	SD	n	SD	A	SD	n	SD	A	n
4 YO	156.82	60.62	0.37	0.13	163.11	78.05	0.36	0.13	0.622	0.653
5 YO	153.93	35.38	0.37	0.07	161.43	42.59	0.36	0.11	0.379	0.697
6 YO	136.70	40.67	0.39	0.07	152.69	23.91	0.35	0.08	0.129	0.051
7 YO	143.08	46.51	0.40	0.09	145.63	37.71	0.39	0.07	0.996	0.678
8 YO	125.30	35.14	0.45	0.09	133.76	29.63	0.42	0.07	0.143	0.053
9 YO	132.22	24.14	0.40	0.05	139.74	30.98	0.38	0.08	0.459	0.424
10 YO	156.98	35.45	0.39	0.06	144.82	35.04	0.39	0.08	0.656	0.633
11 YO	136.21	18.23	0.40	0.03	143.72	37.44	0.41	0.1	0.776	0.878

Table 5.6. Mean A and n parameters with their standard deviation (SD) obtained from the peak velocity vs amplitude main sequence for each age group and velocity. Paired t-test p values indicate significant or non-significant differences between right and left parameters.

Because no significant differences were found between the right and left saccades, the main sequence parameters used for the ANOVA statistical analysis were those obtained from the main sequence of all the saccades performed during the task and included both directions.

The results of the ANOVA for the effect of age on horizontal saccadic main sequences are shown in Table 5.6 and further discussed below.

HORIZONTAL MAIN SEQUENCE PARAMETERS		
	F	**p**
SLOPE (S)	1.137	0.346
INTERCEPT (I)	0.604	0.752
Q RATIO	0.345	0.931
A	1.193	0.340
n	1.158	0.360

Table 5.7. ANOVA results for the effect of age on horizontal main sequence parameters.

Duration vs amplitude main sequence (Figure 5.23)

The mean duration vs amplitude main sequence for saccades of different amplitudes is very similar across the age groups, as can be observed in Figure 5.23. All functions follow the same pattern and most of them appear superposed. In addition, the mean duration vs amplitude main sequence functions for all age groups fall in the middle of the area delimited by the dashed lines, which represent the limits of typical adult values (Garbutt et al. 2001). Values above or below these limits suggest saccades with increased or reduced durations and, therefore, faster or slower saccades than those found in typical adults. Parametric ANOVA confirms that there are no significant differences across ages for S or I (Table 5.6).

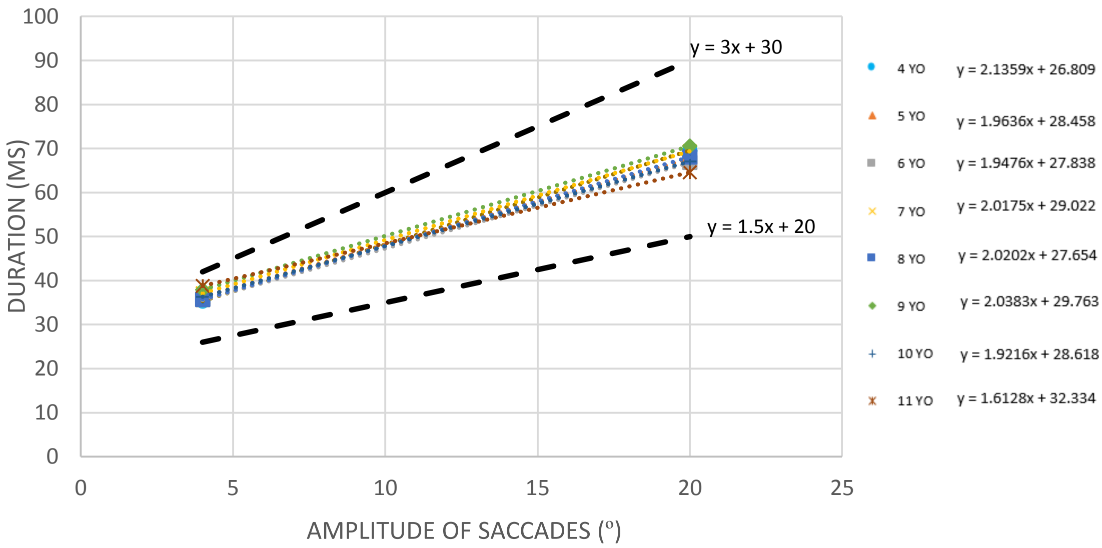


Figure 5.23. Mean duration vs amplitude saccadic main sequences for each age group. The dashed lines represent the typical adult values (Garbutt et al. 2001).

Peak velocity x duration vs amplitude main sequence (Figure 5.24)

The mean peak velocity x duration vs amplitude main sequence for each age group are represented in Figure 5.24. The average slope through the origin (Q ratio) (for more details on this parameter see chapter 1, section 1.2.2 and chapter 4, section 4.3.3) for children aged 4 to 11 years ranges between 1.61 and 1.66 and that suggests that only very small differences (of the order of 0.04) are seen across ages. In any event, all functions fall within the dashed lines that represent the limits for this parameter found in typical adults (Harwood et al. 1999). Parametric ANOVA confirmed that age does not have an effect on Q ratio (Table 5.6).

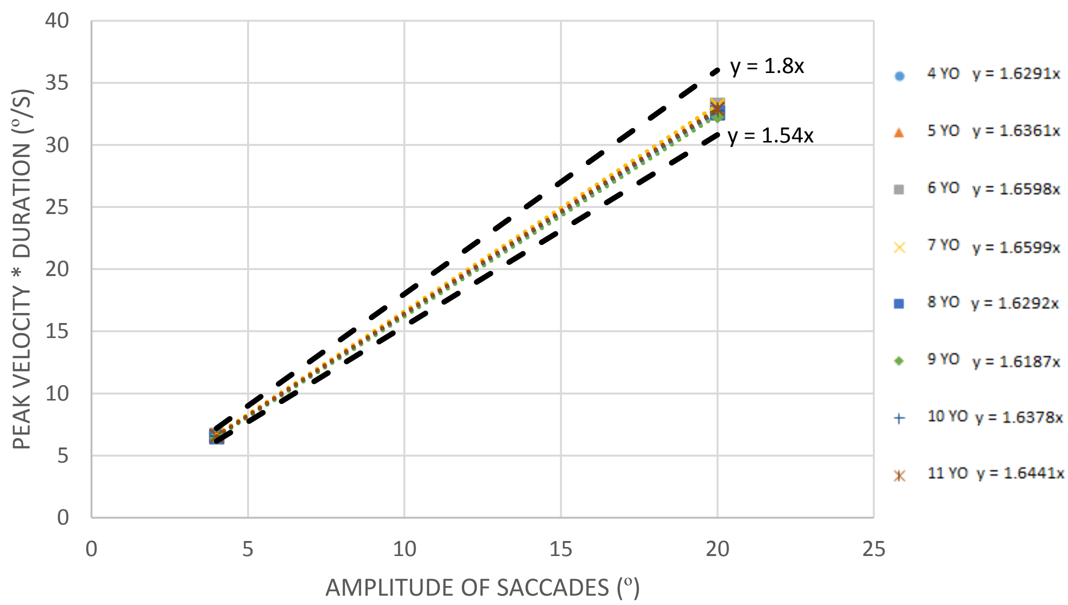


Figure 5.24. Mean peak velocity x duration vs amplitude saccadic main sequences for each age group. The dashed lines represent the typical adult values (Harwood et al. 1999).

Peak velocity vs amplitude main sequence (Figure 5.25)

Figure 5.25 shows the mean peak velocity vs amplitude functions obtained in each age group. For all saccadic amplitudes, peak velocities are within typical adult values for all age groups; adult limits are indicated by the dashed lines in Figure 5.25 (Boghen et al. 1974). However, the data suggest that saccades of small amplitude have slightly higher peak velocities in most age groups as the functions are superposed or very close to the saccadic adult limits represented by the dashed lines. ANOVA results for A and n, also shown in Table 5.6 indicate that there are no significant changes in these parameters across ages.

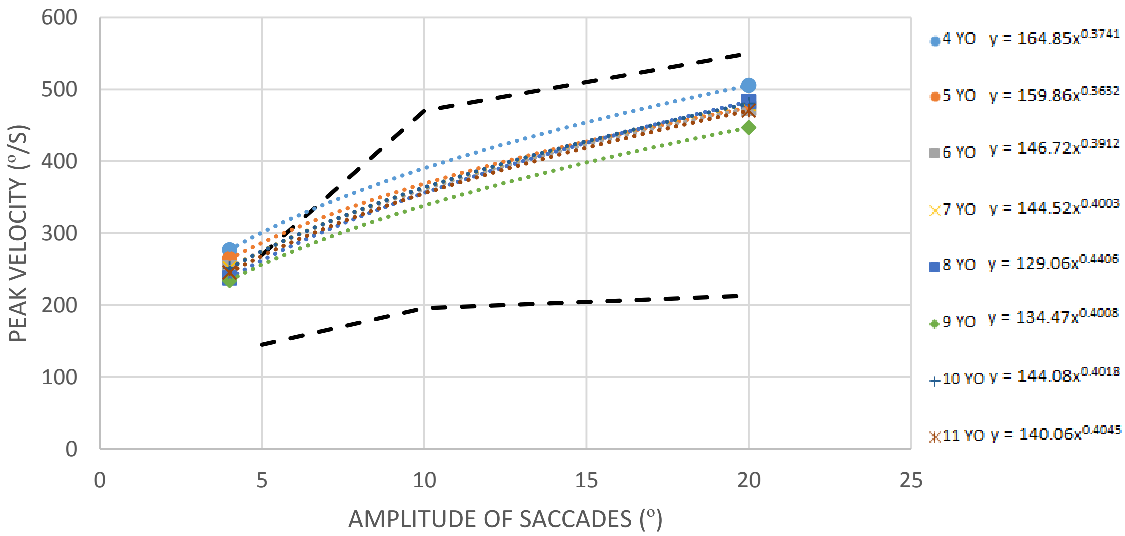


Figure 5.25. Mean peak velocity vs amplitude saccadic main sequences for each age group. The dashed lines represent the typical adult values (Boghen et al. 1974).

<u>Saccadic gain (Figures 5.26 and 5.27)</u>

Figure 5.26 shows data pooled across ages for saccades of different amplitude to the right and to the left. No evident differences in saccadic gains can be observed between saccades in the two directions (Figure 5.26). For example, gains for saccades of 10º are 0.9627 and 0.9687 to the right and to the left, respectively. Paired t-tests for each age group revealed gain asymmetries between saccades to the right and to the left only for saccadic amplitudes of 5º and 10º at the age of 9 ($p=0.001$) and 7 ($p<0.001$) years, respectively.

These results demonstrate that, generally, saccadic gain is not significantly different for saccades to the right and to the left and therefore, gains towards both directions were combined to assess the effect of age on saccadic gain with ANOVA statistical tests.

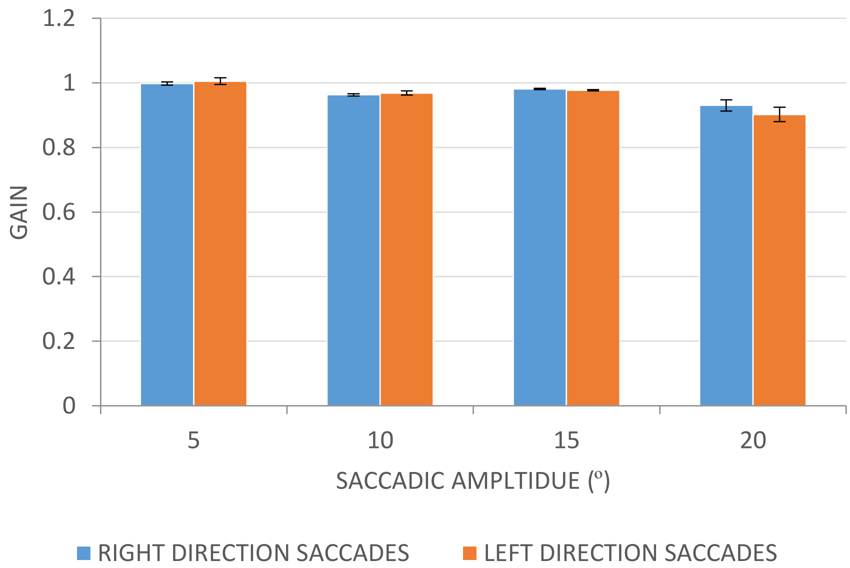


Figure 5.26. Mean (±SE) horizontal saccadic gain obtained from all the participants for saccades of 5º, 10º, 15º and 20º to the right and to the left.

Figure 5.27 presents the mean saccadic gain for each amplitude and age group. In the population studied, mean gains are between 0.8 and 1.0. Saccadic gains for a given amplitude do not appear to change with age. There were no significant differences across ages in the saccadic gain for saccades of 5º (F=0.602, p=0.753), 10º (F=0.766; p=0.617), 15º (F=1.329; p=0.244) or 20º of amplitude (F=0.989; p=0.462).

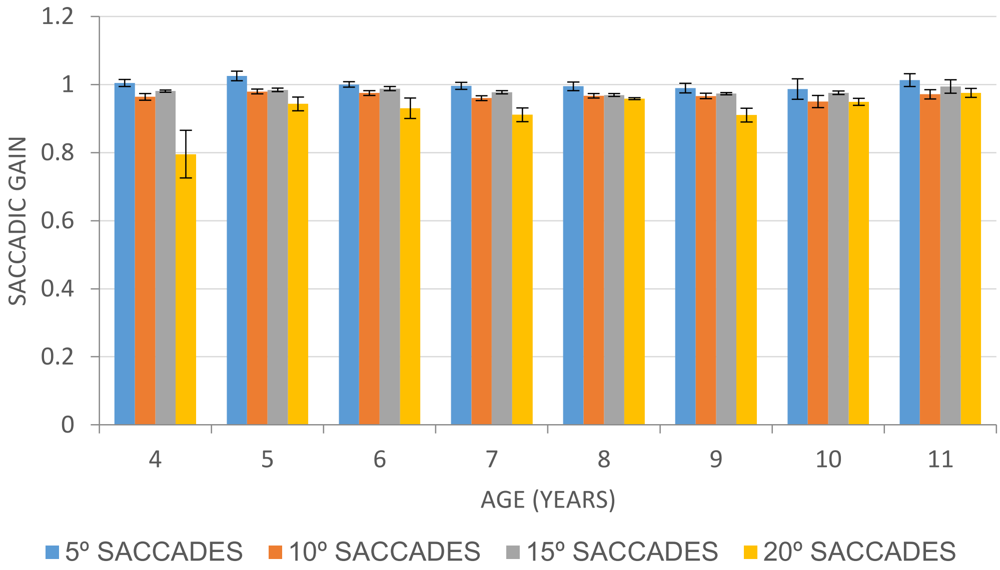


Figure 5.27. Mean (±SE) saccadic gain for each saccadic amplitude and direction for each age group.

Vertical saccades

Main sequence

Table 5.7 shows the mean values for the parameters, S and I, obtained for the vertical duration vs amplitude main sequence. Both S and I, appear to be slightly higher for upward than downward saccades. The p values of the paired t-tests performed to assess up-down asymmetries are also presented in Table 5.7 and reveal some significant differences in these parameters between upward and downward saccades for some age groups.

The mean Q ratios for each vertical direction and age are shown in Table 5.8 together with the paired t-test p values. Similarly, the Q values appear to be slightly higher for the upward than for the downward saccadic direction. Paired t-tests revealed significant differences between upward and downward Q ratios for some ages (Table 5.8). The mean for the parameters, A and n, obtained from the peak velocity x duration vs amplitude main sequence also appeared to be different depending on the vertical direction (Table 5.9). The p values obtained from the statistical results are also shown in Table 5.9 and they confirm significant up-down differences in A and n.

DURATION – AMPLITUDE MAIN SEQUENCE										
AGE	UPWARD DIRECTION				DOWNWARD DIRECTION				P	
GROUP	S	SD	I	SD	S	SD	I	SD	S	I
4 YO	2.44	0.97	26.94	11.05	2.16	0.52	26.55	10.19	0.412	0.918
5 YO	2.32	1.00	30.11	8.71	1.92	0.65	31.38	8.71	**0.023**	0.549
6 YO	2.13	1.12	32.28	14.67	1.94	0.78	28.81	9.53	0.417	0.279
7 YO	2.29	0.67	33.05	10.78	2.34	0.68	27.85	8.14	0.806	**0.040**
8 YO	2.40	0.60	28.47	10.29	2.04	0.65	27.83	8.56	0.176	0.826
9 YO	2.61	1.27	29.50	13.30	2.31	0.68	25.66	11.48	0.421	0.268
10 YO	2.29	0.57	30.85	7.58	1.97	0.65	28.08	9.02	**0.030**	0.201
11 YO	2.84	0.45	20.66	2.83	2.62	0.47	20.98	4.89	0.120	0.870

Table 5.8. Mean slope (S) and intercept (I) parameters with their standard deviation (SD) obtained from the duration vs amplitude main sequence for each age group and direction. Paired t-test p values indicate significant or non-significant differences between up and down parameters.

PEAK VELOCITY X DURATIION – AMPLITUDE MAIN SEQUENCE					
AGE	UP DIRECTION		DOWN DIRECTION		
GROUP	Q	SD	Q	SD	p
4 YO	1.94	0.22	1.97	0.21	0.717
5 YO	1.97	0.19	1.90	0.10	**0.038**
6 YO	2.04	0.19	1.88	0.17	**0.040**
7 YO	2.09	0.20	2.00	0.22	0.166
8 YO	1.95	0.14	1.84	0.18	0.152
9 YO	2.16	0.24	1.91	0.17	**0.003**
10 YO	1.95	0.24	1.86	0.10	0.121
11 YO	2.18	0.23	1.83	0.08	**0.043**

Table 5.9. Mean Q ratio with its standard deviation (SD) obtained from the peak velocity x duration vs amplitude main sequence for each age group and direction. Paired t-test p values indicate significant or non-significant differences between up and down parameters.

PEAK VELOCITY – AMPLITUDE MAIN SEQUENCE										
AGE	UP DIRECTION				DOWN DIRECTION				p	
GROUP	A	SD	n	SD	A	SD	n	SD	A	n
4 YO	151.25	81.25	0.45	0.18	200.75	64.81	0.32	0.14	**0.045**	**0.042**
5 YO	134.88	28.43	0.43	0.08	136.90	41.79	0.45	0.19	0.960	0.628
6 YO	152.29	58.70	0.42	0.15	169.24	39.99	0.36	0.09	0.279	0.169
7 YO	98.29	39.09	0.60	0.17	168.37	62.44	0.38	0.16	**0.003**	**0.006**
8 YO	146.51	85.99	0.47	0.22	155.48	71.57	0.41	0.13	0.646	0.275
9 YO	159.26	102.20	0.43	0.25	143.31	73.04	0.53	0.40	0.684	0.551
10 YO	113.52	40.77	0.53	0.15	140.99	42.64	0.44	0.11	**0.029**	**0.049**
11 YO	227.97	141.80	0.31	0.20	209.21	74.34	0.29	0.07	0.758	0.831

Table 5.10. Mean A and n parameters with their standard deviation (SD) obtained from the peak velocity vs amplitude main sequence for each age group and velocity. Paired t-test p values indicate significant or non-significant differences between up and down parameters.

Because paired t-tests revealed significant differences in the mean sequence parameters depending on the direction of the vertical saccades for several age groups, the upward and downward main sequence parameters were not combined. Further analysis with ANOVA to determine changes in the vertical main sequence with age was performed for upward and downward saccades separately.

The results of the ANOVA for the effect of age on vertical saccadic main sequence parameters are shown in Table 5.10 and further discussed below.

VERTICAL MAIN SEQUENCE PARAMETERS				
	UPWARD SACCADES		DOWNWARD SACCADES	
	F	p	F	p
SLOPE (S)	0.437	0.877	1.125	0.354
INTERCEPT (I)	0.812	0.579	0.724	0.625
Q	2.135	0.051	1.554	0.158
A	2.427	0.051	2.200	0.051
n	2.357	0.056	1.571	0.153

Table 5.11. ANOVA results for the effect of age on vertical main sequence parameters.

Duration vs amplitude main sequence (Figure 5.28)

The mean duration vs amplitude main sequence for upwards and downward saccades is presented in Figure 5.28. Mean S and I for upward saccades are generally higher and this results in "steeper" functions for this direction. Figure 5.28 shows that no evident differences can be observed in the duration vs amplitude functions for upward or downward saccades across the age groups. The ANOVA results (Table 5.10) confirm that S and I do not significantly change with age for upward or downward saccades.

The dashed lines in Figure 5.28 represent the typical adult limits for the horizontal duration vs amplitude main sequence. Vertical saccades have been less studied than horizontal saccades, and detailed normative values for these eye movements have not been published. However, vertical saccades have been suggested to have very similar dynamics to horizontal saccades (Garbutt et al. 2003b). It can be further observed that the mean duration vs amplitude main sequences found for all age groups fall within these limits.

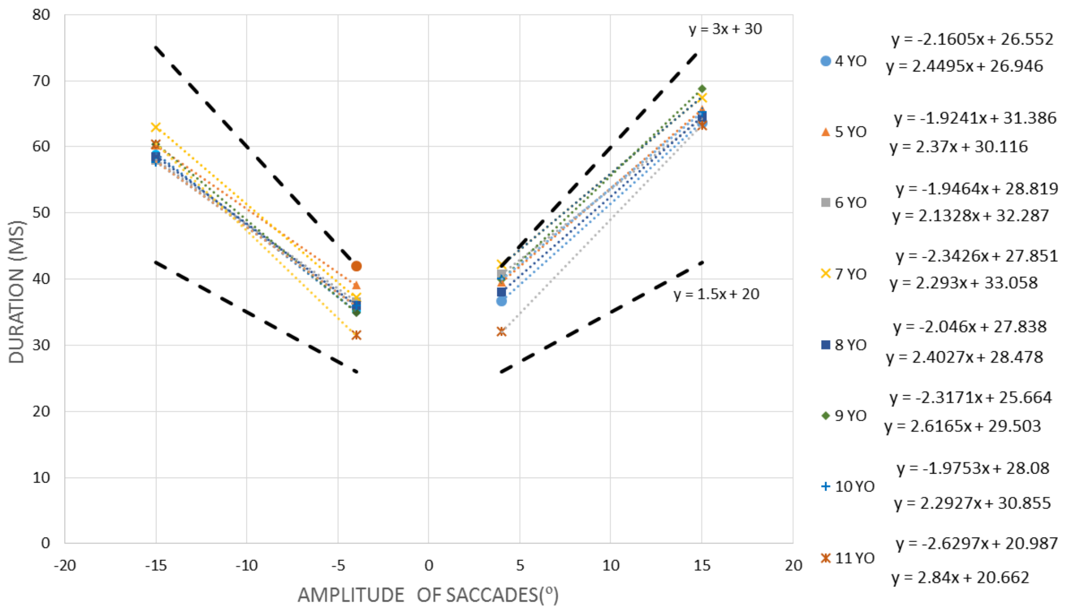


Figure 5.28. Mean duration vs amplitude saccadic main sequences for each age group for upward and downward saccades separately. Negative and positive amplitudes of saccades correspond to downward and upward directions, respectively. The dashed lines represent the typical adult values for horizontal saccades (Garbutt et al. 2003b).

Peak velocity x duration vs main sequence (Figure 5.29)

The mean slopes through the origin (Q ratios) for upward saccades appear to be higher than for downward saccades. This finding is illustrated in Figure 5.29 where it can be observed that the peak velocity x duration vs amplitude functions are steeper for upward saccades. However, these functions do not appear to change with age for upward or downward saccades. Moreover, these are very close and clearly overlap with each other in both directions. ANOVA revealed no significant differences in upward and downward Q ratios across all age groups (Table 5.10).

The peak velocity x duration vs amplitude mean regression lines through the origin for each age group lie above the dashed lines that represent the horizontal typical upper limit in adults. While the main sequences appear just outside of the typical horizontal adult limits for downward saccades, the same functions fall much further away from these limits for upward saccades.

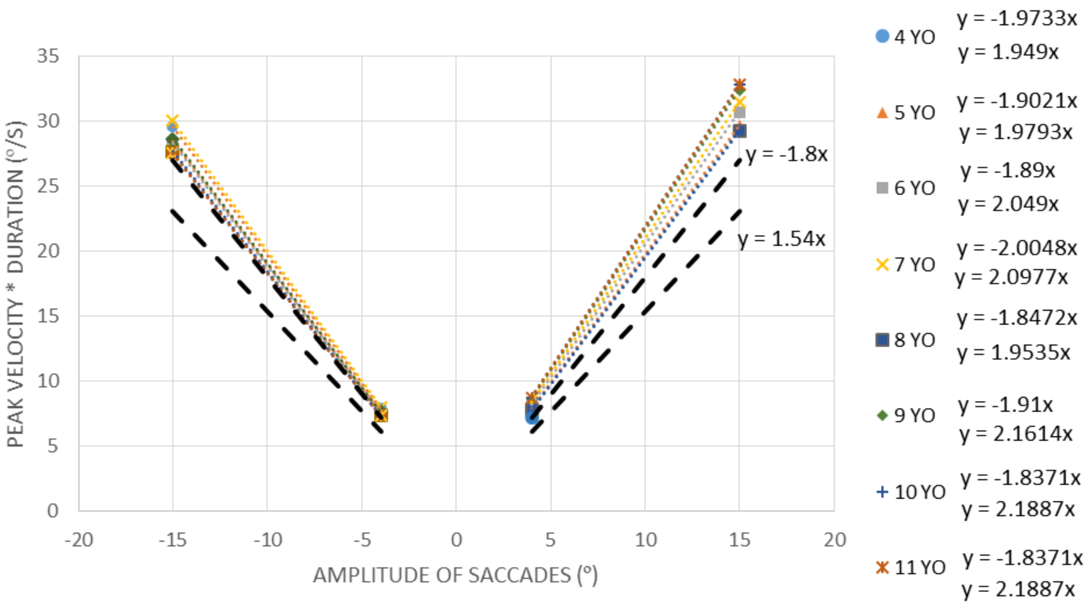


Figure 5.29. Mean peak velocity x duration vs amplitude saccadic main sequences for each age group for upward and downward saccades separately. Negative and positive amplitudes of saccades correspond to downward and upward, respectively. The dashed lines represent the typical adult values for horizontal saccades (Harwood et al. 1999).

Peak velocity vs amplitude main sequence (Figures 5.30 and 5.31)

The mean peak velocities vs amplitude functions obtained for the upward saccades show that peak velocities are very similar across ages. However, the power fit functions for upward saccades (Figure 5.30) are more scattered than those found for downward saccades (Figure 5.31). The peak velocities vs amplitude relationships found for downward saccades appear to be very similar across age groups (Figure 5.31). Only the mean peak velocity vs amplitude main function obtained for the 9 year old group appears to be very different from the rest. ANOVA confirms that no differences across groups are observed in the parameters, A and n, for upwards or downward saccades (Table 5.10).

The functions plotted in Figures 5.30 and 5.31 represent the mean vertical peak velocity vs amplitude main sequences for each age group and vertical direction. It can be observed that, for some age groups, the upward main sequences (Figure 5.30) fall outside the typical horizontal adult limits (dashed lines). In contrast, for the downward saccades, most age groups have a peak velocity main sequence function within the typical horizontal adult limits (except 9 year olds) (Figure 5.31).

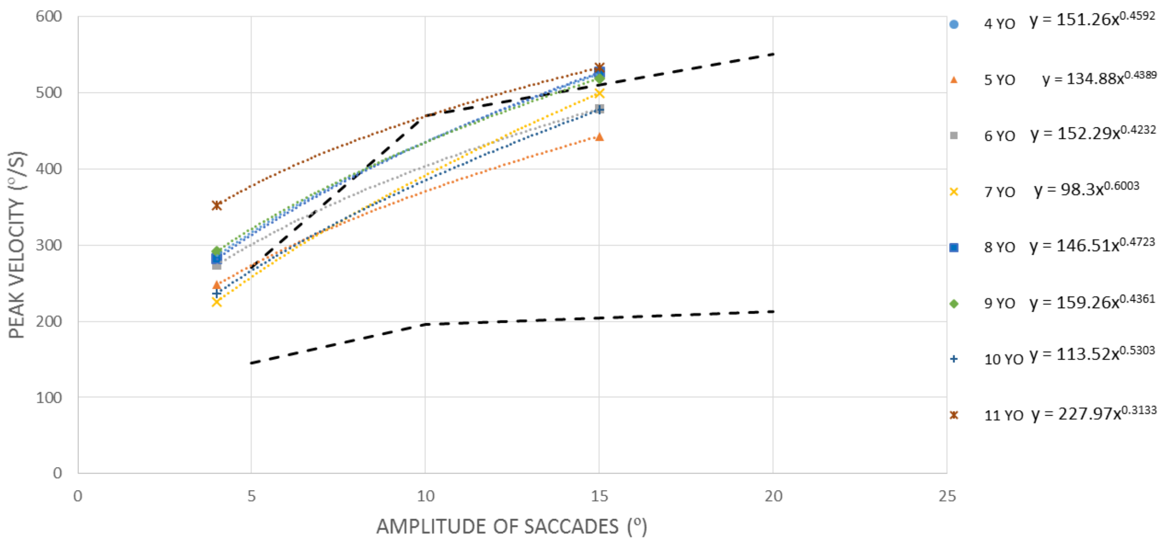


Figure 5.30. Mean peak velocity vs amplitude saccadic main sequences for each age group for upward saccades. The dashed lines represent the typical adult values for the horizontal saccades (Boghen et al. 1974).

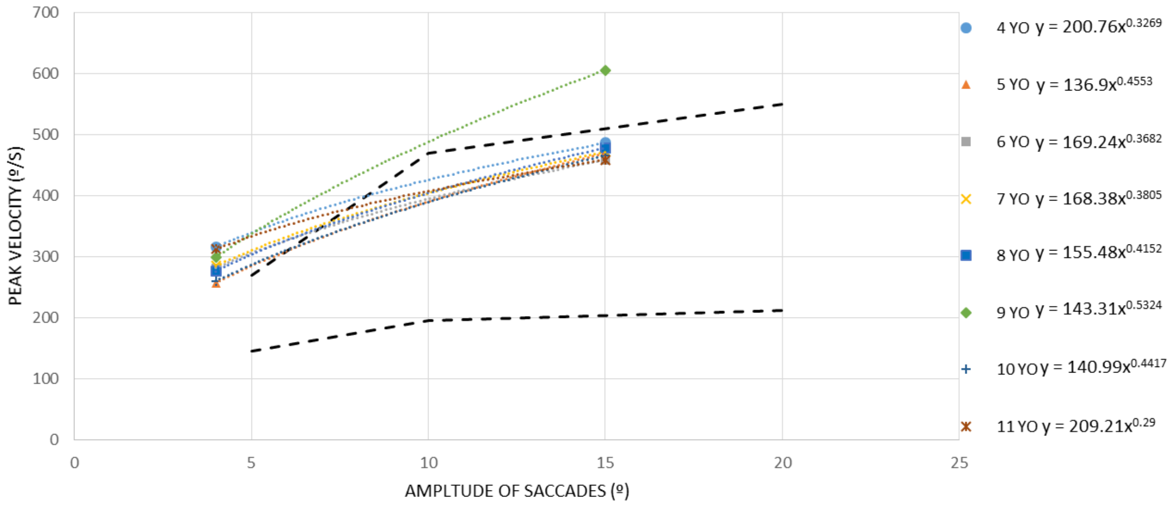


Figure 5.31. Mean peak velocity vs amplitude saccadic main sequences for each age group for downward saccades. The dashed lines represent the typical adult values for the horizontal saccades (Boghen et al. 1974).

<u>Saccadic gain (Figure 5.32 and 5.33)</u>

Figure 5.32 shows data pooled across ages for upward and downward saccadic gains. The data do not reveal an evident vertical asymmetry in saccadic gain. Paired t-tests only found significant differences between up and down gains in saccades of 10º (p=0.041) and 15º (p=0.021) amplitude at the age of 5 years and also in saccades of 5º of amplitude at the age of 9 (p=0.046) and 10 (p=0.021). The same statistical test did not find significant up-down gain asymmetries for the other age groups or for saccadic amplitudes (p>0.05).

Similar to the results obtained from the horizontal saccadic gain, these results demonstrate that, generally, vertical saccadic gain is not significantly different between upward and downward saccades. Hence, gains towards both directions were combined to assess the effect of age on saccadic gain using ANOVA.

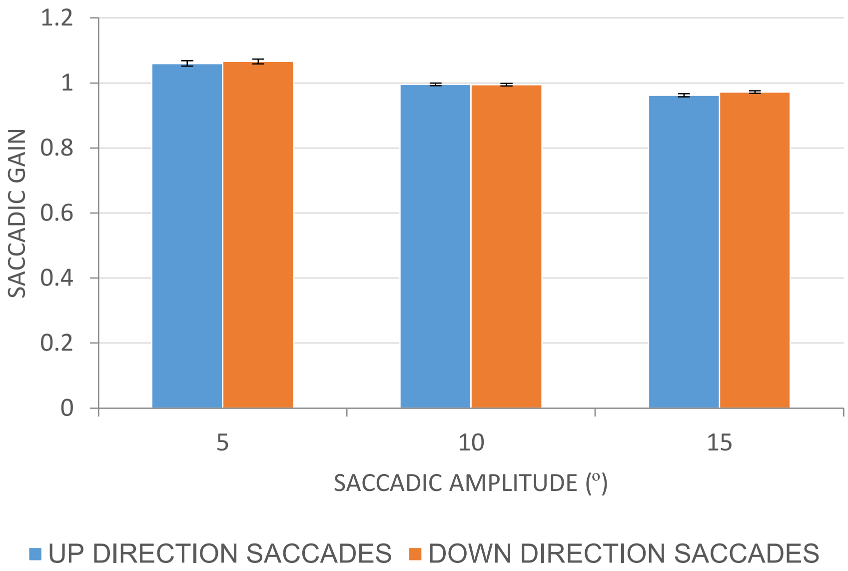


Figure 5.32. Mean (±SE) vertical saccadic gain obtained from all the participants for saccades of 5º, 10º and 15º (upward and downward).

Figure 5.33 shows that gains are above 1 for saccades of 5º in all age groups, and gains for saccades of 10º are also very close to 1. Although lower gains are observed for the 15º saccades (upward and downward), these appear to be very similar across ages. Parametric ANOVA did not show any significant differences across ages in vertical saccadic gain for 5º ($F=0.770$; $p=0.614$), 10º ($F=0.337$; $p=0.935$), 15º ($F=1.174$; $p= 0.325$).

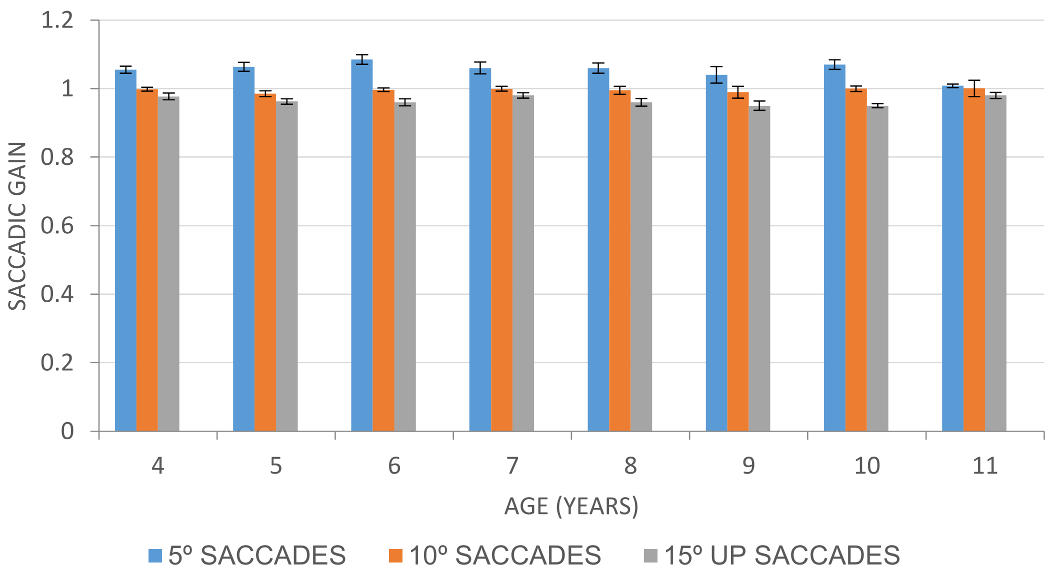


Figure 5.33. Mean (±SE) saccadic gain for each saccadic amplitude and vertical direction for each age group.

Summary

Overall, there is no evidence for development of saccades in primary school age children. Hence, from our study, saccades in children aged 4 have the same characteristics as those found in children aged 11 and both are similar to the published characteristics of adults.

In addition, the results show that horizontal saccadic performance is symmetric in children, as there is no effect of direction on saccadic main sequences and little effect (significant only for two amplitudes at two ages) of direction on gains. In contrast, the results show that vertical asymmetries do exist, particularly in the saccadic main sequence. Upward saccades are slower and less well controlled than downward saccades.

5.6.5. Visual fixation

Statistical tests

The purpose of this section is to determine the effect of age on the parameters of fixation eye movements. Fixation stability was defined as the scatter of the horizontal and vertical eye position and was calculated by using the MEP (horizontal and vertical) and its corresponding SD. The number of saccades, the mean amplitude of the saccades, and the number of microsaccades throughout the task were obtained for each participant. The means for these parameters were obtained for each age group.

Normality tests, including histograms and Shapiro-Wilk tests, were performed on all fixation parameters. Most parameters were non-normally distributed and therefore a non-parametric ANOVA Kruskal-Wallis test was used to assess differences in the fixation parameters across ages. When Kruskal-Wallis was found to be significant, Mann-Whitney paired tests were performed to assess differences between age groups. A Bonferroni correction on the p value was also performed, and significance was set at $p<0.001$.

The results of the ANOVA for the effect of age on fixation eye movement parameters are shown in Table 5.11 and further discussed below.

FIXATION EYE MOVEMENTS		
	X^2	p
HORIZONTAL MEP	4.401	0.733
VERTICAL MEP	5.847	0.558
SD OF THE HORIZONTAL MEP	5.574	0.590
SD OF THE VERTICAL MEP	11.558	0.116
NUMBER OF SACCADES	13.082	0.070
AMPLITUDE OF SACCADES	13.648	0.058
NUMBER OF MICROSACCADES	16.055	**0.025**

Table 5.12. ANOVA results for the effect of age on fixation eye movement parameters.

Fixation stability

For illustration purposes, Figure 5.34 shows the mean eye position with respect to the centre of the screen monitor obtained from each participant. The data points are presented superposed on a picture of the stimulus that was displayed in the centre of the screen as represented in the figure. The fixation point within the animated stimulus (small dot located in the middle of the animal character nose) was positioned in the exact horizontal centre of the screen, and 1º above the vertical centre of the screen (the eyes of the animal character were 1.32º from the centre of the screen) (Figure 5.34). It can be observed in Figure 5.34, that the MEP for most children was between the -1º and 1º from the geometric centre of the screen (coordinates 0,0) in the x axis and between 0º and 2º in the y axis direction. This suggests that for most children their MEP was within the stimulus presented. However, for some children the MEP was not within the stimulus suggesting that they were looking away from it during most of the fixation task.

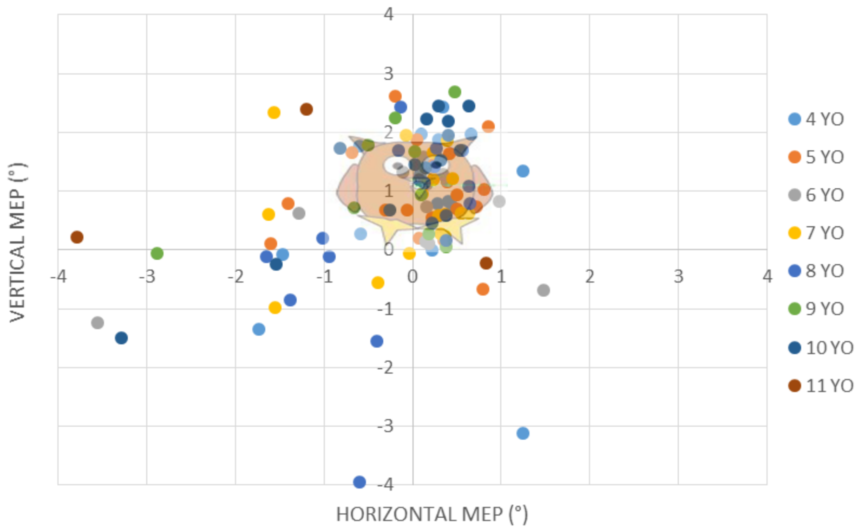


Figure 5.34. Mean horizontal and vertical eye position of all the participants of the study separated by age groups (colour coded).

<u>Horizontal and vertical MEP (Figure 5.35 and 5.36)</u>

Horizontal MEP were very close to 0 for all ages and suggest that the mean horizontal eye position was close to the geometric centre of the monitor, independently of the age (Figure 5.35). The vertical MEP for all age groups is shown in Figure 5.36. In general, the vertical MEP is located very close to 1º upward from the centre of the screen for most age groups. This vertical MEP corresponds to the area of the animal character that contains the fixation point, nose and eyes.

Non-parametric ANOVA found no significant differences across age groups in either the mean horizontal and vertical eye position (Table 5.11) suggesting that children of different ages directed their gaze at the same areas of the monitor and stimulus.

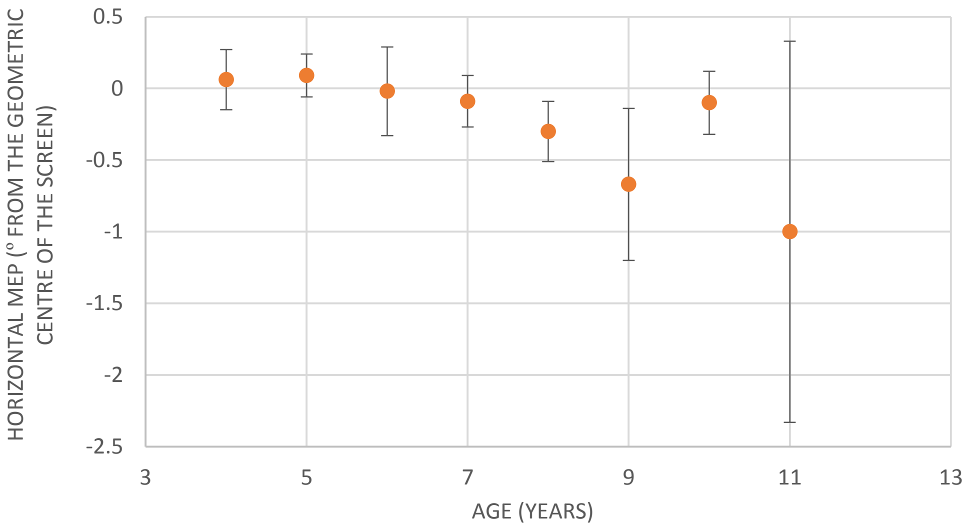


Figure 5.35. Horizontal MEP (±SE) throughout the fixation test for each age group.

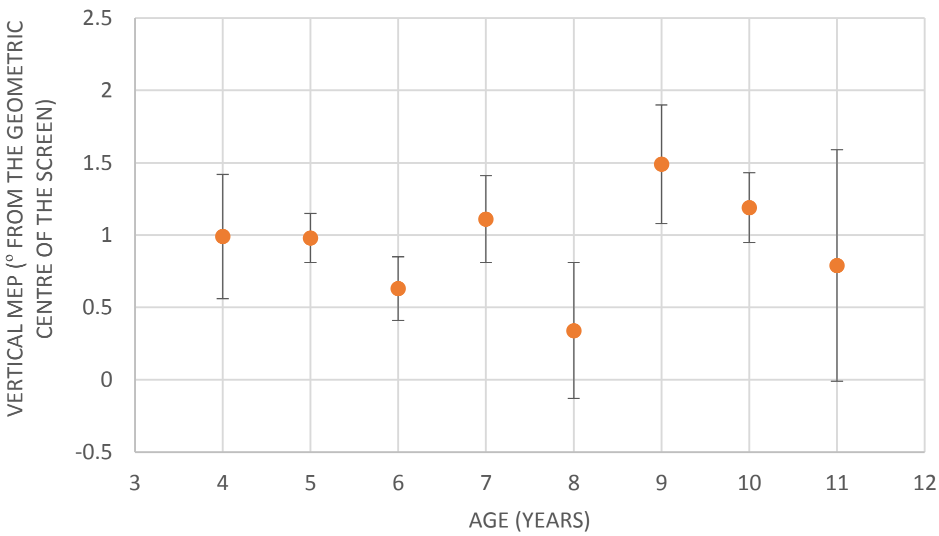


Figure 5.36. Vertical MEP (±SE) throughout the fixation test for each age group.

<u>SD of the horizontal and vertical MEP (Figure 5.37 and 5.38)</u>

The mean SD of the MEP was another parameter used to study fixation stability. Small mean SD of the MEP indicate low variability and therefore a stable fixation with small changes in eye position and/or small gaze drifts. In contrast, large mean SD from the MEP suggest that fixation is not stable and that changes in eye position and large gaze drifts are present.

Mean SD for both, the horizontal and the vertical MEP are below 2º for most age groups (Figure 5.37 and 5.38). No evident differences across ages are observed in these parameters. Non-parametric ANOVA confirmed that no significant differences across ages were found in the mean SD of the horizontal or the vertical MEP.

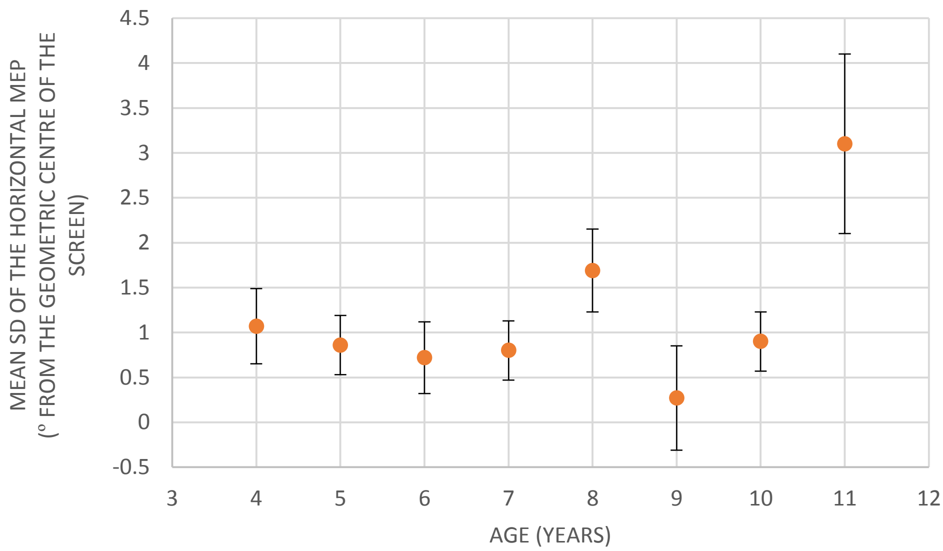


Figure 5.37. Mean (±SE) SD of the horizontal MEP obtained from the fixation test for each age group.

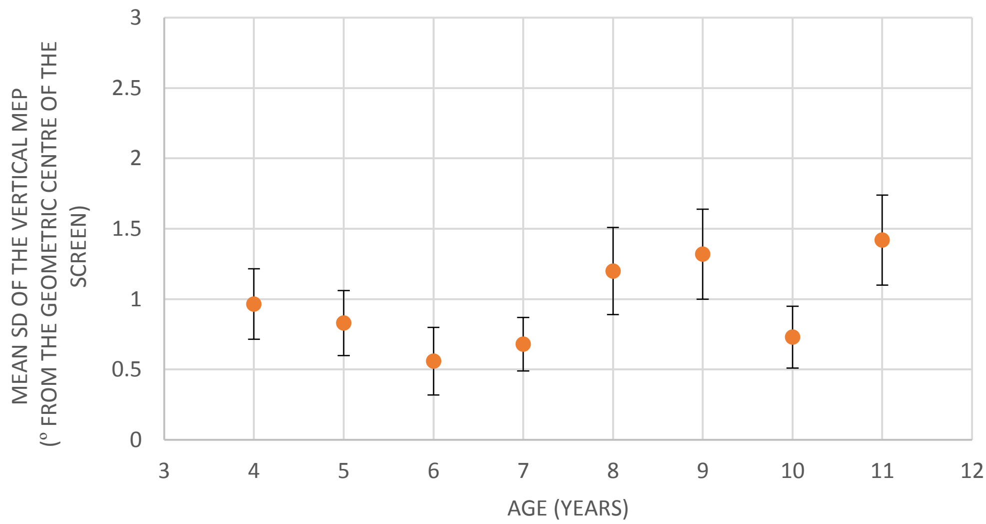


Figure 5.38. Mean (±SE) SD of the vertical MEP position obtained from the fixation test for each age group.

Saccadic events during fixation

Number of saccades during fixation (Figure 5.39)

The mean number of saccades during the fixation task is below 4 for all ages. Children in the youngest age group (aged 4) had the highest mean number of saccades (3.5). After that age, the mean number of saccades ranged between 1 and 2.5 (Figure 5.39), except for 9 year olds who exhibited an increase in the number of saccades. Non-parametric ANOVA did not find significant differences in the mean number of saccades across the age groups.

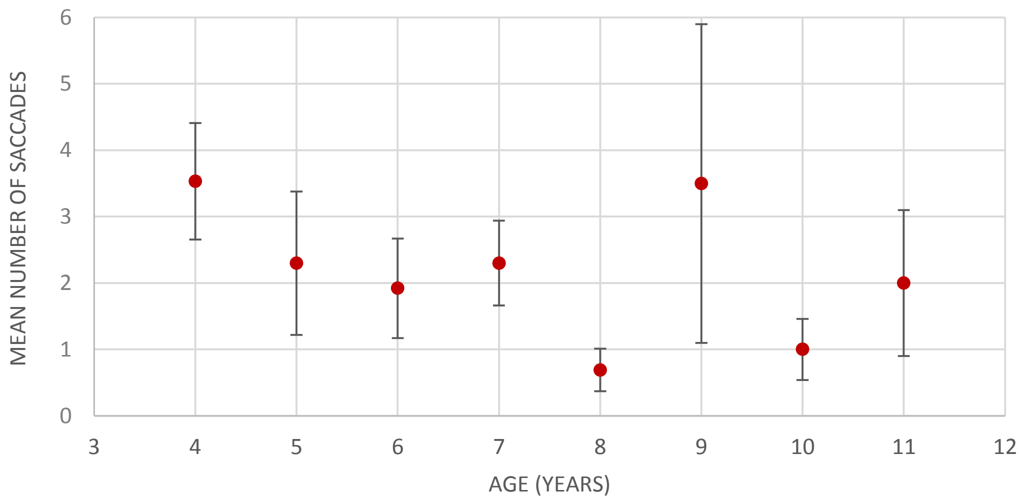


Figure 5.39. Mean (±SE) number of saccades detected during the fixation task for each age group.

Mean amplitude of saccades during fixation (Figure 5.40)

A tendency towards a decrease in the mean amplitude of the saccades with age for the fixation task can be observed in Figure 5.40. Mean saccadic amplitudes are close to 2º in children age 4 and 5 years, while the same parameter is close to 1º in children aged 6 and above. However, ANOVA did not find significant differences in this parameter across the ages (Table 5.11).

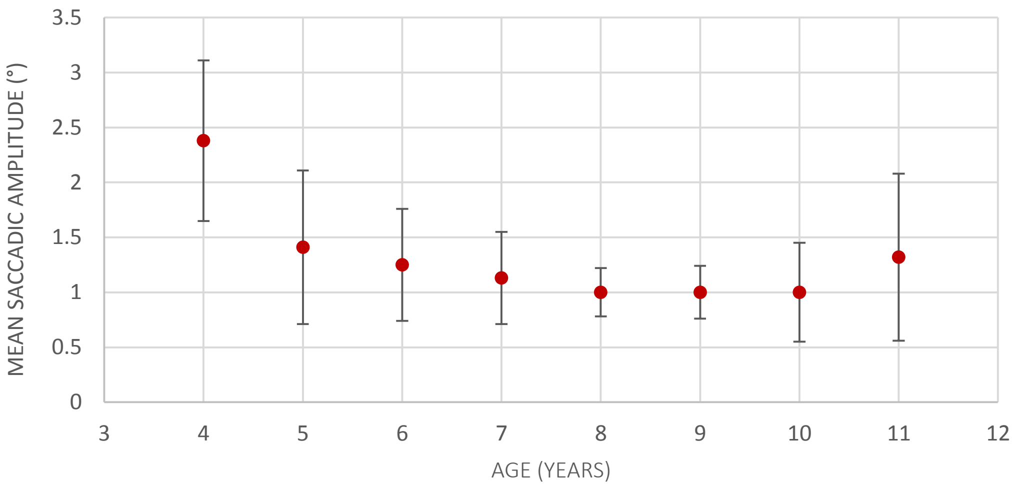


Figure 5.40. Mean (±SE) amplitude of saccades detected during the fixation task for each age group.

<u>Number of microsaccades during fixation (Figure 5.41)</u>

Figure 5.41 presents the mean number of microsaccades produced during the fixation task for each age group. Some age groups have a larger mean number of saccades than others but there is not a clear trend across ages. ANOVA did reveal significant differences in the mean number of microsaccades across ages (Table 5.11). Post Hoc tests revealed that the mean number of microsaccades was different between children aged 4 and 8 ($p<0.001$), 6 and 7 ($p<0.001$) and 6 and 8 ($p<0.001$).

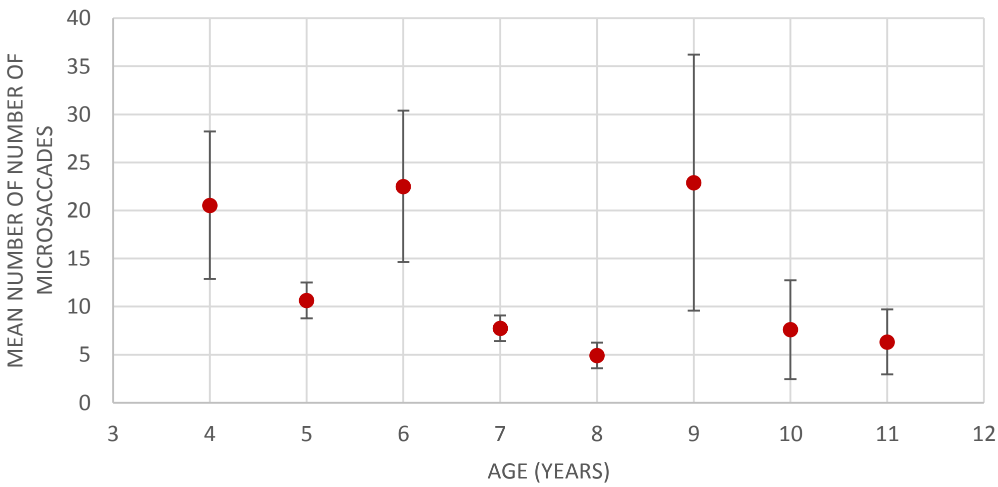


Figure 5.41. Mean (±SE) number of micosaccades detected during the fixation task for each age group.

Summary

During fixation, mean eye position and its standard deviation do not change with age. In addition, the mean number of saccades and their mean amplitude are not significantly different across the age groups. Significant differences were found in the mean number of microsaccades between some age groups but there is no evidence for a developmental trend with age. Note that as indicated by the error bars, large standard deviations are found for some fixation parameters especially at the age 9 and 11 years (e.g. Figure 5.35 and 5.39). This finding can be explained by the fact these two age groups have smallest number of successful eye movement recordings, and consequently smallest sample size for this eye movement task (9 years old n=11 and 11 years old n=4).

Overall, during the fixation task, the children directed their gaze at the animal's nose which contained the central fixation dot.

5.7. Normative values for eye movements in school age children

The 95% of values or observations obtained from a sample generally fall within the two standard deviation limits regardless of the distribution (Altman and Bland 2005). Moreover, the same limits estimate the range in which 95% of observations from a similar population would be expected to fall (Jekel 2007). According to this, eye movement normative values were defined as the intervals contained between the upper and lower 95% confidence intervals, (Mean ± 1.96 x SD) and were calculated for each eye movement parameter and age group.

The following tables (Tables 5.12 to 5.21) present the 95% confidence limits calculated for each eye movement parameter.

NORMATIVE 6º/S HORIZONTAL SMOOTH VALUES FOR CHILDREN AGED 4-11 YEARS									
	95% CONFIDENCE LIMIT	4 YO	5 YO	6 YO	7 YO	8 YO	9 YO	10 YO	11 YO
VELOCITY GAIN	UPPER	1	1	0.97	1	0.96	0.99	0.98	0.92
	LOWER	0.68	0.68	0.74	0.75	0.78	0.8	0.81	0.87
POSITION GAIN	UPPER	0.98	0.96	1	1	1.02	1	1	1.05
	LOWER	0.65	0.7	0.64	0.64	0.69	0.74	0.56	0.69
PROPORTION OF SP	UPPER	0.99	1	0.94	0.98	1	0.94	1	0.88
	LOWER	0.52	0.49	0.59	0.64	0.65	0.74	0.65	0.73
NUMBER OF SACCADES	UPPER	16.22	16.7	15.38	23.7	10	11.14	12	6.8
	LOWER	0	0	0	0	0	0	0	0
MEAN AMPLITUDE OF SACCADES	UPPER	3.84	10.57	12.82	6.12	6.4	2.5	6.63	3.5
	LOWER	0	0	0	0	0	0	0	0
NUMBER OF MICROSACCADES	UPPER	39.6	15.5	16.8	38.2	33.6	29.6	26.1	21.7
	LOWER	0	0	0	0	0	0	0	0

Table 5.13. Upper and lower 95% confidence limits for 6º/s horizontal smooth pursuit parameters for children aged 4-11 years. The eye movement normative values for each parameter are defined as the intervals contained between the upper and lower 95% confidence limits (Mean ± 1.96 x SD)

NORMATIVE 12º/S HORIZONTAL SMOOTH PURSUIT VALUES FOR CHILDREN AGED 4-11 YEARS									
	95% CONFIDENCE LIMIT	4 YO	5 YO	6 YO	7 YO	8 YO	9 YO	10 YO	11 YO
VELOCITY GAIN	UPPER	1.05	0.97	1	0.97	0.95	1	0.99	1
	LOWER	0.64	0.68	0.67	0.70	0.77	0.78	0.71	0.68
POSITION GAIN	UPPER	1	0.94	1.1	0.92	0.92	1	0.93	1
	LOWER	0.60	0.61	0.32	0.58	0.69	0.66	0.62	0.45
PROPORTION OF SP	UPPER	1	1	1	1	1	1	1	1
	LOWER	0.50	0.57	0.57	0.61	0.61	0.70	0.67	0.80
NUMBER OF SACCADES	UPPER	15.08	17	14.87	19.87	16.09	12.15	14.12	12.02
	LOWER	0	0	0	0	0	0	0	0
MEAN AMPLITUDE OF SACCADES	UPPER	8	4.86	5.21	5.89	3.32	6.40	3.69	1.79
	LOWER	0	0	0	0	0	0	0	0
NUMBER OF MICROSACCADES	UPPER	8.60	4.34	7.23	11.98	16.7	5.50	7.52	5.20
	LOWER	0	0	0	0	0	0	0	0

Table 5.14. Upper and lower 95% confidence limits for 12º/s horizontal smooth pursuit parameters for children aged 4-11 years. The eye movement normative values for each parameter are defined as the intervals contained between the upper and lower 95% confidence limits (Mean ± 1.96 x SD).

NORMATIVE 6º/S VERTICAL SMOOTH PURSUIT VALUES FOR CHILDREN AGED 4-11 YEARS									
	95% CONFIDENCE LIMIT	4 YO	5 YO	6 YO	7 YO	8 YO	9 YO	10 YO	11 YO
VELOCITY GAIN	UPPER	0.94	1	0.94	0.98	0.99	1	0.93	0.93
	LOWER	0.57	0.61	0.65	0.53	0.65	0.53	0.67	0.68
POSITION GAIN	UPPER	0.94	1	1	1	1.1	1	1.1	1
	LOWER	0.59	0.62	0.63	0.56	0.60	0.55	0.60	0.73
PROPORTION OF SP	UPPER	0.93	0.88	0.91	0.99	0.94	0.90	0.87	0.73
	LOWER	0.59	0.41	0.41	0.56	0.48	0.32	0.46	0.63
NUMBER OF SACCADES	UPPER	51.12	36.92	23.78	27.51	14.88	47.07	39.20	49.56
	LOWER	0	0	0	0	0	0	0	0
MEAN AMPLITUDE OF SACCADES	UPPER	5.60	7.75	6.15	5.46	5.48	4.01	4.4	3.27
	LOWER	0	0	0	0	0	0	0	0
NUMBER OF MICROSACCADES	UPPER	63.08	73.48	47.05	58.42	104.88	88.56	107.9	23
	LOWER	0	0	0	0	0	0	0	0

Table 5.15. Upper and lower 95% confidence limits for 6º/s vertical smooth pursuit parameters for children aged 4-11 years. The eye movement normative values for each parameter are defined as the intervals contained between the upper and lower 95% confidence limits (Mean ± 1.96 x SD).

NORMATIVE 12º/S VERTICAL SMOOTH PURSUIT VALUES FOR CHILDREN AGED 4-11 YEARS									
	95% CONFIDENCE LIMIT	4 YO	5 YO	6 YO	7 YO	8 YO	9 YO	10 YO	11 YO
VELOCITY GAIN	UPPER	0.94	0.87	0.95	0.94	0.89	0.92	0.98	0.97
	LOWER	0.42	0.55	0.60	0.50	0.63	0.59	0.45	0.53
POSITION GAIN	UPPER	0.88	0.87	1	0.94	0.87	0.87	0.99	0.91
	LOWER	0.47	0.52	0.50	0.48	0.59	0.59	0.42	0.55
PROPORTION OF SP	UPPER	1	0.86	0.95	0.93	0.94	0.98	0.91	0.83
	LOWER	0.12	0.34	0.46	0.35	0.50	0.41	0.34	0.33
NUMBER OF SACCADES	UPPER	22.65	19.35	16.72	18.33	30.90	21.54	24.10	38.82
	LOWER	0	0	0	0	0	0	0	0
MEAN AMPLITUDE OF SACCADES	UPPER	11.39	5.44	6.79	5.85	8.50	4.45	8.19	3.99
	LOWER	0	0	0	0	0	0	0	0
NUMBER OF MICROSACCADES	UPPER	31.04	22.45	24.80	42.88	32.04	44.67	51.72	53.78
	LOWER	0	0	0	0	0	0	0	0

Table 5.16. Upper and lower 95% confidence limits for 12º/s vertical smooth pursuit parameters for children aged 4-11 years. The eye movement normative values for each parameter are defined as the intervals contained between the upper and lower 95% confidence limits (Mean ± 1.96 x SD).

NORMATIVE HORIZONTAL MAIN SEQUENCE VALUES FOR CHILDREN AGED 4-11 YEARS									
	95% CONFIDENCE LIMITS	4 YO	5 YO	6 YO	7 YO	8 YO	9 YO	10 YO	11 YO
DURATION VS AMPLITUDE MAIN SEQUENCE SLOPE (S)	UPPER	2.95	2.83	2.49	2.53	2.28	2.5	2.57	2.35
	LOWER	1.31	1.09	1.4	1.51	1.75	1.76	1.65	1.4
DURATION VS AMPLITUDE MAIN SEQUENCE INTERCEPT (I)	UPPER	40.69	39.73	37	40.02	34	36.23	38	39
	LOWER	13.37	17.18	18.67	17.79	22.96	23.29	21	21.5
PEAK VELOCITY X DURATION VS AMPLTIDUE MAIN SEQUENCE SLOPE THROUGH ORIGIN (Q RATIO)	UPPER	1.82	1.84	1.82	1.85	1.72	1.74	1.79	1.91
	LOWER	1.42	1.43	1.49	1.45	1.53	1.49	1.47	1.37
PEAK VELOCITY VS DURATION MAIN SEQUENCE POWER FIT A	UPPER	277.8	242.77	190.58	220.22	160	175.8	175.93	209.14
	LOWER	44.33	76.94	102.84	66.63	98	93	79.01	104.31
PEAK VELOCITY VS DURATION MAIN SEQUENCE POWER FIT n	UPPER	0.66	0.49	0.50	0.55	0.51	0.51	0.53	0.48
	LOWER	0.08	0.22	0.28	0.25	0.36	0.25	0.26	0.31

Table 5.17.Upper and lower 95% confidence limits for horizontal main sequence parameters for children aged 4-11 years. The eye movement normative values for each parameter are defined as the intervals contained between the upper and lower 95% confidence limits (Mean ± 1.96 x SD).

NORMATIVE HORIZONTAL SACCADIC GAIN VALUES FOR CHILDREN AGED 4-11 YEARS									
	95% CONFIDENCE LIMITS	4 YO	5 YO	6 YO	7 YO	8 YO	9 YO	10 YO	11 YO
GAINS SACCADES 5º AMPLITUDE	UPPER	1.11	1.16	1.096	1.09	1.09	1.08	1.11	1.11
	LOWER	0.90	0.89	0.89	0.89	0.86	0.87	0.91	0.89
GAINS SACCADES 10º AMPLITUDE	UPPER	1.06	1.06	1.04	1.03	1.03	1.02	1.10	1.03
	LOWER	0.87	0.90	0.89	0.88	0.90	0.89	0.79	0.89
GAINS SACCADES 15º AMPLITUDE	UPPER	1.02	1.03	1.03	1.03	1.02	1.01	1.03	1.05
	LOWER	0.93	0.93	0.94	0.92	0.91	0.93	0.90	0.92
GAINS SACCADES 20º AMPLITUDE	UPPER	1.03	1.01	1.02	1.01	1.01	1.01	1.03	1.01
	LOWER	0.89	0.92	0.90	0.90	0.91	0.90	0.91	0.91

Table 5.18. Upper and lower 95% confidence limits for horizontal saccadic gain parameters for children aged 4-11 years. The eye movement normative values for each parameter are defined as the intervals contained between the upper and lower 95% confidence limits (Mean ± 1.96 x SD).

NORMATIVE UPWARD MAIN SEQUENCE VALUES FOR CHILDREN AGED 4-11 YEARS									
	95% CONFIDENCE LIMITS	4 YO	5 YO	6 YO	7 YO	8 YO	9 YO	10 YO	11 YO
DURATION VS AMPLITUDE MAIN SEQUENCE SLOPE (S)	UPPER	4.36	4.29	4.33	3.61	3.59	5.32	3.41	3.83
	LOWER	0.53	0.34	0.5	0.96	1.2	0	1.16	1.74
DURATION VS AMPLITUDE MAIN SEQUENCE INTERCEPT (I)	UPPER	48.6	47.20	61.05	54.18	48.66	58.72	45.71	25.98
	LOWER	5.28	13.029	3.50	11.92	8.29	1.52	15.99	15.80
PEAK VELOCITY X DURATION VS AMPLTIDUE MAIN SEQUENCE SLOPE THROUGH ORIGIN (Q RATIO)	UPPER	2.39	2.36	2.42	2.50	2.24	2.70	2.44	3.32
	LOWER	1.50	1.59	1.67	1.69	1.66	1.63	1.46	1.61
PEAK VELOCITY VS DURATION MAIN SEQUENCE POWER FIT A	UPPER	305.09	190.62	267.34	174.92	315.05	371.58	193.43	486.17
	LOWER	72.58	79.13	37.23	21.67	0	0	33.6	0
PEAK VELOCITY VS DURATION MAIN SEQUENCE POWER FIT n	UPPER	0.51	0.59	0.71	0.93	0.91	0.99	0.83	0.68
	LOWER	0.06	0.28	0.12	0.26	0.03	0	0.22	0

Table 5.19. Upper and lower 95% confidence limits for upward main sequence parameters for children aged 4-11 years. The eye movement normative values for each parameter are defined as the intervals contained between the upper and lower 95% confidence limits (Mean ± 1.96 x SD).

NORMATIVE DOWNWARD MAIN SEQUENCE VALUES FOR CHILDREN AGED 4-11 YEARS									
	95% CONFIDENCE LIMITS	4 YO	5 YO	6 YO	7 YO	8 YO	9 YO	10 YO	11 YO
DURATION VS AMPLITUDE MAIN SEQUENCE SLOPE (S)	UPPER	3.19	3.21	3.48	3.67	3.33	3.55	3.25	3.52
	LOWER	1.12	0.63	0.47	1.01	0.76	0.83	0.69	1.76
DURATION VS AMPLITUDE MAIN SEQUENCE INTERCEPT (I)	UPPER	46.53	47.43	47.49	43.8	44.63	51.00	45.76	30.32
	LOWER	6.57	15.34	10.1	11.89	11.04	2.5	10.39	10.13
PEAK VELOCITY X DURATION VS AMPLTIDUE MAIN SEQUENCE SLOPE THROUGH ORIGIN (Q RATIO)	UPPER	2.39	2.11	2.23	2.44	2.20	2.25	2.07	1.97
	LOWER	1.54	1.69	1.54	1.56	1.48	1.52	1.64	1.67
PEAK VELOCITY VS DURATION MAIN SEQUENCE POWER FIT A	UPPER	327.8	218.81	247.62	297.62	295.76	259.26	222.61	449.99
	LOWER	73.71	54.99	90.86	45.98	15.18	0	59.37	15.84
PEAK VELOCITY VS DURATION MAIN SEQUENCE POWER FIT n	UPPER	0.61	0.83	0.56	0.70	0.69	1.4	0.65	0.49
	LOWER	0.04	0.07	0.17	0.06	0.15	0	0.22	0.02

Table 5.20.Upper and lower 95% confidence limits for downward main sequence parameters for children aged 4-11 years. The eye movement normative values for each parameter are defined as the intervals contained between the upper and lower 95% confidence limits (Mean ± 1.96 x SD).

NORMATIVE VERTICAL SACCADIC GAIN VALUES FOR CHILDREN AGED 4-11 YEARS									
	95% CONFIDENCE LIMITS	4 YO	5 YO	6 YO	7 YO	8 YO	9 YO	10 YO	11 YO
GAINS SACCADES 5º AMPLITUDE	UPPER	1.17	1.2	1.23	1.25	1.22	1.24	1.22	1.08
	LOWER	0.92	0.92	0.93	0.88	0.90	0.85	0.91	0.92
GAINS SACCADES 10º AMPLITUDE	UPPER	1.08	1.05	1.06	1.07	1.09	1.13	1.08	1.03
	LOWER	0.85	0.86	0.84	0.88	0.87	0.80	0.88	0.89
GAINS SACCADES 15º AMPLITUDE	UPPER	1.09	1.07	1.04	1.05	1.06	1.02	1.02	1.02
	LOWER	0.88	0.88	0.89	0.89	0.88	0.89	0.88	0.95

Table 5.21. Upper and lower 95% confidence limits for vertical saccadic gain parameters for children aged 4-11 years. The eye movement normative values for each parameter are defined as the intervals contained between the upper and lower 95% confidence limits (Mean ± 1.96 x SD).

NORMATIVE FIXATION EYE MOVEMENT VALUES FOR CHILDREN AGED 4-11 YEARS									
	95% CONFIDENCE LIMITS	4 YO	5 YO	6 YO	7 YO	8 YO	9 YO	10 YO	11 YO
HORIZTONAL MEP	UPPER	1.72	1.41	2.27	1.56	1.21	2.82	1.76	3.14
	LOWER	-1.6	-1.22	-2.33	-1.75	-1.81	-4.8	-1.9	-5.9
VERTICAL MEP	UPPER	4.33	2.48	2.29	3.76	3.71	4.17	3.21	3.53
	LOWER	-2.30	-0.50	-1.03	-1.53	-3.03	-1.18	-0.82	-1.95
HORIZONTAL SD OF MEP	UPPER	4.68	4.04	4.18	3.71	5.5	8.59	4.84	10.51
	LOWER	-2.50	-2.32	-2.73	-2.09	-2.50	-4.00	-3.30	-4.30
VERTICAL SD OF MEP	UPPER	3.08	3.06	2.91	2.60	4.10	4.90	3.58	3.62
	LOWER	-1.10	-1.39	-1.78	-1.20	-1.53	-2.29	-2.10	-0.78
NUMBER OF SACCADES	UPPER	10.10	11.77	7.44	7.90	3.00	19.74	4.86	5.92
	LOWER	0	0	0	0	0	0	0	0
MEAN AMPLITUDE OF THE SACCADES	UPPER	8.63	11.40	5.54	5.90	2.67	2.84	4.70	3.90
	LOWER	0	0	0	0	0	0	0	0
NUMBER OF MICROSACCADES	UPPER	8.63	11.40	5.54	5.90	2.67	2.84	4.70	3.90
	LOWER	0	0	0	0	0	0	0	0

Table 5.22. Upper and lower 95% confidence limits for fixation eye movement parameters for children aged 4-11 years. The eye movement normative values for each parameter are defined as the intervals contained between the upper and lower 95% confidence limits (Mean ± 1.96 x SD).

5.8. Discussion

This chapter presents the results of one the main studies of this project. The aims and objectives proposed in section 5.2 have been achieved and normative values for eye movements in primary school age children (without IEP related to delayed reading) measured using the novel child-friendly setup designed are presented.

5.8.1. Smooth pursuit eye movements in primary school age children

The literature shows conficting results with regards to the mean smooth pursuit perfomance parameters in children of different ages. Some studies evaluating smooth pursuit in children ranging from 4 years of age to early-mid adolesence (12-15 years old) report lower smooth pursuit gains (Irving et al. 2011) and higher number of saccades (Tajik-Parvinchi et al. 2003) than the ones found in this study. In contrast, other published results evaluating smooth pursuit in children of specific age groups report very similar mean smooth pursuit parameters to the ones found for the equivalent age groups in our study (Rutsche et al. 2006; Salman et al. 2006a).

These discrepancies could be attributed to the fact that this population is strongly affected by the nature of the stimulus and procedures used. Thus, significant differences in eye movement performance can be found between studies investigating the same or similar eye movement parameters if the stimulus, the procedures and/or the setup are different, as demonstrated and discussed in chapter 3.

Another possible explanation for the differences found between studies is associated with the population recruited. While most studies have recruited their participants through local advertising (Ross et al. 1993; Katsanis et al. 1998; Tajik-Parvinchi et al. 2003; Salman et al. 2006a; Irving et al. 2011), only two published studies have recorded smooth pursuit eye movements in children recruited from educational institutions (Rutsche et al. 2006; Ingster-Moati et al. 2009). In our study, most child participants (135 children out of 169) were recruited from a school located in a semi-rural enviroment. The other 34 children were recruited from a school located in the city of Cardiff that provided a more ethnically diverse sample. Results can potentially be extrapolated to the general child population. In agreement with this suggestion, the smooth pursuit eye movement values from two large samples of children recruited from schools published by Rutsche et al. (2006) and Ingster-Moati et al. (2009) seem to be consistent with the data presented here. This consistency is illustrated in figure 5.42 which presents our data alongside that obtained by Ingster-Moati et al. (2009). Although our velocity gains appear to be higher than those found by Inster-Moati et al. (2009), both data sets suggest that horizontal smooth pursuit does not further develop after the age of 6 years (Figure 5.42).

There is also some contradiction with regards to the age at which smooth pursuit eye movements reach maturation and adult values. For instance, two studies proposed that this type of eye movement reaches adult values in terms of gains at the age of 17-18 (Katsanis et al. 1998; Salman et al. 2006a). However, other studies have found higher gains in children (Ross et al. 1993; Accardo et al. 1995; Langaas et al. 1998; Salman et al. 2006a) suggesting that maturation is reached close to the age of 10 years. A study assessing smooth pursuit in the first 6 years of life showed a rapid development of this type of eye movement (Rutsche et al. 2006). Furthermore, the authors cautiously proposed that smooth pursuit in children could potentially reach adult values for most parameters by the age of 6 or soon after that age (Rutsche et al. 2006). Consistent with this suggestion, the study described in this chapter produced results suggesting that, after the age of 7 years, all smooth pursuit parameters are adult-like (Figure 5.42). This finding corroborates a smooth pursuit maturation happening much earlier than generally accepted, and it is possible that the use of a child-friendly stimulus is a critical feature in demonstrating this early maturation.

With regard to the choice of the statistical test, One-way ANOVA was considered to be the most appropriate for assessing the effect of age on smooth pursuit parameters. This statistical approach allowed the development of each of the smooth pursuit parameters to be characterised. However, a multiple factor ANOVA could have also been used. Although interactions between different factors such as age, velocity and direction might have been identified by using a multiple factor ANOVA, such an analysis was outside the scope of the present study.

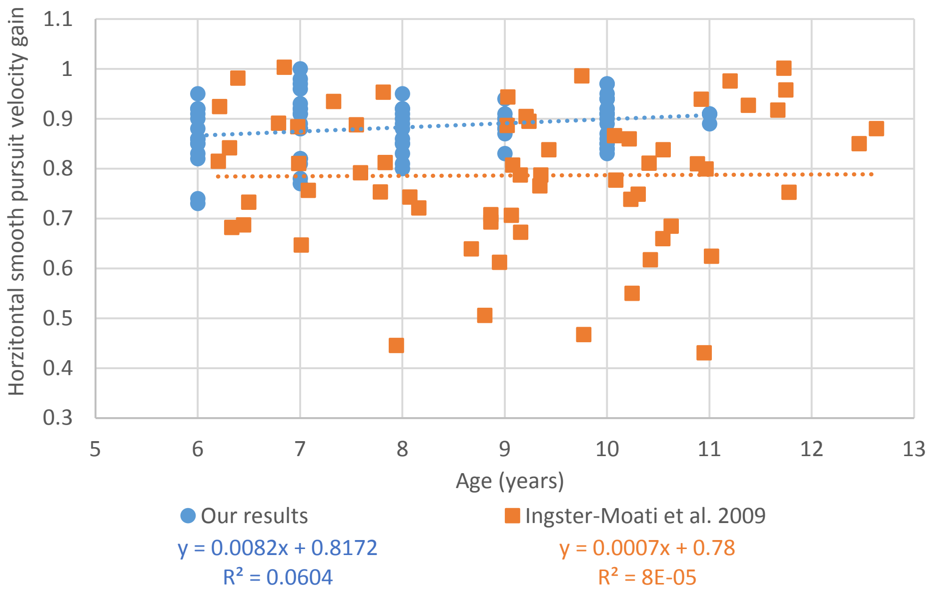


Figure 5.42. Horizontal smooth pursuit gain obtained from all children aged 6 to 13 years who took part in the study by Ingster-Moati et al. 2009 (orange squares) and our study (blue circles). Both graphs suggest that smooth pursuit velocity gain does not further develop after the age of 6.

5.8.2. Saccadic eye movements in primary school age children

In this chapter, we presented a full characterization of the saccadic main sequence (which is considered to define the "normalcy of the saccades") and saccadic gain (measure of saccadic accuracy). Saccadic latency can also be studied to characterise and assess this eye movement type, but this parameter was not studied in this project as its development and full characteristics in children have been widely reported.

It is well accepted that most saccadic parameters assessed should be fully developed and equivalent to those found in adults by the age of 4 years (Fukushima et al. 2000). The present results show that main sequence parameters do not change in children during primary school. Moreover, the figures illustrating the results from the mean saccadic main sequences at different ages showed that these not only fell within the established adult typical values (Boghen et al. 1974; Harwood et al. 1999; Garbutt et al. 2001) but that, in most cases, they were also right in the middle of the area delimited by the typical adult saccade limits. In general, therefore, it seems that saccadic main sequences in children are equivalent to those found in adults even in children as young as 4.

The gains obtained for all amplitudes tested show a slight undershoot and match those observed in earlier studies (Accardo et al. 1992; Salman et al. 2006b). Similar to the results obtained from the main sequence, no significant differences with age were found for saccadic gain for any amplitude studied.

Some studies are available investigating horizontal saccades in infants and children (Black et al. 1984b; Accardo et al. 1992; Fioravanti et al. 1995; Katsanis et al. 1998; Fukushima et al. 2000; Yang et al. 2002; Irving et al. 2011). In contrast, studies on the characteristics of vertical saccades in children are lacking, and we are only aware of two recent studies evaluating the development of saccades in this direction (Salman et al. 2006b; Bucci and Seassau 2014). While the study by Salman et al. (2006b) reported no differences in saccadic gains and peak velocities between upwards and downward saccades, a very recent study by Bucci and Sessau (2014) reported the opposite and showed a significant up-down asymmetry in the same parameters. Interestingly, both studies agreed that these saccadic parameters are stable during childhood, and no changes were detected between age groups. The findings presented in this chapter, which suggest no development of vertical saccades in primary school age children, mirror those of the previous studies above. However, our findings are more in line with the more recent published study (Bucci and Sessau 2014) in also showing vertical saccadic asymmetries.

The presence of asymmetries in vertical saccades in adults is also unclear, as different findings have been reported amongst authors (e.g. Yang et al. 2002a; Garbutt et al. 2003b). These rather contradictory results may be due to the increased variability observed not only for vertical saccades but also for vertical smooth pursuit. The data presented in our study clearly demonstrate that variability within a group (in our case age groups) is increased for vertical eye movements when compared to horizontal. In addition, it has been suggested that some technical difficulties arise when recording saccades in this direction due to the vertical distortions produced by the eyelids (Bucci and Seassau 2014).

Another important finding was that, although our saccadic test was adapted to children as described in chapter 4, section 4.3.2, the results obtained were not different from those obtained using the traditional saccadic gap paradigm in the same age groups (Fukushima et al. 2000; Salman et al. 2006b). The main difference in the saccadic paradigm used in here was that not all the saccades started from the centre of the monitor, and some saccades started from eccentric positions. This approach, which gave rise to intense discussion within the research group and its collaborators, was taken in order to reduce the task time and minimise any potential fatigue effect in the participants. Fortunately, our saccadic values mirror those of previous studies and suggest that this newly designed paradigm can be used to quantitatively study saccades in populations that might benefit from a shorter version of the full length saccadic paradigm.

5.8.3. Visual fixation in primary school age children

Finally, this chapter also produced normative values for fixation eye movements and fixation stability in school age children. This eye movement type is possibly the least studied, and we are not aware of many studies evaluating fixation eye movements in children or adults. Although many aspects of oculomotor function have been reported to change with age in adults (Sharpe and Sylvester 1978; Muñoz et al. 1998; Ross et al. 1999; Schik et al. 2000), fixation stability has been reported to be maintained in older adults (Kosnik et al. 1986). However, it has been suggested that "large interindividual variations" can be found in fixation stability when the same fixation task is repeated (Moller et al. 2006). To our knowledge, there is only one study that quantitatively evaluates fixation eye movements and fixation stability in children (Ygge et al. 2005). This study reported the presence of differences across the ages studied in the mean number of saccades and the mean distance (in degrees) from the mean horizontal and vertical MEP. In contrast, our study found no differences across ages in the number of saccades, the amplitude of the saccades, the horizontal and vertical MEP and the SD of the MEP. However, significant differences were found in the mean number of microsaccades between different ages but these did not not follow a clear developmental pattern. Hence, the mean number of microsaccades in children aged 4 was found to be only different from that found in 8 year olds, and the same parameter appears to be different between children aged 6 and children aged 7 and 8. Having said that, the mean number of saccades found in our study for young children aged between 4 and 6 is much lower than those reported by Ygge et al. (2005), but differences in this parameter are not found for other age groups. It is difficult to explain the differences in these results, but it might again be related to our use of a child-friendly stimulus in the current study and the potential improvement in eye movement performance in children obtained when this stimulus is used (described in chapter 3).

5.9. Summary

This chapter provides normative values for eye movements in primary school age children. These normative values are achieved by calculating the 95% confidence limits (mean±1.96*SD) and define the confidence interval for each eye movement parameter. The confidence interval acts as a good estimate of the range of a parameter on the population.

These normative values will be used in subsequent chapters of this thesis to assess eye movement differences in children with reading difficulties, atypical children and children with suspected eye movement anomalies. In addition, the normative values provided in this study will be also valuable in future studies that aim to investigate the effectiveness of interventions provided to improve eye movements and educational achievements in children

Chapter 6 Eye movements in children with an Individual Education Plan (IEP) related to delayed reading skills

6.1. Introduction

Several attempts have been made to investigate the relationship between oculomotor control and delayed reading skills, and it is generally accepted that eye movements during reading differ between poor and good/average readers (Ciuffreda et al. 1976; Kulp and Schmidt 1996; Rayner 1998). However, it can be argued that these differences in eye movements between individuals of different reading abilities could arise from deficits in higher cognitive processes involved in reading (Garzia et al. 1990) rather than from oculomotor control deficits (chapter 1, section 1.3). Hence, it is still unclear if eye movements are the cause or just the effect of reading difficulties (Medland et al. 2010).

6.2. Aim

- To determine the extent to which eye movements in non-reading tasks in children with delayed reading skills are different to those obtained from school children with good or average reading skills

6.3. Participants

Forty-three children (18 females and 25 males) ages ranging from 4 to 11 years (mean age 8.21 SD±1.99) with delayed reading skills were recruited from the same schools (Kitchener Primary School and White Rose Primary School). These children were identified as those that benefited from an *IEP related to delayed reading skills* in their schools. The age distribution of these children is illustrated in a histogram in chapter 5 (section 5.5 and Figure 5.3).

Details on the recruitment and the procedure used to unmask the children who had an IEP related to delayed reading skills are provided in chapter 5, section 5.5. For the rest of this chapter, the simple term IEP will refer only to IEP related to delayed reading skills (see details in chapter 5, section 5.5.).

6.4. Optometric test

The visual acuity of the 43 children with IEP, measured with Kay Pictures and Keeler logMAR, was between logMAR +0.3 and logMAR -0.1 for distance (mean RE VA logMAR 0.05 (SD±0.08), mean LE VA logMAR 0.03 (SD±0.08)), mean binocular VA logMAR 0.02 (SD±0.08)) and near (mean RE VA logMAR 0.00 (SD±0.05), mean LE VA logMAR 0.005 (SD±0.05)), mean binocular VA logMAR 0.00 (SD±0.04)).

The mean absolute spherical refractive error found in this group of children was of 0.58DS (SD±0.66) for the RE and of 0.54DS (SD±0.77) for the LE. A significant cylinder higher than 1DC was only found in one child (cylinder of 1.5DC).

Distance cover test revealed that 40 (93.02%) children were orthophoric, 2 (4.65%) had high exophorias and only 1 (2.32%) had a small esophoria. The same test at near found that 31 (72.09%) children were orthophoric, 9 (20.93%) children had low phorias and 3 children had high phorias. The NPC break up point in most children was under 5 cm but a NPC of more than 5 cm (with a maximum value of 8 cm) was found in 4 (9.30%) of these children. Out of the 43 children, 9 (20.93%) did not see the third plate on the Frisby stereotest (equivalent to 85") but they did see the second plate (equivalent to 170"). Only 1 child aged 4 years did not see the first plate of this test.

Accommodation was accurate (lag or lead <1D) in 40 children using dynamic retinoscopy placing the UC cube at 25 cm. However, 3 (9.30%) children had a lag of more than 1D the maximum being lag 2D. Finally, the results of the motility test were recorded as "SPEC" (Smooth, Precise, Extense and Complete) in 38 (88.34%) children, "significant head movement" in 4 (9.30%) children and "jerky" in one child.

The individual results of the optometric tests of the 43 children with IEP are presented in Appendix G.

Table 6.1 shows the mean visual acuity and refractive error (absolute spherical refractive error) found for the children with and without IEP. The same table presents the statistical p values of the independent t-tests used to compare differences between the two groups. The statistical results showed no significant differences in visual acuity or the absolute spherical refractive error (monocular and binocular) between children with and without IEP.

Table 6.2 presents the results from the other optometric tests in the children with and without IEP. This table presents the frequency of children with and without IEP that had cylindrical refractions >1DC, NPC >5 cm, stereoacuity >85”, phorias and accommodative lags >1D. Chi-square tests were used to assess any associations between holding an IEP and the results of the optometric examination. These statistical tests showed that there were no significant associations between holding an IEP and the different results of the optometric tests performed.

		RE D.VA	LE N. VA	BINO D.VA	RE N.VA	LE N.VA	BINO N.VA	RE SPH	LE SPH
NO IEP	MEAN ±SD	**0.029** ±0.089	**0.030** ±0.090	**0.017** ±0.086	**0.011** ±0.056	**0.011** ±0.055	**0.007** ±0.051	**0.67** ±0.95	**0.71** ±1.09
IEP	MEAN ±SD	**0.051** ±0.089	**0.036** ±0.080	**0.028** ±0.086	**0.006** ±0.053	**0.005** ±0.053	**0.002** ±0.046	**0.58** ±0.66	**0.54** ±0.77
P VALUES		0.193	0.492	0.296	0.536	0.540	0.865	0.985	0.514

Table 6.1. Mean monocular (RE - right eye; LE - left eye), binocular (BINO) distance (D) and near (N) VA (±SD) and mean absolute (ABS) monocular absolute spherical (SPH) refractive error (±SD) in children with and without IEP.

FREQUENCY OF CHILDREN		CYL <1DC	CYL >1DC	NPC <5CM	NPC >5CM	STEREO 85”	STEREO 170”&340”
NO IEP	NUM	117	3	111	9	107	16
IEP	NUM	42	1	39	4	33	10
P VALUES		X^2=0; p=1.00		X^2=0.002; p=0.963		X^2=0.883; p=0.347	
FREQUENCY OF CHILDREN		**CT DISTANCE ORTHO**	**CT DISTANCE NO ORTHO**	**CT NEAR ORTHO**	**CT NEAR NO ORTHO**	**ACC LAG<1D**	**ACC LAG<1D**
NO IEP	NUM	119	1	86	34	117	3
IEP	NUM	40	3	31	12	40	3
P VALUES		X^2=2.75; p=0.097		X^2=0; p=1.00		X^2=0.749; p=0.387	

Table 6.2. Contingency table summarising the results for the cylindrical refractive error (CYL), NPC, steroacuity (STEREO), CT and accommodation (Acc).

6.5. Eye movement recording success rate

Successful eye movement recordings from 40 (90.02%) and 37 (86.04%) children with IEP were obtained for the 6º/s and 12º/s horizontal smooth pursuit, respectively and also from 40 (90.02%) and 37 (88.08%) children for the vertical condition following the same velocities. For the saccadic test, successful eye movement recordings were obtained from 42 (97.67%) and 31 (72.09%) children for the horizontal and vertical direction, respectively. Finally, for the fixation task, successful eye movement recordings were obtained from 41 (95.34%) children out of the 43 children included in this study.

The success rate in the group of children with IEP was very similar to the group of children with no IEP for the smooth pursuit, horizontal saccades and fixations (success rate >85%). In contrast, the success rate of the group of children with IEP was slightly lower than that found in children with no IEP for vertical saccades (children no IEP: 85.83%; children IEP: 72.09%).

6.6. Age-matched group comparisons between children with and without IEP

6.6.1. Statistical analysis

The purpose of the analysis in this section is to determine whether eye movements (smooth pursuits, saccades and visual fixation) in children with IEP are different to eye movements in age-matched children without such education plan.

Independent t-tests were the most appropriate tests for this. For instance, the mean value (median in the case of non-parametric independent t-tests) for each eye movement parameter obtained from all 8-year-old participants with IEP was compared to the mean value (or median) obtained from children of the same age who did not have such IEP. This comparison was performed for each age group studied. Because multiple comparisons were performed for each age group and eye movement task (one comparison for each parameter studied in each eye movement task) the p value considered to be statistically significant was adjusted accordingly with the Bonferroni correction method.

Before independent t-tests were performed, the distribution of each eye movement parameter, reading skill (children IEP and no IEP) and age group was assessed using histograms and Shapiro-Wilk tests. When an eye movement parameter was normally distributed (Shapiro-Wilk $p>0.05$) for most age and reading skill (IEP and no IEP) groups, parametric independent t-tests were used. In contrast, when the distribution was in general non-normal, the non-parametric equivalent statistical test (Mann-Whitney test) was used.

Smooth pursuit

Data for horizontal and vertical smooth pursuit gains (velocity and position) and proportion of SP were normally distributed for children with and without IEP across all age groups (Shapiro-Wilk $p>0.05$). In contrast, the number of saccades and microsaccades throughout the smooth pursuit tasks as well as the mean amplitude of the saccades were non-normally distributed (Shapiro-Wilk tests $p<0.05$). Hence, parametric and non-parametric independent t-tests were used accordingly.

In order to determine whether smooth pursuit eye movements were different between children with and without an IEP, multiple independent t-tests (six tests: (1) velocity gain, (2) position gain, (3) proportion of SP, (4) number of saccades, (5) mean amplitude of saccades and (6) number of microsaccades) were performed for each age group and smooth pursuit stimulus velocity. The procedure of performing multiple independent comparisons like the ones here, results in an increase in type I error (Ludbrook 1998). The explanation being that when a p value is set to $p<0.05$, by the laws of probability, there is 1 in 20 chance to observe a significant result. For instance, when 20 independent comparisons are performed (e.g. 20 groups, 20 variables or 20 expected outcomes in the experiment), the chance of having one significant value is no longer 0.05, but 0.64 ($1 - (1 - 0.05)^{20}$) (Perneger 1998). Hence, there is a 64% probability of obtaining a statistically significant result (type I error). Following this rationale, in the smooth pursuit statistical analysis (for both horizontal and vertical) performed here, there is a 26.5% probability that one of the parameters studied (velocity gain, position gain, proportion of SP, number of saccades, mean amplitude of saccades and number of microsaccades) appears to be significantly different between the two groups. Hence, a Bonferroni correction was applied to maintain the α level over all sets of age-matched comparisons at 0.05 (Benjamini and Hochberg 1995; Armstrong 2014). With this correction, a p value <0.008 was considered to be statistically significant for both the horizontal and the vertical smooth pursuit.

Saccades

The parameters of the saccadic eye movements (horizontal and vertical), which included the main sequence functions parameters (S, I, Q, A, n) and gains for different saccadic amplitudes (for 5º, 10º, 15º and 20º), were normally distributed for all groups (age and IEP group). Therefore, parametric independent t-tests were performed to determine whether saccadic eye movements were different between age-matched groups of children with and without IEP. Similar to the issue described above, the multiple independent comparisons performed for the main sequence parameters and saccadic gains increase the risk of "making statistical false inferences" (Ludbrook 1998), which is the same as increasing the type I error. To avoid this, a Bonferroni correction following the same methods described in the above section was also performed and a p value <0.01 was considered statistically significant.

Visual fixation

For visual fixation, all the parameters assessed were non-normally distributed for most age and IEP groups and the non-parametric approach was taken. Seven non parametric independent t-tests (horizontal and vertical MEP), mean SD of the MEP (for horizontal and vertical), number of saccades, mean amplitude of saccades and number of microsaccades) were performed to determine whether visual fixation was significantly different between age-matched groups of children with and without IEP. A Bonferroni correction was performed in order to control for type I error and a p value <0.007 was considered to be statistically significant.

6.6.2. *Results*

Smooth pursuit

Horizontal smooth pursuit

The results of the age-matched independent t-tests for the horizontal smooth pursuit parameters between children with and without an IEP are shown in Table 6.3.

Three p values (highlighted in bold type in Table 6.3) were <0.05. These corresponded to position gain (6º/s) and proportion of SP (12º/s) in 6 year olds and mean amplitude of saccades (12º/s) 5 year olds. However, after the Bonferroni correction these parameters were not statistically significant ($p>0.008$).

Hence, it can be concluded that there are no statistically significant differences between children with and without IEP of any age for the 6º/s and 12º/s horizontal smooth pursuit.

	AGE	VELOCITY GAIN t	VELOCITY GAIN p	POSITION GAIN t	POSITION GAIN p	PROPORTION OF SP t	PROPORTION OF SP p	NUMBER OF SACCADES Z	NUMBER OF SACCADES p	AMPLITUDE OF SACCADES Z	AMPLITUDE OF SACCADES p	NUMBER OF MICROSACCADES Z	NUMBER OF MICROSACCADES p
HORIZONTAL 6°/S	4	0.319	0.754	-0.205	0.840	0.545	0.593	-0.495	0.641	0.00	1.0	-1.901	0.052
	5	0.872	0.394	1.435	0.167	1.183	0.252	-0.770	0.464	-1.961	0.530	-0.288	0.787
	6	-0.367	0.717	-2.214	**0.039**	1.802	0.087	-1.339	0.208	-1.073	0.313	-1.370	0.179
	7	1.242	0.227	1.406	0.173	0.885	0.385	-0.682	0.530	-0.613	0.575	-0.205	0.869
	8	0.377	0.711	0.067	0.947	1.396	0.182	1.153	0.289	-0.148	0.924	-0.395	0.703
	9	0.145	0.886	-1.541	0.140	-0.376	0.771	-0.752	0.464	-0.071	0.972	-0.643	0.554
	10	-0.183	0.856	0.410	0.685	-0.05	0.960	-0.365	0.722	-0.294	0.790	-0.250	0.824
	11	-1.449	0.207	-0.411	0.698	-2.689	0.043	-0.185	0.857	-0.178	0.857	-1.440	0.229
HORIZONTAL 12°/S	4	1.301	0.212	1.163	0.262	1.720	0.105	-1.010	0.499	-0.141	0.941	-1.143	0.327
	5	-0.966	0.346	0.501	0.622	0.011	0.991	-0.130	0.833	-2.278	**0.010**	-0.064	0.952
	6	1.642	0.117	0.685	0.502	2.639	**0.016**	-0.178	0.852	-0.578	0.603	-0.593	0.603
	7	-0.562	0.579	-0.802	0.431	-0.309	0.760	0.431	0.670	-1.493	0.139	-0.436	0.679
	8	-1.346	0.506	-0.163	0.873	0.998	0.335	0.884	0.392	-1.816	0.082	-0.626	0.611
	9	2.021	0.059	1.934	0.070	1.569	0.135	-1.907	0.074	-0.889	0.408	-0.713	0.492
	10	-0.141	0.889	0.126	0.901	-0.693	0.495	0.644	0.525	-0.211	0.835	-0.793	0.444
	11	0.093	0.932	-1.732	0.157	-1.292	0.253	0.450	0.666	-0.707	0.629	-0.900	0.400

Table 6.3. Age-matched independent t-test results for the horizontal smooth pursuit parameters (velocity gain, position gain, proportion of SP, number of saccades, amplitude of saccades and number of microsaccades) between children with and without IEP.

Vertical smooth pursuit

The results of the age-matched independent t-tests for the vertical smooth pursuit parameters between age-matched children with and without an IEP are shown in Table 6.4.

It can be observed in the table that for the 6º/s vertical smooth pursuit, p values <0.05 (highlighted in bold type in Table 6.4) were found for the mean amplitude of the saccades (5 and 9 years) and velocity gain (4 years). For the 12º/s vertical condition, p values <0.05 were found for velocity gain (5 years) and the mean amplitude of the saccades (5, 6 and 7 years). These parameters were not significant after the Bonferroni adjustment on the p value that set the significance threshold to 0.008.

It can be concluded that there were no statistically significant differences between children with and without IEP of any age for the 6º/s and 12º/s vertical smooth pursuit.

		VELOCITY GAIN		POSITION GAIN		PROPORTION OF SP		NUMBER OF SACCADES		AMPLITUDE OF SACCADES		NUMBER OF MICROSACCADES	
	AGE	t	p	t	p	t	p	Z	p	Z	p	Z	p
VERTICAL 6º/s	4	-2.227	**0.042**	-0.709	0.489	-0.609	0.552	-0.298	0.824	-0.298	0.824	-0.075	0.941
	5	-1.259	0.223	-0.671	0.510	-0.481	0.633	-0.101	0.962	-2.211	**0.024**	-1.408	0.185
	6	-0.286	0.789	-0.197	0.846	-0.322	0.751	-0.497	0.660	-1.486	0.153	-0.991	0.354
	7	-0.923	0.366	-1.101	0.283	-0.026	0.980	-0.961	0.367	-0.533	0.629	-1.460	0.160
	8	0.049	0.961	0.072	0.944	1.751	0.099	-0.451	0.703	-0.542	0.633	-0.148	0.924
	9	-1.457	0.162	-0.602	0.555	-1.931	0.069	-1.525	0.131	-1.976	**0.046**	-1.751	0.080
	10	1.559	0.156	1.992	0.057	0.815	0.423	-1.834	0.070	-0.076	0.940	-0.916	0.381
	11	0.602	0.574	0.568	0.594	0.104	0.926	-0.900	0.400	0.00	1.00	-0.714	0.629
VERTICAL 12º/s	4	1.10	0.914	-0.135	0.894	-0.270	0.791	0.00	1.00	-0.635	0.600	-0.653	0.600
	5	-2.379	**0.029**	-1.200	0.247	-1.216	0.241	2.176	**0.044**	-1.230	0.254	-1.281	0.254
	6	1.679	0.110	1.244	0.229	1.201	0.245	-2.633	**0.016**	-0.537	0.603	-0.671	0.548
	7	0.354	0.727	0.499	0.623	0.901	0.377	-2.299	**0.031**	-0.462	0.677	-0.821	0.446
	8	1.034	0.318	0.761	0.459	0.906	0.379	0.378	0.711	-1.359	0.202	-0.057	0.956
	9	1.087	0.291	0.684	0.502	0.893	0.383	-0.775	0.448	-0.604	0.554	-0.751	0.464
	10	0.148	0.884	-0.173	0.864	-0.706	0.486	-0.284	0.777	-0.519	0.627	-0.286	0.799
	11	0.959	0.381	0.714	0.507	0.317	0.764	0.701	0.515	-0.354	0.857	-1.061	0.400

Table 6.4. Age-matched independent t-test results for the vertical smooth pursuit parameters (velocity gain, position gain, proportion of SP, number of saccades, amplitude of saccades and number of microsaccades) between children with and without IEP.

Summary

The results above showed that horizontal and vertical smooth pursuit eye movements were not significantly different between children of the same age with and without IEP when compared as a group.

Saccades

Horizontal saccades main sequence

In agreement with the results obtained in chapter 5, section 5.6.4, for the children without IEP, the main sequence parameters obtained for saccades to the right and to the left were also very similar in children with IEP. Paired t-tests confirmed no significant differences in the main sequence parameters between right and left saccades for any age group (p>0.05). Thus, the main sequence parameters (S, I, Q, A, n) used for the independent t-tests were those obtained from the main sequence of all the saccades performed during the task and included saccades to both directions (right and left).

The results of the age-matched independent t-tests for the horizontal main sequence parameters between children with and without IEP are shown in Table 6.5.

		S		I		Q		A		n	
	AGE	t	p	t	p	t	p	t	p	t	p
HORIZONTAL MAIN SEQUENCE	4	-0.395	0.699	-0.269	0.791	-0.989	0.338	0.551	0.591	-0.270	0.791
	5	0.699	0.493	-1.981	0.062	-1.770	0.211	1.969	0.063	-3.229	**0.040**
	6	0.392	0.700	0.097	0.924	-0.747	0.466	-0.190	0.852	-0.463	0.649
	7	1.797	0.085	0.170	0.866	-0.118	0.907	-0.821	0.420	0.443	0.662
	8	0.141	0.890	0.885	0.389	-1.025	0.321	-1.273	0.221	0.970	0.347
	9	0.408	0.686	1.512	0.148	-1.604	0.126	-1.116	0.288	-0.054	0.957
	10	-1.078	0.290	0.415	0.681	0.817	0.421	-0.033	0.974	0.523	0.605
	11	-0.558	0.601	-0.147	0.889	-0.087	0.934	1.525	0.188	-1.731	0.144

Table 6.5. Age-matched independent t-test results for the horizontal main sequence parameters (S, I, Q, A and n) between children with and without IEP.

The statistical results presented in Table 6.5 show that only one parameter (highlighted in bold in Table 6.5) was below <0.05. This p value corresponded to the comparison of the coefficient n obtained from the peak velocity vs amplitude main sequence between children with and without IEP aged 5 years. However, after the Bonferroni adjustment on the p value, none of the parameters studied were found to be significant different between children with and without IEP at any age (p>0.01).

Horizontal saccadic gains

In children with IEP, paired t-test only found a significant horizontal asymmetry in gains for saccades of 20º amplitude at the age of 4 years (t=30.479; p=0.021). For this amplitude and age, gains for saccades to the right were significantly higher (and hypermetric) than saccades to the left. Thus, similar to the analysis performed in chapter 5, section 5.6.4 saccadic gains towards both directions were combined for each amplitude. The combined right and left gains were used in the statistical analysis aiming to assess differences in saccadic gains between children with and without IEP. The gain values obtained for the saccades of different amplitude and direction were normally distributed for all age groups according to Shapiro-Wilk tests (p>0.05). Therefore, parametric independent t-test were used to assess the differences in mean saccadic gains for each amplitude between age-matched children with and without IEP.

The results of the age-matched independent t-tests for the horizontal mean saccadic gains between children with and without IEP are shown in Table 6.6.

		5º		10º		15º		20º	
	AGE	t	p	t	p	t	p	t	p
HORIZONTAL SACCADIC GAINS	4	-1.036	0.319	-1.823	0.091	-3.132	**0.008**	-2.422	**0.035**
	5	-0.193	0.850	-1.009	0.325	-0.176	0.855	-0.471	0.643
	6	3.057	**0.008**	2.286	**0.037**	-0.627	0.540	0.865	0.401
	7	0.056	0.956	-0.522	0.606	-0.254	0.802	-0.624	0.539
	8	0.757	0.460	-0.059	0.954	-1.826	0.087	-2.173	0.450
	9	0.591	0.562	0.543	0.594	0.090	0.929	-1.069	0.299
	10	-0.530	0.601	-0.244	0.809	0.799	0.431	0.375	0.771
	11	1.025	0.363	0.632	0.562	-0.118	0.912	1.231	0.286

Table 6.6. Age-matched independent t-test results for the horizontal saccadic gains (saccades of 5º, 10º, 15º and 20º) between children with and without IEP.

The p value was <0.05 in the age-matched comparisons for saccadic gains of 15º and 20º of amplitude at the age of 4 and for saccadic gains of 5º and 10º at the age of 6 (highlighted in bold type in Table 6.6). However, only two of these p values appeared to be significant after applying the Bonferroni correction on the p value (highlighted in yellow in Table 6.6). Hence, independent t-tests revealed significant differences in saccadic gains between 4 year old children with and without IEP for saccades of 15º ($t=-3.123$; $p=0.008$). The same statistical tests revealed significant differences between 6 year old children with and without IEP for saccades of 5º of amplitude ($t=3.057$; $p=0.008$). No significant differences between children with and without IEP were found for the other age groups and saccadic amplitudes.

Figure 6.1 shows the mean gains for the different saccadic amplitudes obtained from 4 year olds with and without IEP. The mean saccadic gains were very close to a value of 1 for both groups of children. In general, no large differences can be observed in saccadic gains between the 4 year olds with IEP and without IEP for any saccadic amplitude. However, it can be suggested that for this age group children with IEP had higher gains than their age matched non-IEP children. Moreover, for some saccadic amplitudes (5º and 10º) the 4 year old children with IEP showed hypermetric saccades. Independent t-tests revealed significant differences in gains between these age-matched groups of children only for saccadic amplitudes of 15º (Table 6.6). Although the difference found between both age-matched groups for the 15º saccadic amplitude is very small and very similar to that found for the other saccadic amplitudes, the standard errors are extremely small for this amplitude.

Figure 6.2 shows the mean gains obtained from the 6 year olds with and without IEP. The gains were also between 0.9 and 1 for all saccadic amplitudes and reading ability groups. In this case, the mean saccadic gain was lower in the group of 6 year olds with IEP than in age-matched group without IEP for all saccadic amplitudes. Independent t-tests revealed that for this age group saccadic gain was significantly lower in children with IEP than in age-matched controls only for amplitudes of 5º (Table 6.6).

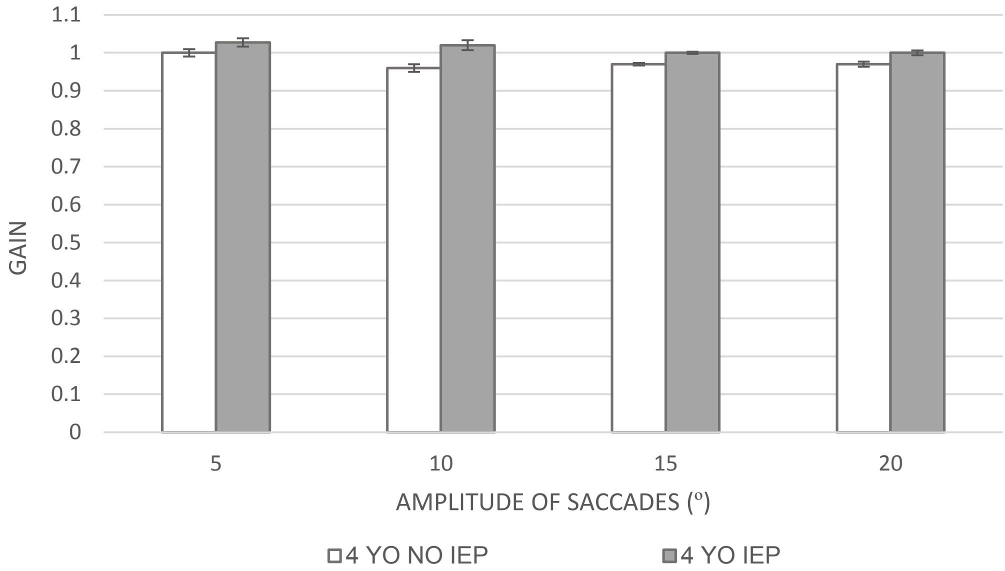


Figure 6.1. Mean (±SE) saccadic gain for horizontal saccades of different amplitude (5º, 10º, 15º and 20º) in children aged 4 years with (solid grey bars) and without IEP (solid white bars).

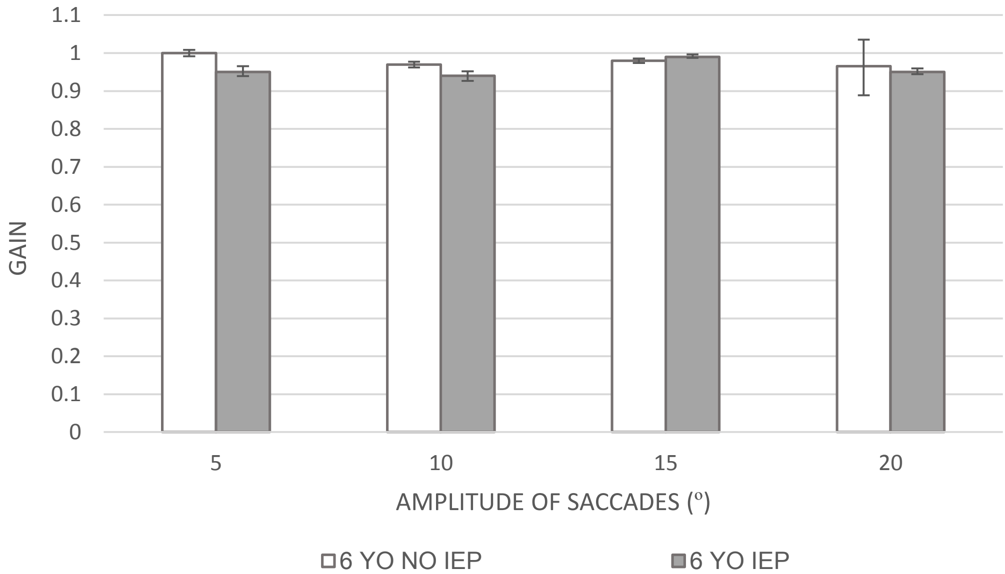


Figure 6.2. Mean (±SE) saccadic gain for horizontal saccades of different amplitude (5º, 10º, 15º and 20º) in children aged 6 years with (solid grey bars) and without IEP (solid white bars).

Vertical saccades main sequence

Shapiro-Wilk tests showed that the distribution of the upward and downward S, I, Q, A and n parameters obtained from the vertical saccadic main sequences were normally distributed. Hence, vertical asymmetries were studied with parametric statistics.

Similar to the results presented for the children without IEP in the previous chapter (chapter 5, section 5.6.4), paired t-tests revealed an asymmetry in vertical saccades in children with IEP. This vertical asymmetry also suggests a better performance for downward than upward saccades. This statistical test revealed that the coefficient A obtained from the power fit was significantly different between upward and downward saccades at the age of 8 ($p<0.001$) and 10 ($p=0.017$) years. Paired t-tests also revealed vertical asymmetries in the Q ratio (slope through the origin for peak velocity x duration vs amplitude relationship) and I (intercept for duration vs amplitude relationship) at the age of 5 ($p=0.027$) and 11 ($p=0.028$) years, respectively. Hence, upward and downward main sequence parameters were analysed separately following the same procedures described in chapter 5, section 5.6.4.

The results of the age-matched independent t-tests for the vertical main sequence parameters between children with and without IEP are shown in Table 6.7.

		S		I		Q		A		n	
	AGE	t	p	t	p	t	p	t	p	t	p
UPWARD SACCADES	4	0.622	0.545	-1.021	0.326	-0.393	0.700	0.722	0.483	-0.547	0.594
	5	-0.003	0.999	-1.425	0.172	-2.891	**0.010**	1.700	0.107	-1.831	0.085
	6	-1.316	0.208	0.984	0.341	-0.323	0.751	1.729	0.104	-1.269	0.287
	7	-1.044	0.310	0.917	0.371	0.247	0.808	-1.625	0.121	1.248	0.228
	8	-1.011	0.330	-0.593	0.563	-0.960	0.510	1.601	0.135	-0.290	0.777
	9	-0.219	0.830	0.039	0.969	0.868	0.401	-0.210	0.837	0.745	0.469
	10	0.396	0.695	-0.713	0.482	-0.798	0.432	-0.652	0.520	0.565	0.557
	11	1.797	0.132	-6.441	**0.001**	1.286	0.255	1.635	0.243	-2.111	0.089
DOWNWARD SACCADES	4	-1.671	0.119	0.137	0.893	0.881	0.394	0.740	0.473	0.112	0.912
	5	0.434	0.670	-1.735	0.101	-3.280	**0.004**	0.111	0.913	0.058	0.954
	6	-2.405	**0.030**	1.203	0.248	-1.348	0.198	-0.400	0.695	0.841	0.414
	7	1.391	0.181	-0.504	0.620	-0.040	0.969	0.553	0.587	-0.536	0.599
	8	-0.656	0.523	0.892	0.389	0.616	0.549	-0.923	0.373	1.419	0.179
	9	-0.473	0.644	0.483	0.637	-0.448	0.662	0.002	0.998	0.317	0.756
	10	-0.564	0.578	0.164	0.871	-1.828	0.080	-1.459	0.157	0.969	0.342
	11	-0.251	0.812	-0.463	0.663	-1.145	0.304	1.621	0.166	-2.085	0.092

Table 6.7. Age-matched independent t-test results for the vertical main sequence parameters (S, I, Q, A and n) between children with and without IEP.

The statistical results presented in Table 6.7 show that the p value was <0.05 for four comparisons (highlighted in bold type in Table 6.7). However, only two of these p values were found to be <0.01 and therefore statistically significant after the Bonferroni correction (highlighted in yellow in Table 6.7). Hence, independent t-tests found significant differences in I for upward saccades between children with and without IEP at the age of 11. The same statistical procedures revealed that the Q ratio was significantly different between the two groups of children with different reading abilities at the age of 5 for downward saccades.

Figure 6.3 shows the results obtained for I (intercept of the regression line for the duration vs amplitude saccadic main sequence) for upward saccades. It can be observed that in general, children with IEP showed slightly higher mean I values (upward saccades) than children with no IEP (e.g. 4, 5 and 11 years) (Figure 6.3). In addition, large standard errors can be observed in children with IEP. Independent t-tests revealed that this parameter was significantly higher in children with IEP than in age-matched controls at the age of 11 years only (Table 6.7).

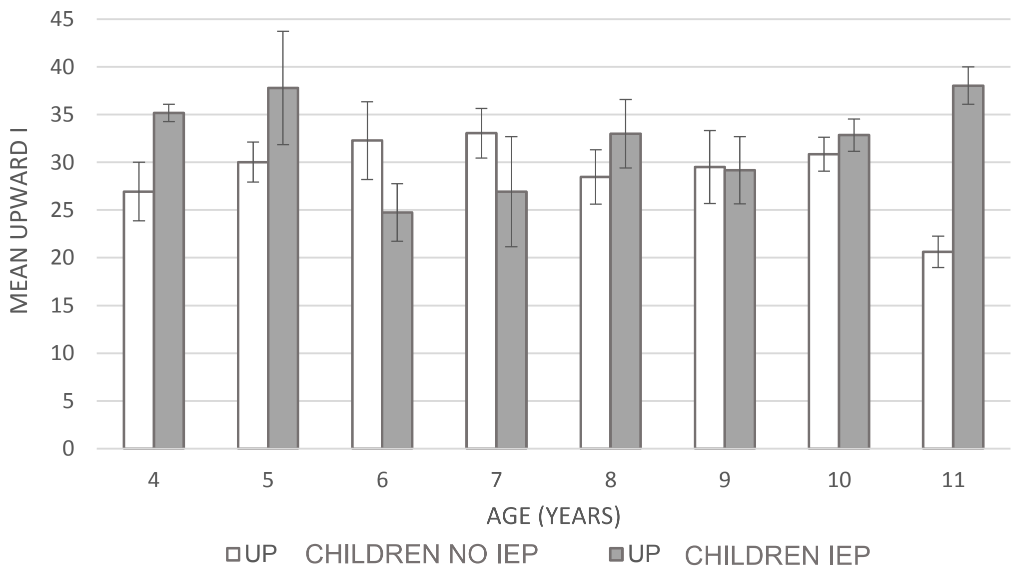


Figure 6.3. Mean (±SE) intercept (I) of the linear regression fitted to the duration vs amplitude upward main sequence relationship in children of different ages (4-11 years) with (solid grey bars) and without IEP (solid white bars).

The Q ratio (slope of the linear regression through the origin of the peak velocity x duration vs amplitude main sequence) for downward saccades was found to be very similar in children with and without an IEP, independently of the age group (Figure 6.4). It can be suggested that the only potential differences in this parameter between children with and without IEP are observed at the age 5 and 6 years. Independent t-tests revealed that Q ratio was significantly higher in children with IEP than in children without IEP at the age of 5 (Table 6.7).

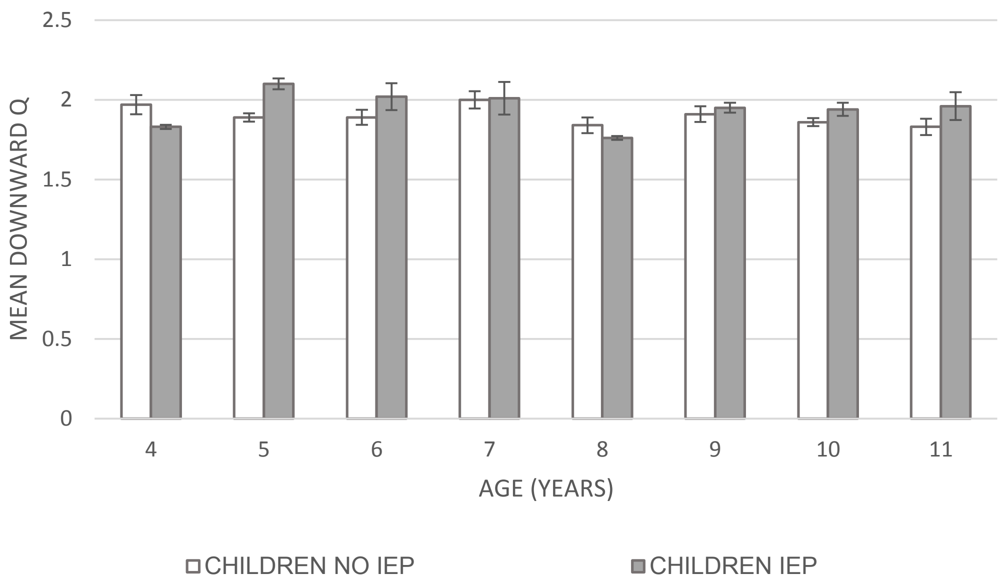


Figure 6.4. Mean (±SE) slope through the origin (Q) of the liner regression fitted to the peak velocity x duration vs amplitude downward main sequence relationship in children of different ages (4-11 years) with (solid grey bars) and without IEP (solid white bars).

Vertical saccadic gains

Directional asymmetries were also assessed for vertical saccadic gains. The mean gains of the upward saccades were compared to the mean gains of the downward saccades. Parametric t-test revealed an up-down asymmetry in saccadic gains only for saccades of 15º of amplitude at the age of 6 (t=-10.448; p=0.009). Hence, gains for both direction saccades (up and down) in children with IEP were combined and compared to the gains obtained for children with no IEP of different ages. The results of the age-matched independent t-tests for the mean vertical saccadic gains between children with and without an IEP are shown in Table 6.8.

This statistical analysis showed no significant differences in vertical saccadic gains between children with and without IEP for any age group.

VERTICAL SACCADIC GAINS		5º		10º		15º	
	AGE	t	p	t	p	t	p
	4	0.952	0.359	1.304	0.215	1.517	0.153
	5	1.067	0.302	0.155	0.878	0.327	0.747
	6	1.194	0.252	-1.287	0.219	-0.523	0.609
	7	0.701	0.492	-1.184	0.252	0.993	0.334
	8	-0.701	0.493	-0.402	0.693	0.114	0.910
	9	0.560	0.583	0.514	0.615	0.534	0.601
	10	1.143	0.264	0.373	0.712	-1.138	0.266
	11	-1.049	0.342	-0.608	0.570	1.774	0.136

Table 6.8. Age-matched independent t-test results for the vertical saccadic gains (saccades of 5º, 10º and 15º) between children with and without IEP.

<u>Summary</u>

The results show that horizontal saccadic main sequences do not differ between age-matched groups of children with and without IEP. In contrast, significant differences were found between the same groups of children in mean saccadic gains. These differences were only found at two age groups (4 and 6 years). Moreover, the differences in saccadic gains between children with and without IEP in these age groups were not found across all saccadic amplitudes but only for one saccadic amplitude.

The results for the vertical saccades show that in general vertical main sequences do not differ between children of the same age with and without IEP. Only two parameters were found to be significantly different between children with and without IEP at the ages of 5 and 11 years (one parameter significantly different for each age group). In contrast, no significant differences were found for saccadic gains between children with and without IEP at any age group.

Overall, the results suggest horizontal and vertical saccades were not significantly different between age-matched groups of children with and without IEP.

Visual Fixation

The parameters studied in the visual fixation task were non-normally distributed in children with IEP for all age groups (Shapiro-Wilk test $p<0.05$). Hence, Mann-Whitney tests were the most appropriate tests to assess differences in these parameters between children with and without IEP.

The results of the age-matched Mann-Whitney tests for the fixation parameters between children with and without IEP are shown in Table 6.9 and 6.10. In order to correct for an increase in type I error arising from the multiple comparisons, a Bonferroni correction was used. Hence, a p value <0.007 was considered to be significant.

Mann-Whitney tests showed no differences in the visual fixation parameters between children with and without IEP at any age group. Moreover, p values were generally >0.1.

		HORIZONTAL MEP		VERTICAL MEP		MEAN SD OF HORIZONTAL MEP		MEAN SD OF VERTICAL MEP	
	AGE	Z	p	Z	p	Z	p	Z	p
FIXATION STABILITY	4	-0.298	0.824	-0.149	0.941	-0.075	0.941	-1.419	0.176
	5	-0.228	0.866	-0.571	0.623	-1.942	0.052	-0.971	0.364
	6	-1.250	0.219	-1.436	0.156	-0.185	0.893	-0.278	0.823
	7	-0.542	0.627	-1.086	0.309	-0.310	0.794	-0.970	0.347
	8	0.936	0.387	0.936	0.387	-0.247	0.849	-0.345	0.775
	9	-0.950	0.370	-1.026	0.331	-0.304	0.761	-0.419	0.710
	10	-1.486	0.146	-0.791	0.436	-0.768	0.464	-0.648	0.524
	11	-0.707	0.629	-0.791	0.436	-0.707	0.629	-0.767	0.500

Table 6.9. Age-matched independent t-test results for the fixation stability (horizontal and vertical MEP; horizontal and vertical SD of MEP) between children with and without IEP.

SACCADIC EVENTS DURING FIXATION	MEAN NUMBER OF SACCADES		MEAN AMPLITUDE OF SACCADES		MEAN NUMBER OF MICROSACCADES	
AGE	Z	p	Z	p	Z	p
4	-0.226	0.824	-0.747	0.529	-0.299	0.824
5	-1.062	0.424	-1.060	0.424	-0.973	0.364
6	-0.767	0.500	-0.654	0.559	-0.928	0.391
7	-0.437	0.682	-0.592	0.575	-0.897	0.388
8	-1.144	0.336	-0.812	0.503	-1.558	0.143
9	-0.200	0.882	-0.996	0.370	-0.114	0.941
10	-1.038	0.356	-0.877	0.436	-0.699	0.494
11	0.000	1.000	-1.101	0.400	-2.121	0.057

Table 6.10. Age-matched independent t-test results for the saccadic events during fixation (mean number of saccades, mean amplitude of saccades and mean number of microsaccades) between children with and without an IEP.

Summary

Table 6.9 and 6.10 showed no significant differences in the fixation parameters (fixation stability or saccadic events during fixation) between children with and without IEP of any age. Hence, visual fixation is not significantly different between age-matched groups of children with IEP and without IEP.

6.7. Individual comparisons between children with delayed reading skills and age-matched normative eye movement values

In the previous section differences in eye movement behaviour between groups of age-matched children with and without IEP were evaluated. These sets of age-matched comparisons indicate if eye movements in children with an IEP are different as a group (their means or medians) from those obtained from a group of children of the same age without such educational plan. However, it could be the case that within an age group, some children with IEP have different eye movement parameters to those expected for their age while others do not.

In the following section the data obtained from each child were individually studied and compared to the eye movement norms provided in the previous chapter (chapter 5, section 5.7). An Excel file was created for each eye movement task (smooth pursuit, saccade and fixation). The files contained the eye movements parameters obtained for each child participant (only those with successful eye movement recordings). The data were organised in separate Excel sheets according to the age groups and contained the confidence limits of the parameters for each age group (95% confidence limits presented in chapter 5, section 5.7). Excel formulas were used so the file automatically compared the parameters of each child (each Excel row corresponded to the results of one child) with the corresponding confidence intervals. The words "IN CI" (standing for within confidence intervals) and "OUT CI" (standing for outside confidence intervals) were displayed accordingly (Figure 6.5).

PARTICIPANT ID	VELOCITY GAIN	POSITION GAIN	PROPORTION SP	NUMBER OF SACCADES	MEAN AMPLITUDE SACCADES	MICROSACCADES	VELOCITY GAIN	POSITION GAIN	PROPORTION SP	NUMBER OF SACCADES	MEAN AMPLITUDE SACCADES	MICROSACCADES
P22	0.858383333	0.9323	0.9327	2	1.0382	13	IN CI	IN CI	IN CI	IN CI	IN CI	IN CI
P32	0.741133333	0.725	0.68335	8	1.293	23	IN CI	IN CI	IN CI	IN CI	IN CI	IN CI
P33	0.8385	0.811	0.79427	2	1.074	16	IN CI	IN CI	IN CI	IN CI	IN CI	IN CI
P38	0.715116667	0.784	0.6297	9	4.75	1	IN CI	IN CI	IN CI	IN CI	OUT CI	IN CI
P146	0.878333333	0.86	0.6935	6	3.08	14	IN CI	IN CI	IN CI	IN CI	IN CI	IN CI
P148	0.8605	0.84	0.838	8	2.29	9	IN CI	IN CI	IN CI	IN CI	IN CI	IN CI
P149	0.773333333	0.73	0.623	8	2.9	0	IN CI	IN CI	IN CI	IN CI	IN CI	IN CI
P150	0.881666667	0.866	0.78775	3	1.47	13	IN CI	IN CI	IN CI	IN CI	IN CI	IN CI
P152	0.965	0.9	0.912	3	1.1	4	IN CI	IN CI	IN CI	IN CI	IN CI	IN CI
P153	0.796666667	0.75	0.7285	12	2.4	10	IN CI	IN CI	IN CI	IN CI	IN CI	IN CI
P156	0.995	0.9	0.826	14	1.6	31	IN CI	IN CI	IN CI	IN CI	IN CI	IN CI
P157	0.856666667	0.82	0.5285	18	4.68	51	IN CI	IN CI	IN CI	OUT CI	OUT CI	OUT CI
P158	0.848333333	0.842	0.8255	9	2	5	IN CI	IN CI	IN CI	IN CI	IN CI	IN CI
P159	0.9395	0.88	0.796	0	0	4	IN CI	IN CI	IN CI	IN CI	IN CI	IN CI
P163	0.893333333	0.8	0.766	3	1.048	10	IN CI	IN CI	IN CI	IN CI	IN CI	IN CI
P164	0.834666667	0.792	0.7865	1	1	18	IN CI	IN CI	IN CI	IN CI	IN CI	IN CI
P165	0.898333333	0.92	0.9085	2	1.03	18	IN CI	IN CI	IN CI	IN CI	IN CI	IN CI
P167	0.655	0.622	0.5575	7	1.51	20	OUT CI	OUT CI	IN CI	IN CI	IN CI	IN CI
UPPER CONFIDENCE LIMIT	1.008000053	0.981414681	0.997711219	16.22366518	3.845758186	35.6037053						
LOWER CONFIDENCE LIMIT	0.688856197	0.657372819	0.526235031	0	0	0						

4YO 5YO 6YO 7YO 8YO 9YO 10YO 11 YO

Figure 6.5. Excel file containing the data obtained from all the participants recruited from schools with successful eye movement recordings for the 6°/s horizontal smooth pursuit together with the confidence limits. Highlighted rows show children with one or more parameters outside the confidence intervals for that task.

The frequency of children with and without IEP that had eye movements within and outside their age-matched norms (95% confidence limits) was obtained. Contingency tables were then created revealing the frequency of children with and without IEP that were found to have one or more eye movement parameters outside their age-matched confidence limits. Chi-square test of independence incorporating Yates correction of continuity (Salkind 2010) were used to determine the existence of an association between holding an IEP and having eye movement parameters outside the respective confidence intervals. This procedure was carried out for each eye movement task: horizontal smooth pursuit, vertical smooth pursuit, horizontal saccades, vertical saccades and visual fixation.

In addition, the upper and lower 95% confidence limits for each eye movement parameter studied were plotted. The individual results of those children with IEP were plotted in the same figures so they were superimposed to the confidence limits (examples are shown in Figures 6.6 and 6.7). This approach was taken in order to visualise the eye movement parameters of each child with IEP, so more information with regard to their eye movement performance (i.e. if their individual eye movement parameter results corresponded to those of another age group) could be obtained. These plots are not presented in the main body of this chapter but are attached in Appendix H.

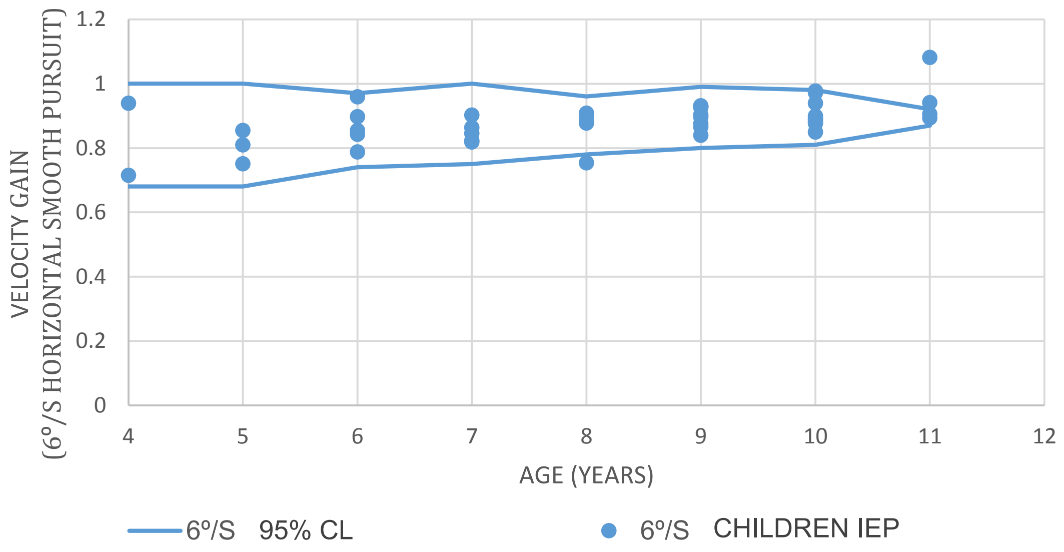


Figure 6.6. Velocity gain for each participant with IEP for the 6°/s horizontal smooth pursuit superimposed of the eye movement norms (95% confidence limits (CL)) produced from children with no IEP.

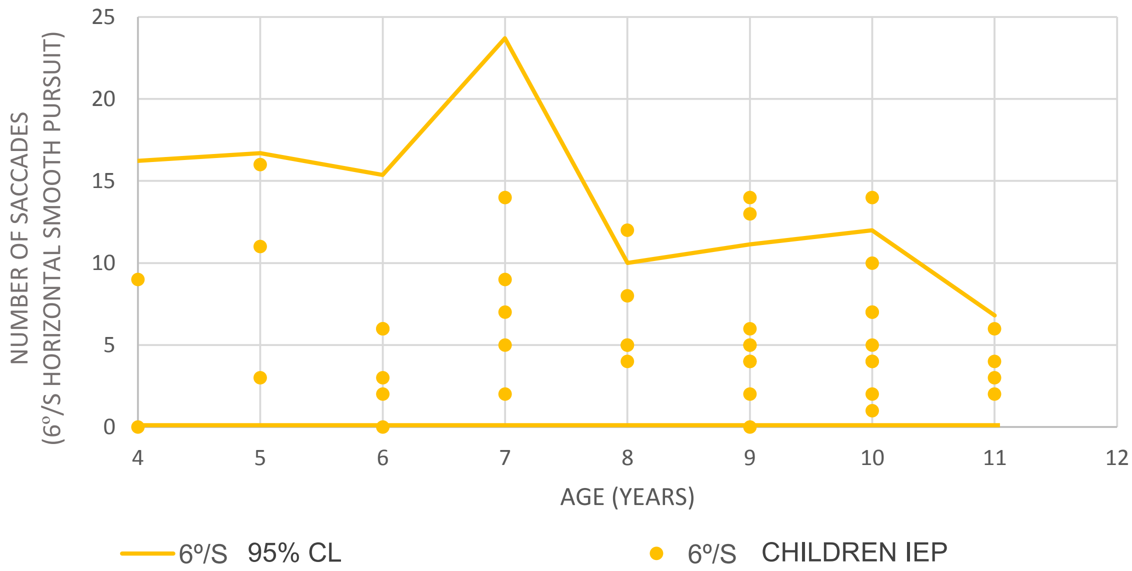


Figure 6.7. Number of saccades for each participant with IEP for the 6°/s horizontal smooth pursuit superimposed of the eye movement norms (95% confidence limits (CL)) produced from children with no IEP.

6.7.1. Smooth pursuit

Children who had one or more smooth pursuit parameters outside the expected values for their age for both the 6º/s **and** the 12º/s horizontal smooth pursuit were considered to have different horizontal smooth pursuit eye movements to typical developing children of the same age. Children with one or more parameters outside the confidence limits for one velocity only (6º/s **or** 12º/s) were not considered to have different horizontal smooth pursuit as they demonstrated good eye movement performance at least for one of the velocities. This situation could, for example, indicate that the child was not paying attention/not looking at the stimulus for the velocity in which the performance was found to be below average. Children who did not have successful eye movement recordings for both velocities tested were discarded from this analysis. A total of 154 children (117 children no IEP and 37 children IEP) had successful eye movement recordings for both 6°/s and 12°/s horizontal smooth pursuit.

The same procedure was used for vertical smooth pursuit. Thus, children who had one or more eye movement parameters outside their age-matched confidence limits for both vertical velocities (6º/s or 12º/s) were considered to have different vertical smooth pursuit to their non IEP peers. A total of 152 children (117 children no IEP and 37 children no IEP) had successful eye movement recordings for both, 6°/s and 12°/s vertical smooth pursuit.

The contingency Tables 6.11 and 6.12 show the frequency of children with and without IEP that had one or more parameters for horizontal and vertical smooth pursuit outside the 95% confidence limits calculated from the children with no IEP. The same tables present chi-square statistical results.

HORIZONTAL SMOOTH PURSUIT OUTSIDE NORMATIVE VALUES			
	OUTSIDE NORMS	WITHIN NORMS	TOTAL
IEP	10	27	37
NO IEP	9	108	117
TOTAL	19	135	154
X^2=8.011; **p=0.005**			

Table 6.11. Contingency table showing the frequency of participants with and without an IEP who were found to have one or more horizontal smooth pursuit parameters outside their age-matched norms (95% confidence limits).

VERTICAL SMOOTH PURSUIT OUTSIDE NORMATIVE VALUES			
	OUTSIDE NORMS	WITHIN NORMS	TOTAL
IEP	3	34	37
NO IEP	8	107	115
TOTAL	11	141	152
X^2=0.001; p=1.00			

Table 6.12. Contingency table showing the frequency of participants with and without an IEP who were found to have one or more vertical smooth pursuit parameters outside their age-matched norms (95% confidence limits).

Chi-square statistical tests revealed an association between holding an IEP and having horizontal smooth pursuit parameters outside the age-matched confidence limits (X^2=8.011; p=0.005). Further, Table 6.11 shows that 27% of children with IEP were found to have one or more smooth pursuit parameters outside the normative values (95% confidence limits) in both horizontal smooth pursuit velocities, while only 8% of children without IEP were found to have these parameters outside the norms.

The same statistical procedures found no association between IEP and vertical smooth pursuit parameters outside the confidence limits (X^2=0.001; p=1.00). Table 6.12 shows that the frequency of children with IEP that have one or more vertical smooth pursuit parameters for both velocities outside their age matched norms is very similar to that in children without IEP (children IEP with vertical smooth pursuit parameters outside the norms: 8%: children no IEP with vertical smooth pursuit parameters outside the norms: 7%).

Figures like those shown at the beginning of this section that are attached in Appendix H suggest that when the number and amplitude of saccades in children with IEP are outside the age-matched confidence limits, these seem to be within the limits for another age group, generally a younger one (Figure 6.7 and see figures in Appendix H). For the smooth pursuit gains, it can be suggested that in children with IEP when gains are below the 95% lower confidence limit, these are within the limits of another age group, also generally younger. In contrast, some children with IEP have gains above their age-matched 95% upper confidence limit that generally do not appear to lie within the confidence limits of any other age group (see Figure 6.6 and Figures Appendix H).

6.7.2. Saccades

Similar to the procedures followed for the smooth pursuit tasks, the association between IEP and saccadic parameters being outside the 95% confidence limits were evaluated using contingency tables. Those children who had at least one of the saccadic main sequence parameters (S, I, Q, A and n) outside the 95% confidence limits for their age were considered to have some eye movement differences compared to their peers. A separate contingency table was produced for saccadic gains as saccadic accuracy can be low with typical saccadic dynamics (i.e. normal velocity saccades). Children with mean saccadic gains outside their age-matched confidence limits for one or more saccadic amplitudes were considered to have different saccadic accuracy to children of the same age with no IEP.

The procedures described above were taken for the horizontal and vertical saccadic main sequence and gains to produce the contingency tables presented in the following page (Tables 6.13 to 6.16).

HORIZONTAL MAIN SEQUENCE OUTSIDE NORMATIVE VALUES			
	OUTSIDE NORMS	WITHIN NORMS	TOTAL
IEP	16	26	42
NO IEP	23	91	114
TOTAL	39	117	156
X^2 =4.344; **p=0.037**			

Table 6.13. Contingency table showing the frequency of participants with and without IEP who were found to have one or more horizontal main sequence parameters outside their age-matched norms (95% confidence limits).

HORIZONTAL SACCADIC GAIN OUTSIDE NORMATIVE VALUES			
	OUTSIDE NORMS	WITHIN NORMS	TOTAL
IEP	6	36	42
NO IEP	21	93	114
TOTAL	27	129	156
X^2=0.135; p=0.714			

Table 6.14. Contingency table showing the frequency of participants with and without IEP who were found to have one or more horizontal saccadic gains outside their age-matched norms (95% confidence limits).

VERTICAL MAIN SEQUENCE OUTSIDE NORMATIVE VALUES			
	OUTSIDE NORMS	WITHIN NORMS	TOTAL
IEP	13	18	31
NO IEP	14	89	103
TOTAL	27	107	134
X^2=10.201; **p=0.001**			

Table 6.15. Contingency table showing the frequency of participants with and without IEP who were found to have one or more vertical main sequence parameters outside their age-matched norms (95% confidence limits).

VERTICAL SACCADIC GAIN OUTSIDE NORMATIVE VALUES			
	OUTSIDE NORMS	WITHIN NORMS	TOTAL
IEP	8	23	31
NO IEP	11	92	103
TOTAL	18	116	134
X^2= 3.324; p=0.068			

Table 6.16. Contingency table showing the frequency of participants with and without IEP who were found to have one or more vertical saccadic gains outside their age-matched norms(95% confidence limits).

Chi-square tests revealed a significant association between holding an IEP and having one or more horizontal main sequence parameters outside the age-matched confidence limits (Table 6.13). The horizontal main sequence parameters of children with IEP were more frequently outside the confidence intervals for their age (38%) than was the case for the children without IEP (20%). In contrast, the same statistical test showed that there was not a significant association between having horizontal saccadic gains outside the age-matched confidence limits and holding an IEP (Table 6.14). The frequency of children that had saccadic gains outside their age confidence limits was independent of whether these children had or not an IEP (children IEP with horizontal gains outside the norms: 14%: children no IEP with horizontal gains outside the norms: 18%)

For the vertical saccades, chi-square tests revealed a significant association between holding an IEP and having vertical main sequence parameters outside the age-matched norms (Table 6.15). Further, 42% of children with IEP were found to have one or more vertical main sequence parameters outside their age matched norms compared to 14% of the children with no IEP. Having vertical saccadic gains outside the confidence limits was not associated with holding an IEP (Table 6.16).

The figures presented in Appendix H that show the individual results of the saccadic parameters obtained from each child with IEP suggest that when these parameters are outside the confidence limits in this population, these parameters are frequently within the confidence limits for another age group.

6.7.3. Visual Fixation

Finally, the association between holding an IEP and having visual fixation parameters outside the age-matched norms was also evaluated. Those children who had one or more of the fixation parameters outside (fixation stability parameters or saccadic events during fixation) the calculated 95% confidence limits for their age were considered to have differences in visual fixation compared to their peers.

Table 6.17 presents the frequency of children with and without IEP that were found to have some (at least one) fixation parameters outside the expected confidence limits for their age.

FIXATION PARAMETERS OUTSIDE NORMATIVE VALUES			
	OUTSIDE NORMS	WITHIN NORMS	TOTAL
IEP	16	25	41
NO IEP	20	95	115
TOTAL	36	120	156
X^2=6.795; **p=0.009**			

Table 6.17. Contingency table showing the frequency of participants with and without IEP who were found to have one or more fixation eye movement parameters outside the age-matched norms (95% confidence limits).

Chi-square test also revealed that some visual fixation parameters are more frequently outside the age-matched 95% confidence limits for their age in children with IEP than in children no IEP (Table 6.17). The table above shows that 39% of children with IEP have one or more fixation parameters outside the norms for their age compared to 17.4% of children without IEP.

6.8. Discussion

This chapter has investigated eye movement differences between school age children with and without an *IEP related to delayed reading skills*. The results from the two analyses performed to investigate this are summarised and discussed below.

6.8.1. Eye movements in children with and without an IEP related to delayed reading skills – age group comparisons

As shown in the literature review of this thesis, debate continues about the causality or the effect of oculomotor deficits in reading difficulties (see chapter 1, section 1.3.1). However, it is well established that there are differences in eye movements during reading between good/average readers and poor readers (e.g. Poynter et al. 1982; Solan 1985a; Solan 1985b; Kulp and Schmidt 1996). In general, individuals with good/average reading skills make fewer fixations and regressions and also that fixations are briefer than in poor readers (Rayner 1998). However, it can be argued that these differences might be related to text difficulty (Rayner 1998; Rayner and Liversedge 2011), text format (Ashby et al. 2005; Huestegge et al. 2009) or higher order linguistic characteristics such as syntactic difficulty and/or plausibility (Clifton and Staud 2011; Juhasz and Pollatsek 2011) rather than to oculomotor deficits. For that reason, findings from eye movement behaviour during reading in individuals with different reading abilities should be cautiously interpreted, because reading is a complex process that not only involves effective oculomotor control but also requires an effective integration of sensory, perceptual and cognitive information (Callu et al. 2005). Consequently, an increased number of saccades or an increased fixation duration during reading in children with delayed reading skills may indicate difficulties in other visual or non-visual aspects rather than poor oculomotor control. For that reason, the eye movements in children with delayed reading skills in non-reading conditions should be studied in order to provide a quantitative evaluation of "pure" eye movement deficits, eliminating any potential effect arisen from external factors (text related or individual related (vocabulary and language skills) factors).

There are not many available studies evaluating saccades in children with delayed reading skills during non-reading tasks (Brown et al. 1983; Black et al. 1984b). These studies recorded eye movements during a task that elicited sequential saccadic eye movements simulating a reading situation. The results suggested that sequential saccadic eye movements are essentially the same between good/average readers and poor readers as none of the parameters studied were found to be significantly different between the two groups. Although the saccadic eye movement results presented in this chapter were obtained using a very different saccadic task, they further support the view that the saccadic dynamic characteristics are generally not different between groups of age-matched children of different reading abilities.

Not surprisingly, most studies assessing eye movements in children with delayed reading skills have only evaluated saccadic eye movements. Although it has been proposed that smooth pursuit and reading skills share similar cognitive components including attention and working memory (Callu et al. 2005; Luna et al. 2008), little is known about a possible association between deficits in these type of eye movements and reading difficulties. To our knowledge, there is only one study that investigated smooth pursuit eye movements and reading abilities (Callu et al. 2005). The authors cautiously concluded that children with below average smooth pursuit were at higher risk of having reading difficulties. However, their eye movement assessment performed was based on direct and gross observation and the reading ability measures were obtained from non-reading tasks (e.g. oral comprehension, vocabulary). Finally, the authors related the oculomotor deficits found to an atypical development of some cognitive processes that are involved in both reading and smooth pursuit rather than to a deficit in oculomotor control. The smooth pursuit eye movement results presented in this chapter, which were obtained quantitatively and objectively with an eye tracker, further support the view that children with delayed reading skills do not have different smooth pursuit eye movements to those found in age-matched controls when compared as a group.

Other than eye movement difficulties, vision problems such as refractive error and accommodation or vergence deficits can also interfere with the reading process. Moreover, while vision deficits may not be the main cause of reading difficulties (Quaid and Simpson 2013), it is reasonable to suggest that these play an important role in learning abilities. Hyperopic refractive error has been found to be strongly correlated with delayed reading skills and lower academic performance in children (Rosner 1997; Quaid and Simpson 2013). In addition, a recently published study also found a correlation between astigmatism and reading difficulties (Orlansky et al. 2015). In contrast, our study did not find a significant difference in the spherical or cylindrical refractive error between children with and without IEP. Unlike the above mentioned studies, non-cycloplegic retinoscopy was used in our optometric test to obtain the participants' refractive error. Moreover, Mohindra retinoscpy was not possible in the schools, as complete darkness could not be achieved. Therefore, the refractive errors obtained from the non-cycloplegic distance retinoscopy in our study might underestimate the hyperopia levels in our population and these results cannot be directly compared.

Overall, the results presented in this chapter provide additional evidence to support the view that the eye movements and the optometric parameters commonly assessed in optometric practice are not different between a group of children with an IEP related to delayed reading difficulties and a group of age matched controls without such education plan. Although these two can interfere with reading and learning abilities, our results further support that vision and/or eye movement problems are not the main cause of delayed reading/academic performance.

6.8.2. Choice of statistical procedures for the independent age-matched multiple comparisons

As proposed and discussed in section 6.6.1 of this chapter, a Bonferroni adjustment was performed to the considered significant p value (p=0.05) in order to reduce the type I error (Benjamini and Hochberg 1995; Ludbrook 1998; Armstrong 2014).

There is a continuous controversy regarding the adjustment of the statistical p value with Bonferroni or other procedures when performing multiple independent comparisons (Armstrong 2014). While some authors are extremely reluctant to use Bonferroni (Perneger 1998) or make adjustments at all on the p values (Rothman 1990), others consider these procedures compulsory (Moye 1998; Ottenbacher 1998).

In this chapter the p value considered to be significant was adjusted to the number of multiple comparisons performed for each age group and eye movement task. This was performed for several reasons. First, because as described in section 6.6.1 of this chapter, when we perform 6 comparisons (like in the case of our smooth pursuit statistical analysis), there is a 26.5% probability to obtain a significant result by chance (opposed to the typical 5% chance from a p value =0.05). Therefore, it is reasonable to suggest that in our results independent comparisons found to have p<0.05 may not indicate a "true significant difference" (Ludbrook 1998). Second, because the majority of the statistical results presented in the tables of this chapter (from Tables 6.3 to 6.10) accepted the null hypothesis (i.e. no significant differences between age-matched groups). This may potentially suggest that the small number of significant p values found were not due to a genuine difference between groups in these parameters but to chance. If genuine differences existed in the eye movement performance between children with and without IEP, p values <0.05 would be seen across ages and in several parameters, rather than in single/isolated comparisons as seen in here. In addition, it has been suggested that when many of the hypotheses tested using multiple comparisons are rejected (i.e. significant differences in many comparisons), the adjustment is less relevant than when only few parameters are rejected (i.e. significant differences in not many comparisons) (Benjamini et al. 2001). Finally, the multiple independent t-tests in this chapter aimed to determine whether eye movements (smooth pursuits, saccades and visual fixation) were generally different in children with different reading abilities. Hence, the statistical results should be considered together and not independently. Moreover, it has been suggested that adjustments should be performed in situations like the one here, in which a family of multiple tests are collated to summarise one single conclusion (whether smooth pursuits/saccades/ visual fixation are different between groups of age-matched children with and without IEP) (Bender and Lange 2001).

6.8.3. <u>Eye movements in children with and without an IEP related to delayed reading skills – individual comparisons</u>

As discussed above, eye movements in children with an IEP related to delayed reading skills are mostly no different from those in children without such education plan when they are compared as a group. However, it can be argued that in the group of children with IEP, some children could have a good/average and others a below average eye movement performance. Moreover, if the number of children with a good/above average eye movement performance is much higher than the number of children with below average performance, age-matched t-tests (in which two populations means are compared) might mask below-average eye movement in some of these children. For that reason, a second analysis was performed in which eye movement parameters from each child were compared to the eye movement norms obtained from children without IEP (chapter 5, section 5.7).

The findings showed that *some, but not all,* children with IEP have their eye movements (one or more parameters) outside the 95% confidence limits for their age. These results were found for all eye movement types (smooth pursuits, saccades and visual fixation). Chi-square statistical analysis revealed an association between holding an IEP and the likelihood of obtaining eye movement values outside the norms. Further, these results demonstrate that although not all children with IEP will show eye movements outside their age-matched confidence limits, this population has a *two-fold increased risk* of having one or more eye movement parameters outside the confidence intervals than children with good/average reading skills.

This finding was somehow unexpected but results reported by another research group (Wilson et al. 2014; James Gilchrist, personal communication) also support the idea that when data from children with delayed reading skills are individually analysed, some, but not all will show a "non-typical profile" of oculomotor function. In addition, this does not only apply to oculomotor function but also to some other optometric measures including visual perception or binocular vision tests. Finally, collating these similar results, it can be suggested that due to the potential multifactorial nature of reading difficulties, eye movement/optometric measures different from those expected for their age in children with delayed reading might reflect impairments affecting one or several aspects of vision and cognitive processing.

With regards to the dynamic characteristics of eye movements in children with IEP, it can be argued that the children from our study whose eye movements were outside the normative values for their age, did not have abnormal/atypical eye movements. This can be supported by the fact that in most cases, the parameters found in these children were just slightly above or below the confidence limits for their age. In addition, by observing the graphs presented in Appendix H, it can be proposed that the values seen outside the age-matched confidence limits are generally within the confidence limits for another age group, generally younger. (see Figures 6.6 and 6.7 and Appendix H). Thus, this does not suggest an abnormal eye movement behaviour but for example a potential *different eye movement developmental rate* or an *immaturity of the eye movement system* in some children with IEP.

6.9. Summary

The results of this study indicate that eye movements in children with an IEP related to delayed reading skills are in general, not significantly different (as a group) to those obtained from children of the same age without such education plan. However, when the results from the eye movement recordings in children with IEP are individually studied, some but not all of these children have their eye movements outside the age-matched eye movement norms. Further, the results indicate that children with an IEP related to delayed reading skills have a two-fold increased risk of having their eye movements outside their age-matched norms if compared to children without such education plan. Finally, it can be argued that the eye movement differences found in these children do not suggest abnormal/atypical eye movement but perhaps a *different development* and/or an *immaturity of the eye movement system*.

Chapter 7 Eye movements in children referred with suspected eye movement difficulties

7.1. Introduction

Debate continues about the presence of oculomotor deficits in children with below average reading skills. In contrast, there is a growing body of literature that recognises eye movement difficulties in children diagnosed with more specific learning difficulties (Fukushima et al. 2005) and developmental disorders (Scharre and Creedon 1992; Langaas et al. 1998; Sweeney et al. 2004; Robert et al. 2014).

As discussed in chapter 2, children, in particular those with learning difficulties, are increasingly being referred to Eye Care Professionals with suspected eye movement difficulties, and in this chapter, we evaluate eye movements in children who have been referred for this reason.

7.2. Aims

- To quantitatively evaluate eye movements in children referred to Eye Care Professionals with suspected eye movement difficulties

7.3. Methods

7.3.1. Participants

The researcher went through the Special Assessment Clinic (Cardiff University) patient database and identified those children who were referred to that clinic with suspected eye movement difficulties (such as "tracking difficulties") or who were referred for an "eye movement assessment". In addition, 10 Educational Psychologists, 3 Occupational Therapists, the heads of the Visual Impairment team in Cardiff and Gwent and the heads of the Orthoptist departments at the University Hospital of Wales (Cardiff) and at the Princess of Wales Hospital (Bridgend) were invited to refer additional participants. However, only an Orthoptist at the Princess of Wales Hospital (Bridgend) agreed to collaborate with the recruitment for the study.

The protocol and procedures for the study (previously described in chapter 4) were approved by the South East Wales NHS Research Ethics Committee (REC) and the Research and Development Departments of the University Health Boards that acted as Participant Identification Centres (PIC) (Cardiff and Vale and Abertawe Bro Morgannwg). All procedures were undertaken in accordance with the guidelines of the Declaration of Helsinki. The participant invitation letter, the information sheets and consent forms (for parents and children) were also approved by the above-mentioned Ethics Committee and the Research and Development Departments of the involved Health Boards. Confirmation was also obtained from the aforementioned Health Boards (Cardiff and Vale and Abertawe Bro Morgannwg) to act as PIC for the study. The documents related to the NHS REC (invitation letter, information sheets and consent forms) can be found in Appendix F.

A study invitation letter, a parent information sheet and a child information sheet were posted to the parents of the potential participants who were referred to the Special Assessment Clinic (Cardiff University). The same documents were posted to those parents who were invited by the Orthoptist in Bridgend and agreed to have their contact details passed on to the researcher. Alternatively, parents attending the Orthoptist in Bridgend who did not give consent to pass on their contact details were given a parent information sheet with the researcher's contact details.

If no answer with regards to the participation in the study was obtained within two weeks of posting the documents, the researcher phoned to personally invite the participants and their parents to take part in the study. The participants and their parents were invited to visit the researcher at the School of Optometry and Vision Sciences, Cardiff University, in order to meet her and see the setup, before deciding whether or not to take part in the study. Once the participants and their parents agreed to take part, an appointment was scheduled at their convenience. During the appointment, the researcher explained the study to the participants and their parents and addressed any of their questions. Signed consent forms were obtained from the participants and their parents before the study was started.

Children with visually impairing conditions (logMAR >0.3), strabismus, refractive errors >8D in the most powerful meridian, and/or diagnosed/suspected photosensitive epilepsy were not recruited for the study. A total of eleven children (6 females and 5 males) aged between 5 and 15 (mean age 9.54±SD 2.33) were recruited for this study. Eight of these children were recruited from the Special Assessment Clinic (Cardiff University). The additional participants were recruited through the Orthoptist (n=3) collaborating in the study recruitment.

7.3.2. Optometric test and eye movement recording

An optometric test was performed prior to the eye movement recording. Both tasks (optometric test and eye movement recording) followed exactly the same procedures described in chapter 4. A short break between the eye examination and the eye movement recording was given, if necessary.

7.4. Results

7.4.1. Optometric test

The visual acuity with their prescription (if any) of the 11 children recruited, measured with their preferred test (Kay Pictures or Keeler logMAR) was between logMAR 0.3 and logMAR -0.1 for distance (mean RE VA logMAR +0.08 (SD±0.17), mean LE VA logMAR +0.06 (SD±0.14) and mean binocular VA logMAR +0.03 (SD±0.15)) and between logMAR 0.3 and logMAR -0.1 for near (mean RE VA logMAR 0.00 (SD±0.12), mean LE VA logMAR 0.00 (SD±0.11) and mean binocular VA logMAR 0.00 (SD±0.11)).

The mean spherical refractive error in these 11 children ranged from +5.00DS to plano in the RE (mean absolute sphere +1.55DS (SD±1.40)) and from +6.00DS to plano in the LE (mean absolute sphere +1.59 (SD±1.77)). Eight children had astigmatism <1DC while 3 children were found to have an astigmatic component >1.50DC in the RE and LE (RE: -2DC, -2.50DC and -4DC; LE: -1.75DC, -2.00DC, -4.00DC).

Very different optometric results were obtained from each one of these children, and Table 7.1 presents the results for each participant. In addition, Table 7.2 shows the details regarding the suspected or diagnosed difficulties/reason for referral in each child participant. For the 8 children who were recruited from the Special Assessment Clinic, the suspected or diagnosed difficulties/reason for referral shown in Table 7.2 were obtained from the record cards/referral letters. As we did not have access to the medical records of the other 3 children, the details regarding their attendance to the Orthoptist were obtained from the participant's parents during their visit. For the children that were referred to the Special Assessment Clinic, the same table provides the origin of the referral.

ID NUM	AGE	RE D.VA	LE D.VA	BINO D.VA	RE N.VA	LE N.VA	BINO N.VA	D. CT	N. CT	NPC	STEREO	RET RE SPH	RET RE CYL	RET LE SPH	RET LE CYL	Acc	MOTILITY
P01	12	0	0	0	0	0	0	ORTO	ORTO	<5 CM	85”	+0.5	-0.25	+0.5	-0.25	<1D	SPEC
P02	9	0.3	0.3	0.3	0.3	0.3	0.3	ORTO	ORTO	<5 CM	NONE	+1	-0.5	+1.5	-0.5	<1D	HEAD MOV
P03	8	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	ORTO	ORTO	7 CM	170”	+1	-0.75	+1	-0.5	<1D	SPEC
P04	9	-0.1	0	-0.1	-0.1	-0.1	-0.1	ORTO	LOW SOP	<5 CM	170”	+1	∞	+1	∞	<1D	SPEC
P05	9	0.2	0.24	0.2	0.1	0.1	0.1	ORTO	LOW SOP	<5 CM	170”	+1	∞	+1	-0.5	<1D	HEAD MOV
P06	14	0.2	0.1	0.1	0.1	0	0	ORTO	ORTO	6 CM	85”	+0.5	∞	0+.5	∞	<1D	SPEC
P07	10	0.1	0.1	0	0	0	0	ORTO	LOW SOP	<5 CM	85”	∞	-0.75	+0	-0.5	<1D	JERKY
P08	8	0	0	0	-0.1	-0.1	-0.1	ORTO	MED XOP	<5 CM	85”	+2.5	-4	+2.25	-4	<1D	HEAD MOV
P09	10	0	0	0	0	0	0	ORTO	LOW SOP	<5 CM	85”	+2.5	-2	+3.5	-1.75	<1D	SPEC
P10	11	0.3	0.1	0	0	0	0	ORTO	LOW SOP	<5 CM	340”	+5	-2.5	+6	-2	3D LAG	SPEC
P11	5	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	ORTO	ORTO	<5 CM	170”	+0.5	∞	+0.25	∞	<1D	SPEC

Table 7.1. Optometric parameters obtained from the child participants with suspected eye movement difficulties.

ID NUM	DIAGNOSED OR SUSPECTED DIFFICULTIES	REFERRAL FROM
P01	UNSPECIFIED LEARNING DIFFICULTIES. DELAYED READING SKILLS	N/A
P02	SUSPECTED VISUAL PROCESSING DISORDER. DIAGNOSED DYSPRAXIA AND SPEECH AND LANGUAGE DIFFICULTIES	SPEECH THERAPIST
P03	DIAGNOSED WITH DYSLEXIA AND VISUAL STRESS	N/A
P04	DIAGNOSED WITH "TRACKING" DIFFICULTIES	ORTHOPTIST
P05	UNSPECIFIED LEARNING DIFFICULTIES. DELAYED READING SKILLS	PAEDIATRICIAN
P06	DIAGNOSED WITH DYSLEXIA, DYSCALCULIA AND DYSPRAXIA	EDUCATIONAL PSYCHOLOGIST
P07	GLOBAL DEVELOPMENTAL DELAY	OCCUPATIONAL THERAPIST
P08	SUSPECTED "TRACKING DIFFICULTIES". DELAYED READING SKILLS	EDUCATIONAL PSYCHOLOGIST
P09	SUSPECTED "TRACKING DIFFICULTIES". DELAYED READING SKILLS	N/A
P10	DELAYED READING SKILLS. SUSPECTED DYSLEXIA	REGULAR SPECIAL ASSESSMENT CLINIC PATIENT
P11	GLOBAL DEVELOPMENTAL DELAY	OCCUPATIONAL THERAPIST

Table 7.2. Diagnosed/suspected difficulties in the child participants with suspected eye movement difficulties.

7.4.2. Eye movement recording

Eye movement recording success rates

Successful eye movement recordings were obtained from all tasks in nine of the eleven children. Eye movement traces resembling the one in Figure 7.1 were obtained in two child participants (P04 and P11) for the vertical saccadic test. These two eye movement recordings (for vertical saccades) were discarded from the analysis because the eyes were not detected by the eye tracker throughout the vertical saccadic test (Figure 7.1). Successful eye movement recordings were obtained in these two children for the other eye movement tasks.

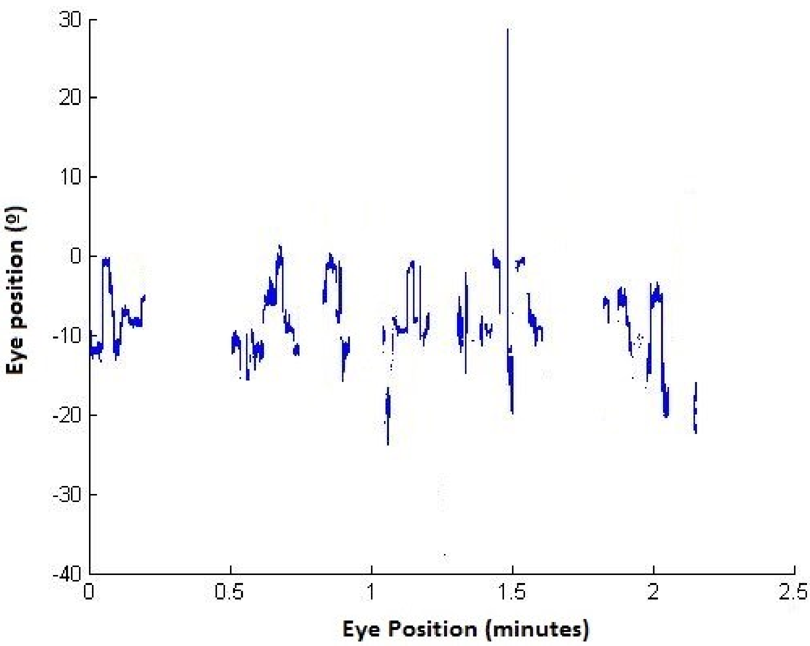


Figure 7.1. Data obtained for the vertical saccadic eye movement task from participant P11 that were discarded from the analysis.

Statistics

Age-matched group comparisons, as previously performed in chapter 6, section 6.6 were not possible in this study due to the small sample size. Similar to the procedure folloed in chapter 6, section 6.7, the eye movement results from the participants were individually compared to their age-matched eye movement norms.

Individual tables with the eye movement values obtained for each participant and task (horizontal and vertical smooth pursuit, horizontal and vertical saccades, and fixations) together with the normative values for each age group were produced (Table 7.3).

HORIZONTAL SMOOTH PURSUIT 6º/S								
	4 YO	**5 YO**	**6 YO**	**7 YO**	**8 YO**	**9 YO**	**10 YO**	**11 YO**
MEAN VELOCITY GAIN	1-0.68	1-0.68	0.97-0.74	1-0.75	0.96-0.78	0.99-0.80	0.98-0.81	0.92-0.87
						0.58		
MEAN POSITION GAIN	0.98-0.65	0.96-0.70	1-0.64	1-0.64	1.02-0.69	1-0.74	1-0.56	1.05-0.69
						0.61		
MEAN PROPORTION OF SP	0.99-0.52	1-0.49	0.94-0.59	0.98-0.64	1-0.65	0.94-0.74	1-0.65	0.88-0.73
						0.49		
MEAN NUMBER OF SACCADES	16.2-0	16.7-0	15.38-0	23.7-0	10-0	11.1-0	12-0	6.8-0
						14		2
MEAN AMPLITUDE OF SACCADES	3.84-0	10.5-0	12.82-0	6.12-0	6.4-0	2.5-0	6.63-0	3.5-0
						1.17		
MEAN NUMBER OF MICROSACCADES	39.6-0	15.5-0	16.8-0	38.2-0	33.6-0	29.6-0	26.1-0	21.7-0
						15		
HORIZONTAL SMOOTH PURSUIT 12º/S								
	4 YO	**5 YO**	**6 YO**	**7 YO**	**8 YO**	**9 YO**	**10 YO**	**11 YO**
MEAN VELOCITY GAIN	1.05-0.64	0.97-0.68	1-0.67	0.97-0.70	0.95-0.77	1-0.78	0.99-0.71	1-0.68
						0.46		
MEAN POSITION GAIN	1-0.60	0.94-0.61	1.1-0.32	0.92-0.58	0.92-0.69	1 -0.66	0.93-0.62	1-0.45
						0.59		
MEAN PROPORTION OF SP	1-0.50	1-0.57	1-0.57	1-0.61	1-0.61	1-0.70	1-0.67	1-0.80
						0.31		
MEAN NUMBER OF SACCADES	15.0-0	17-0	14.8-0	19.8-0	16.-0	12.1-0	14.1-0	12.02-0
						12		
MEAN AMPLITUDE OF SACCADES	8-0	4.86-0	5.21-0	5.89-0	3.32-0	6.40-0	3.69-0	1.79-0
						5.77		
MEAN NUMBER OF MICROSACCADES	8.60-0	4.34-0	7.23-0	11.9-0	16.7-0	5.50-0	7.52-0	5.20-0
						4		

Table 7.3. Eye movement parameters obtained for the horizontal smooth pursuit task for 9yo participant P02 together with the 95% confidence limits (norms) for each age group. The parameters outside the participant age-matched 95% confidence limits (norms) are marked in red.

Seven of the eleven children referred with suspected eye movement difficulties were found to have some eye movement parameters outside their corresponding age norms (P02, P03, P06, P07, P08, P10, P11). Tables summarizing the individual results of these participants, indicating which parameters were within the age-matched confidence limits (highlighted in green) and which were not (highlighted in red), are presented below. The same tables also indicate whether the eye movements that were outside the age-matched norms for a participant were within the norms for any other age group.

The summary tables for the 4 children that had all their eye movement parameters within their age-matched norms (P01, P04, P05, P09) are not presented in this chapter but are available in Appendix I.

Results from the eye movement recording for Participant P02 (9 years old)

SMOOTH PURSUIT					
HORIZONTAL 6º/S					
VELOCITY GAIN	POSITION GAIN	PROPORTION OF SP	NUMBER OF SACCADES	MEAN AMPLITUDE SACCADES	NUMBER OF MICROSACC.
0.58 ×× outside all age group norms	0.61 ×× outside all age group norms	0.49 × within 5 YO group norms	14 × within 5 -7 YO groups norms	1.17 ✓ within age-matched norms	15 ✓ within age-matched norms
HORIZONTAL 12º/S					
0.46 ×× outside all age group norms	0.59 ×× outside all age group norms	0.31 ×× outside all age group norms	12 ✓ within age-matched norms	5.77 ✓ within age-matched norms	4 ✓ within age-matched norms
VERTICAL 6º/S					
VELOCITY GAIN	POSITION GAIN	PROPORTION OF SP	NUMBER OF SACCADES	MEAN AMPLITUDE SACCADES	NUMBER OF MICROSACC.
0.78 ✓ within age-matched norms	0.72 ✓ within age-matched norms	0.50 ✓ within age-matched norms	5 ✓ within age-matched norms	1.5 ✓ within age-matched norms	5 ✓ within age-matched norms
VERTICAL 12º/S					
0.75 ✓ within age-matched norms	0.75 ✓ within age-matched norms	0.44 ✓ within age-matched norms	7 ✓ within age-matched norms	2.45 ✓ within age-matched norms	22 ✓ within age-matched norms

Table 7.4. Summary table showing the smooth pursuit parameters obtained from participant P02.

<table>
<tr><td colspan="6">SACCADES</td></tr>
<tr><td colspan="6">HORIZONTAL SACCADES</td></tr>
<tr><td>SLOPE</td><td>INTERCEPT</td><td>Q RATIO</td><td>A</td><td>n</td><td>GAIN</td></tr>
<tr><td>1.14

× within
5 YO group
norms</td><td>40.87

×× outside
all age group
norms</td><td>1.87

×× outside
all age group
norms</td><td>226.9

× within
4 -5 YO groups
norms</td><td>0.22

× within
4 -5 YO
groups norms</td><td>1.05/0.97/
0.94/0.96
✓ within
age-
matched
norms</td></tr>
<tr><td colspan="6">VERTICAL SACCADES (UP)</td></tr>
<tr><td rowspan="2">1.48

✓within
age-matched
norms</td><td rowspan="2">36.8

✓within
age-matched
norms</td><td rowspan="2">2.09

✓within
age-matched
norms</td><td rowspan="2">135.4

✓within
age-matched
norms</td><td rowspan="2">0.16

✓within
age-matched
norms</td><td>GAIN
VERTICAL</td></tr>
<tr><td rowspan="3">1.10/1/1.07

× outside
all age
groups
(15º GAIN)</td></tr>
<tr><td colspan="5">VERTICAL SACCADES (DOWN)</td></tr>
<tr><td>0.32

×× outside
all age group
norms</td><td>60.42

×× outside
all age group
norms</td><td>1.9

✓within
age-matched
norms</td><td>135.4

✓within
age-matched
norms</td><td>0.16

✓within
age-matched
norms</td></tr>
</table>

Table 7.5. Summary table showing the saccadic parameters obtained from participant P02.

<table>
<tr><td colspan="4">VISUAL FIXATION</td></tr>
<tr><td>HORIZONTAL MEP</td><td>VERTICAL MEP</td><td>HORIZONTAL SD OF MEP</td><td>VERTICAL SD OF MEP</td></tr>
<tr><td>0.41

✓ within age-matched norms</td><td>1.36

✓ within age-matched norms</td><td>0.17

✓ within age-matched norms</td><td>0.42

✓ within age-matched norms</td></tr>
</table>

<table>
<tr><td>MEAN NUMBER OF SACCADES</td><td>MEAN AMPLITUDE OF SACCADES</td><td>MEAN NUMBER OF MICROSACCADES</td></tr>
<tr><td>2
✓ within age-matched norms</td><td>2.82
✓ within age-matched norms</td><td>18
✓ within age-matched norms</td></tr>
</table>

Table 7.6. Summary table showing the visual fixation parameters obtained from participant P02.

Most horizontal smooth pursuit and saccadic parameters were found to be outside the age-matched norms for participant P02. The results indicate that when the eye movements were outside of his age-matched norms, these values were generally within the norms for younger children (aged 4, 5, 6 and 7). However, some parameters were lower than those found in the youngest age groups (e.g. gains for 6°/s horizontal smooth pursuit).

Results from the eye movement recording for Participant P03 (8 years old)

SMOOTH PURSUIT					
HORIZONTAL 6°/S					
VELOCITY GAIN	POSITION GAIN	PROPORTION OF SP	NUMBER OF SACCADES	MEAN AMPLITUDE SACCADES	NUMBER OF MICROSACC
0.81 ✓ within age-matched norms	0.86 ✓ within age-matched norms	0.39 ×× outside all age group norms	17 × within 7 YO group norms	4.96 ✓ within age-matched norms	65 ×× outside all age group norms
HORIZONTAL 12°/S					
0.75 × within 4-7; 10 & 11 YO group norms	0.82 ✓ within age-matched norms	0.45 ×× outside all age group norms	25 ×× outside all age group norms	2.82 ✓ within age-matched norms	32 ×× outside all age group norms
VERTICAL 6°/S					
VELOCITY GAIN	POSITION GAIN	PROPORTION OF SP	NUMBER OF SACCADES	MEAN AMPLITUDE SACCADES	NUMBER OF MICROSACC.
0.77 ✓ within age-matched norms	0.85 ✓ within age-matched norms	0.55 ✓ within age-matched norms	10 ✓ within age-matched norms	2.13 ✓ within age-matched norms	17 ✓ within age-matched nomrs
VERTICAL 12°/S					
0.60 × within any other a ge group norms	0.63 ✓ within age-matched norms	0.47 × within any other age group norms	13 ✓ within age-matched norms	3.62 ✓ within age-matched norms	10 ✓ within age-matched norms

Table 7.7. Summary table showing the smooth pursuit parameters obtained from participant P03.

SACCADES					
HORIZONTAL SACCADES					
SLOPE	INTERCEPT	Q RATIO	A	n	GAIN
1.35 ✗ within 5; 10 & 11 YO groups norms	32.13 ✓ within age-matched norms	1.69 ✓ within age-matched norms	250 ✗ within 4 YO group norms	0.1 ✗ within 4 YO group norms	1.04/0.91/ 1/0.95 ✓ within age-matched norms
VERTICAL SACCADES (UP)					
N/A POOR EYE MOVEMENT TRACE					GAIN VERTICAL

Table 7.8. Summary table showing the saccadic parameters obtained from participant P03.

VISUAL FIXATION			
HORIZONTAL MEP	VERTICAL MEP	HORIZONTAL SD OF MEP	VERTICAL SD OF MEP
0.93 ✓ within age-matched norms	0.01 ✓ within age-matched norms	1.55 ✓ within age-matched norms	0.98 ✓ within age-matched norms

SACCADIC EVENTS DURING FIXATION		
MEAN NUMBER OF SACCADES	MEAN AMPLITUDE OF SACCADES	MEAN NUMBER OF MICROSACCADES
0 ✓ within age-matched norms	- ✓ within age-matched norms	0 ✓ within age-matched norms

Table 7.9. Summary table showing the fixation parameters obtained from participant P03.

Participant P03 had lower gains and a higher number of saccades than his age-matched eye movement norms for most smooth pursuit tasks (horizontal and vertical). Some of these parameters were found to be within the norms for younger children aged 4-7, but other smooth pursuit parameters were found to be outside all the age norms. The vertical eye movement saccadic trace was discarded in this participant due to poor data quality (eye trace resembling the one in Figure 7.1). But the results from the horizontal saccadic task indicate that participant P03 had eye movements within 4 year old norms.

Results from the eye movement recording for participant P06 (14 years old)

SMOOTH PURSUIT					
HORIZONTAL 6º/S					
VELOCITY GAIN	POSITION GAIN	PROPORTION OF SP	NUMBER OF SACCADES	MEAN AMPLITUDE SACCADES	NUMBER OF MICROSACC.
0.76 × within 4-7 YO groups norms	0.68 × within 5&7 YO groups norms	0.61 × within 4 -6 YO groups norms	13 × within 4 -7 YO groups norms	7.1 × within 5&6 YO groups norms	6 ✓ within age-matched norms
HORIZONTAL 12º/S					
0.50 ×× outside all age group norms	0.53 ✓ within age-matched norms	0.41 ×× outside all age group norms	8 ✓ within age-matched norms	4.37 × within 4 -8 YO groups norms	28 ×× outside all age group norms
VERTICAL 6º/S					
VELOCITY GAIN	POSITION GAIN	PROPORTION OF SP	NUMBER OF SACCADES	MEAN AMPLITUDE SACCADES	NUMBER OF MICROSACC.
1.28 ×× outside all age group norms	1.13 ×× outside all age group norms	0.45 × within 5&6 YO groups norms	17 ✓ within age-matched norms	3.51 × within 4-10 YO groups norms	30 × within 4-10 YO groups norms
VERTICAL 12º/S					
0.48 × within 10 YO group norms	0.70 ✓ within age-matched norms	0.26 × within 4 YO group norms	10 ✓ within age-matched norms	4.91 × within 4-10 YO groups norms	0 ✓ within age-matched norms

Table 7.10. Summary table showing the smooth pursuit parameters obtained from participant P06.

SACCADES					
HORIZONTAL SACCADES					
SLOPE	INTERCEPT	Q RATIO	A	n	GAIN
1.36 ✓ within age-matched norms	44.35 ✓ within age-matched norms	1.79 ✓ within age-matched norms	204.2 × within 4,5 & 7 YO groups norms	0.24 × within 4&5 YO groups norms	1.05/1/ 0.98/0.97 ✓ within age-matched norms
VERTICAL SACCADES (UP)					
0.99 × within 4-7&9 YO groups norms	54.13 × within 6,7,9 YO groups norms	1.82 ✓within age-matched norms	52.22 ✓within age-matched norms	0.74 × within 7,8,9&10 YO groups norms	GAIN VERTICAL 1.1/1.01/0.94 × within 4-9 YO groups norms (5º, 10º GAIN)
VERTICAL SACCADES (DOWN)					
1.39 × within 4-9 YO groups norms	54.5 ×× outside all age group norms	1.8 ✓within age-matched norms	76.16 ✓within age-matched norms	0.53 × within 4-9 YO groups norms	

Table 7.11. Summary table showing the saccadic parameters obtained from participant P06.

VISUAL FIXATION			
HORIZONTAL MEP	VERTICAL MEP	HORIZONTAL SD OF MEP	VERTICAL SD OF MEP
-0.49 ✓ within age-matched norms	-1.30 ✓ within age-matched norms	0.23 ✓ within age-matched norms	0.47 ✓ within age-matched norms

SACCADIC EVENTS DURING FIXATION		
MEAN NUMBER OF SACCADES	MEAN AMPLITUDE OF SACCADES	MEAN NUMBER OF MICROSACCADES
2 ✓ within age-matched norms	1.3 ✓ within age-matched norms	11 ✓ within age-matched norms

Table 7.12. Summary table showing the fixation parameters obtained from participant P06.

Participant P06 is 14 years old, and according to the results presented in the previous chapters, by this age she should have achieved adult values. However, several parameters for the smooth pursuit and saccadic eye movements were found to be outside the 11 year old normative values. Moreover, most of her eye movement parameters are within the norms for much younger children (generally between 4-8 years).

Results from the eye movement recording for Participant P07 (10 years old)

SMOOTH PURSUIT					
HORIZONTAL 6º/S					
VELOCITY GAIN	POSITION GAIN	PROPORTION OF SP	NUMBER OF SACCADES	MEAN AMPLITUDE SACCADES	NUMBER OF MICROSACC.
0.83 ✓ within age-matched norms	0.77 ✓ within age-matched norms	0.65 ✓ within age-matched norms	13 × within 4 -7 YO groups norms	5.17 ✓ within age-matched norms	3 ✓ within age-matched norms
HORIZONTAL 12º/S					
0.67 × within 6 YO group norms	0.72 ✓ within age-matched norms	0.57 × within 4-5 YO groups norms	16 × within 5,7&8 YO group norms	3.19 ✓ within age-matched norms	4 ✓ within age-matched norms
VERTICAL 6º/S					
VELOCITY GAIN	POSITION GAIN	PROPORTION OF SP	NUMBER OF SACCADES	MEAN AMPLITUDE SACCADES	NUMBER OF MICROSACC.
0.58 × within 9 YO group norms	0.59 × within 7&9 YO groups norms	0.32 × within 9 YO group norms	8 ✓ within age-matched norms	7.36 × within 5 YO group norms	0 ✓ within age-matched norms
VERTICAL 12º/S					
0.67 ✓ within age-matched norms	0.68 ✓ within age-matched norms	0.47 ✓ within age-matched norms	12 ✓ within age-matched norms	1.79 ✓ within age-matched norms	15 ✓ within age-matched norms

Table 7.13. Summary table showing the smooth pursuit parameters obtained from participant P07.

<table>
<tr><td colspan="6">SACCADES</td></tr>
<tr><td colspan="6">HORIZONTAL SACCADES</td></tr>
<tr><td>SLOPE</td><td>INTERCEPT</td><td>Q RATIO</td><td>A</td><td>n</td><td>GAIN</td></tr>
<tr><td>2.06
✓ within age-matched norms</td><td>29.43
✓ within age-matched norms</td><td>1.76
✓ within age-matched norms</td><td>178.4
✓ within age-matched norms</td><td>0.32
✓ within age-matched norms</td><td>1.02/0.93/ 0.92/0.92
✓ within age-matched norms</td></tr>
<tr><td colspan="6">VERTICAL SACCADES (UP)</td></tr>
<tr><td>2.98
✓ within age-matched norms</td><td>31.22
✓ within age-matched norms</td><td>1.88
✓within age-matched norms</td><td>159.97
✓within age-matched norms</td><td>0.29
✓ within age-matched norms</td><td>GAIN VERTICAL</td></tr>
<tr><td colspan="5">VERTICAL SACCADES (DOWN)</td><td rowspan="2">1.01/0.96/0.95
✓within age-matched norms</td></tr>
<tr><td>1.79
✓ within age-matched norms</td><td>35.85
✓ within age-matched norms</td><td>2.1
× within 4-9 YO groups norms</td><td>175.57
✓within age-matched norms</td><td>0.43
✓within age-matched norms</td></tr>
</table>

Table 7.14. Summary table showing the saccadic parameters obtained from participant P07.

<table>
<tr><td colspan="4">VISUAL FIXATION</td></tr>
<tr><td>HORIZONTAL MEP</td><td>VERTICAL MEP</td><td>HORIZONTAL SD OF MEP</td><td>VERTICAL SD OF MEP</td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
<tr><td>0.34
✓ within age-matched norms</td><td>0.52
✓ within age-matched norms</td><td>0.39
✓ within age-matched norms</td><td>0.39
✓ within age-matched norms</td></tr>
</table>

<table>
<tr><td colspan="3">SACCADIC EVENTS DURING FIXATION</td></tr>
<tr><td>MEAN NUMBER OF SACCADES</td><td>MEAN AMPLITUDE OF SACCADES</td><td>MEAN NUMBER OF MICROSACCADES</td></tr>
<tr><td>0
✓ within age-matched norms</td><td>-
✓ within age-matched norms</td><td>2
✓ within age-matched norms</td></tr>
</table>

Table 7.15. Summary table showing the fixation parameters obtained from participant P07.

Some of the horizontal and vertical smooth pursuit parameters were found to be outside the age-matched norms for participant P07, while only one of all saccadic parameter (Q ratio for downward saccades) was outside his age-matched norms. The parameters that were found to be outside the confidence limits for the participant age were within the norms for younger children. Hence, horizontal and vertical smooth pursuit parameters were within the norms of 4-7 year old children.

Results from the eye movement recording for Participant P08 (8 years old)

SMOOTH PURSUIT					
HORIZONTAL 6º/S					
VELOCITY GAIN	POSITION GAIN	PROPRTION OF SP	NUMBER OF SACCADES	MEAN AMPLITUDE SACCADES	NUMBER OF MICROSACC.
1.04 ×× outside all age group norms	1.05 ×× outside all age group norms	0.99 ✓ within age-matched norms	0 ✓ within age-matched norms	0 ✓ within age-matched norms	2 ✓ within age-matched norms
HORIZONTAL 12º/S					
0.94 ✓ within age-matched norms	1.12 ×× outside all age group norms	0.94 ✓ within age-matched norms	5 ✓ within age-matched norms	8.6 ×× outside all age group norms	6 ✓ within age-matched norms
VERTICAL 6º/S					
VELOCITY GAIN	POSITION GAIN	PROPORTION OF SP	NUMBER OF SACCADES	MEAN AMPLITUDE SACCADES	NUMBER OF MICROSACC.
0.71 ✓ within age-matched norms	0.76 ✓ within age-matched norms	0.62 ✓ within age-matched norms	1 ✓ within age-matched norms	1.72 ✓ within age-matched norms	44 ✓ within age-matched norms
VERTICAL 12º/S					
0.63 ✓ within age-matched norms	0.68 ✓ within age-matched norms	0.55 ✓ within age-matched norms	7 ✓ within age-matched norms	1.62 ✓ within age-matched norms	29 ✓ within age-matched norms

Table 7.16. Summary table showing the smooth pursuit parameters obtained from participant P08.

SACCADES					
HORIZONTAL SACCADES					
SLOPE	INTERCEPT	Q RATIO	A	n	GAIN
2.21 ✓ within age-matched norms	32 ✓ within age-matched norms	1.48 × within any other age group norms	97.52 × within any other age group norms	0.45 ✓ within age-matched norms	1.1/1.05/ 1.08/0.97 ×× outside all age group norms (15º)
VERTICAL SACCADES (UP)					
3.56 ✓ within age-matched norms	27.66 ✓ within age-matched norms	2.03 ✓within age-matched norms	227.37 ✓within age-matched norms	0.13 ✓ within age-matched norms	GAIN VERTICAL
					1.1/0.99/0.92 ✓within age-matched norm
VERTICAL SACCADES (DOWN)					
3 ✓ within age-matched norms	22.71 ✓ within age-matched norms	1.78 ✓within age-matched norms	187.84 ✓within age-matched norms	0.25 ✓within age-matched norms	

Table 7.17. Summary table showing the saccadic parameters obtained from participant P08.

VISUAL FIXATION			
HORIZONTAL MEP	VERTICAL MEP	HORIZONTAL SD OF MEP	VERTICAL SD OF MEP
0.73 ✓ within age-matched norms	0.52 ✓ within age-matched norms	0.1 ✓ within age-matched norms	0.1 ✓ within age-matched norms

SACCADIC EVENTS DURING FIXATION		
MEAN NUMBER OF SACCADES	MEAN AMPLITUDE OF SACCADES	MEAN NUMBER OF MICROSACCADES
0 ✓ within age-matched norms	- ✓ within age-matched norms	5 ✓ within age-matched norms

Table 7.18. Summary table showing the fixation parameters obtained from participant P08.

Horizontal eye movements (smooth pursuits and saccades) were outside the age-matched norms of participant P08. Interestingly, her horizontal smooth pursuit gains were above the upper confidence limit for her age, suggesting that her eyes were ahead of the target during the task (i.e. inaccurate saccades). In addition, the mean values obtained in this participant were not within the norms of any other age group studied. In contrast, the parameters found to be outside the confidence intervals for horizontal saccades were within the norms for most age groups (except that of the participant's age group).

Results from the eye movement recording for Participant P10 (11 years old)

SMOOTH PURSUIT					
HORIZONTAL 6°/S					
VELOCITY GAIN	POSITION GAIN	PROPORTION OF SP	NUMBER OF SACCADES	MEAN AMPLITUDE SACCADES	NUMBER OF MICROSACC.
0.86 ✗ within 4-10 YO groups norms	0.91 ✓ within age-matched norms	0.75 ✓ within age-matched norms	10 ✗ within 4 -10 YO groups norms	3.94 ✗ within 5-8 YO groups norms	25 ✗ within 7-10 YO groups norms
HORIZONTAL 12°/S					
0.83 ✓ within age-matched norms	0.85 ✓ within age-matched norms	0.80 ✓ within age-matched norms	12 ✓ within age-matched norms	3.36 ✗ within 4 -10 YO groups norms	3 ✓ within age-matched norms
VERTICAL 6°/S					
VELOCITY GAIN	POSITION GAIN	PROPORTION OF SP	NUMBER OF SACCADES	MEAN AMPLITUDE SACCADES	NUMBER OF MICROSACC.
0.68 ✓ within age-matched norms	0.90 ✓ within age-matched norms	0.37 ✗ within 9 YO group norms	11 ✓ within age-matched norms	3.74 ✗ within 4 -10 YO groups norms	14 ✓ within age-matched nomrs
VERTICAL 12°/S					
0.61 ✓ within age-matched norms	0.64 ✓ within age-matched norms	0.52 ✓ within age-matched norms	11 ✓ within age-matched norms	2.63 ✓ within age-matched norms	33 ✓ within age-matched norms

Table 7.19. Summary table showing the smooth pursuit parameters obtained from participant P10.

<table>
<tr><td colspan="6">SACCADES</td></tr>
<tr><td colspan="6">HORIZONTAL SACCADES</td></tr>
<tr><td>SLOPE</td><td>INTERCEPT</td><td>Q RATIO</td><td>A</td><td>n</td><td>GAIN</td></tr>
<tr><td>1.77

✓ within age-matched norms</td><td>34.64

✓ within age-matched norms</td><td>1.81

✓ within age-matched norms</td><td>135.6

✓ within age-matched norms</td><td>0.41

✓ within age-matched norms</td><td>1.05/0.98/ 1.01/0.95
✓ within age-matched norms</td></tr>
<tr><td colspan="6">VERTICAL SACCADES (UP)</td></tr>
<tr><td>0.77

× within 4,5,6 & 9 YO groups norms</td><td>46.25

× within 4,5,7 & 9 YO groups norms</td><td>2.02

✓within age-matched norms</td><td>102.01

✓within age-matched norms</td><td>0.50

✓within age-matched norms</td><td>GAIN VERTICAL
1.1/1/0.98

× within 4-10 YO groups norms (5º GAIN)</td></tr>
<tr><td colspan="5">VERTICAL SACCADES (DOWN)</td><td></td></tr>
<tr><td>2.36

✓within age-matched norms</td><td>31.68

× within 4 -10 YO groups norms</td><td>2.08

× within 4 -9 YO groups norms</td><td>102.62

✓within age-matched norms</td><td>0.58

× within 4 -10 YO groups norms</td><td></td></tr>
</table>

Table 7.20. Summary table showing the saccadic parameters obtained from participant P10.

<table>
<tr><td colspan="4">VISUAL FIXATION</td></tr>
<tr><td>HORIZONTAL MEP</td><td>VERTICAL MEP</td><td>HORIZONTAL SD OF MEP</td><td>VERTICAL SD OF MEP</td></tr>
<tr><td>0.06

✓ within age-matched norms</td><td>-1.19

✓ within age-matched norms</td><td>0.29

✓ within age-matched norms</td><td>0.17

✓ within age-matched norms</td></tr>
</table>

<table>
<tr><td colspan="3">SACCADIC EVENTS DURING FIXATION</td></tr>
<tr><td>MEAN NUMBER OF SACCADES</td><td>MEAN AMPLITUDE OF SACCADES</td><td>MEAN NUMBER OF MICROSACCADES</td></tr>
<tr><td>0

✓ within age-matched norms</td><td>-

✓ within age-matched norms</td><td>20
× within 4,5,6&9 YO groups norms</td></tr>
</table>

Table 7.21. Summary table showing the fixation parameters obtained from participant P10.

For participant P10, one or more eye movement parameters were found to be outside the confidence limits for his age in every eye movement task. The values obtained for the eye movement parameters that were outside the norms were within the norms for younger children (4-10 years).

Results from the eye movement recording for Participant P11 (5 years old)

SMOOTH PURSUIT					
HORIZONTAL 6°/S					
VELOCITY GAIN	POSITION GAIN	PROPORTION OF SP	NUMBER OF SACCADES	MEAN AMPLITUDE SACCADES	NUMBER OF MICROSACC.
0.87 ✓ within age-matched norms	0.8 ✓ within age-matched norms	0.40 ×× outside all age group norms	14 ✓ within age-matched norms	2.90 ✓ within age-matched norms	22 × within 4 YO group norms
HORIZONTAL 12°/S					
0.72 ✓ within age-matched norms	0.72 ✓ within age-matched norms	0.64 ✓ within age-matched norms	12 ✓ within age-matched norms	1.88 ✓ within age-matched norms	1 ✓ within age-matched norms
VERTICAL 6°/S					
VELOCITY GAIN	POSITION GAIN	PROPORTION OF SP	NUMBER OF SACCADES	MEAN AMPLITUDE SACCADES	NUMBER OF MICROSACC.
0.73 ✓ within age-matched norms	0.69 ✓ within age-matched norms	0.44 ✓ within age-matched norms	17 ✓ within age-matched norms	3.82 ✓ within age-matched norms	59 × within 4 YO group norms
VERTICAL 12°/S					
0.73 ✓ within age-matched norms	0.70 ✓ within age-matched norms	0.26 × within 4 YO group norms	20 × within Any other age group norms	3.36 ✓ within age-matched norms	33 × within any other age group norms

Table 7.22. Summary table showing the smooth pursuit parameters obtained from participant P11.

SACCADES					
HORIZONTAL SACCADES					
SLOPE	INTERCEPT	Q RATIO	A	n	GAIN
2.93 × within 4 YO group norms	23.40 ✓ within age-matched norms	1.93 × outside all age groups	255.93 × within 4 YO group norms	0.19 × within 4 YO group norms	1.16/0.91/ 0.95/0.98 ✓ within age-matched norms
VERTICAL SACCADES (UP)					
N/A POOR EYE MOVEMENT TRACE					GAIN VERTICAL

Table 7.23. Summary table showing the saccadic parameters obtained from participant P11.

VISUAL FIXATION			
HORIZONTAL MEP	VERTICAL MEP	HORIZONTAL SD OF MEP	VERTICAL SD OF MEP
1.21 ✓ within age-matched norms	0.88 ✓ within age-matched norms	0.33 ✓ within age-matched norms	0.28 ✓ within age-matched norms

SACCADIC EVENTS DURING FIXATION		
MEAN NUMBER OF SACCADES	MEAN AMPLITUDE OF SACCADES	MEAN NUMBER OF MICROSACCADES
3 ✓ within age-matched norms	1.1 ✓ within age-matched norms	19 ✓ within age-matched norms

Table 7.24. Summary table showing the fixation parameters obtained from participant P11.

Some smooth pursuit parameters (horizontal and vertical) and some horizontal saccadic parameter were outside the age-matched norms of participant 11. This participant was the youngest in this study, and the eye movement parameters that were found to be outside her age matched norms were in most cases within 4 year old norms. However, some of the parameters found to be outside the norms for smooth pursuit eye movements did not fall within any of the age-matched norms. According to the results presented in chapter 6, at the age of 5 years smooth pursuit are still in development. Her eye movement results suggest that, in some cases, her eye movement performance might be below that normally found for 4 year olds.

7.5. Discussion

In this chapter we evaluated eye movements in children referred to two Eye Care Professionals (an Optometrist in Cardiff and an Orthoptist in Bridgend) with suspected eye movement difficulties.

Unfortunately, the sample was too small to allow us to compare the eye movement parameters of this group of children with age-matched primary school children. Hence, the results from the participants were individually compared to the eye movement normative values obtained from the primary school population (children without IEP) presented in chapter 5, section 5.7. The results demonstrated again that some, but not all of these children, had eye movement parameters outside their age-matched norms.

Table 7.25 summarizes the eye movement results for the 11 participants in this study, indicating which eye movement types were within (highlighted in green - all parameters within the norms) or outside (highlighted in red - one or more parameters outside the norms) their age-matched normative values. Participants P01, P04, P05 and P09 (eye movement results presented in Appendix I) had all of their eye movement parameters within the expected values for their age, while the other participants with suspected eye movement difficulties (n=7) had some eye movements outside their age-matched confidence limits.

	HORIZONTAL SP		VERTICAL SP		SACCADES		FIXATION
	6°/s	12°/s	6°/s	12°/s	HZT	VTC	
P01	✓	✓	✓	✓	✓	✓	✓
P02	×	×	✓	✓	×	✓	✓
P03	×	×	✓	×	×	NA	✓
P04	✓	✓	✓	✓	✓	✓	✓
P05	✓	✓	✓	✓	✓	✓	✓
P06	×	×	×	×	×	×	✓
P07	×	×	×	✓	✓	×	✓
P08	×	×	✓	✓	×	✓	✓
P09	✓	✓	✓	✓	✓	✓	✓
P10	×	×	×	✓	✓	×	×
P11	×	✓	✓	×	×	NA	✓

Table 7.25. Summary table showing the children that had eye movement parameter within (green) and outside (red) their age-matched norms for each eye movement task.

The results show that children with suspected eye movement difficulties were frequently outside the confidence age-matched limits for their age. Additionally, those children who showed different eye movements for their age frequently showed several of the parameters outside the norms for more than one eye movement type (Table 7.25). Having said that, parameters for horizontal smooth pursuit and horizontal saccades were more frequently outside the norms in these children than those for other eye movement types and direction. For instance, half of children referred with suspected eye movement difficulties had horizontal smooth pursuit (for both velocities) and horizontal saccades outside of their age-matched confidence limits, respectively. Parameters for vertical eye movements were expected to be less frequently outside norms because, as previously discussed, the 95% confidence limits are much wider due to the increased variability found in this direction. Finally, the fixation parameters were outside the age-matched norms in only one participant (and only one parameter), suggesting that this eye movement type is less likely to be outside of the age-matched norms. Although no statistical analyses were performed in this chapter, if the sample size of this study were to be increased in the future, further statistical analysis would be possible. For instance, logistic regression could be used to predict the probability of having eye movements outside the age-matched norms in children who have been referred to Eye Care Professionals with suspected eye movement difficulties. Alternatively, Chi-square tests could be used to study which eye movement parameters more frequently lie outside the norms.

Notwithstanding, if we relate the eye movement results summarized in Table 7.25 the diagnosed/suspected difficulties of the participants (Table 7.2) a clear conclusion can be drawn: *participants who showed eye movements different to those expected for their age, generally corresponded to those participants with diagnosed/suspected specific learning difficulties or a global developmental delay*. For example, participant P06 had one or more parameters outside her age-matched confidence intervals for all eye movement types except for fixation (see Table 7.25). This participant was recruited from the Special Assessment Clinic, and she was diagnosed with dyslexia, dyscalculia and dyspraxia. Similarly, participant P02 had several eye movement parameters outside his age-matched norms for all horizontal eye movement tasks (horizontal smooth pursuit and saccades), and he was diagnosed with dyspraxia, speech and language difficulties and had a suspected visual processing disorder. In general, these results are in agreement with previously published research suggesting that children with specific learning disabilities such as dyslexia (Fukushima et al. 2005), dyspraxia and/or developmental coordination disorder (Langaas et al. 1998; Robert et al. 2014) are highly likely to have oculomotor control anomalies. Further, children with general developmental delays, including children born prematurely, have also been found to have lower than expected smooth pursuit gains and difficulties in some saccadic aspects (Langaas et al. 1998). It can be argued that these difficulties do not originate from a "pure" oculomotor control deficit but from a combination of difficulties in several visual and sensory-motor aspects (Sweeney et al. 2004; Rommelse et al. 2008). Finally, these findings support the idea that eye movement behaviour in children referred to Eye Care Professionals (by Educational Professionals) with suspected eye movement difficulties and associated specific learning difficulties are likely to exhibit different eye movements compared to typical developing children of the same age. Thus, the eye movement differences found in these children are generally not presented in isolation but comorbid with one or more learning difficulties. Nevertheless, that does not imply that *all* children with learning difficulties will have eye movements outside of their age-matched norms, but the findings do indicate that at least some children with learning difficulties will strongly benefit from objective and quantitative eye movement assessments.

It can also be observed from Tables 7.25 and 7.2 that the participants who had all of their eye movements parameters within their age-matched norms (n=4) corresponded to four of the five children who were referred on the grounds of suspected "tracking difficulties" and/or suspected eye movement difficulties associated to delayed reading skills (Table 7.2). These children did not have any diagnosed/suspected specific learning difficulty. Three of these children were being seen by an Orthoptist on a regular basis. Although we did not have the complete records and history for any of these children (as they were not attending the Special Assessment Clinic, Cardiff University), their parents indicated during their visit that their children reading delay/difficulty was their main concern and the reason why they regularly attended the appointments with the Orthoptist. On the other hand, only one child attending the

Orthoptist for the same reasons was found to have her horizontal smooth pursuit and saccades outside her age-matched confidence limits (P08).

The results from this final study raise the question that perhaps those children with delayed reading skills who have their eye movements outside the norms are, in general, children who have a more general developmental delay or impairments in other visual or non-visual aspects. Hence, we hypothesise that children with delayed reading skills who have eye movements different from those found in school children of the same age, might be behind their age-matched peers not only in reading but possibly in several educational aspects. Furthermore, the tables presented in the results section of this chapter show that, in general, when the eye movement parameters were outside the age-matched confidence limits, those were within the confidence limits of another, frequently younger, age group. Thus, it can be proposed that these children generally do not have entirely “abnormal eye movements” as their eye movements are frequently within the norms for younger age groups. In addition, our results are in line with those described by Luna et al. (2008) and further support the idea that in children with learning difficulties (specific and unspecified), eye movements have followed a different, atypical “developmental trajectory” and therefore their oculomotor system is immature. This could be investigated in a future project by longitudinally recording the eye movements from the children that had below-average (age-matched) eye movement performance to assess if these children eventually reach adult-like eye movements.

7.6. Summary

The results of this study show that *some, but not all*, children referred to Eye Care Professionals with suspected/diagnosed eye movement difficulties have different eye movements to those obtained from a typically developing child population of the same age. Moreover, those children whose eye movement parameters were frequently found outside their age-matched 95% confidence limits were those who have been diagnosed with more specific learning difficulties such as dyspraxia and dyslexia, global developmental delay, etc. In contrast, the children who were found to have all their eye movement parameters within the norms for their age were generally those who were referred on the basis of suspected eye movement difficulties mainly associated with delayed reading skills.

More importantly, these findings emphasise the importance of quantitatively assessing eye movements through eye movement recording methods not only in children referred to clinics with “tracking”/eye movement deficits but also in atypical children in order to obtain a better understanding of their visual abilities and difficulties.

Chapter 8 Discussion and future work

8.1. Introduction

The principal aim of this research was to investigate eye movements in children with reading and learning related difficulties and compare their properties with those of typical children. There was a clinical need for this research as a number of Educational Professionals and Eye Care Professionals consider these children at risk of eye movement disorders. The importance of this research is further justified by a growing interest in quantitatively assessing and therefore understanding oculomotor control in children with learning difficulties of different origin (specific and non-specific) and severity (mild to severe).

In this chapter, the major findings of the present study, the clinical implications, and the limitations are discussed. Based on the results, actionable recommendations to support Eye Care Professionals to effectively recognise genuine eye movement disorders in children are proposed. Finally, suggestions for future research are made.

The main findings of the current study (in the order they have been presented in the previous chapters) are as follows:

1. Eye movement performance can be significantly improved with attention-grabbing stimuli (i.e. animated stimuli) (chapter 3).

2. Eye movements (smooth pursuit, saccades and visual fixation) are all fully mature by the age of 7 years in typically developing children (chapter 5).

3. Children with an Individual Education Plan (IEP) related to delayed reading skills do not have different eye movements to children of the same age without such education plan, when compared as a group (chapter 6).

4. When studied individually, children with an IEP related to delayed reading skills have an increased risk of having eye movement properties (smooth pursuit: 4x increased risk, horizontal saccades: 1.7x increased risk, vertical saccades: 3x increased risk and visual fixation: 2x increased risk) outside their age-matched norms than children without such education plan (chapter 6).

5. Children with an IEP related to delayed reading skills whose eye movements are outside their age-matched norms do not have abnormal oculomotor control, but perhaps a different "developmental trajectory" or an immaturity of the oculomotor system (chapter 6).

6. Children diagnosed with specific learning difficulties are highly likely to have eye movement properties outside their age-matched norms (chapter 7).

7. Children referred to Eye Care Professionals with suspected eye movement/"tracking" difficulties and who have co-occurring disorders (e.g. specific learning difficulties or global developmental delays), are likely to have eye movement properties outside their age-matched norms. These children seem to also have an immaturity/different "developmental trajectory" of the oculomotor system. In contrast, children referred with suspected eye movement/"tracking" difficulties who have delayed reading or below average academic achievement (e.g. slow reading, losing words, general poor academic performance, etc.), but not a diagnosed specific learning difficulty or condition (i.e. apparent typical children who have reading and learning related difficulties only), generally have eye movements properties within the norms for their age (chapter 7).

8.2. Eye movements in school age children using a novel child-friendly setup

Our first study investigated eye movements in a typical primary school sample. Hence, children with reading related difficulties (i.e. IEP related to delayed reading skills), who were masked until the data collection and analysis was completed, were excluded. Although eye movements in typically developing school age children have been widely investigated, the reason to undertake this was three-fold. First, although it is clear that eye movements are still in development during childhood, it is unknown when the maturation of eye movements is reached as different studies have reported contradictory results. The lack of agreement amongst the published studies investigating eye movement maturation in children can be attributed to the different stimuli designs, setups, and procedures used. Second, while stimuli and setups have been adjusted to study eye movements in infants, these have not been adjusted when eye movements have been investigated in children. For that reason, it can be argued that the results obtained to date have not provided an optimal characterisation of eye movements in this population. This is further supported by our pilot studies presented earlier in this thesis (chapter 3), which demonstrated that eye movement performance can be improved with a more interesting and attention-grabbing stimuli. Finally, because our stimuli, setup and procedures are very different to those previously used, we needed to establish our own norms. Obtaining baseline data using our novel child-friendly setup allowed us to compare eye movements between groups of children (controls – typical school age children and children with reading/learning related difficulties), and ensure the ability to identify genuine rather than setup-related eye movement differences between the groups. For these reasons, normative values for smooth pursuit, saccades and visual fixation were obtained with our setup from a large primary school population.

The results from this study showed that saccadic eye movements achieve adult values early in life. None of the parameters studied in this research project showed a change with age for horizontal or vertical saccades. These results are in agreement with those previously published by other authors (Accardo et al. 1995; Fukushima et al. 2000; Salman et al. 2006b). In addition, this thesis presents, to our knowledge, the largest child sample in which vertical saccades have been investigated. Our results confirm that vertical saccades are also mature in children as young as 4 years, and further support an up-down asymmetry in this population suggesting slower and possibly less controlled upward saccades than downward saccades (Bucci and Sessau 2014). Visual fixation has been much less studied than smooth pursuit and saccades. Hence, our study is, to our knowledge, also the largest to date providing normative parameters for visual fixation in children. Nonetheless, our results are in line with those from other authors showing improvements in visual fixation with age until 8-10 years (Paus et al. 1990; Ygge et al. 2005).

The most significant findings from this first study are those obtained from the smooth pursuit eye movements. Unlike most published results (e.g. Ross et al. 1993; Katsanis et al. 1998; Salman et al. 2006a), our findings show that children have adult-like smooth pursuit eye movements as young as 7 years. Hence, this thesis presents definitive evidence to support the findings from Rustche et al. (2006) and, therefore, corroborate a smooth pursuit maturation occurring much earlier than generally believed. Further, it can be hypothesised that the use of a child-friendly method for assessing eye movements is the critical and key feature in demonstrating this early maturation.

8.3. Eye movements in children with an IEP related to delayed reading skills

Once the eye movement normative values were established for children aged 4-11 years, the second study investigated oculomotor control in children with an IEP related to delayed reading skills. These children were recruited at the same time and from the same educational establishments as the children from whom we produced the eye movement normative values.

There are extant studies investigating eye movements in children and adults with poor/below average reading skills, however two main features make our study different from those previously published. First, and as previously discussed, the introduction of a novel child-friendly setup to record eye movements in children. Second, unlike most studies investigating oculomotor control in below-average readers, our study recorded eye movements in this population during non-reading related tasks. The objective was that this design would control for confounding factors arising from the reading task. Hence, eye movement differences observed between children with and without IEP in this study, would reveal genuine differences in oculomotor performance, and not eye movement differences resulting from the inherent characteristics of the text. In addition, the eye movement recording tasks performed in this study also controlled for other external factors such as the child's vocabulary/lexical richness. It is reasonable to propose that such factors may also have an impact on eye movement performance during reading, especially in young children who are learning to read, children with delayed reading skills, and children with below-average academic performance.

The first results of this study showed that, in general, children with an IEP related to delayed reading skills do not have different eye movements to those found in children of the same age without such education plan, when compared as a group. In addition, the results of the optometric tests performed prior to the eye movement recording did not differ between children with and without IEP. These findings provide robust evidence to support the view that neither eye movements nor visual problems are the main cause of reading difficulties. Although we anticipate controversy with regard to these results and conclusions, these are in line with those found by a number of authors (e.g. Kiely et al. 2001; Callu et al. 2005; Henderson et al. 2014; Creavin et al. 2015; Monger et al. 2015), and further suggest that delayed reading skills in this population may arise from deficits in phonological, processing, and/or cognitive aspects rather than visual problems. Finally, it has been very recently shown that in general, reading difficulties and dyslexia are not associated to "ophthalmic abnormalities" (Creavin et al. 2015) or "routine optometric measures" (Monger et al. 2015), and in agreement with these, our study provides additional evidence to question interventions that target the visual system, which are generally non-evidence based and widespread by the general public and the media (Henderson et al. 2014). Having said that, it has to be pointed out that the study presented in this thesis to investigate the relationship between reading difficulties and eye movements is a cross-sectional study. Hence, although this study informs this debate, a longitudinal study is needed to provide a final answer to this question.

Surprisingly, however, when the eye movements of children with an IEP related to delayed reading skills were studied individually, some, but not all of these children, had eye movements outside their age-matched norms. For instance, the eye movement parameters of children with delayed readings skills were more frequently outside the confidence intervals for their age. These results can be extrapolated to the overall primary school population as our sample was recruited from two different schools in

South Wales. The school participation was determined by the schools' interest in participating, and although this does not involve a randomised selection, we do not expect large variations of the results depending on the location of the schools. Therefore, we propose that, overall, children with an IEP related to delayed reading skills have a two-fold increased risk of having eye movement properties outside their age-matched norms.

The final conclusion drawn from this study is that children with an IEP related to delayed reading skills, whose eye movements are outside their age-matched norms, do not necessarily have abnormal oculomotor control. First, when the eye movement parameters were outside the age-matched norms in children with IEP, these were not exceptionally above or below the 95% confidence limits for their age. Further to this, when the eye movement parameters were outside the age-matched norms, these were generally within the norms for a younger age group. Thus, it can be suggested that eye movements in these children were not remarkably different to those from children without the IEP. Finally, and linked to the aforementioned findings, none of the children that took part in this study showed eye movements similar to those found in some clinical disorders that are known to affect oculomotor control. For instance, the eye movement performance found in children with IEP (with eye movements outside age-matched norms) is very different to that described as "abnormal" (Ramat et al. 2007). Hence, it can be hypothesised that those children with IEP whose eye movements are outside the age-matched norms do not have an abnormal oculomotor control, per se, but possibly a delayed maturation or a different "developmental trajectory" (Luna et al. 2008) of the oculomotor system.

Finally, the fact that only a percentage of children with an IEP (approximately 30%) have immature/different eye movements for their age (i.e. eye movement properties outside the age-matched 95% confidence limits), raises the question as to whether these children may correspond to a subset of children within this specific population that have other common features. For example, the severity of the reading difficulty, co-occurring disorders and/or having other IEPs might determine whether or not these children have different than average eye movement performance. This question leads, however, to the main limitation of the study that will be discussed at the end of this chapter.

8.4. Eye movements in children referred with suspected eye movement difficulties

The last study presented in this thesis investigated eye movements in children with suspected eye movement/“tracking” difficulties. The participants were recruited from the Special Assessment Clinic at Cardiff University and the Orthoptist Unit at the Princess of Wales Hospital. The child participants were all referred to these clinics with suspected eye movement/“tracking” difficulties. Thus, the study aimed to determine whether or not these children had similar learning difficulties and eye movement characteristics to those in school children with an IEP related to delayed reading skills.

The sample recruited comprised a heterogeneous group of children with difficulties of different origin, severity, and characteristics. For instance, some children were only referred with suspected eye movement difficulties on the grounds of “poor tracking”, and/or delayed reading/academic achievement, while others were referred with suspected eye movement deficits on the grounds of more specific difficulties (e.g. dyslexia, dyspraxia, and global developmental delay). Undoubtedly, the most relevant finding in this last study was that children referred to Eye Care Professionals with suspected eye movement difficulties that had co-occurring difficulties/disorders, were found to have eye movements properties outside their age-matched norms. In contrast, those who were referred with suspected eye movement disorders only associated/related to below average reading/academic achievements were found to have eye movements within their age-matched norms. This finding further supports the understanding that eye movements are more likely to be different in children with specific, more complex and/or global difficulties. In addition, the results reported that eye movements in these children resemble those of younger children. Thus, the results corroborate the views of other authors and further support the existence of eye movement differences in these children if compared to age-matched typical developing children (Sweeney et al. 2004; Luna et al. 2008).

The findings, revealing that children with specific, more severe and global learning difficulties corresponded to the children who had eye movement properties outside the age-matched norms, strongly support the idea proposed in the previous section that, within a group of children with an IEP related to delayed reading skills, there may be a subgroup of children with eye movement difficulties. Moreover, it is reasonable to suggest that, if this is the case, children in this subgroup may share other common features. Therefore, collating the results of both studies (children with IEP and children referred with eye movement difficulties), it can be proposed that children with an IEP related to delayed reading skills, and also children referred with suspected eye movement deficits who genuinely have eye movement properties outside their age-matched norms, may correspond to children who have specific, more complex and/global difficulties (e.g. dyspraxia, ADHD, global developmental delay). Hence, in these children, the reading difficulty may arise from the one or more underlying conditions/disorders that also happen to affect oculomotor control rather than from an isolated oculomotor control disorder. It can be hypothesised that, in children with delayed reading/academic performance whose eye movements were within the norms (in children with an IEP and children referred to clinics), the origin of the difficulties is not visual or as a result of poor oculomotor performance, but the result of deficits in higher order processes involved in reading/learning (e.g. cognitive, processing, and phonological processes). Further, this additional and definitive evidence supports the view that the origin of reading difficulties does not lie in oculomotor control deficits, and challenges the dominant view that eye movement difficulties can be found in isolation (i.e. in individuals without other difficulties/condition/disorders) in children with reading/academic delays.

As suggested in the previous section, the real cause-and-effect relationship between learning/reading difficulties and eye movements might be only determined performing a longitudinal study. The study presented here is a cross-sectional study and therefore further research is needed to fully understand this relationship. Although, cross-sectional studies are very useful to inform whether or not there are links/associations between reading/learning related difficulties and eye movements they cannot be used on their own to investigate causation.

8.5. Limitations of this study

As proposed above, children with an IEP and children referred with suspected eye movement/“tracking” difficulties, who were found to have different eye movements to those expected for their age, may also share other common characteristics (e.g. the severity of the reading difficulty and/or co-occurring IEP/conditions).

The main limitation of this study is that, due to a confluence of issues in respect of ethical approvals and confidentiality, we were unable to further investigate the common characteristics that might be present in children with reading/learning related difficulties and eye movements outside their age-matched norms. This is due to the fact that the only information we held about the children recruited from the schools was their age and whether or not they had an IEP related to delayed reading skills. No other details related to the severity of the reading/learning related difficulty and co-occurring difficulties/conditions that could have an impact on their eye movement performance were obtained during the research. There are three main reasons why this information was not available for our data analysis. First, as one of the principal objectives of this project was to investigate eye movements in children with delayed reading, the protocol submitted and approved by the School of Optometry and Vision Sciences Research and Audit Ethics Committee stated that only children with reading related difficulties would be identified from the sample. Consequently, after the results suggested, unexpectedly, that some children with IEP had eye movement differences when compared to controls, we were limited by our ethical approval with regard to the information we could gather from these children. Second, even after the parents gave consent for their children to take part in the study, the schools were very sensitive to disclose any information with regard to the children’s difficulties and conditions. Finally, while the schools can provide detailed information related to the severity of the reading difficulty, the schools are not in a position to provide detailed information about other conditions/difficulties that the children had. In order to acquire this information, it would have been necessary to directly contact the parents of the children and obtain their consent to access their children’s medical records through either a General Practitioner or Paediatrician. Such additional procedures were not contained in the study protocol that received ethical approval, and therefore could not be undertaken.

Nevertheless, the results of the last study presented in this thesis show that children with difficulties in several academic aspects, and children with suspected/diagnosed conditions, are highly likely to have eye movements outside the norms, while those that have isolated reading difficulties are not. Although further research is needed to confirm these findings, our results support the view that children with reading difficulties only have eye movements different to those expected for their age in the event that they have underlying conditions.

8.6. Suggested guidelines for the clinical assessment of eye movements in children referred with suspected eye movement/"tracking" difficulties

The following section presents actionable insight in the form of clinical guidelines to improve the examination of eye movements in children based on the sum of the results obtained throughout the research project. Although the eye movement differences found between children with and without an IEP related to delayed reading skills were in some cases very small and potentially undetectable during an optometric examination, we believe the following guidelines will improve Optometrists' abilities to recognise genuine eye movement deficits.

8.6.1. Stimuli for the assessment of eye movements

The importance of using appropriate stimuli to assess eye movements in children has been emphasised throughout this thesis. This was first described in the literature review presented in chapter 1, followed by the pilot studies showing that smooth pursuit can be improved in adults using an animated stimulus (chapter 3), and finally in the results suggesting that an animated stimulus may be the key factor in demonstrating an early maturation of the eye movement system (chapter 4). Hence, the first recommendation for the assessment of eye movements in children is the fundamental importance of using interesting and attention-grabbing stimuli.

Some of the observational eye movement assessments/tests (with and without standardised procedures and scorings) have already recommended using targets such as cartoon characters to examine eye movements in children (for details see chapter 1, section 1.4). However, based on the results of this thesis, more attention-grabbing and dynamic targets should also be used in children, as well as in adults with special needs. The use of an animated cartoon such as employed in the present studies would be ideal. However, this is not always feasible clinically, as a monitor or a tablet device is required, and moreover, these devices should be placed in front of the patient's line of sight, which would limit the practitioner's observation of the eye movements. An alternative for this would be to use a simpler target that nonetheless maintained the "morphing"/animated qualities, for example changing lights (lights that change their colour over time). The targets that are currently being used by the researchers and practitioners in the Special Assessment Clinic, Cardiff University, with the purpose of increasing patients' attention are a "flashing pattern fan" (Figure 8.1a), "flashing gloves" (Figure 8.1b), and a "toy with a flashing light" (Figure 8.1c). The targets have flashing lights that change colour, and the optometrist can increase the child's attention and engagement by encouraging him/her to name the different colours that the items display.

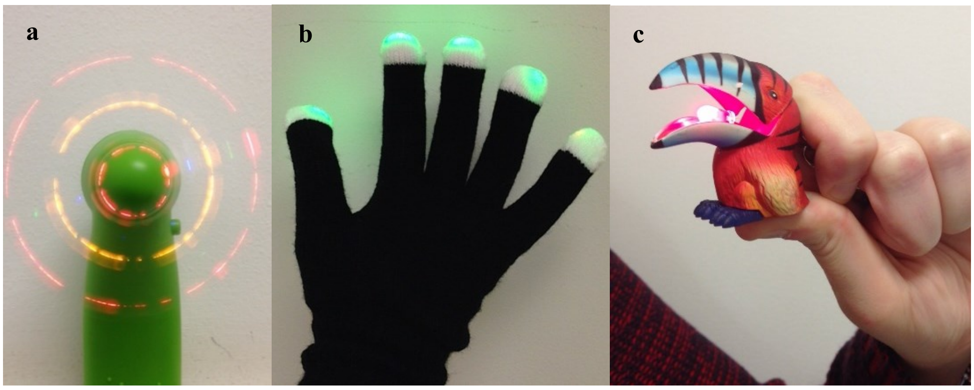


Figure 8.1. Examples of recommended targets for the assessment of eye movements in optometric practice: "flashing pattern fan" (Figure 8.1a), "flashing gloves" (Figure 8.1b) and "toy with a flashing light (Figure 8.1c).

8.6.2. Assessment of smooth pursuit, saccades and visual fixation

Observational tests

Various procedures that involve a direct observation of eye movements are widely used in practice (for details see chapter 1, sections 1.4.1 and 1.4.2). Some of these include the examination of eye movements only in the horizontal direction, others in horizontal and vertical, and some have even proposed examination in horizontal, vertical and diagonal directions.

The results presented in this thesis have shown that vertical eye movements (smooth pursuit and saccades) are more variable than horizontal eye movements. This variability resulted in very wide confidence intervals that defined the norms for eye movements in the vertical direction. Consequently, it is less likely to find vertical smooth pursuit parameters outside the norms. For that reason, we recommend focusing on the examination of horizontal rather than vertical eye movements in children referred with suspected eye movement deficits. Although diagonal eye movements (at 45 and 135 meridians) have not been investigated in this research, it is reasonable to suggest that these may also be more variable than horizontal eye movements.

The findings from our studies suggest that visual fixation might also be outside the age-matched norms in children referred to clinics with suspected eye movement deficits and therefore it should also be assessed. Based on our results and the personal experience of the researcher in the course of this work, the protocol for assessing eye movements in clinical practice is:

Smooth pursuit examination

- Use a changing/flickering/flashing based target (examples shown in figures 8.1a and 8.1b).

- Maintain patient attention and engagement by asking questions about the target (e.g. the different colours of the flashing lights that appear in the target).

- Concentrate on the horizontal meridian rather than the vertical meridian.

- Move the target back and forth horizontally in line of sight of the patient, passing through the patient median plane (straight ahead position).

- Move the target aiming to maintain a constant velocity of approximately 10 cm per second. Maximum amplitude of the target should be approximately 40 cm and the distance target-patient should be approximately 60-70 cm. This resembles the smooth pursuit task performed in our studies.

- Look for an increased number or amplitude of saccades (i.e. intrusive saccades) during the smooth pursuit.

<u>Saccades</u>

- Use a changing/flickering/flashing based target (example shown in Figure 8.1c).

- Examine saccades on command. If using illuminated targets that can be switched on and off instantaneously, saccades can be also examined as a response to one of the lights switching on or off (Figure 8.2).

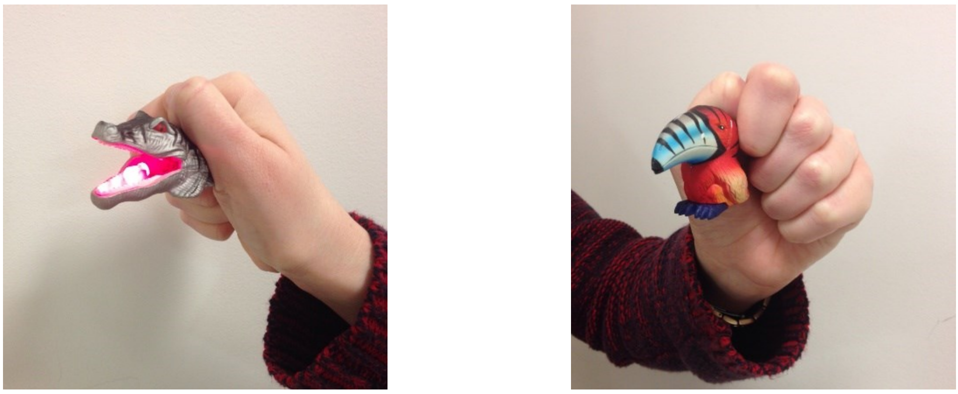


Figure 8.2. Targets that can be switched on and off instantaneously by the examiner that can be used to examine saccades in children.

- Request the patient to perform a series of saccades with the two targets separated by a certain distance. More research needs to be completed to determine if there is an optimal saccadic amplitude that would facilitate the recognition of saccadic deficits, therefore currently no guidelines can be provided with regard to this.

- Look for hypermetric, hypometric saccades.

Visual fixation

- Visual fixation can be assessed during Cover Test and/or Hirschberg.

- Use a changing/flickering/flashing based target (examples shown in Figures 8.1a and 8.1b) or a picture with a lot of detail.

- Maintain patients' attention and engagement by asking questions about the target (e.g. the different colours of the flashing lights that appear in the target, details on the picture).

- Present the target for a period of 10 seconds in the patient's straight ahead position.

- Look for an increased number or amplitude of saccades (i.e. intrusive saccades) during the visual fixation task.

Visual-verbal tests to assess eye movements

Our study showed that, in general, most children with delayed reading skills do not have oculomotor control deficits, but they may have difficulties in higher level processes involved in reading (e.g. cognitive, processing, and phonological processes). Consequently, the use of visual-verbal tests (see chapter 1, section 1.4.3) is not recommended in these guidelines for two clear reasons. First, it has been suggested that the results of visual-verbal tests correlate well with reading performance, but not with the eye movement parameters obtained from eye trackers (see chapter 1, section 1.4.3). This suggests that they are not a measure of "real oculomotor control". Second, these tests involve a reading task, and we have already discussed that, when eye movements are measured during reading, differences in eye movements may reflect difficulties in other non-visual aspects. Hence, these tests are likely to fail to differentiate between deficits in oculomotor control and deficits in processing, phonological, and decoding difficulties. In other words, below average results in these tests may not indicate eye movement difficulties, and these should be used with caution. Notwithstanding, we do not intend for these tests to be removed from the Optometrists' battery of tests as they are a useful measure of reading performance, but to ensure that Optometrists are aware of these tests' limitations in terms of recognising/diagnosing eye movement deficits.

Eye movement recording

Thirty percent of children with an IEP related to delayed reading skills had eye movements properties outside their age-matched norms. However, as previously discussed, their eye movement behaviour cannot be considered "abnormal" as the properties studied were outside but generally close to the 95% confidence limits, and generally lay within the norms for a younger age group. A similar issue was found for eye movement properties in children with suspected eye movement difficulties. Therefore, it is reasonable to suggest that eye movement performance outside the age-matched norms may be difficult to recognise in a routine eye examination, which frequently assesses eye movements based on direct observation rather than with an eye tracker. For instance, a smooth pursuit deficit that shows a slower velocity or position gain will be very difficult to recognise subjectively unless visible saccades are performed during the smooth pursuit. Similarly, saccadic difficulties will only be recognisable when saccades are significantly slower than average or when these are largely hypermetric or hypometric. Finally, when visual fixation is assessed in clinical practice (observational procedures), fixation stability difficulties would only be recognised if large drifts and/or numerous intrusive saccades are present. In these situations, eye movement recordings are the only feasible approach to quantitatively evaluate eye movements and recognise non-average performance. Eye movement recording systems are not widely available to Eye Care Professionals in the UK and the rest of Europe, but to our knowledge, eye departments in several hospitals and a number of universities have access to these instruments. Hence, eye movement recordings can be obtained through referral, if necessary. However, in order to avoid an unnecessary increase in the number of referrals (false negatives) a very simple referral criteria is suggested below.

<u>Referral criteria for an eye movement recording:</u>

- Children with suspected eye movement/"tracking" difficulties who have deficits in several academic areas (e.g. delayed skills in reading, speech, language, etc.)

- Children with suspected eye movement/"tracking" difficulties who have been diagnosed with specific difficulties/conditions (e.g. dyspraxia, autism, dyslexia, etc.) or more severe difficulties/conditions (e.g. global developmental delay, preterm children, etc.)

- Children with suspected eye movement/"tracking" difficulties who are found to have a not-average eye movement performance during the observational clinical tests

- Atypical children for whom the Optometrist considers than an eye movement recording would provide additional and necessary information to better understand their visual abilities and difficulties

8.7. Future work

1. *Investigation of common characteristics in the population of children with IEP related to delayed reading skills whose eye movements are outside the age-matched norms*

As previously discussed, due to a confluence of factors, we were not able to identify common characteristics within the children with IEP related to delayed reading skills who had eye movement properties outside their age-matched norms. It has been argued in this thesis that these children could have had diagnosed/suspected additional difficulties/conditions and/or similar reading/academic performance levels (e.g. 1 year behind in their reading/learning, 2 years behind their reading/learning). Moreover, the thesis goes on to suggest that the possible common features in these children may further demonstrate that eye movement difficulties are not found in isolation and therefore might not be the main cause of reading/learning related difficulties. For that reason, a study should be carried out in which eye movements and optometric parameters are examined, and further details on the difficulties/conditions of these children are obtained. This proposed study offers the potential to provide a definitive answer to the relationship between eye movements and reading difficulties.

2. *Investigation of the eye movement development in children with IEP*

The results of the studies presented in this thesis lead to the conclusion that eye movements in some children with delayed reading skills are not "abnormal", but are immature (corresponding to values for younger children). This suggests that, in some of these children, the eye movement developmental trajectory is not the same as in children of the same age without such education plan. Children with an IEP who took part in our study, and whose eye movements were outside their age-matched norms, could be contacted again and asked to repeat the eye movement recording 1-2 years after their eye movements were first recorded. In contrast, if these children could not be identified, another study could be started in which the eye movements in children with an IEP related to delayed reading skills were recorded every 6 months, for example. These proposed studies, in which eye movements are studied longitudinally offer the potential to further investigate and understand the suggested different maturation/developmental trajectory in children with delayed reading skills. Moreover, to our knowledge, these will be the first studies to characterise the development of eye movements in children with reading/learning related difficulties.

3. *Investigation of binocular and functional vision in children with an IEP related to delayed reading skills*

In our study, all children underwent an optometric examination, however binocular and functional vision were not assessed in detail. These measurements may contribute to better understanding the global visual abilities of these children. In addition, if working in conjunction with other professionals (Psychologists, Teachers of the Visually Impaired), other tests could be performed to measure phonological awareness, attention, visual perception, etc. A study of this type, in which not only eye movements and optometric parameters are studied, may explain the areas in which these children often have difficulties, and consequently provide a better understanding of their global visual, cognitive and intellectual abilities.

4. *Investigation of eye movements in children with Down's syndrome*

Our results have confirmed that children with learning difficulties are highly likely to have different eye movements to those found in typical developing school age children. Hence, it is reasonable to suggest that eye movement differences might also be observed between children with severe learning difficulties and/or disabilities, and typical children. Interestingly, children with Down's syndrome are reported by parents and teachers to struggle with scanning strategies when confronted with arrays of pictures or complex scenes. Although we have not been able to find any published evidence regarding this in the literature, this is reported anecdotally as a very common problem in a large number of children who attend the Special Assessment Clinic (Cardiff University), and suggest a potential eye movement deficit in this population. This hypothesis is further supported by a recent study that has shown the existence of eye movement deficits in this population (Weiss AH et al. ARVO Abstract [2913],

[2015]). In addition, our research group has a special interest in understanding vision in children with Down's syndrome, and eye movements have not been widely investigated in this population. For these given reasons, a study investigating eye movements in children with Down's syndrome in near and distance tasks will not only offer the potential of understanding oculomotor control in this population, but also the stability of focusing and control of eye movements (accommodation and convergence) in near viewing tasks.

5. *Develop terminology and new definitions to be used for all professionals involved in the health care of children reading/learning related difficulties*

As shown earlier in this thesis, there is a significant misunderstanding and miscommunication between professionals working with children who have reading/learning related difficulties. After the studies presented in this thesis, the author strongly suspects that a large number of false negative referrals of children with suspected eye movement difficulties arise from this misunderstanding and miscommunication. Furthermore, the author believes that there is a significant issue in that "we speak a different language". Consequently, the next fundamental step is to further investigate the terminology used in the referrals by the professionals who work with this population, and produce meaningful terminology/definitions in order to improve communication. This evidence-based recommendation is ambitious and complex, and currently it is unclear to the author how this could be achieved. However, if the field recognises this as an overarching issue and takes the appropriate steps, a study aiming to standardise the terminology would have a significant impact on the management of children with suspected eye movement difficulties.

References

Accardo, A. P., Pensiero, S., Da Pozzo, S. and Perissutti, P. (1992) 'Some characteristics of saccadic eye movements in children of primary school age', *Documenta Ophthalmologica,* 80(2), 189-99.

Accardo, A. P., Pensiero, S., Da Pozzo, S. and Perissutti, P. (1995) 'Characteristics of horizontal smooth pursuit eye movements to sinusoidal stimulation in children of primary school age', *Vision Research,* 35(4), 539-48.

Adler, P., Scally, A. D., Barrett, B. T. (2013) 'Test-retest reproducibility of accommodation measurements in an unselected sample of UK primary school children', *British Journal of Ophthalmology*, 97(5), 592-7.

Altman, D. G. and Bland, J. M. (2005) 'Standard deviations and standard errors', *British Medical Journal,* 331(7521), 903.

American Psychiatric Association (2013) *ADHD. Parents Medication Guide*. http://www.psychiatry.org/adhd [Accessed: 02 June 2015].

Anderson, T. J. and MacAskill, M. R. (2013) 'Eye movements in patients with neurodegenerative disorders', *Nature Reviews Neurology,* 9(2), 74-85.

Aring, E., Gronlund, M. A., Hellstrom, A. and Ygge, J. (2007) 'Visual fixation development in children', *Graefe's Archive for Clinical and experimental Ophthalmology,* 245(11), 1659-65.

Armstrong, R. A. (2014) 'When to use the Bonferroni correction', *Ophthalmic and Physiological Optics,* 34(5), 502-8.

Ashby, J., Rayner, K. and Clifton, C. (2005) 'Eye movements of highly skilled and average readers: differential effects of frequency and predictability', *Quarterly Journal of Experimental Psychology,* 58(6), 1065-86.

Aslin, R. N. and Salapatek, P. (1975) 'Saccadic localization of visual targets by the very young human infant', *Perception and Psychophysics,* 17(3), 293-302.

Ayton, L. N., Abel, L. A., Fricke, T. R. and McBrien, N. A. (2009) 'Developmental eye movement test: what is it really measuring?', *Optometry and Vision Science,* 86(6), 722-30.

Bahill, A. (1975) 'The main sequence, a tool for studying human eye movements', *Mathematical Biosciences,* 24(3-4), 191-204.

Barber, A. R. (1995) *Vision Theraphy: Pursuits and Saccades, theories and testing,* Santa Ana: Optometric Extension Program.

Barnes, G. R. (2011) 'Ocular pursuit movements' in Liversedge, S., Gilchrist, I. and Everling, S., eds., *The Oxford Handbook of Eye Movements*, New York: Oxford University Press, pp. 115-134.

Barrett, B. T. (2009) 'A critical evaluation of the evidence supporting the practice of behavioural vision therapy', *Ophthalmic and Physiological Optics,* 29(1), 4-25.

Basra-Badh, A. K., Whitaker, D. J., Barrett, B. T., Bruce, A. (2014) 'Vision Screening - what are we missing?', *Ophthalmic and Physiological Optics,* 34, 108.

Becker, W. and Fuchs, A. F. (1969) 'Further properties of the human saccadic system: eye movements and correction saccades with and without visual fixation points', *Vision Research,* 9(10), 1247-58.

Behrens, F. and Weiss, L. R. (1992) 'An algorithm separating saccadic from nonsaccadic eye movements automatically by use of the acceleration signal', *Vision Research,* 32(5), 889-93.

Behrens, F., Mackeben, M. and Schroder-Preikschat, W. (2010) 'An improved algorithm for automatic detection of saccades in eye movement data and for calculating saccade parameters', *Behavior Research Methods,* 42(3), 701-8.

Bender, R. and Lange, S. (2001) 'Adjusting for multiple testing--when and how?', *Journal of Clinical Epidemiology,* 54(4), 343-9.

Benjamini, Y. and Hochberg, Y. (1995) 'Controlling the False Discovery Rate: A Practical and Powerful Approach to Multiple Testing', *Journal of the Royal Statistical Society. Series B (Methodological),* 57(1), 289-300.

Benjamini, Y., Drai, D., Elmer, G., Kafkafi, N. and Golani, I. (2001) 'Controlling the false discovery rate in behavior genetics research', *Behavioural Brain Research,* 125(1-2), 279-84.

Berg, P. and Scherg, M. (1991) 'Dipole models of eye movements and blinks', *Electroencephalography and Clinical Neurophysiology,* 79(1), 36-44.

Biscaldi, M., Fischer, B. and Aiple, F. (1994) 'Saccadic eye movements of dyslexic and normal reading children', *Perception,* 23(1), 45-64.

Black, J. L., Collins, D. W., De Roach, J. N. and Zubrick, S. R. (1984a) 'Smooth pursuit eye movements in normal and dyslexic children', *Perceptual and Motor Skills,* 59(1), 91-100.

Black, J. L., Collins, D. W., De Roach, J. N. and Zubrick, S. (1984b) 'A detailed study of sequential saccadic eye movements for normal- and poor-reading children', *Perceptual and Motor Skills,* 59(2), 423-34.

Boghen, D., Troost, B. T., Daroff, R. B., Dell'Osso, L. F. and Birkett, J. E. (1974) 'Velocity characteristics of normal human saccades', *Investigative Ophthalmology and Visual Science,* 13(8), 619-23.

Brandt, T., Dieterich, M. and Strupp, M. (2005) 'Introductory remaks' in Brandt, T ed., *Vertigo and Dizzines: Common Complaints*, 1st ed., Springer-verlag London, pp. 1-39.

Brown, B., Haegerstrom-Portnoy, G., Adams, A. J., Yingling, C. D., Galin, D., Herron, J. and Marcus, M. (1983) 'Predictive eye movements do not discriminate between dyslexic and control children', *Neuropsychologia,* 21(2), 121-8.

Bucci, M. P., Nassibi, N., Gerard, C. L., Bui-Quoc, E. and Seassau, M. (2012) 'Immaturity of the oculomotor saccade and vergence interaction in dyslexic children: evidence from a reading and visual search study', *PLoS ONE,* 7(3), e33458.

Bucci, M. P. and Seassau, M. (2014) 'Vertical saccades in children: a developmental study', *Experimental Brain Research,* 232(3), 927-34.

Byrne, J. H. and Dafny, N. (1997) 'Neuroscience Online: an electronic textbook for the neurosciences' [Online] available: http://nba.uth.tmc.edu/neuroscience/ [accessed 17 May 2015].

Cambridge Research Systems (2015) 'High Speed Video Eye-tracker', [online], available: http://www.crsltd.com/tools-for-vision-science/eye-tracking/high-speed-video-eye-tracker-toolbox/ [accessed 10 June 2015].

Callu, D., Giannopulu, I., Escolano, S., Cusin, F., Jacquier-Roux, M. and Dellatolas, G. (2005) 'Smooth pursuit eye movements are associated with phonological awareness in preschool children', *Brain and Cognition,* 58(2), 217-25.

Carpenter, R. H. S. (1988) 'Saccades' in Carpenter, R. H. S. *Movements of the eyes*, 2nd ed., London: Pion Limited, pp. 69-101.

Casanova, M. F., Buxhoeveden, D. P., Switala, A. E. and Roy, E. (2002) 'Minicolumnar pathology in autism', *Neurology,* 58(3), 428-32.

Castellanos, F. X. (2001) 'Neural substrates of attention-deficit hyperactivity disorder', *Advances in Neurology,* 85, 197-206.

Catts, H. W., Fey, M. E. and Proctor-Williams, K. (2000) 'The relationship between language and reading. Preliminary results from a longitudinal investigation', *Logopedics, Phoniatrics, Vocology,* 25(1), 3-11.

Ciuffreda, K. J., Bahill, A. T., Kenyon, R. V. and Stark, L. (1976) 'Eye movements during reading: case reports', *American Journal of Optometry and Physiological Optics,* 53(8), 389-95.

Clifton, C. and Staud, A. (2011) 'Syntactic influences on eye movements during reading' in in Liversedge, S., Gilchrist, I. and Everling, S., eds., *The Oxford handbook of eye movements*, New York: Oxford University Press, Inc, pp. 895-909.

Cody, H., Pelphrey, K. and Piven, J. (2002) 'Structural and functional magnetic resonance imaging of autism', *International Journal of Developmental Neuroscience,* 20(3-5), 421-38.

Cohen, M. E. and Ross, L. E. (1978) 'Latency and accuracy characteristics of saccades and corrective saccades in children and adults', *Journal of Experimental Child Psychology,* 26(3), 517-27.

Cohen, A. H., Lieberman, S., Stolzberg, M. and Ritty, J. M. (1983) 'The NYSOA vision screening battery: a total approach', *Journal of the American Optometric Association,* 54(11), 979-84.

Creavin, A. L., Lingam, R., Steer, C. and Williams, C. (2015) 'Ophthalmic abnormalties and reading impairment', *Pediatrics,* 135(6), 1057-65.

Dayton, G. O., Jr., Jones, M. H., Steele, B. and Rose, M. (1964) 'Developmental study of coordinated eye movements in the human infant: II. An electro-oculographyic study of the fixation reflex in the newborn', *Archieves of Ophthalmology,* 71(6), 871-5.

de Brouwer, S., Missal, M., Barnes, G. and Lefèvre, P. (2002) 'Quantitative Analysis of Catch-Up Saccades During Sustained Pursuit', *Journal of Neurophysiology,* 87(4), 1772-80.

Dick, S., Ostendorf, F., Kraft, A. and Ploner, C. J. (2004) 'Saccades to spatially extended targets: the role of eccentricity', *Neuroreport,* 15(3), 453-6.

Di Stasi, L. L., Catena, A., Cañas, J. J., Macknik, S. L. and Martinez-Conde, S. (2013) 'Saccadic velocity as an arousal index in naturalistic tasks', *Neuroscience and Biobehavioral Reviews,* 37(5), 968-75.

Dodge, R. (1903) 'Five types of eye movements in the horizontal meridian plane of the field of regard', *Journal of Physiology,* 8(4), 307-29.

Duchowski, A. T. (2007) 'Eye Tracking techniques' in Duchowsky, A. T. *Eye Tracking methodology: Theory and Practice*, New York: Springer-Verlag London, pp. 51-59.

Eden, G. F., Stein, J. F., Wood, H. M. and Wood, F. B. (1994) 'Differences in eye movements and reading problems in dyslexic and normal children', *Vision Research,* 34(10), 1345-58.

Eggert, T. (2007) 'Eye movement recordings: methods', *Developments in Ophthalmology,* 40, 15-34.

Ego, C., Orban de Xivry, J. J., Nassogne, M. C., Yuksel, D. and Lefevre, P. (2013) 'The saccadic system does not compensate for the immaturity of the smooth pursuit system during visual tracking in children', *Journal of Neurophysiology,* 110(2), 358-67.

Ettinger, U., Kumari, V., Crawford, T. J., Davis, R. E., Sharma, T. and Corr, P. J. (2003) 'Reliability of smooth pursuit, fixation, and saccadic eye movements', *Psychophysiology,* 40(4), 620-8.

Fellows, B. J. (1967) 'Chance stimulus sequences for discrimination tasks', *Psychological Bulletin,* 67(2), 87-92.

Fioravanti, F., Inchingolo, P., Pensiero, S. and Spanio, M. (1995) 'Saccadic eye movement conjugation in children', *Vision Research,* 35(23-24), 3217-28.

Fischer, B., Biscaldi, M. and Gezeck, S. (1997) 'On the development of voluntary and reflexive components in human saccade generation', *Brain Res,* 754(1-2), 285-97.

Flax, N. (2006) 'The relationship between vision and learning: general issues' in Scheiman, M. M. and Rouse, M. W., eds., *Optometric Management of Learning-Related Vision Problems*, 2nd ed., St. Louis: Mosby Elsevier, pp. 183-240.

Flechtner, K. M., Steinacher, B., Sauer, R. and Mackert, A. (2002) 'Smooth pursuit eye movements of patients with schizophrenia and affective disorder during clinical treatment', *European Archives of Psychiatry and Clinical Neuroscience,* 252(2), 49-53.

Fuchs, A. F. and Luschei, E. S. (1970) 'Firing patterns of abducens neurons of alert monkeys in relationship to horizontal eye movement', *Journal of Neurophysiology,* 33(3), 382-92.

Fukushima, J., Hatta, T. and Fukushima, K. (2000) 'Development of voluntary control of saccadic eye movements. I. Age-related changes in normal children', *Brain and Development,* 22(3), 173-80.

Fukushima, J., Tanaka, S., Williams, J. D. and Fukushima, K. (2005) 'Voluntary control of saccadic and smooth-pursuit eye movements in children with learning disorders', *Brain and Development,* 27(8), 579-88.

Garbutt, S., Harwood, M. R. and Harris, C. M. (2001) 'Comparison of the main sequence of reflexive saccades and the quick phases of optokinetic nystagmus', *British Journal of Ophthalmology,* 85(12), 1477-83.

Garbutt, S., Harwood, M. R., Kumar, A. N., Han, Y. H. and Leigh, R. J. (2003a) 'Evaluating small eye movements in patients with saccadic palsies', *Annnals of the New York Academy of Sciences,* 1004, 337-46.

Garbutt, S., Han, Y., Kumar, A. N., Harwood, M., Harris, C. M. and Leigh, R. J. (2003b) 'Vertical optokinetic nystagmus and saccades in normal human subjects', *Investigative Ophthalmology and Visual Science,* 44(9), 3833-41.

Garbutt, S., Harwood, M. R. and Harris, C. M. (2006) 'Infant saccades are not slow', *Developmental Medicine and Child Neurology,* 48(8), 662-7.

Garzia, R. P., Richman, J. E., Nicholson, S. B. and Gaines, C. S. (1990) 'A new visual-verbal saccade test: the development eye movement test (DEM)', *Journal of the American Optometry Association,* 61(2), 124-35.

Garzia, R. P. (2006) 'The relationship between visual efficency problems and learning' in Scheiman, M. M. and Rouse, M. W., eds., *Optometric Management of Learning-Related Vision Problems* 2nd ed., St. Louis: Mosby Elsevier, pp. 209-240.

Gaymard, B. and Pierrot-Deseilligny, C. (1999) 'Neurology of saccades and smooth pursuit', *Current Opinion in Neurology,* 12(1), 13-19.

Gilchrist, I. D. (2011) 'Saccades' in Liversedge, S., Gilchrist, I. and Everling, S., eds., *The Oxford Handbook of Eye Movements*, New York: Oxford University Press, pp. 85-94.

Glass, G. V., Peckham, P. D. and Sanders, J. R. (1972) 'Consequences of failure to meet assumptions underlying the fixed effects analyses of variance and covariance', *Review of Educational Research,* 42(3), 237-88.

Goldberg, M. C., Lasker, A. G., Zee, D. S., Garth, E., Tien, A. and Landa, R. J. (2002) 'Deficits in the initiation of eye movements in the absence of a visual target in adolescents with high functioning autism', *Neuropsychologia,* 40(12), 2039-49.

Gredebäck, G., Ornkloo, H. and von Hofsten, C. (2006) 'The development of reactive saccade latencies', *Experimental Brain Research,* 173(1), 159-64.

Griffin, D. C., Walton, H. N. and Ives, V. (1974) 'Saccades as related to reading disorders', *Journal of Learning Disabilities,* 7(5), 310-6.

Griffin, J. R. and Grisham, J. D. (2002a) 'Visual skills efficency' in Griffin, J.R. ed. *Binocular Anomalies. Diagnosis and vision therapy*, Woburn: Butterworth-Heinemann, pp. 19-65.

Griffin, J. R. and Grisham, J. D. (2002b) 'Diagnosis of a deviation of the visual axes' in Griffin, J.R. ed. *Binocular Anomalies. Diagnosis and vision therapy*, Woburn: Butterworth-Heinemann, pp. 101-53.

Grisham, J. D., Powers, M. and Riles, P. (2007) 'Visual skills of poor readers in high school', *Optometry - Journal of the American Optometric Association,* 78(10), pp. 542-9.

Grönqvist, H., Gredebäck, G. and Hofsten, C. (2006) 'Developmental asymmetries between horizontal and vertical tracking', *Vision Research,* 46(11), 1754-61.

Grönqvist, H., Brodd, K. S. and Rosander, K. (2011) 'Development of smooth pursuit eye movements in very prematurely born infants: 2. The low-risk subgroup', *Acta Paediatrica,* 100(7), e5-11.

Hainline, L., Turkel, J., Abramov, I., Lemerise, E. and Harris, C. M. (1984) 'Characteristics of saccades in human infants', *Vision Research,* 24(12), 1771-80.

Haishi, K. and Kokubun, M. (1995) 'Developmental trends in pursuit eye movements among preschool children', *Perceptual and Motor Skills,* 81(3 Pt 2), 1131-7.

Hamstra, S. J., Sinha, T. and Hallett, P. E. (2001) 'The joint contributions of saccades and ocular drift to repeated ocular fixations', *Vision Research,* 41(13), 1709-21.

Harwood, M. R., Mezey, L. E. and Harris, C. M. (1999) 'The spectral main sequence of human saccades', *Journal of Neuroscience,* 19(20), 9098-106.

Henderson, L. M., Taylor, R. H., Barrett, B. T. and Griffiths, P. G. (2014) 'Treating reading difficulties with colour', *British Medical Journal,* 349, g5160.

Hertle, R. W. and Dell'Osso, L. F. (2013) 'Appendix A. Eye-movement recording systems and criteria' in Hertle, R. W. and Dell'Osso, L. F. eds., *Nystagmus in Infancy and Childhood: Current Concepts in Mechanisms, Diagnoses, and Management*, New York: Oxford University Press, Inc. pp. 259-61.

Hoffman, L. G. and Rouse, M. W. (1980) 'Referral recommendations for binocular function and/or developmental perceptual deficiencies', *Journal of the American Optometric Association,* 51(2), 119-26.

Holland, K. (2011) 'Factsheet: Learning Diabilities', 7. British Institute of Learning Disabilities (BILD). http://www.bild.org.uk/information/factsheets/ [Accessed: 10 June 2015]

Hölmqvist, K., Nyström, M., Andersson, R., Dewhurst, R., Jarodzka, H. and van de Weijer, J. (2011) *Eye Tracking: A comprehensive guide to methods and measures,* OUP Oxford.

Houben, M. M., Goumans, J. and van der Steen, J. (2006) 'Recording three-dimensional eye movements: scleral search coils versus video oculography', *Investigative Ophthalmology and Visual Science,* 47(1), 179-87.

Howard, I. P. and Evans, J. A. (1963) 'The measurement of eye torsion', *Vision Research,* 61, 447-55.

Huestegge, L., Radach, R., Corbic, D. and Huestegge, S. M. (2009) 'Oculomotor and linguistic determinants of reading development: a longitudinal study', *Vision Research,* 49(24), 2948-59.

Hutzler, F., Kronbichler, M., Jacobs, A. M. and Wimmer, H. (2006) 'Perhaps correlational but not causal: no effect of dyslexic readers' magnocellular system on their eye movements during reading', *Neuropsychologia,* 44(4), 637-48.

Hyde, J. E. (1959) 'Some characteristics of voluntary human ocular movements in the horizontal plane', *American Journal of Ophthalmology,* 48(1), 85-94.

Ingster-Moati, I., Vaivre-Douret, L., Bui Quoc, E., Albuisson, E., Dufier, J. L. and Golse, B. (2009) 'Vertical and horizontal smooth pursuit eye movements in children: a neuro-developmental study', *European Journal of Paediatric Neurology,* 13(4), 362-6.

Irving, E. L., Steinbach, M. J., Lillakas, L., Babu, R. J. and Hutchings, N. (2006) 'Horizontal saccade dynamics across the human life span', *Investigative Ophthalmology and Visual Science,* 47(6), 2478-84.

Irving, E. L., Gonzalez, E. G., Lillakas, L., Wareham, J. and McCarthy, T. (2011) 'Effect of stimulus type on the eye movements of children', *Investigative Ophthalmology and Visual Science,* 52(2), 658-64.

Jacobs, M., Harris, C., Shawkat, F. and Taylor, D. (1992) 'The objective assessment of abnormal eye movements in infants and young children', *Austalian and New Zealand Journal of Ophthalmology,* 20(3), 185-95.

Jekel, J. F. (2007) 'Statistical interference and hypothesis testing' in Jekel, J. F. *Epidemiology, Biostatistics, and Preventive Medicine*, Philadelphia: Saunders/ Elsevier, pp. 157-73.

Jones, D., Westall, C., Averbeck, K. and Abdolell, M. (2003) 'Visual acuity assessment: a comparison of two tests for measuring children's vision', *Ophthalmic and Physiological Optics,* 23(6), 541-6.

Jones, P. (2011) *The impact of stress on visual function in Nystagmus*, Unpublished PhD Thesis, Cardiff University.

Judge, J., Caravolas, M. and Knox, P. C. (2006) 'Smooth pursuit eye movements and phonological processing in adults with dyslexia', *Cognitive Neuropsychology,* 23(8), 1174-89.

Juhasz, B. and Pollatsek, A. (2011) 'Lexical influences on eye movements in reading' in Liversedge, S., Gilchrist, I. and Everling, S., eds., *The Oxford hanbood of eye movements*, New York: Oxford University Press, Inc, pp. 873-93.

Karatekin, C. (2007) 'Eye tracking studies of normative and atypical development', *Developmental Review,* 27(3), 283-48.

Katsanis, J., Iacono, W. G. and Harris, M. (1998) 'Development of oculomotor functioning in preadolescence, adolescence, and adulthood', *Psychophysiology,* 35(1), 64-72.

Ke, S. R., Lam, J., Pai, D. K. and Spering, M. (2013) 'Directional asymmetries in human smooth pursuit eye movements', *Investigative Ophthalmology and Visual Science,* 54(6), 4409-21.

Keller, E. L. (1974) 'Participation of medial pontine reticular formation in eye movement generation in monkey', *Journal of Neurophysiology,* 37(2), 316-32.

Kiely, P. M., Crewther, S. G. and Crewther, D. P. (2001) 'Is there an association between functional vision and learning to read?', *Clinical and Experimental Optometry,* 84(6), 346-53.

Klin, A., Jones, W., Schultz, R., Volkmar, F. and Cohen, D. (2002) 'Visual fixation patterns during viewing of naturalistic social situations as predictors of social competence in individuals with autism', *Archieves of General Psychiatry,* 59(9), 809-16.

Kosnik, W., Fikre, J. and Sekuler, R. (1986) 'Visual fixation stability in older adults', *Investigative Ophthalmology and Visual Science,* 27(12), 1720-5.

Kowler, E. and Blaser, E. (1995) 'The accuracy and precision of saccades to small and large targets', *Vision Research,* 35(12), 1741-54.

Kowler, E. and Martins, A. J. (1982) 'Eye movements of preschool children', *Science,* 215(4535), 997-9.

Kremenitzer, J. P., Vaughan, H. G., Jr., Kurtzberg, D. and Dowling, K. (1979) 'Smooth-pursuit eye movements in the newborn infant', *Child Development,* 50(2), 442-8.

Kulp, M. T. and Schmidt, P. P. (1996) 'Effect of oculomotor and other visual skills on reading performance: a literature review', *Optometry and Vision Science,* 73(4), 283-92.

Kulp, M. T. and Schmidt, P. P. (1997) 'Reliability of the NYSOA King-Devick saccadic eye movement test in kindergartners and first graders', *Journal of the American Optometric Association,* 68(9), 589-94.

Kuperman, V. and Van Dyke, J. A. (2011) 'Effects of individual differences in verbal skills on eye-movement patterns during sentence reading', *Journal of Memory and Language,* 65(1), 42-73.

Lanca, C., Serra, H., Prista, J. (2014) 'Strabismus, visual acuity and uncorrected refractive error in portuguese children aged 6 to 11 years', *Strabismus*, 22(3),115-9.

Langaas, T., Mon-Williams, M., Wann, J. P., Pascal, E. and Thompson, C. (1998) 'Eye movements, prematurity and developmental co-ordination disorder', *Vision Research,* 38(12), 1817-26.

Lappe-Osthege, M., Talamo, S., Helmchen, C. and Sprenger, A. (2010) 'Overestimation of saccadic peak velocity recorded by electro-oculography compared to video-oculography and scleral search coil', *Clinical Neurophysiology,* 121(10), 1786-7.

Leat, S. J., Shute, R. H. and Westall, C. A. (1999) *Assessing children's vision - a handbook,* Oxford: Butterworth-Heinemann.

Lefton, L. A., Nagle, R. J., Johnson, G. and Fisher, D. F. (1979) 'Eye movement dynamics of good and poor readers: Then and Now', *Journal of Literacy Research,* 11(4), 319-28.

Leigh, R. J. and Zee, D. S. (1999) *The neurology of eye movements,* 3rd ed., New York: Oxford University Press, Inc.

Lengyel, D., Weinacht, S., Charlier, J. and Gottlob, I. (1998) 'The development of visual pursuit during the first months of life', *Graefe's Archive for Clinical and Experimental Ophthalmology,* 236(6), 440-4.

Lieberman, S., Cohen, A. H. and Rubin, J. (1983) 'NYSOA K-D test', *Journal of the American Optometric Association,* 54(7), 631-7.

Lions, C., Bui-Quoc, E., Wiener-Vacher, S., Seassau, M. and Bucci, M. P. (2013) 'Smooth pursuit eye movements in children with strabismus and in children with vergence deficits', *PLoS ONE,* 8(12), e83972.

Lisberger, S. G. and Pavelko, T. A. (1989) 'Topographic and directional organization of visual motion inputs for the initiation of horizontal and vertical smooth-pursuit eye movements in monkeys', *Journal of Neurophysiology,* 61(1), 173-85.

Lix, L. M., Keselman, J. C. and Keselman, H. J. (1996) 'Consequences of assumption violations revisited: a quantitative review of alternatives to the One-Way Analysis of Variance "F" test', *Review of Educational Research,* 66(4), 579-619.

Ludbrook, J. (1998) 'Multiple Comparison Procedures Updated', *Clinical and Experimental Pharmacology and Physiology,* 25(12), 1032-7.

Luna, B., Doll, S. K., Hegedus, S. J., Minshew, N. J. and Sweeney, J. A. (2007) 'Maturation of executive function in autism', *Biological Psychiatry,* 61(4), 474-81.

Luna, B., Velanova, K. and Geier, C. F. (2008) 'Development of eye-movement control', *Brain and Cognition,* 68(3), 293-308.

Luna, B., Velanova, K. (2011) 'Development from reflexive to controlled eye movements' in Liversedge, S., Gilchrist, I. and Everling, S., eds., *The Oxford Handbook of Eye Movements*, New York: Oxford University Press, pp. 621-42.

Lundy, B. L., Jackson, J. W. and Haaf, R. A. (2001) 'Stimulus properties, attentional limitations, and young children's face recognition', *Perceptual and Motor Skills,* 92(3 Pt 1), 919-29.

Luo, H. D., Gazzard, G., Liang, Y., Shankar, A., Tan, D. T., Saw, S. M., 'Defining myopia using refractive error and uncorrected logMAR visual acuity >0.3 from 1334 Singapore school children ages 7-9 years, *Bristish Journal of Ophthalmology*, 2006, 90(3), 362-6.

Mahone, E. M., Mostofsky, S. H., Lasker, A. G., Zee, D. and Denckla, M. B. (2009) 'Oculomotor anomalies in attention-deficit/hyperactivity disorder: evidence for deficits in response preparation and inhibition', *Journal of the American Academy of Child and Adolescent Psychiatry,* 48(7), 749-56.

Malmivuo, J. and Plonsey, R. (1995) 'The electric signals originating in the eye ' in Malmivuo, J. and Plosney, R. *Bioelectromagnetism: Principles and Applications of Bioelectric and Biomagnetic Fields*, New York: Oxford University Press, Inc. pp. 437-42.

Maples, W. C. and Ficklin, T. W. (1988) 'Interrater and test-retest reliability of pursuits and saccades', *Journal of the American Optometric Association,* 59(7), 549-52.

Maples, W. C. and Flicklin, T. (1990) 'Comparison of eye movement skills between avobe average and below average average readers', *Journal of Behavioural Optometry,* 1(4), 87-91.

Martinez-Conde, S., Macknik, S. L. and Hubel, D. H. (2004) 'The role of fixational eye movements in visual perception', *Nature Reviews in Neuroscience,* 5(3), 229-40.

Martinez-Conde, S., Macknik, S. L., Troncoso, X. G. and Hubel, D. H. (2009) 'Microsaccades: a neurophysiological analysis', *Trends in Neurosciences,* 32(9), 463-75.

Masson, G., Montagnini, A. and Ilg, U. (2010) 'When the brain meets the eye: tracking object motion' in Ilg, U. J. and Masson, G. S., eds., *Dynamics of Visual Motion Processing*, Springer US, pp. 161-88.

May, P. J. and Corbett, J. J. (1996) 'Visual motor systems' in Haines, D. E., ed. *Fundamental Neuroscience*, Philadelphia: Churchill Livingstone, pp. 399-416.

McClelland, J. F. and Saunders, K. J. (2004) 'Accommodative lag using dynamic retinoscopy: age norms for school-age children', *Optometry and Vision Science,* 81(12), 929-33.

McGinnis, J. M. (1930) 'Eye movements and optic nystagmus in early infancy', *Genetic Psychology Monographs,* 8, 321-430.

McGowan, J. W., Kowler, E., Sharma, A. and Chubb, C. (1998) 'Saccadic localization of random dot targets', *Vision Research,* 38(6), 895-909.

Medland, C., Walter, H. and Woodhouse, J. M. (2010) 'Eye movements and poor reading: does the Developmental Eye Movement test measure cause or effect?', *Ophthalmic and Physiological Optics,* 30(6), 740-7.

Moller, F., Sjolie, A. K. and Bek, T. (1996) 'Quantitative assessment of fixational eye movements by scanning laser ophthalmoscopy', *Acta Ophthalmologica Scandinavica,* 74(6), 578-83.

Moller, F., Laursen, M. L. and Sjolie, A. K. (2006) 'Fixation topography in normal test persons', *Graefe's Archive for Clinical and experimental Ophthalmology,* 244(5), 577-82.

Monger, L., Wilkins, A. and Allen, P. (2014) 'Identifying visual stress during a routine eye examination', *Journal of Optometry,* 8(2), 140-5.

Moye, L. A. (1998) 'P-value interpretation and alpha allocation in clinical trials', *Annals of Epidemiology,* 8(6), 351-7.

Muñoz, D. P., Broughton, J. R., Goldring, J. E. and Armstrong, I. T. (1998) 'Age-related performance of human subjects on saccadic eye movement tasks', *Experimental Brain Research,* 121(4), 391-400.

Muñoz, D. P., Armstrong, I. T., Hampton, K. A. and Moore, K. D. (2003) 'Altered control of visual fixation and saccadic eye movements in attention-deficit hyperactivity disorder', *Journal of Neurophysiology,* 90(1), 503-14.

Muñoz, D. P. and Everling, S. (2004) 'Look away: the anti-saccade task and the voluntary control of eye movement', *Nature Reviews Neuroscience,* 5(3), 218-28.

O'Donoghue, L., McClelland, J. F., Logasn, N. S., Rudnicka, A. R., Owen, C. G., Saunders, K. J. (2010) 'Refractive error and visual impairment in school children in Northern Ireland', *British Journal of Ophthalmology*, 94(9), 1155-9.

O'Driscoll, G. A., Depatie, L., Holahan, A. L., Savion-Lemieux, T., Barr, R. G., Jolicoeur, C. and Douglas, V. I. (2005) 'Executive functions and methylphenidate response in subtypes of attention-deficit/hyperactivity disorder', *Biological Psychiatry,* 57(11), 1452-60.

Oh, K., Trent, S. C. and Tai, R. H. (2013) 'Eye movements of students with learning disabilities in reading: a study of problem solving strategies', *Procedia - Social and Behavioral Sciences,* 93, 252-6.

Olson, R. K., Kliegl, R. and Davidson, B. J. (1983) 'Dyslexic and normal readers' eye movements', *Journal of Experimental Psychology: Human Perception and Performance,* 9(5), 816-25.

Oride, M. K., Marutani, J. K., Rouse, M. W. and DeLand, P. N. (1986) 'Reliability study of the Pierce and King-Devick saccade tests', *American Journal of Optometry and Physiological Optics,* 63(6), 419-24.

Orlansky, G., Wilmer, J., Taub, M. B., Rutner, D., Ciner, E. and Gryczynski, J. (2015) 'Astigmatism and early academic readiness in preschool children', *Optometry and Vision Science,* 92(3), 279-85.

Ottenbacher, K. J. (1998) 'Quantitative evaluation of multiplicity in epidemiology and public health research', *American Journal of Epidemiology,* 147(7), 615-9.

Paus, T., Babenko, V. and Radil, T. (1990) 'Development of an ability to maintain verbally instructed central gaze fixation studied in 8- to 10-year-old children', *International Journal of Psychophysiology,* 10(1), 53-61.

Pavlidis, G. T. (1981) 'Do eye movements hold the key to dyslexia?', *Neuropsychologia,* 19(1), 57-64.

Pelak, V. S. (2010) 'Ocular motility of aging and dementia', *Current Neurology Neuroscience Reports,* 10(6), 440-7.

Pelphrey, K., Sasson, N., Reznick, J. S., Paul, G., Goldman, B. and Piven, J. (2002) 'Visual scanning of faces in autism', *Journal of Autism and Developmental Disorders,* 32(4), 249-61.

Perneger, T. V. (1998) 'What's wrong with Bonferroni adjustments', *British Medical Journal,* 316(7139), 1236-8.

Phillips, J. O., Finocchio, D. V., Ong, L. and Fuchs, A. F. (1997) 'Smooth pursuit in 1- to 4-month-old human infants', *Vision Research,* 37(21), 3009-20.

Pieh, C., Proudlock, F. and Gottlob, I. (2012) 'Smooth pursuit in infants: maturation and the influence of stimulation', *British Journal of Ophthalmology,* 96(1), 73-7.

Pola, J. and Wyatt, H. J. (1985) 'Active and passive smooth eye movements: effects of stimulus size and location', *Vision Research,* 25(8), 1063-76.

Powers, M., Grisham, D. and Riles, P. (2008) 'Saccadic tracking skills of poor readers in high school', *Optometry,*79(5), 228-34.

Poynter, H. L., Schor, C., Haynes, H. M. and Hirsch, J. (1982) 'Oculomotor functions in reading disability', *American Journal of Optometry and Physiological Optics,* 59(2), 116-27.

Prado, C., Dubois, M. and Valdois, S. (2007) 'The eye movements of dyslexic children during reading and visual search: impact of the visual attention span', *Vision Research,* 47(19), 2521-30.

Prior, M. (1996) 'Introduction: Specific learning difficulties defined' in Prior, M. *Understanding Specific Learning Difficulties*, Hove: Psychology Press, pp. 1-19.

Pritchard, R. (1962) 'Stabilized retinal images and visual perception' in Bernard, E. and Kare, M., eds., *Biological Prototypes and Synthetic Systems*, Springer US, 119-125.

Purves, D., Augustine, G. J., Fitzpatrick, D., Katz, L. C., LaMantia, A. S., McNamara, O. and Williams, S. M. (2001) 'Types of eye movements and their function' in *Neurosciences*, 2nd ed., Sunderland: Sinauer Associates. Available from http://www.ncbi.nlm.nih.gov/books/NBK10991/ [Accessed 04 June 2015].

Quaid, P. and Simpson, T. (2013) 'Association between reading speed, cycloplegic refractive error, and oculomotor function in reading disabled children versus controls', *Graefe's Archive for Clinical and Experimental Ophthalmology,* 251(1), 169-87.

Radant, A. D. and Hommer, D. W. (1992) 'A quantitative analysis of saccades and smooth pursuit during visual pursuit tracking. A comparison of schizophrenics with normals and substance abusing controls', *Schizophrenia Research,* 6(3), 225-35.

Ramat, S., Leigh, R. J., Zee, D. S. and Optican, L. M. (2007) 'What clinical disorders tell us about the neural control of saccadic eye movements', *Brain,* 130(1), 10-35.

Rashbass, C. (1961) 'The relationship between saccadic and smooth tracking eye movements', *Journal of Physiology,* 159, 326-38.

Rayner, K. (1985) 'Do faulty eye movements cause dyslexia?', *Developmental Neuropsychology,* 1(1), 3-15.

Rayner, K. (1998) 'Eye movements in reading and information processing: 20 years of research', *Psychological Bulletin,* 124(3), 372-422.

Rayner, K. and Liversedge, S. (2011) 'Linguistic and cognitive influences on eye movements during reading' in Liversedge, S., Gilchrist, I. and Everling, S., eds., *The Oxford Handbook of Eye Movements*, New York: Oxford University Press, 751-66.

Riby, D. M. and Hancock, P. J. (2008) 'Viewing it differently: social scene perception in Williams syndrome and autism', *Neuropsychologia,* 46(11), 2855-60.

Richman, J. E., Walker, A. J. and Garzia, R. P. (1983) 'The impact of automatic digit naming ability on a clinical test of eye movement functioning', *Journal of the American Optometric Association,* 54(7), 617-22.

Richman, J. E. and Grazia, R. P. (1987) 'The developmental Eye Movement Test (DEM)', *Version 1.*

Robert, M. P., Ingster-Moati, I., Albuisson, E., Cabrol, D., Golse, B. and Vaivre-Douret, L. (2014) 'Vertical and horizontal smooth pursuit eye movements in children with developmental coordination disorder', *Developmental Medicine and Child Neurology,* 56(6), 595-600.

Robinson, D. A. (1963) 'A Method of Measuring Eye Movement Using a Scleral Search Coil in a Magnetic Field', *Transactions on Biomedical Engineering,* 10(4), 137-45.

Rommelse, N. N., Van der Stigchel, S. and Sergeant, J. A. (2008) 'A review on eye movement studies in childhood and adolescent psychiatry', *Brain and Cognition,* 68(3), 391-414.

Rose, J. (2009) *Identifying and Teaching Children and Young People with Dyslexia and Literacy difficulties: an independent report from Sir Jim Rose to the Secretary of State for Children, Schools and Families.* *http://webarchive.nationalarchives.gov.uk/20130401151715/http://www.education.gov.uk/publications/eOrderingDownload/00659-2009DOM-EN.pdf* [Accessed 20 May 2015].

Rosner, J. (1997) 'The relationship between moderate hyperopia and academic achievement: how much plus is enough?', *Journal of the American Optometric Association,* 68(10), 648-50.

Ross, R. G., Radant, A. D. and Hommer, D. W. (1993) 'A developmental study of smooth pursuit eye movements in normal children from 7 to 15 years of age', *Journal of the American Academy of Child and Adolescent Psychiatry,* 32(4), 783-91.

Ross, R. G., Radant, A. D., Young, D. A. and Hommer, D. W. (1994) 'Saccadic eye movements in normal children from 8 to 15 years of age: a developmental study of visuospatial attention', *Journal of Autism and Developmental Disorders,* 24(4), 413-31.

Ross, R. G., Hommer, D., Radant, A., Roath, M. and Freedman, R. (1996) 'Early expression of smooth-pursuit eye movement abnormalities in children of schizophrenic parents', *Journal of the American Academy of Child and Adolescent Psychiatry,* 35(7), 941-9.

Ross, R. G., Harris, J., Olincy, A., Radant, A., Adler, L. and Freedman, R. (1997) 'Smooth pursuit eye movements in parents of schizophrenic probands; a most likely carrier approach', *Schizophrenia Research,* 24(1), 244-5.

Ross, R. G., Olincy, A., Harris, J. G., Radant, A., Adler, L. E., Compagnon, N. and Freedman, R. (1999) 'The effects of age on a smooth pursuit tracking task in adults with schizophrenia and normal subjects', *Biological Psychiatry,* 46(3), 383-91.

Rothman, K. J. (1990) 'No adjustments are needed for multiple comparisons', *Epidemiology,* 1(1), 43-6.

Roucoux, A., Culee, C. and Roucoux, M. (1983) 'Development of fixation and pursuit eye movements in human infants', *Behavioural Brain Research,* 10(1), 133-9.

Rouse, M. W., Nestor, E. M., Parot, C. J. and Deland, P. N. (2004) 'A reevaluation of the Developmental Eye Movement (DEM) test's repeatability', *Optometry and Vision Science,* 81(12), 934-8.

Rouse, M. W. (2006) 'Optometric assessment: visual efficiency problems' in Scheiman, M. M. and Rouse, M. W., eds., *Optometric Management of Learning-Related Vision Problems*, 2nd ed., St. Louis: Mosby Elsevier, 183-240.

Russo, J. E. (1975) 'The limbus reflection method for measuring eye position', *Behavior Research Methods and Instrumentation,* 7(2), 205-8.

Rutherford, M. D. and Towns, A. (2008) 'Scan path differences and similarities during emotion perception in those with and without autism spectrum disorders', *Journal of Autism and Developmental Disorders,* 38(7), 1371-1381.

Rutsche, A., Baumann, A., Jiang, X. and Mojon, D. S. (2006) 'Development of visual pursuit in the first 6 years of life', *Graefe's Archive for Clinical and Experimental Ophthalmology,* 244(11), 1406-11.

Salapatek, P., Aslin, R. N., Simonson, J. and Pulos, E. (1980) 'Infant saccadic eye movements to visible and previously visible targets', *Child Development,* 51(4), 1090-94.

Salkind, N. J. (2010) *Encyclopedia of research design,* California: SAGE Publications.

Salman, M. S., Sharpe, J. A., Lillakas, L., Dennis, M. and Steinbach, M. J. (2006a) 'Smooth pursuit eye movements in children', *Experimental Brain Research,* 169(1), 139-43.

Salman, M. S., Sharpe, J. A., Eizenman, M., Lillakas, L., Westall, C., To, T., Dennis, M. and Steinbach, M. J. (2006b) 'Saccades in children', *Vision Research,* 46(8-9), 1432-9.

Saunders, K. J. and Westall, C. A. (1992) 'Comparison between near retinoscopy and cycloplegic retinoscopy in the refraction of infants and children', *Optometry & Vision Science,* 69(8), 615-22.

Saunders, K. J., Woodhouse, J. M. and Westall, C. A. (1996) 'The modified frisby stereotest', *Journal of Pediatrric Ophthalmology and Strabismus,* 33(6), 323-7.

Saunders, K. J. (2010) 'Testing Visual Acuity of Young Children: An Evidence-based Guide for Optometrists.', *Optometry in Practice,* 11(4), 161-8.

Scharre, J. E. and Creedon, M. P. (1992) 'Assessment of visual function in autistic children', *Optometry and Vision Science,* 69(6), 433-9.

Scheiman, M. M. and Rouse, M. W. (2006) *Optometric management of learning-related vision problems,* 2nd Edition ed., St. Louis: CV Mosby.

Scheiman, M. M. and Wick, B. (2008a) 'Eye movement disorders' in Scheiman, M. M. and Wick, B.*Clinical Management of Binocular Vision Heterophoric, Accommodative and Eye Movement disorders*, 3rd ed., Philadelphia: Lippincott Williams & Wilkins, pp. 382-405.

Scheiman, M. M. and Wick, B. (2008b) 'Diagnostic testing' in Scheiman, in Scheiman M. M. and Wick, B. *Clinical Management of Binocular Vision Heterophoric, Accommodative and Eye Movement disorders*, 3rd ed., Philadelphia: Lippincott Williams & Wilkins, pp. 3-49.

Schik, G., Mohr, S. and Hofferberth, B. (2000) 'Effect of aging on saccadic eye movements to visual and auditory targets', *International Tinnitus Journal,* 6(2),154-9.

Scott, C. A., Bondy, L. S. and Severtson, E. (1995) *Vision Therapy: Pursuits and Saccades, testing and training,* Santa Ana: Optometric extension program Inc.

Shaimin, M. M. (2012) *Development and validation of a digital quantitative orthoptics workstation*, Unpublished PhD Thesis, Cardiff University.

Shagass, C., Roemer, R. A. and Amadeo, M. (1976) 'Eye-tracking performance and engagement of attention', *Archives of General Psychiatry,* 33(1), 121-5.

Sharpe, J. A. and Sylvester, T. O. (1978) 'Effect of aging on horizontal smooth pursuit', *Investigative Ophthalmology and Visual Science,* 17(5), 465-8.

Shea, S. L. and Aslin, R. N. (1990) 'Oculomotor responses to step-ramp targets by young human infants', *Vision Research,* 30(7), 1077-92.

Sherman, A. (1973) 'Relating vision disorders to learning disability', *Journal of the American Optometric Association,* 44(2), 140-1.

Solan, H. A. (1985a) 'Deficient eye-movement patterns in achieving high school students: three case histories', *Journal of Learning Disabilities,* 18(2), 66-70.

Solan, H. A. (1985b) 'Eye movement problems in achieving readers: an update', *American Journal of Optometry & Physiological Optics,* 62(12), 812-9.

Squire, L. R., Bloom, F. E., Spitzer, N. C., Du Lac, S., Ghosh, A. and Berg, D. (2008) 'Eye movements' in *Fundamental Neuroscience*, San Diego: Elsevier, pp. 775-94.

SR-Research. (2015) 'EyeLink 1000' [Online] available: http://www.sr-research.com /EL_1000.html [accessed 10 June 2015].

Stanley, G., Smith, G. A. and Howell, E. A. (1983) 'Eye-movements and sequential tracking in dyslexic and control children', *British Journal of Psychology,* 74(2), 181-187.

Stuart, J. A. and Burian, H. M. (1962) 'A study of separation difficulty. Its relationship to visual acuity in normal and amblyopic eyes', *American Journal of Ophthalmology,* 53, 471-7.

Subramanian, V., Jost, R. M. and Birch, E. E. (2013) 'A quantitative study of fixation stability in amblyopia', *Investigative Ophthalmology and Visual Sciences,* 54(3), 1998-2003.

Sweeney, J. A., Haas, G. L., Li, S. and Weiden, P. J. (1994) 'Selective effects of antipsychotic medications on eye-tracking performance in schizophrenia', *Psychiatry Research,* 54(2), 185-98.

Sweeney, J. A., Takarae, Y., Macmillan, C., Luna, B. and Minshew, N. J. (2004) 'Eye movements in neurodevelopmental disorders', *Current Opinion in Neurology,* 17(1), 37-42.

Tajik-Parvinchi, D. J., Lillakas, L., Irving, E. and Steinbach, M. J. (2003) 'Children's pursuit eye movements: a developmental study', *Vision Research,* 43(1), 77-84.

Takarae, Y., Minshew, N. J., Luna, B., Krisky, C. M. and Sweeney, J. A. (2004) 'Pursuit eye movement deficits in autism', *Brain,* 127(Pt 12), 2584-94.

Tannock, R. (1998) 'Attention deficit hyperactivity disorder: advances in cognitive, neurobiological, and genetic research', *Journal of Child Psychology and Psychiatry and Allied Disciplines,* 39(1), 65-99.

Tassinari, J. T. and DeLand, P. (2005) 'Developmental Eye Movement test: reliability and symptomatology', *Optometry,* 76(7), 387-99.

Taub, M. B. (2012) 'Comprehensive examination procedures' in Taub, M. B., Bartuccio, M. and Maino, D. M., eds., *Visual Diagnosis and Care of the Patient with Special Needs,* Philadelpia: Wolters Kluwer Health. pp. 155-84.

Taylor, S. E. (1965) 'Eye movements in reading: facts and fallacies', *American Educational Research Journal,* 2(4), 187-202.

Tobii Technology (2015a) 'Tobii TX300 Eye Tracker', [online] available: http://www.tobii.com/en/eye-tracking-research/global/products/hardware/tobii-tx300-eye-tracker/ [accessed 01 June 2015].

Tobii Technology. (2015b) 'Tobii TX300 Eye Tracker Technical Specification', [online], available:http://www.tobii.com/Global/Analysis/Marketing/Brochures/ProductBrochures/Tobii_TX300_Technical_Specification_Leaflet.pdf [accessed 01 June 2015].

Traisk, F., Bolzani, R. and Ygge, J. (2005) 'A comparison between the magnetic scleral search coil and infrared reflection methods for saccadic eye movement analysis', *Graefe's Archive for Clinical and Experimental Ophthalmology,* 243(8), 791-7.

van der Geest, J. N., Kemner, C., Camfferman, G., Verbaten, M. N. and van Engeland, H. (2001) 'Eye movements, visual attention, and autism: a saccadic reaction time study using the gap and overlap paradigm', *Biological Psychiatry,* 50(8), 614-9.

van der Geest, J. N. and Frens, M. A. (2002) 'Recording eye movements with video-oculography and scleral search coils: a direct comparison of two methods', *Journal of Neuroscience Methods,* 114(2), 185-95.

von Hofsten, C. and Rosander, K. (1997) 'Development of smooth pursuit tracking in young infants', *Vision Research,* 37(13), 1799-810.

Webber, A., Wood, J., Gole, G. and Brown, B. (2011) 'DEM test, visagraph eye movement recordings, and reading ability in children', *Optometry and Vision Science,* 88(2), 295-302.

Wilson, C., Barrett, B. T. and Gilchrist, J. M. (2014) *Reading ability in children: individual performance measures and graphical profiles.* Unpublished poster presentation at: *Optometry Tomorrow 2014*, March 16-17, 2014, York, UK.

Wilson, C. E., Palermo, R. and Brock, J. (2012) 'Visual scan paths and recognition of facial identity in autism spectrum disorder and typical development', *PLoS One,* 7(5), e37681.

Wong, A. (2008) 'The Six Eye Movement Systems' in *Eye Movement Disorders*, New York: Oxford University Press, 3-81.

Yang, Q., Bucci, M. P. and Kapoula, Z. (2002) 'The latency of saccades, vergence, and combined eye movements in children and in adults', *Investigative Ophthalmology and Visual Science,* 43(9), 2939-49.

Ygge, J., Aring, E., Han, Y., Bolzani, R. and Hellstrom, A. (2005) 'Fixation stability in normal children', *Annals of the New York Academy of Sciences,* 1039, 480-3.

Zackon, D. H. and Sharpe, J. A. (1987) 'Smooth pursuit in senescence. Effects of target acceleration and velocity', *Acta Otolaryngologica,* 104(3-4), 290-7.

Appendix A: Scoping exercise interview sheets

ORTHOPTIST

"SCOPING EXERCISE". WHAT ARE EYE MOVEMENT/ "TRACKING" DIFFICULTIES?

- What do you understand by "tracking difficulties"? Could you describe it to me?

  Difficulties in reading

- What do you understand by learning difficulties? Do you think that learning difficulties can be associated with "tracking difficulties" and eye movement difficulties?

  Difficulties in learning (specific or unspecific). Delayed performance for the age.

  yes. Strong association.

- How do you think that "tracking difficulties" and eye movement difficulties may affect the children or the individual's vision? What do you think they experience?

  Losing place when reading, missing word, reading words twice, use finger pointing for reading.

- Do you think that "tracking difficulties" and eye movement difficulties are always associated to another condition such as cerebral palsy, or they also exist in children or individuals without any other associated condition?

  They can be found isolated but this is less common and less frequent.

- Do you receive "tracking difficulties" and eye movement difficulties referrals from other specialists? Which specialists (mainly)?

  yes. From GP, optoms, Paediatrician, Psychologists.

- Do you assess eye movements in all patients or only in particular cases, circumstances etc…? Which cases? Which circumstances?

  yes. In all patients.

- How do you asses, evaluate, examine "tracking" eye movements in individuals? What technique do you use? Any particular test? Any particular stimulus? (demonstration)

  Horizontal & vertical smooth pursuit as in motility tests. Using toy / pentorch. keeping speed constant.

- Do you use any "treatment", therapy, or technique to improve tracking difficulties in children that are referred with it or in children that you expect they may have it? (Which one?) Are they successful?

  yes. Sheets and text in which the patient has to circle certain words. Follow paths with moving their eyes.

- If they do any treatment or therapy, after it how do you measure if their tracking is improved?

  yes. check again after exercises by performing the same motility.

- Do you also measure saccades and fixation? How?

  yes most of the time.

  2 pens of different color or pen to nose → saccades

  Burning candle test → fixation.

ORTHOPTIST

"SCOPING EXERCISE". WHAT ARE EYE MOVEMENT/ "TRACKING" DIFFICULTIES?

- What do you understand by "tracking difficulties"? Could you describe it to me?

  Tracking difficulties are difficulties when following moving objects. Possibly due to a deficit in muscle function.

- What do you understand by learning difficulties? Do you think that learning difficulties can be associated with "tracking difficulties" and eye movement difficulties?

  • Difficulties in progress at school.

  • yes, tracking / EM difficulties can significantly impact on children learning.

- How do you think that "tracking difficulties" and eye movement difficulties may affect the children or the individual's vision? What do you think they experience?

  These children normally would have head postures or ↑ head movement / body posture and movement to compensate for the "visual deficit".

- Do you think that "tracking difficulties" and eye movement difficulties are always associated to another condition such as cerebral palsy, or they also exist in children or individuals without any other associated condition?

  No. Tracking & EM difficulties are only found in children with underlying conditions.

- Do you receive "tracking difficulties" and eye movement difficulties referrals from other specialists? Which specialists (mainly)?

  Yes, in all patients. However, she believes that, in general, orthoptists in the community do not do it as her.

  → Mainly referrals from paediatrician

- Do you assess eye movements in all patients or only in particular cases, circumstances etc…? Which cases? Which circumstances?

  ~~Paediatrician~~

  Yes, all patients. However, she believes that, in general, orthoptists do not do so.

- How do you asses, evaluate, examine "tracking" eye movements in individuals? What technique do you use? Any particular test? Any particular stimulus? (demonstration)

  Stimulus: 2-3 yo — illuminated target / toy; older children — pentorch

  Horizontal and vertical to check smooth pursuit and extreme positions for muscle actions.

- Do you use any "treatment", therapy, or technique to improve tracking difficulties in children that are referred with it or in children that you expect they may have it? (Which one?) Are they successful?

  No. She posts report to paediatrician.

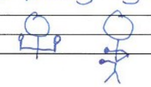
  However, she thinks that there is no therapy for it and that these children learn to compensate / should be helped with new strategies to compensate for the deficit.

- If they do any treatment or therapy, after it how do you measure if their tracking is improved?

  N/A

- Do you also measure saccades and fixation? How?

  Yes. Saccades measured in horizontal & vertical. Pens and/or toys separated 30/40cm. Switch from one to the other. Fixation → fixating toy / pen at midline.



ORTHOPTIST

“SCOPING EXERCISE”. WHAT ARE EYE MOVEMENT/ “TRACKING” DIFFICULTIES?

- What do you understand by “tracking difficulties”? Could you describe it to me?
  Difficulties in literacy.

- What do you understand by learning difficulties? Do you think that learning difficulties can be associated with “tracking difficulties” and eye movement difficulties?
  Difficulties in catching up in school. Delayed learning.
  Yes, there is an association.

- How do you think that “tracking difficulties” and eye movement difficulties may affect the children or the individual’s vision? What do you think they experience?
  Mainly in reading.
  Losing place when reading, re-read words, slow, skipping words.

- Do you think that “tracking difficulties” and eye movement difficulties are always associated to another condition such as cerebral palsy, or they also exist in children or individuals without any other associated condition?
  Yes, the exist independently.

- Do you receive “tracking difficulties” and eye movement difficulties referrals from other specialists? Which specialists (mainly)?
  OT, optometrists, GP, Ed. Psychologists.

- Do you assess eye movements in all patients or only in particular cases, circumstances etc…? Which cases? Which circumstances?
  Assessed smooth pursuit in every patient but tracking only in those with reading difficulties.

- How do you asses, evaluate, examine “tracking” eye movements in individuals? What technique do you use? Any particular test? Any particular stimulus? (demonstration)
  Smooth pursuit: horizontal, vertical and oblique. Very slow motion and holding patient’s head.
  Tracking: two pens at 2 distances. First, very close between them, then very far. Also test for antisaccades with pentorch.

- Do you use any “treatment”, therapy, or technique to improve tracking difficulties in children that are referred with it or in children that you expect they may have it? (Which one?) Are they successful?
  Yes. Word searches, paths, circle letters on a text, “visual tracking cards”, “dinosaur tracking card”. These exercises done 5 min. a day and follow up in 2 months.
  Most of the time there is a good improvement.

- If they do any treatment or therapy, after it how do you measure if their tracking is improved?
  Using the Developmental Eye Movement (DEM) test

- Do you also measure saccades and fixation? How?
  Yes. As explained previously.

Orthoptist

"SCOPING EXERCISE". WHAT ARE EYE MOVEMENT/ "TRACKING" DIFFICULTIES?

- What do you understand by "tracking difficulties"? Could you describe it to me?
  Difficulty in following a target. Also in sustaining fixation when fixating.

- What do you understand by learning difficulties? Do you think that learning difficulties can be associated with "tracking difficulties" and eye movement difficulties?
  They are global difficulties and include a long list of problems. Most common are reading, writing.
  yes. EM difficulties produce learning difficulties.

- How do you think that "tracking difficulties" and eye movement difficulties may affect the children or the individual's vision? What do you think they experience?
  In following the text on a page, missing words, slow reading. Also interfere with sports by failure in grabbing / picking balls when thrown.

- Do you think that "tracking difficulties" and eye movement difficulties are always associated to another condition such as cerebral palsy, or they also exist in children or individuals without any other associated condition?
  More likely to be found in individuals with underlying conditions but can be found alone.

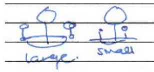
- Do you receive "tracking difficulties" and eye movement difficulties referrals from other specialists? Which specialists (mainly)?
  Mainly from OT

- Do you assess eye movements in all patients or only in particular cases, circumstances etc…? Which cases? Which circumstances?
  yes. In all patients

- How do you asses, evaluate, examine "tracking" eye movements in individuals? What technique do you use? Any particular test? Any particular stimulus? (demonstration)
  Using light or illuminated target.
  First check muscle action/palsy in all meridians (extreme position)
  Then tracking target (only in horizontal) at 2 different speeds ⟷ (slow and fast)

- Do you use any "treatment", therapy, or technique to improve tracking difficulties in children that are referred with it or in children that you expect they may have it? (Which one?) Are they successful?
  No. Report sent to paediatrician and school. Sometimes OT referral.

- If they do any treatment or therapy, after it how do you measure if their tracking is improved?
  N/A

- Do you also measure saccades and fixation? How?
  Saccades: 2 pens in horizontal and vertical and also two different amplitudes.
  

  Fixation in cover test

OPTOM

"SCOPING EXERCISE". WHAT ARE EYE MOVEMENT/ "TRACKING" DIFFICULTIES?

- What do you understand by "tracking difficulties"? Could you describe it to me?
  They refer to conditions like nystagmus, convergence, squint, difficulty in ~~...~~ following moving objects.

- What do you understand by learning difficulties? Do you think that learning difficulties can be associated with "tracking difficulties" and eye movement difficulties?
  - Difficulties associated with processing problems/deficits also sometimes associated with other visual problems.
  - there is indeed an association.

- How do you think that "tracking difficulties" and eye movement difficulties may affect the children or the individual's vision? What do you think they experience?
  - Difficulties in sports but also in reading. they will have poor stereopsis, convergence and they will be more likely to have "accidents"/falls, trips. Difficulties in crowded environments, to scan for pictures.

- Do you think that "tracking difficulties" and eye movement difficulties are always associated to another condition such as cerebral palsy, or they also exist in children or individuals without any other associated condition?
  Tracking/EM difficulties can occur in isolation.

- Do you receive "tracking difficulties" and eye movement difficulties referrals from other specialists? Which specialists (mainly)?
  ~~In all~~ No. only referrals from schools.

- Do you assess eye movements in all patients or only in particular cases, circumstances etc…? Which cases? Which circumstances?
  In all children and also in adults with H&S that require this assessment.

- How do you asses, evaluate, examine "tracking" eye movements in individuals? What technique do you use? Any particular test? Any particular stimulus? (demonstration)
  Motility · typical star shape using a pentorch

- Do you use any "treatment", therapy, or technique to improve tracking difficulties in children that are referred with it or in children that you expect they may have it? (Which one?) Are they successful?
  No but refers to orthoptist unit

- If they do any treatment or therapy, after it how do you measure if their tracking is improved?
  N/A

- Do you also measure saccades and fixation? How?
  Saccades, never
  fixation is assessed during Cover Test

OPTOM

"SCOPING EXERCISE". WHAT ARE EYE MOVEMENT/ "TRACKING" DIFFICULTIES?

- What do you understand by "tracking difficulties"? Could you describe it to me?

  Difficulties in following moving objects / target.

- What do you understand by learning difficulties? Do you think that learning difficulties can be associated with "tracking difficulties" and eye movement difficulties?

  Difficulties and delays in the learning process

  Yes. If you cannot control well your eyes it will be more difficult to read, keep attention, etc.

- How do you think that "tracking difficulties" and eye movement difficulties may affect the children or the individual's vision? What do you think they experience?

  They will affect children in reading but mainly in sports, several coordination and fine motor skills.

  For older people it will result in difficulties in tasks such as driving

- Do you think that "tracking difficulties" and eye movement difficulties are always associated to another condition such as cerebral palsy, or they also exist in children or individuals without any other associated condition?

  Generally they will be associated to medical conditions or other difficulties but can be found isolated.

- Do you receive "tracking difficulties" and eye movement difficulties referrals from other specialists? Which specialists (mainly)?

  ~~Everybody~~. No. Schools only

- Do you assess eye movements in all patients or only in particular cases, circumstances etc…? Which cases? Which circumstances?

  Almost everybody. But focuses on children and adults who have relevant H&S

- How do you asses, evaluate, examine "tracking" eye movements in individuals? What technique do you use? Any particular test? Any particular stimulus? (demonstration)

  Horizontal, vertical and obliques using the traditional motility star shape.

  Use a penlight

- Do you use any "treatment", therapy, or technique to improve tracking difficulties in children that are referred with it or in children that you expect they may have it? (Which one?) Are they successful?

  No. Refer accordingly

- If they do any treatment or therapy, after it how do you measure if their tracking is improved?

  N/A

- Do you also measure saccades and fixation? How?

  Saccades never assessed.

  Fixation when severe phoria.

OPTOM

"SCOPING EXERCISE". WHAT ARE EYE MOVEMENT/ "TRACKING" DIFFICULTIES?

- What do you understand by "tracking difficulties"? Could you describe it to me?
  Difficulties when following moving objects but also trouble with reading.

- What do you understand by learning difficulties? Do you think that learning difficulties can be associated with "tracking difficulties" and eye movement difficulties?
  · Difficulties in several areas that affect daily life activities.
  · Tracking/EM difficulties can affect ~~tracki~~ learning. Better tracking/EM performance, "easier learning is".

- How do you think that "tracking difficulties" and eye movement difficulties may affect the children or the individual's vision? What do you think they experience?
  They affect the individuals in many different areas/levels. However, their main problem/difficulty is related with reading.

- Do you think that "tracking difficulties" and eye movement difficulties are always associated to another condition such as cerebral palsy, or they also exist in children or individuals without any other associated condition?
  They can be isolated but are found more frequently when underlying conditions are present.

- Do you receive "tracking difficulties" and eye movement difficulties referrals from other specialists? Which specialists (mainly)?
  No. Only referrals from schools

- Do you assess eye movements in all patients or only in particular cases, circumstances etc…? Which cases? Which circumstances?
  Not using a specific test. ~~[illegible]~~ Tested only in children and adults with reading problems.

- How do you asses, evaluate, examine "tracking" eye movements in individuals? What technique do you use? Any particular test? Any particular stimulus? (demonstration)
  Subjectively observe the eye movements on following moving objects and on performing tasks such as reading

- Do you use any "treatment", therapy, or technique to improve tracking difficulties in children that are referred with it or in children that you expect they may have it? (Which one?) Are they successful?
  Referral to orthoptist or behavioural optometrist.

- If they do any treatment or therapy, after it how do you measure if their tracking is improved?
  N/A.

- Do you also measure saccades and fixation? How?
  Fixation assessed during Cover Test
  Saccades very rarely assessed.

ED PSYCHOLOG

"SCOPING EXERCISE". WHAT ARE EYE MOVEMENT/ "TRACKING" DIFFICULTIES?

- What do you understand by "tracking difficulties"? Could you describe it to me?

  Difficulties related with literacy. Poor "tracking" along the lines and unability to read.

- What do you understand by learning difficulties? Do you think that learning difficulties can be associated with "tracking difficulties" and eye movement difficulties?

  Global term — specific: difficulties in a particular area
  — general: global / general delay
  Difficulties in execution, understanding, processing, etc.

  yes, there is an association

- How do you think that "tracking difficulties" and eye movement difficulties may affect the children or the individual's vision? What do you think they experience?

  In reading, gross motor skills and also problems in general daily life activities such as walking stairs.

- Do you think that "tracking difficulties" and eye movement difficulties are always associated to another condition such as cerebral palsy, or they also exist in children or individuals without any other associated condition?

  Not necessarily. They can be presented in isolation.

- Do you receive "tracking difficulties" and eye movement difficulties referrals from other specialists? Which specialists (mainly)?

  Most of them from school. From Teachers of VI too.

- Do you assess eye movements in all patients or only in particular cases, circumstances etc…? Which cases? Which circumstances?

  He does not test it. Referral for Eye Test.

- How do you asses, evaluate, examine "tracking" eye movements in individuals? What technique do you use? Any particular test? Any particular stimulus? (demonstration)

  N/A

- Do you use any "treatment", therapy, or technique to improve tracking difficulties in children that are referred with it or in children that you expect they may have it? (Which one?) Are they successful?

  No.

- If they do any treatment or therapy, after it how do you measure if their tracking is improved?

  N/A

- Do you also measure saccades and fixation? How?

  N/A

Teacher VI

"SCOPING EXERCISE". WHAT ARE EYE MOVEMENT/ "TRACKING" DIFFICULTIES?

- What do you understand by "tracking difficulties"? Could you describe it to me?
  Problems in general control of eye movements.

- What do you understand by learning difficulties? Do you think that learning difficulties can be associated with "tracking difficulties" and eye movement difficulties?
  Difficulties in processing, language, memory but average intellectual ability.
  ET difficulties add an extra barrier to the learning process.

- How do you think that "tracking difficulties" and eye movement difficulties may affect the children or the individual's vision? What do you think they experience?
  Difficulties in scanning, in reading, in finding objects on cluttered / busy environment.

- Do you think that "tracking difficulties" and eye movement difficulties are always associated to another condition such as cerebral palsy, or they also exist in children or individuals without any other associated condition?
  No, they can also be found in isolation

- Do you receive "tracking difficulties" and eye movement difficulties referrals from other specialists? Which specialists (mainly)?
  Ophthalmologist, orthoptists, GPs. Also schools.

- Do you assess eye movements in all patients or only in particular cases, circumstances etc…? Which cases? Which circumstances?
  Do not assess EM. Refer accordingly

- How do you asses, evaluate, examine "tracking" eye movements in individuals? What technique do you use? Any particular test? Any particular stimulus? (demonstration)
  N/A

- Do you use any "treatment", therapy, or technique to improve tracking difficulties in children that are referred with it or in children that you expect they may have it? (Which one?) Are they successful?
  N/A

- If they do any treatment or therapy, after it how do you measure if their tracking is improved?
  N/A

- Do you also measure saccades and fixation? How?
  N/A.

TEACHER OF VI

"SCOPING EXERCISE". WHAT ARE EYE MOVEMENT/ "TRACKING" DIFFICULTIES?

- What do you understand by "tracking difficulties"? Could you describe it to me?
  Reading but also diff in daily life activities.

- What do you understand by learning difficulties? Do you think that learning difficulties can be associated with "tracking difficulties" and eye movement difficulties?
  Delayed learning. Below average performance in educational aspects.
  Yes Association

- How do you think that "tracking difficulties" and eye movement difficulties may affect the children or the individual's vision? What do you think they experience?
  Difficulties in reading and writing. But also in sports, difficulties in scanning.

- Do you think that "tracking difficulties" and eye movement difficulties are always associated to another condition such as cerebral palsy, or they also exist in children or individuals without any other associated condition?
  Can be found in isolation but are less frequent

- Do you receive "tracking difficulties" and eye movement difficulties referrals from other specialists? Which specialists (mainly)?
  Schools, OT, Optoms, GP

- Do you assess eye movements in all patients or only in particular cases, circumstances etc…? Which cases? Which circumstances?
  No Test of EM. But refer to Eye Care Professional for a full visual assessment

- How do you asses, evaluate, examine "tracking" eye movements in individuals? What technique do you use? Any particular test? Any particular stimulus? (demonstration)
  N/A

- Do you use any "treatment", therapy, or technique to improve tracking difficulties in children that are referred with it or in children that you expect they may have it? (Which one?) Are they successful?
  N/A
  No treatment but she thinks they should be ~~test~~ taught strategies

- If they do any treatment or therapy, after it how do you measure if their tracking is improved?
  N/A

- Do you also measure saccades and fixation? How?
  N/A

OT

"SCOPING EXERCISE". WHAT ARE EYE MOVEMENT/ "TRACKING" DIFFICULTIES?

- What do you understand by "tracking difficulties"? Could you describe it to me?

  Being able to follow an object, up, down, diagonal and left, right.

- What do you understand by learning difficulties? Do you think that learning difficulties can be associated with "tracking difficulties" and eye movement difficulties?

  Specific or unspecific difficulties that affect learning.

  yes there is an association.

- How do you think that "tracking difficulties" and eye movement difficulties may affect the children or the individual's vision? What do you think they experience?

  Difficulties in fine and gross motor skills

  Reading, writing, maths, spelling (fine motor skills)

  Playground, coordination (gross motor skills)

- Do you think that "tracking difficulties" and eye movement difficulties are always associated to another condition such as cerebral palsy, or they also exist in children or individuals without any other associated condition?

  All children she sees have tracking difficulties / EM diff but underlying conditions. However, she believes they exist in isolation.

- Do you receive "tracking difficulties" and eye movement difficulties referrals from other specialists? Which specialists (mainly)?

  Schools. but other specialists such as: Paediatrician, Speech and language therapists.

- Do you assess eye movements in all patients or only in particular cases, circumstances etc…? Which cases? Which circumstances?

  only in patients who have suspected conditions/ difficulties related to eye movements

- How do you asses, evaluate, examine "tracking" eye movements in individuals? What technique do you use? Any particular test? Any particular stimulus? (demonstration)

  Target → penlight.

  Move pen in all axis (star shape)

  Asking patient to keep head still.

- Do you use any "treatment", therapy, or technique to improve tracking difficulties in children that are referred with it or in children that you expect they may have it? (Which one?) Are they successful?

  yes. Given texts and ask patient to circle certain letters. F.ex. circle letter @ from a text. Ask parents to throw a ball at him/her so he/she can pick it in the air. Follow paths, lines with finger/pen.

  In the clinic some children go onto a platform that hangs from the ceiling and they are required to perform tasks while platform moving.

- If they do any treatment or therapy, after it how do you measure if their tracking is improved?

  Repeat the initial tests she did. Eg. walking on top (stepping) on line in the floor. Crawling, etc.

- Do you also measure saccades and fixation? How?

  Not particularly. She just looks at their EM behaviour while performing different tasks.

  OKN is assessed normally.

Appendix B: Repeatabilty and agreement studies

Summary of methods

- 11 adults ages ranging from 21 to 27 (mean 24.76 ± SD1.42)
- Animated stimulus moving horizontally at 6°/s following a ramp motion paradigm
- Animated stimulus moving horizontally following a sinusoidal motion paradigm (peak velocity 6°/s).
- Exact same setup and eye movement analysis as that described in chapter 3.

Test re-test eye movement parameters (Paired t-tests)

6°/s ramp	*Test Values*	*Retest values*	*P value*
% Time smooth pursuit	95.17 ± 4.04	93.75 ± 6.80	0.360
Position gain	0.82 ± 0.066	0.75± 0.11	0.568
Velocity gain	0.836 ± 0.060	0.81 ± 0.099	0.168
Number of catch-up	6 ± 3.25	4.81 ± 3.45	0.785
Number of back-up	0.81 ± 0.87	0.81 ± 1.25	0.785
Number microsaccades	41.72 ± 39.19	41.00 ± 37.71	0.939

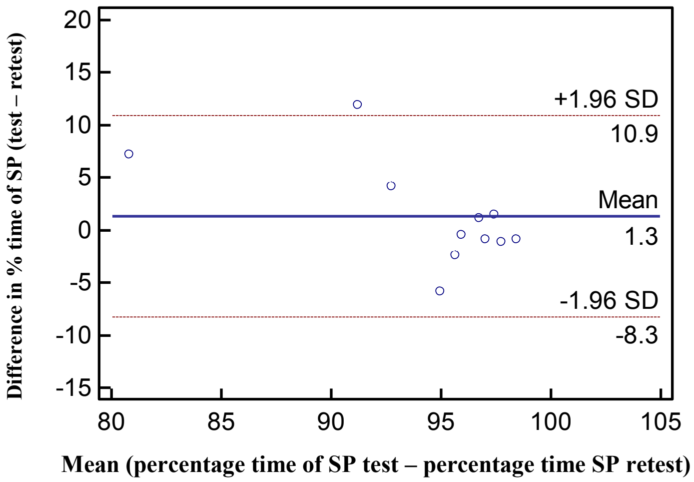
Smooth pursuit performance parameters for the 6°/s ramp motion paradigm using the animated stimulus. Test and retest values and corresponding p-values.

Sinusoidal motion	*Test Values*	*Retest values*	*P value*
% Time smooth pursuit	93.67 ± 5.91	92.77 ± 7.16	0.591
Position gain	0.82 ± 0.11	0.78± 0.10	0.231
Number of catch-up	2.5 ± 2.76	4.72 ± 3.97	0.054
Number of back-up	0.72 ± 1.27	0.72 ± 1.19	1.00
Number microsaccades	46.63 ± 40.72	47.45± 40.75	0.934

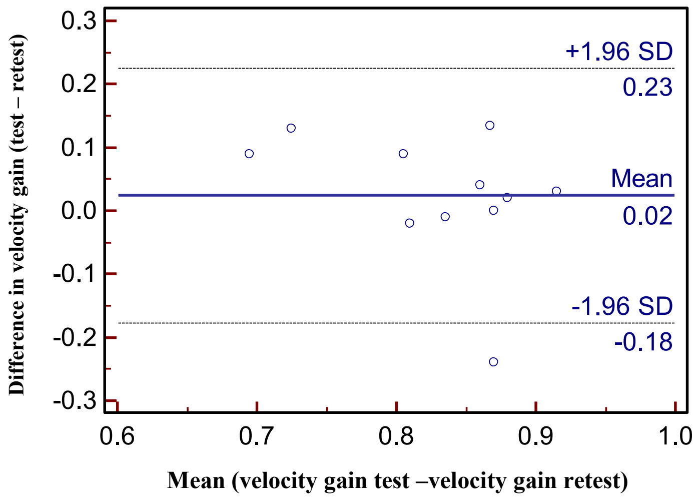
Smooth pursuit performance parameters for the sinusoidal motion paradigm using the animated stimulus. Test and retest values and corresponding p-values.

Bland and Altman plots

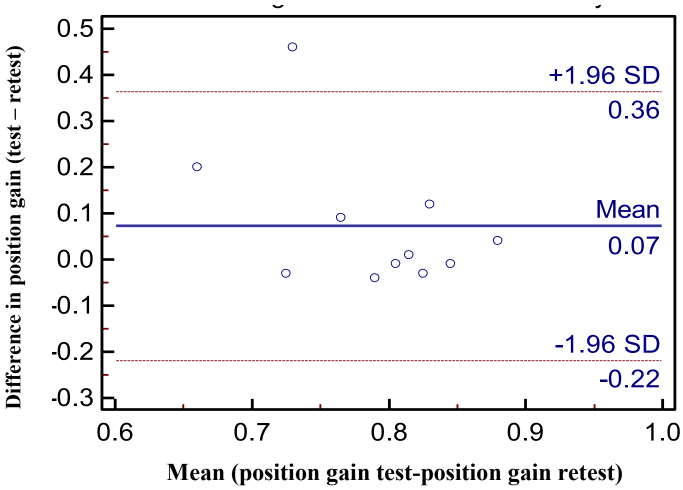
Percentage of smooth pursuit test-retest



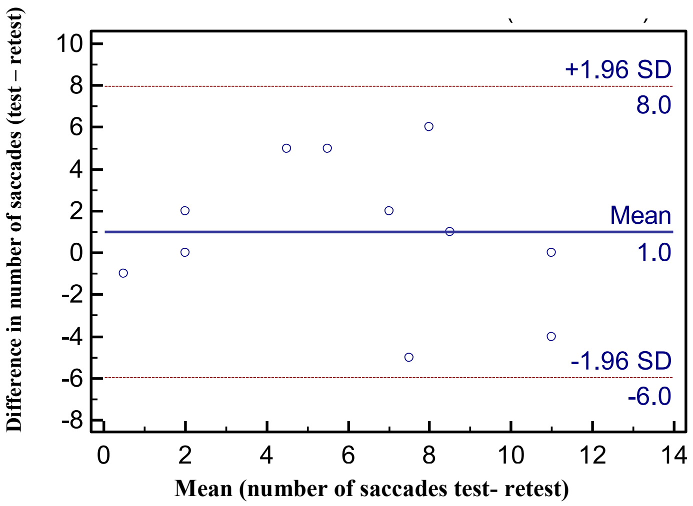
Velocity gain test-retest



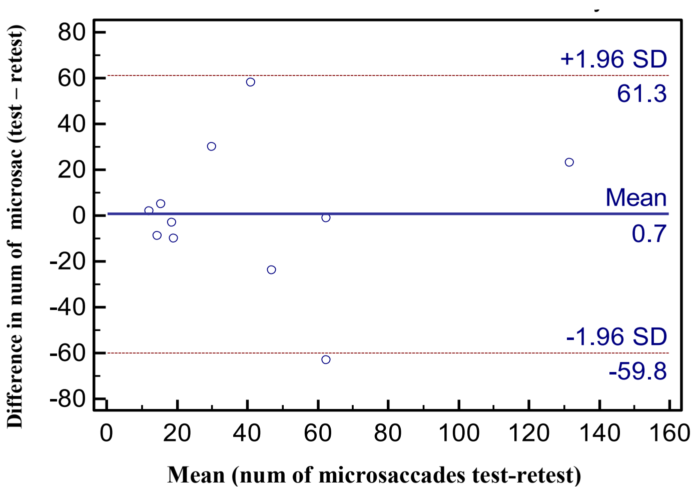
Position gain test-retest



Number of saccades test-retest



Number of microsaccades test-retest



Appendix C: School of Optometry and Vision Sciences Research and Audit Ethics Committee approval to recruit typical adults and typically developing children from non-NHS sites

Ethical approval

SCHOOL OF OPTOMETRY AND VISION SCIENCES

HUMAN SCIENCE ETHICAL COMMITTEE

CARDIFF UNIVERSITY
PRIFYSGOL CAERDYDD

(old project)

Projec l

Project title: Assessment of tracking difficulties in children

Research

Lead Investigators: Dr Maggie Woodhouse, Jon Erichsen,
Investigators: Ms Valldeflors Vinuela, Ms Cathy Williams

Date: 24^{th} July 2012

With reference to the above application, I am pleased to confirm that approval has been granted,

Please inform the Research Ethics Committee immediately of any changes to the protocol, changes to personnel involved, or of any unforeseen circumstances arising from the study.

Please note the data retention periods specified by the University

- For non-funded non-clinical research, data shall be retained for no less than 5 years, or 2 years post-publication
- Undergraduate project data shall be retained at least until the end of the University appeals process

Signed: [redacted]

Dr Julie Albon
Chairperson

Approval form

Appendix D: Participant Information Sheets for typical adults and typically developing children recruited from non-NHS sites – Adults and pilot studies

Participant Information Sheet for adults

INFORMATION SHEET

Title: The assessment of tracking difficulties in children

Principle investigators Miss. Valldeflors Viñuela Navarro, Dr. Margaret Woodhouse, Dr. Jonathan Erichsen and Mrs. Cathy Williams

Before consent is given to take part, it is important that you understand why the research is being done and what it will involve. Please take time to read the information sheet and talk to others about it if you wish.

<u>What is the purpose of the study?</u>
The main purpose of the study is to establish normative values eye movements in school children. Our study will provide a better understanding of eye movements in children and how these eye movements develop and reach adult levels. The study also aims to assess the effect of targets designed for adults and for children and determine which targets are the best for eye movement research. Therefore, we need adult subjects for comparison between the results obtained in adults and children.

<u>What will I have to do?</u>
Initially, we will take some measurements of your eyes to determine how well you can see (with your specs prescription if any). We will also measure how your eyes move and work together with standard optometric methods. Following this, we will record your eye movements while you are performing one or more visual tasks, for example, tracking a black dot or a picture that moves across the screen or look at some stripes that appear in a screen. Please note that this is not a full eye examination and that you should visit the optometrist when your next test is due.

<u>What are the possible risks of taking part?</u>

There are no possible risks in taking part in this study. The instruments used establish eye orientation and position by measuring the reflection of light from the eye. However, this study is not suitable for individuals with epilepsy due to health and safety issues that arise from the use of computer screens.

<u>How long will it last?</u>
The study will last no more than one hour. In general you will not be asked to come again, however if additional information is required (due to excessive blink or head movements, inattention, etc.) you may be asked to return.

<u>What is the benefit of taking part?</u>
Participating in this study may not benefit you directly but will help to validate the quality of the results obtained in the main study assessing eye movements in children. Overall, this will aid in learning more about eye movement abnormalities in children and their association with learning related difficulties. This may help us to detect and diagnose children with eye movement abnormalities that may present a possible risk to learning.

Will my taking part be confidential?

All data obtained will be stored on a computer and will not be made available to any third party, and no personal information will be stored. Any results published will be anonymous. A copy of the data held on computer about you is available on request in accordance with the Data Protection Act.

Will I have information about the results of the study?

If you are interested in our study and would like to know more about it and the results obtained we are very happy to post you a final short report. This report will be sent to participants on request. If you want to receive the report at the end of the study tick the box below and write your contact details overleaf.

□ *Yes, I would like to receive a report with more information about the project and the results obtained at the end of the study*

Name: ______________________

Address: ____________________

____

____

Contact details

It is up to whether you take part and you are free to withdraw from the study at any time. If you decide to take part you can ask questions at any time. If you have any questions about this research, please contact:

Valldeflors Viñuela Navarro
Email: VinuelaNavarroV@cardiff.ac.uk
School of Optometry and Vision Sciences, Maindy road. CF24 4LU.

Consent form for adults

CONSENT FORM

Title of project: The assessment of tracking difficulties in children
Name of investigator(s):Miss Valldeflors Vinuela Navarro, Dr. Margaret Woodhouse, Dr. Jonathan Erichsen, Mrs. Cathy Williams

---

Please read this form very carefully. If there is anything that you don't understand about the Information sheet or you wish to ask any questions, please speak to one of the investigators named above and in the information sheet. Please check that all the information on the form is correct. If it is, and you understand the explanation, then tick the boxes and sign the form below.

Please tick

I have been given a written explanation of the study (the Information Sheet) by one of the investigators named on this form. ☐

I understand that the decision to take part in the study is soley up to me, and that I can change my mind without a reason at any point without affecting how I will be treated in the future. ☐

I have been assured that all the information collected in the study will be held in confidence, and if presented, my personal details will be removed. ☐

I have read and understood the information given and have had the opportunity to ask questions before proceeding. I agree to participate in the project. ☐

I would like to receive information on the results of this investigation ☐

Address: ______________________________
____
____
Email: ______________________________
Telephone: ______________________________

______________________	______________	______________________
Name of Participant	Date	Signature
______________________	______________	______________________
Name of Researcher	Date	Signature

Parent Information Sheet for the pilot studies (children recruited from non-NHS sites)

PARENT INFORMATION SHEET

Title: The assessment of tracking difficulties in children

Principle investigators Miss. Valldeflors Viñuela Navarro, Dr. Margaret Woodhouse, Dr. Jonathan Erichsen and Mrs. Cathy Williams

Children are invited to take part in a research study. Before consent is given to take part, it is important that you understand why the research is being done and what it will involve. Please take time to read the information and talk to others about it if you wish.

What is the purpose of the study?

The main purpose of this study is to establish normative values for tracking eye movements in school children. Tracking eye movements are the eye movements we perform when we follow a moving object, for example when looking a moving car, a football, etc. The study will provide a better understanding of these particular eye movements in children and improved guidelines for optometrists and their clinical examination.

What will happen to my child if he/she take part?

Initially, we will take some measurements of the child's eyes to determine how well he/she can see (with his/her specs prescription if any). We will also measure how the eyes move and work together using standard optometric methods. Following this, we will record the child's eye movements while the child performs one or more visual tasks. For example, tracking a point or a picture that moves across the screen. Please, note that this is not a full eye examination and that the child should visit the optometrist when his/her next test is due.

What are the possible risks of taking part?

All the instruments which will be used in this research are child-friendly and are currently used in different studies. The instruments used, establish eye orientation and position by measuring the reflection of light from the eye. There are no potential risks in taking part.

How long will it last?

The study visit will last no more than 15 minutes. In general, you will not be asked to come again. However, the child may be invited to return if additional information is required (due to excessive blink or head movements, inattention, etc.).

What is the benefit of taking part?

Participating in this study may not benefit you and/or the child directly but we will learn more about eye movement abnormalities in children and their association with learning related difficulties. This may help us to detect and diagnose children with eye movement abnormalities that may present a possible risk to learning.

Will my taking part be confidential?

All data obtained will be stored on a computer and will not be made available to any third party, and no personal information will be stored. Any results published will be anonymous. A copy of the data held on computer about you is available on request in accordance with the Data Protection Act.

Will I have information about the results of the study?

If you are interested in our study and would like to know more about it and the results obtained we are very happy to post you a final short report. This report will be sent to participants on request. If you want to receive the report at the final of the study tick the box below and write your contact details.

□ *Yes, I would like to receive a report with more information about the project and the results obtained at the end of the study*

Name and contact details:

____

____

____

____

Contact details

It is up to you and the child whether you take part and you are free to withdraw from the study at any time. If you decide to take part you can ask questions at any time. If you have any questions about this research, please contact:

Valldeflors Viñuela Navarro
Email: VinuelaNavarroV@cardiff.ac.uk
School of Optometry and Vision Sciences, Maindy road. CF24 4LU.

Or

Dr Margaret Woodhouse
E-mail: Woodhouse@cardiff.ac.uk
School of Optometry and Vision Sciences, Maindy road. CF24 4LU.

Parent consent form for the pilot studies (children recruited from non-NHS sites)

CONSENT FORM

Title of project: The assessment of tracking difficulties in children

Name of investigator(s):Miss Valldeflors Vinuela Navarro, Dr. Margaret Woodhouse, Dr. Jonathan Erichsen, Mrs. Cathy Williams

---

Please read this form very carefully. If there is anything that you don't understand about the Information sheet or you wish to ask any questions, please speak to one of the investigators named above and in the information sheet. Please check that all the information on the form is correct. If it is, and you understand the explanation, then tick the boxes and sign the form below.

	Please tick
I have been given a written explanation of the study (the Information Sheet) by one of the investigators named on this form.	☐
I understand that the decision of the child's taking part in the study is up to me and him/her, and that we can change our mind without a reason and without affecting how we are treated in the future.	☐
I have been assured that all the information collected in the study will be held in confidence, and if presented, the child's personal details will be removed.	☐
I have read and understood the information given and have had the opportunity to ask questions before proceeding. I agree for the child to participate in the project.	☐
I would like to receive information on the results of this investigation	☐

Name (Printed): ______________________

Address: ____________________________

____

Email: ____________________________

Telephone no.: ______________________

______________________________(NAME OF THE PARTICIPANT)

______________________ ______________ ______________________

Name of the parent or guardian   Date   Signature

______________________ ______________ ______________________

Name of Researcher   Date   Signature

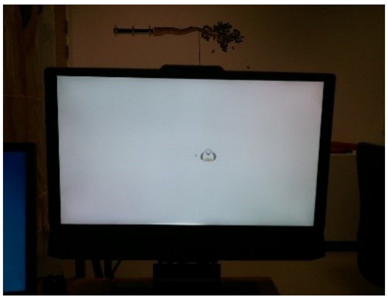
Children Information Sheet for the pilot studies (children recruited from non-NHS sites)

We are Flors, Maggie, Jon and Cathy, we are doing some experiments and you are invited to help us with that!

What are we studying?

We want to know how you and your friends move your eyes when you look at other children running  , footballs rolling  or when you read  .

What do you have to do?



First, we are going to see how well you see, showing you some pictures and afterwards using a special torch. Then, we will start recording how your eyes move.

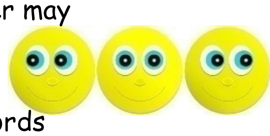
For that, we have a great screen with some nice pictures that move from one side to the other. You only have to sit in front of it and look

How many times do you have to do it?

You only need to do it once. It is very easy, fast and fun!

Are you going to get a reward?

Your reward is knowing that you will join us in the study and at the end we all together may be able to help other children that can't move their eyes as well as you.



Does it hurt?

NO! The only instrument we use is a very modern computer that records your eyes. It is not painful or uncomfortable. It is situated in a table in front of you. So, we do not touch you at all.

Can you leave the experiment once we have already started with it?

Yes, of course. If you don't like it and you don't want to finish the experiment you can withdraw at anytime. It is up to you.

If you want to help us and you are happy to take part in our experiment, you only have to sign below.

______________________ 

Appendix E: Participant Information Sheets for typically developing children recruited from non-NHS sites (Schools studies)

Parent Information Sheets for Schools studies (children recruited from non-NHS sites)

PARENT INFORMATION SHEET

Title: The assessment of tracking difficulties in children

Principle investigators Miss. Valldeflors Viñuela Navarro, Dr. Margaret Woodhouse, Dr. Jonathan Erichsen and Mrs. Cathy Williams

CARDIFF UNIVERSITY PRIFYSGOL CAERDYDD

Your child's school is involved in an exciting study about eye movements in school age children and we would like to know what you think about it. We will come to your child's school to take simple measures of eye movements in a large number of children across ages. Before you and your child decide whether or not you would like to take part, it is important that you understand why the research is being done and what it will involve. Please take time to read the information and talk to others about it if you wish.

<u>What is the purpose of the study?</u>

The main purpose of this study is to establish normative values for eye movements in school age children. Our eyes are never still and we are constantly performing different eye movements. For example, when we read our eyes move across the text line to read each word and when we look at a moving car our eyes move smoothly following its direction. This study will provide baseline data on how eye movements develop in children, what normal responses are in school age children and young people, and determine the relationship between eye movement performance in children and reading difficulties.

<u>What will happen to my child if he/she take part?</u>

Initially, we will take some measurements of the child's eyes to determine how well he/she can see (with his/her specs prescription if any). We will also measure how his/her eyes move and work together using standard optometric methods. Following this, we will record the child's eye movements while the child performs some visual tasks. For example, tracking an animated cartoon that moves across the screen and looking at pictures that appear in different screen locations. At the end of the study, we will be asking the school teachers to tell us whether any of the children we tested have any additional reading support. This information will only be used to compare eye movement recordings between children with and without additional reading support. Please, note that this is not a full eye examination and that the child should visit the optometrist when his/her next test is due.

<u>What are the possible risks of taking part?</u>

All the instruments which will be used in this research are child-friendly and are currently used in different studies. The instruments used, establish eye orientation and position by measuring the reflection of light from the eye. There are no potential risks in taking part.

<u>How long will it last?</u>

The study visit will last no more than 15 minutes. In general, you will not be asked to come again. However, the child may be invited to return if additional information is required (due to excessive blink or head movements, inattention, etc.).

What is the benefit of taking part?

Participating in this study may not benefit you and/or the child directly but we will learn more about eye movement abnormalities in children and their association with reading difficulties. This may help us to detect and diagnose children with eye movement abnormalities that may present a possible risk to learning.

What happens to the data collected?

The data will be analysed by our research team at the School of Optometry and Vision Sciences, Cardiff University. The information about children with additional reading support will not be passed on to any third party and will be only used by the researchers to compare the eye movement recordings between children with and without additional reading support. It is likely that we will write articles for academic and scientific journals based on what we find out in the study. Your child's name will not be used in any of the reports or articles that we write.

Will my taking part be confidential?

All data obtained will be stored on a computer and will not be made available to any third party, and no personal information will be stored. Any results published will be anonymous. A copy of the data held on computer about your child is available on request in accordance with the Data Protection Act.

Will I have information about the results of the study?

If you are interested in our study and would like to know more about it and the results obtained we are very happy to post you a final short report. This report will be sent to participants on request. If you want to receive the report at the final of the study tick the box below and write your contact details.

□ *Yes, I would like to receive a report with more information about the project and the results obtained at the end of the study*

Name: ______________________________
Address: ______________________________
____
____
____
E-mail: ______________________________
Telephone num: ________________________

What happens if me and my child do not want to take part or we change our minds?

It is up to you and the child whether you take part and you are free to withdraw from the study at any time. If you decide to take part you can ask questions at any time. If you have any questions about this research, please contact:

Valldeflors Viñuela Navarro
Email: VinuelaNavarroV@cardiff.ac.uk
School of Optometry and Vision Sciences, Maindy road. CF24 4LU.

Dr Margaret Woodhouse
E-mail: Woodhouse@cardiff.ac.uk
School of Optometry and Vision Sciences, Maindy road. CF24 4LU.

Parent consent form for the schools studies (children recruited from non-NHS sites)

CONSENT FORM

Title of project: The assessment of tracking difficulties in children

Name of investigator(s):Miss Valldeflors Vinuela Navarro, Dr. Margaret Woodhouse, Dr. Jonathan Erichsen, Mrs. Cathy Williams

---

Please read this form very carefully. If there is anything that you don't understand about the Information sheet or you wish to ask any questions, please speak to one of the investigators named above and in the information sheet. Please check that all the information on the form is correct. If it is, and you understand the explanation, then tick the boxes and sign the form below.

Please tick

I have been given a written explanation of the study (the Information Sheet) by one of the investigators named on this form. ☐

I understand that the decision of the child's taking part in the study is up to me and him/her, and that we can change our mind without a reason and without affecting how we are treated in the future. ☐

I have been assured that all the information collected in the study will be held in confidence, and if presented, the child's personal details will be removed. ☐

I have read and understood the information given and have had the opportunity to ask questions before proceeding. I agree for the child to participate in the project. ☐

I would like to receive information on the results of this investigation ☐

Name (Printed): ________________________
Address: ______________________________
____
Email: ______________________________
Telephone no.: _________________________

______________________________(NAME OF THE PARTICIPANT)

______________________________	____________________	______________________________
Name of the parent or guardian	Date	Signature
______________________________	____________________	______________________________
Name of Researcher	Date	Signature

Parent Information Sheet for Schools studies short version for White Rose Primary School (children recruited from non-NHS sites)

PARENT INFORMATION SHEET

CARDIFF UNIVERSITY PRIFYSGOL CAERDYDD

Title: The assessment of "tracking difficulties" in children

Principle investigators Miss. Valldeflors Viñuela Navarro, Dr. Margaret Woodhouse, Dr. Jonathan Erichsen and Mrs. Cathy Williams

White Rose School is involved in an exciting study about eye movements in school age children and we would like to include your child. We will come to the school to take simple measures of eye movements in a large number of children across all ages. Please take time to read the information below and talk to others about it if you wish.

What is the purpose of the study?

The main purpose of this study is to establish normative values for eye movements in school age children. Our eyes are never still and we are constantly performing different eye movements. For example, when we read our eyes make regular jumps to read each word, and when we look at a moving car our, eyes move smoothly following its direction. This study will provide baseline data on how eye movements develop in children, what normal responses are in school age children and young people, and determine the relationship between eye movement performance in children and learning related difficulties.

What will happen to my child if he/she take part?

Initially, we will take some measurements of your child's eyes to determine how well he/she can see (with his/her glasses if any) and how his/her eyes work together. Then, we will record eye movements while the child performs visual tasks such as tracking an animated cartoon that moves across the screen.

At the end of the study, we will be asking teachers to tell us whether any of the children we tested have additional reading support. This information will only be used to compare eye movement recordings between children with and without additional reading support.

PLEASE, NOTE THAT THIS IS NOT A FULL EYE EXAMINATION AND YOUR CHILD SHOULD VISIT THE OPTOMETRIST WHEN HIS/HER NEXT TEST IS DUE.

What are the possible risks of taking part?

All the instruments which will be used in this research are child-friendly and are currently used in many different studies. There are no potential risks in taking part for children without medical problems. If your child has photosensitive epilepsy he/she would not be suitable for this study due to the use of computer monitors.

Will my child's information be confidential?

All data will be stored on a computer and will not be made available to any third party, and no personal information will be stored. Any results published will be anonymous.

What happens if my child and I do not want to take part or we change our minds?

It is up to you and your child whether you take part and you are free to withdraw from the study at any time. If you decide NOT to take part simply complete the form.

More detailed information sheets are available from the school head teacher if you require. If you have any questions or require more information about this research, please contact:

Flors Viñuela-Navarro or Dr. Maggie Woodhouse
Email: VinuelaNavarroV@cardiff.ac.uk Woodhouse@cardiff.ac.uk

School of Optometry and Vision Sciences, Maindy road. CF24 4LU.

If you are interested in our study and you want to know more about the results obtained we are very happy to post you a short report at the end of the study. If you want to receive the report at the end of the study, write to or email us at the above address.

Opting-out form for White Rose Primary School (children recruited from non-NHS sites)

OPTING OUT

Title of project: The assessment of "tracking difficulties" in children.
Name of investigator(s):Miss Valldeflors Vinuela Navarro, Dr. Margaret Woodhouse, Dr. Jonathan Erichsen, Mrs. Cathy Williams

An information sheet is attached to this form. Please read it carefully before you and your child make a decision about taking part. There are additional Parent Information Sheets available from your head teacher. If there is anything you do not understand about the Parent Information Sheet or you wish to ask any questions, please contact one of the researchers named above and in the information sheet. Please also remember that if you decide to take part, you are free to change your mind at any point in the study.

If you and your child are willing to take part in this study, you do not have to do anything at the moment.

If you and you child decide **NOT** to take part, then you need to complete the "Opt-out" form below and return it to the school or post it to:
Miss Flors Vinuela-Navarro
School of Optometry and Vision Sciences. Cardiff University.
Maindy road
CF24 4LU
Cardiff

Alternatively, you can e-mail a copy of the form to: VinuelaNavarroV@cardiff.ac.uk.

This form should only be completed by parents or guardians who decide that they DO NOT WISH their child to take part in the study or parents or guardians who's child DOES NOT WISH to take part in the study

---

MY CHILD AND I DO NOT WISH TO PARTICIPATE in this study.
My details are as follows:
My name: ___________________________________

My child's name _____________________ Child's class _______________

Date: ________________

Signature: __________________

Appendix F: NHS ethics approval and documentation to recruit atypical children from NHS sites

NHS Research Ethics Committee approval

Part of the research infrastructure for Wales funded by the National Institute for Social Care and Health Research, Welsh Government.
Yn rhan o seilwaith ymchwil Cymru a ariannir gan y Sefydliad Cenedlaethol ar gyfer Ymchwil Gofal Cymdeithasol ac Iechyd, Llywodraeth Cymru

NISCHR

Gwasanaeth Moeseg Ymchwil | RES | Research Ethics Service

South East Wales Research Ethics Committee B
6th Floor Churchill House
17 Churchill Way
Cardiff
CF10 2TW

Telephone : 02920 376823
E-mail : carl.phillips@wales.nhs.uk
Website : www.nres.nhs.uk

14 March 2014

Miss Valldeflors Vinuela-Navarro
Cardiff University
School of Optometry and Vision Sciences
Cardiff University
Maindy Road
CF24 4HQ

Dear Miss Vinuela-Navarro

Study title:	**The objective assessment of eye movements in children with delayed reading skills**
REC reference:	**14/WA/0030**
Protocol number:	**SPON 1269-13**
IRAS project ID:	**141249**

Thank you for your letter of the 7 March 2014, responding to the Committee's request for further information on the above research, and for submitting revised documentation.

The further information has been considered on behalf of the Committee by the Chair.

We plan to publish your research summary wording for the above study on the HRA website, together with your contact details, unless you expressly withhold permission to do so. Publication will be no earlier than three months from the date of this favourable opinion letter. Should you wish to provide a substitute contact point, require further information, or wish to withhold permission to publish, please contact the REC Executive Officer, Mr Carl Phillips, Carl.phillips@wales.nhs.uk.

<u>Confirmation of ethical opinion</u>

On behalf of the Committee, I am pleased to confirm a favourable ethical opinion for the above research on the basis described in the application form, protocol and supporting documentation [as revised], subject to the conditions specified below.

<u>Ethical review of research sites</u>

<u>NHS sites</u>

The favourable opinion applies to all NHS sites taking part in the study, subject to management permission being obtained from the NHS/HSC R&D office prior to the start of the study (see "Conditions of the favourable opinion" below).

1

Parent information sheet (children recruited from NHS sites)

School of Optometry and Vision Sciences
Ysgol Optometreg a Gwyddorau'r Golwg

Head of School *Pennaeth Yr Ysgol* Professor *Yr Athro* Gary Baxter

College of Biomedical and Life Sciences
Cardiff University
Maindy Road
Cardiff
CF24 4HQ
Wales UK

Tel *Ffôn* +44(0)29 2087 4374
Fax *Ffacs* +44(0)29 2087 4859
http://www.cardiff.ac.uk/optom/

Prifysgol Caerdydd
Heol Maindy
Caerdydd
CF24 4HQ
Cymru, Y Deyrnas Gyfunol

PARTICIPANT INFORMATION SHEET

The assessment of eye movements in children with delayed reading skills

My name is Flors Vinuela and I am an Optometrist and a PhD student based at the School of Optometry and Vision Sciences, Cardiff University. My research supervisors are Dr. Maggie Woodhouse, Optometrist and Senior Lecturer at Cardiff University, Dr. Jonathan Erichsen, Neuroscientist and Senior Lecturer at Cardiff University and Mrs. Cathy Williams, Consultant Ophthalmologist and Senior Lecturer at University of Bristol. I am writing to invite your child to take part in a research project. This information sheet is to help you decide if you are happy for your child to participate. Before you decide if you want to join in, it is important that you understand why the research is being done and what it will involve. Please take time to read the information, discuss it with your child and talk to others about it if you wish.

What is this study about?

The study aims to investigate eye movements in children with delayed reading skill and/or learning difficulties. Our eyes are never still; we are constantly moving our eyes to perform different daily tasks. For example, we perform eye movements when we track a car driving in the road, when we read or when we scan different objects around us. In order to investigate this I am recording the eye behaviour of school children who have an individual education plan (IEP) in their school. The results obtained from these children will be compared with normative eye movement values previously collected. This study will provide a better understanding of the existence and characteristics of eye movement disorders/difficulties, their relation to learning deficits and ultimately it will provide guidelines for optometrists for the clinical examination of eye movements in children

Why has my child been invited to participate?

Your child has been asked to participate as they are between the age of 4 and 18 years old and has an individual education plan (IEP) in his/her school related to delayed reading skills and/or learning difficulties

Does my child have to take part?

No, it is up to you and your child. We will ask you for your consent and then ask you if you would like to sign a form. We will give you a copy of the information sheet to keep. You and your child are free to stop taking part at any time during the research. If you decide you do not wish your child to participate then this will have no effect upon the care you receive.

What will happen if I decide to give consent for my child to take part?

If you decide that you are happy for your child to take part in the project I will meet with you and your child for approximately 90 minutes on one occasion either at the School of Optometry and Vision Science (Cardiff University) or at Bristol Eye Hospital (Paediatric Department).

Initially, I will take some measurements of your child's eyes to determine how well he/she can see (with his/her specs prescription if any). I will also measure how the eyes move and work together using standard optometric methods. Following this, we will record the child's eye movement behaviour while the performing different visual tasks. For example, tracking a cartoon that moves across the screen or looking at a picture that appears in different screen locations.

Our team has previously obtained eye movement data of 140 children from two primary schools using the same setup. Feedback so far is that children find the experience engaging and enjoyable.

What do I have to do if I am happy for my child to take part?

As your child is under 18, before I can include them in the project I need you to provide written parental consent. I will also ask your child if they are happy to take part and they will also sign a form to give their agreement. Even after receiving your consent if your child decides they do not want to take part then they will not be included.

If you and your child are interested in taking part I will then contact you to discuss the study and answer any questions and concerns you may have. If you and your child are happy to participate then after this I will arrange to meet you and seek written consent and proceed with the study.

How long will the study last?

The study visit will last no more than 2 hours. In general, you will not be asked to come again. However, the child may be invited to return if additional information is required (due to excessive blink, head movements, etc.).

What are the possible benefits of my child taking part?

Participating in this study may not benefit you and/or the child directly but we will learn more about eye movement disorders/difficulties in children and their association with learning difficulties. This may help us to detect and diagnose children with eye movement abnormalities that may present a possible risk to learning.

What are the disadvantages and risks of my child taking part?

All the instruments that will be used in this research are child-friendly and are currently used in different studies. The instruments used, establish eye orientation and position by measuring the reflection of light from the eye.

There are no potential risks in taking part. However, this study is not suitable for individuals with epilepsy due to health and safety issues that arise from the use of computer screens. It is not anticipated that participation will cause distress in any way.

Will information be kept confidentially?

All data obtained will be stored on a computer and will <u>not</u> be made available to any third party, and no personal information will be stored. Any results published will be <u>anonymous</u>. A copy of the data held on computer about you is available on request in accordance with the Data Protection Act.

Will I have information about the results of the study?

If you are interested in our study and would like to know more about it and the results obtained we are very happy to post you a final short report. This report will be sent to participants on request. If you want to receive the report at the final of the study tick the appropriate box in the consent form that will be given for you to sign and write your contact details in the same form.

Who has reviewed the study?

All research in the NHS and at Cardiff University is looked at by an independent group of people called a Research Ethics Committee, to protect your interests. This study has been reviewed and given a favourable opinion by School from the Optometry and Vision Sciences Research Ethics Committee (Cardiff University) and the South East Wales NHS Research Ethics Committee.

Thank you for taking the time to read this information sheet. Should you have any questions I would be very happy to discuss my project further with you and can be contacted on 02920870247 or on VinuelaNavarroV@cardiff.ac.uk.

Parent Consent Form (children recruited from NHS sites)

CONSENT FORM

The assessment of eye movements in children with delayed reading skills.

CARDIFF UNIVERSITY
PRIFYSGOL CAERDYDD

Name of Researchers: Miss Valldeflors Vinuela Navarro, Dr. J. Margaret Woodhouse, Dr. Jonathan Erichsen, Mrs. Cathy Williams

Please initial box

1 I confirm that I have read and understand the Participant Information Sheet (Version: 1 Date December 2013) for the above study. I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily. ☐

2 I understand that my participation is voluntary and that I am free to withdraw at any time without giving any reason, without my medical care or legal rights being affected. ☐

3 I agree to take part in the above study. ☐

4 I would like to receive information on the results of this study ☐

Name : ________________________________

Address: ________________________________

____

Email: ________________________________

____

Name of the participant

Name of Parent/guardian/legal tutor	Date	Signature
Researcher	Date	Signature

Children information sheet 4-10 years old (children recruited from NHS sites)

Participant Information Sheet

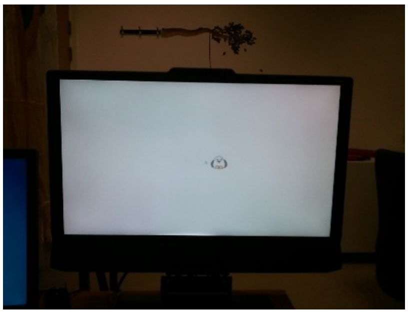
The assessment of eye movements in children with delayed reading skills

CARDIFF UNIVERSITY PRIFYSGOL CAERDYDD

Hello! We are Flors, Maggie, Jon and Cathy. We are doing a study and we would like to ask for your help. It is the way we try to find out the answers to our questions !

We would like to know how your eyes move when you look at other children running  , footballs rolling  or when you read  .

We would like to record how your eyes move and to do that we have a very modern computer.



We are going to show you some pictures that move along this modern computer screen and we would like you to look at these pictures while we record how your eyes move.

You only need to do it once and it is very easy, fast and fun!
If you have any questions or you would like to know more about the project, please ask me face by face or contact me by e-mail to VinuelaNavarroV@cardiff.ac.uk.

If you want to help us and you are happy to take part in our experiment, you only have to sign below.

______________________ 

Children information sheet 11-15 years old (children recruited from NHS sites)

Participant Information Sheet

The assessment of eye movements in children with delayed reading skills

Hello! We are Flors, Maggie, Jon and Cathy. We are doing a study and we would like to ask for your help. It is the way we try to find out the answers to our questions!

Why is the project being done?
We want to know how you move your eyes when you look at other children running , footballs rolling  or when you read . Some children have problems to move their eyes and this can be tricky because it can make school a bit difficult for them. We would like you to help us to find more about this.

What do I have to do to take part?
First, we are going to see how well you can see, showing you some pictures or letters and afterwards using a special torch. Then, we will start recording how your eyes move.
For that, we have a great screen with some nice pictures that move from one side to the other and jump across the screen. You only have to sit in front of it and look at the pictures moving and jumping around. We will record how your eyes move when you look to the pictures.

How many times do you have to do it?
You only need to do it once. It is very easy, fast and fun!

Do I have to take part?
You do not have to take part. You can say no and no one will be cross or upset. If you say yes, but later change your mind then that's ok as well. Just tell your parents or one of us.

Did anyone check that the study is OK to do?
Before any research is allowed to happen, it has to be checked by a group of people called Research Ethics Committee. They make sure that the research

is fair. This project has been checked by Cardiff University Research Ethics Committee and South East Wales NHS Ethics Committee.

Will joining in help me?

We can't promise the study will help you but what we discover might help other children that find school a bit difficult.

Does it hurt?

NO! The only instrument we use is a very modern computer that records your eyes. It is not painful or uncomfortable. It is situated in a table in front of you. So, we do not touch you at all.

Will anyone find out if I am on this study?

Your name and the things about you will be kept a secret. Only people who are doing the research will be able to see this information.

What do I do now?

Take time to decide whether or not you want to take part, and please ask us if there is anything that you don't understand. If you have any question you can ask us face to face when you see us or you can e-mail us at VinuelaNavarroV@cardiff.ac.uk.

CONSENT FORM

- I read and understood all the information above and I have all my questions answered.

- I understand I can stop taking part in the study at any time.

If you understand the statements above, you now need to decide whether you would like to take part in the project.

I have decided that I would like to take part in this study about eye movements in children with delayed reading skills.

Please tick the No or Yes box.

☐ No ☐ Yes

Signed…………………………………………

Please print your name…………………………

Children information sheet 16-18 (children recruited from NHS sites)

Participant Information Sheet

The assessment of eye movements in children with delayed reading skills

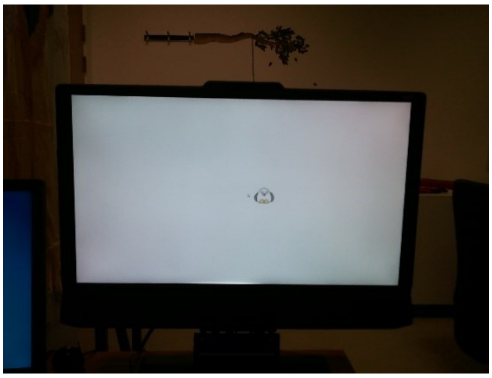
Hello! We are Flors, Maggie, Jon and Cathy. We are doing a study and we would like to ask for your help. It is the way we try to find out the answers to questions!

Why is the project being done?

We want to know how you move your eyes when you look at other children running, footballs rolling, or when you read. Some children have problems to move their eyes and this can be tricky because it can make school a bit difficult for them. We would like you to help us to find more about this.

What do I have to do to take part?

First, we are going to see how well you can see, showing you some pictures or letters and afterwards using a special torch. Then, we will start recording how your eyes move.
For that, we have a big computer that records how your eyes move. We will show you some pictures moving along the screen and jumping from one side to the other across the screen. You only have to sit in front of it and look at the pictures moving and jumping around while we record hoe your eyes move.



How many times do you have to do it?

You only need to do it once and it will take less than two hours.

Do I have to take part?
No, it is up to you. We will ask you for your parents and also your consent. If you give consent but you change your mind during the study it is fine. You can withdraw from the study at any moment. You only have to tell one of us.

Did anyone check that the study is OK to do?
Before any research is allowed to happen, it has to be checked by a group of people called Research Ethics Committee. They make sure that the research is fair. This project has been checked by Cardiff University Research Ethics Committee and South East Wales NHS Ethics Committee.

Will joining in help me?
We can't promise the study will help you but what we discover might help other children that find school a bit difficult.

Does it hurt?
NO! The only instrument we use is a very modern computer that records your eyes. It is not painful or uncomfortable. So, we do not touch you at all.

Will anyone find out if I am on this study?
All the data obtained will be kept secret. It will be stored on a computer and only the researchers will be able to see this information.

What do I do now?
Take time to decide whether or not you want to take part, and please ask us if there is anything that you don't understand. If you have any question you can ask us face to face when you see or you can e-mail us at VinuelaNavarroV@cardiff.ac.uk.

If you want to help us and you are happy to take part in our experiment, sign in the consent form attached.

CONSENT FORM

The assessment of eye movements in children with delayed reading skills.

	TICK
1. I confirm that I have read and understood the participant information sheet for the above study. I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily.	
2. I understand that my participation is voluntary and that I am free to withdraw at any time, without giving a reason.	
3. I agree to take part in the study.	

Name of participant	Date	Signature
Researcher	Date	Signature

Appendix G: Child participants with IEP related to delayed reading skills – Optometric results

ID	AGE	RE VA DISTANCE	LE VA DISTANCE	BEO VA DISTANCE	RE VA NEAR	LE VA NEAR	BINO VA NEAR	CT DITANCE	CT NEAR	NPC	STE REO	RET RE		RET LE		ACC	MOTIL ITY
												SPH	CYL	SPH	CYL		
P38	4	0	0	0	0	0	0	ORTO	LOW XOP	<5 CM	85"	-0.25	<1	∞	<1	WITHIN NORMS	SPEC
P159	4	0.3	0.3	0.3	0	0	0	ORTO	LOX XOP	<5 CM	340"	-1	<1	-1.5	<1	WITHIN NORMS	SPEC
P41	5	0.04	0.04	0.02	0	0	0	ORTO	ORTO	<5 CM	85"	∞	<1	∞	<1	WITHIN NORMS	SPEC
P49	5	0.04	0.04	0.02	0	0	0	ORTO	LOW XOP	<5 CM	85"	1.5	<1	1.5	<1	WITHIN NORMS	SPEC
P64	5	-0.1	-0.1	-0.1	0	0	0	ORTO	ORTO	<5 CM	85"	1	<1	0.5	<1	WITHIN NORMS	SPEC
P02	6	-0.1	-0.1	-0.1	0	0	0	ORTO	ORTO	<5 CM	85"	0.75	<1	0.75	<1	WITHIN NORMS	SPEC
P46	6	0.06	0.04	0.02	0	0	0	MED SOP	HIGH SOP	<5 CM	170"	-0.5	<1	-0.25	<1	WITHIN NORMS	SPEC
P67	6	0.1	0.1	0.1	0	0	0	ORTO	LOW XOP	<5 CM	85"	∞	<1	∞	<1	WITHIN NORMS	SPEC
P98	6	0.2	0.2	0.2	0	0	0	ORTO	ORTO	<5 CM	85"	-3	<1	-3.5	<1	WITHIN NORMS	HEAD
P107	6	0	0	0	-0.1	-0.1	-0.1	ORTO	LOW XOP	<5 CM	85"	0	<1	∞	<1	WITHIN NORMS	SPEC
P03	7	0	0	0	0	0	0	ORTO	ORTO	<5 CM	170"	0.75	<1	0.75	<1	WITHIN NORMS	SPEC
P88	7	-0.1	-0.1	-0.1	0	0	0	ORTO	ORTO	<5 CM	85"	0	<1	∞	<1	WITHIN NORMS	HEAD

ID	AGE	RE VA DISTANCE	LE VA DISTANCE	BEO VA DISTANCE	RE VA NEAR	LE VA NEAR	BINO VA NEAR	CT DITANCE	CT NEAR	NPC	STE REO	RET RE		RET LE		ACC	MOTIL ITY
												SPH	CYL	SPH	CYL		
P93	7	0	0	0	0	0	0	ORTO	ORTO	<5 CM	85"	1	<1	1	<1	WITHIN NORMS	SPEC
P95	7	0	0	0	0	0	0	ORTO	ORTO	<5 CM	85"	0.5	<1	0.5	<1	WITHIN NORMS	HEAD
P19	7	0	-0.1	0	0	0	0	ORTO	ORTO	<5 CM	170"	1	<1	1	<1	WITHIN NORMS	SPEC
P16	8	0.06	0	-0.1	0	0	0	ORTO	LOW SOP	6 CM	85"	∞	<1	∞	<1	WITHIN NORMS	SPEC
P113	8	0	0	0	-0.1	-0.1	-0.1	ORTO	ORTO	<5 CM	85"	∞	<1	∞	<1	WITHIN NORMS	SPEC
P117	8	0	0	0	0	0	0	ORTO	ORTO	<5 CM	85"	∞	<1	∞	<1	WITHIN NORMS	SPEC
P123	8	0.2	0.2	0.2	0	0	0	ORTO	ORTO	<5 CM	85"	∞	<1	∞	<1	WITHIN NORMS	SPEC
p119	**8**	0	0	0	-0.1	-0.1	-0.1	ORTO	ORTO	<5 CM	85"	∞	<1	∞	<1	WITHIN NORMS	SPEC
P17	9	0.16	0.02	0	0	0	0	ORTO	ORTO	<5 CM	85"	1.25	<1	∞	<1	WITHIN NORMS	SPEC
P115	9	0.2	0.14	0.16	0.2	0.2	0.1	ORTO	ORTO	<5 CM	170"	1.5	<1	2	<1	WITHIN NORMS	JERKY
P121	9	0	0	0	0	0	0	ORTO	ORTO	<5 CM	85"	0.5	<1	0.5	<1	WITHIN NORMS	SPEC
P130	9	0.08	0.06	0.02	0	0	0	ORTO	ORTO	<5 CM	85"	0.5	<1	∞	<1	WITHIN NORMS	SPEC
P131	9	0.08	0.04	0	0.06	0.04	0.02	ORTO	ORTO	<5 CM	170"	∞	<1	0.5	<1	WITHIN NORMS	HEAD
P134	9	0	0	0	0	0	0	ORTO	ORTO	<5 CM	85"	∞	<1	∞	<1	WITHIN NORMS	SPEC

ID	AGE	RE VA DISTANCE	LE VA DISTANCE	BEO VA DISTANCE	RE VA NEAR	LE VA NEAR	BINO VA NEAR	CT DITANCE	CT NEAR	NPC	STE REO	RET RE		RET LE		ACC	MOTIL ITY
												SPH	CYL	SPH	CYL		
P135	9	0.1	0	0	0	0	0	ORTO	LOW XOP	<5 CM	85"	∞	<1	0.25	<1	WITHIN NORMS	SPEC
P136	9	0	0	0	0	0	0	ORTO	ORTO	<5 CM	85"	∞	<1	∞	<1	WITHIN NORMS	SPEC
P120	9	0	0.1	0	0	0	0	ORTO	ORTO	<5 CM	85"	0.25	<1	0.75	V	WITHIN NORMS	SPEC
P31	10	0	0	0	0	0	0	ORTO	ORTO	<5 CM	85"	-1.5	<1	-1.5	<1	WITHIN NORMS	SPEC
P59	10	0	0	0	0	0	0	ORTO	ORTO	<5 CM	85"	∞	<1	∞	<1	WITHIN NORMS	SPEC
P70	10	0.1	0	0	0	0	0	ORTO	ORTO	<5 CM	85"	0.75	<1	1	-1.25	WITHIN NORMS	SPEC
P72	10	0	0	0	0	0	0	ORTO	ORTO	<5 CM	85"	0.75	<1	0.75	<1	WITHIN NORMS	SPEC
P80	10	0.04	0.06	0	0	0	0	ORTO	LOW SOP	<5 CM	85"	0.5	<1	∞	<1	WITHIN NORMS	SPEC
P81	10	0.2	0.2	0.2	0	0	0	ORTO	LOW SOP	<5 CM	85"	-1.5	1DC	-1	<1	WITHIN NORMS	SPEC
P82	10	0	0	0	0	0	0	ORTO	ORTO	<5 CM	85"	∞	<1	∞	<1	WITHIN NORMS	SPEC
P85"	10	0.2	0.2	0.2	0.2	0.2	0.2	ORTO	ORTO	<5 CM	170"	1	<1	1.5	<1	1.5D LAG	SPEC
P139	10	0	0	0	0	0	0	ORTO	ORTO	<5 CM	85"	0.25	<1	-0.25	<1	WITHIN NORMS	SPEC
P140	10	0.2	0.1	0.1	0.1	0.1	0.1	HIGH XOP	HIGH XOP	6 CM	170"	1	<1	-0.25	<1	WITHIN NORMS	SPEC
P83	11	0	0	0	0	0	0	ORTO	MED XOP	8 CM	175"	1.75	<1	1	<1	2D LAG	SPEC

ID	AGE	RE VA DISTANCE	LE VA DISTANCE	BEO VA DISTANCE	RE VA NEAR	LE VA NEAR	BINO VA NEAR	CT DITANCE	CT NEAR	NPC	STE REO	RET RE		RET LE		ACC	MOTIL ITY
												SPH	CYL	SPH	CYL		
P141	11	0	0	0	0	0	0	ORTO	ORTO	<5 CM	85"	∞	<1	∞	<1	WITHIN NORMS	SPEC
P142	11	0.04	0.01	0	0	0	0	ORTO	ORTO	<5 CM	85"	∞	<1	∞	<1	WITHIN NORMS	SPEC
P138	11	0.1	0.1	0.1	0	0	0	HIGH XOP	HIGH XOP	7 CM	85"	1	<1	1	<1	WITHIN NORMS	SPEC

Appendix H: Additional plots for eye movements in child participants with IEP related to delayed reading skills

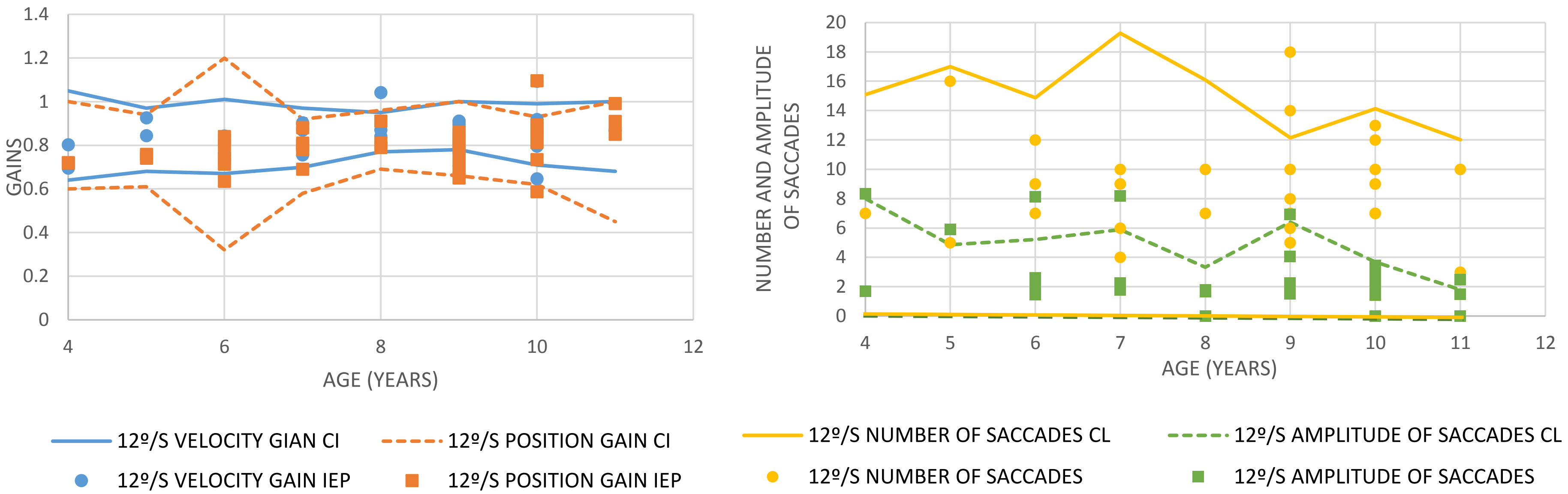


Figure 1. Velocity gain (left – blue circles), position gain (left –orange squares), number of saccades (right – yellow circles) and amplitude of saccades (right – green squares) for each participant with an IEP for the 12°/s horizontal smooth pursuit superimposed on the eye movement norms (95% confidence limits (CL)) produced from the eye movements in children with no IEP.

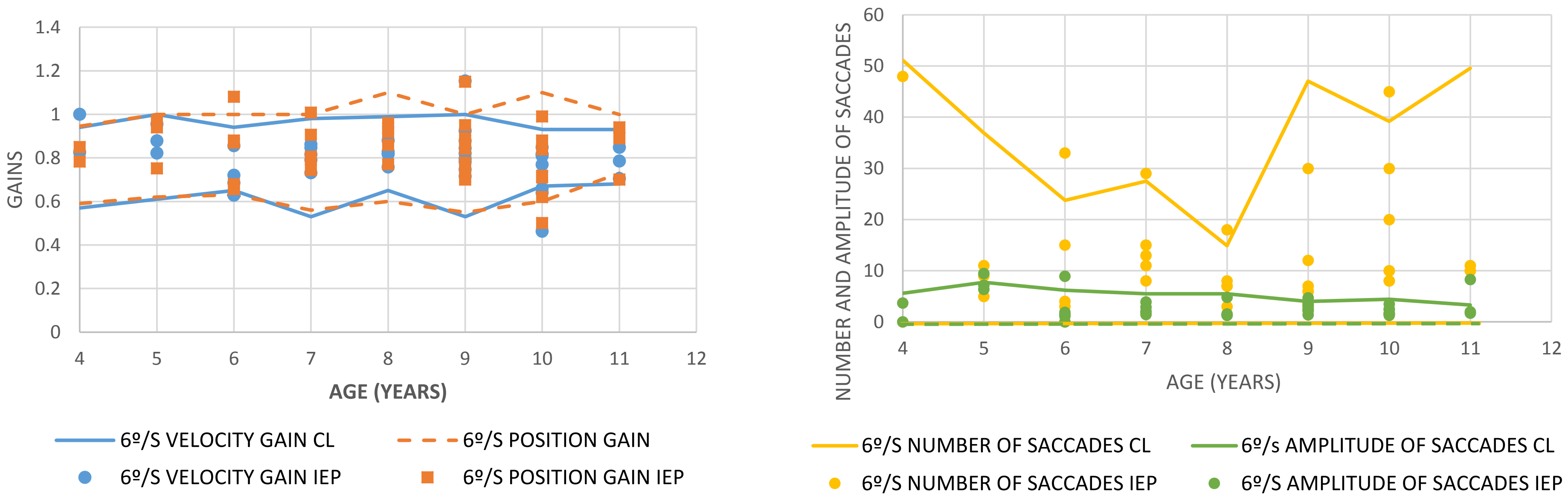


Figure 2. Velocity gain (left – blue circles), position gain (left –orange squares), number of saccades (right – yellow circles) and amplitude of saccades (right – green squares) for each participant with an IEP for the 6º/s vertical smooth pursuit superimposed on the eye movement norms (95% confidence limits (CL)) produced from the eye movements in children with no IEP.

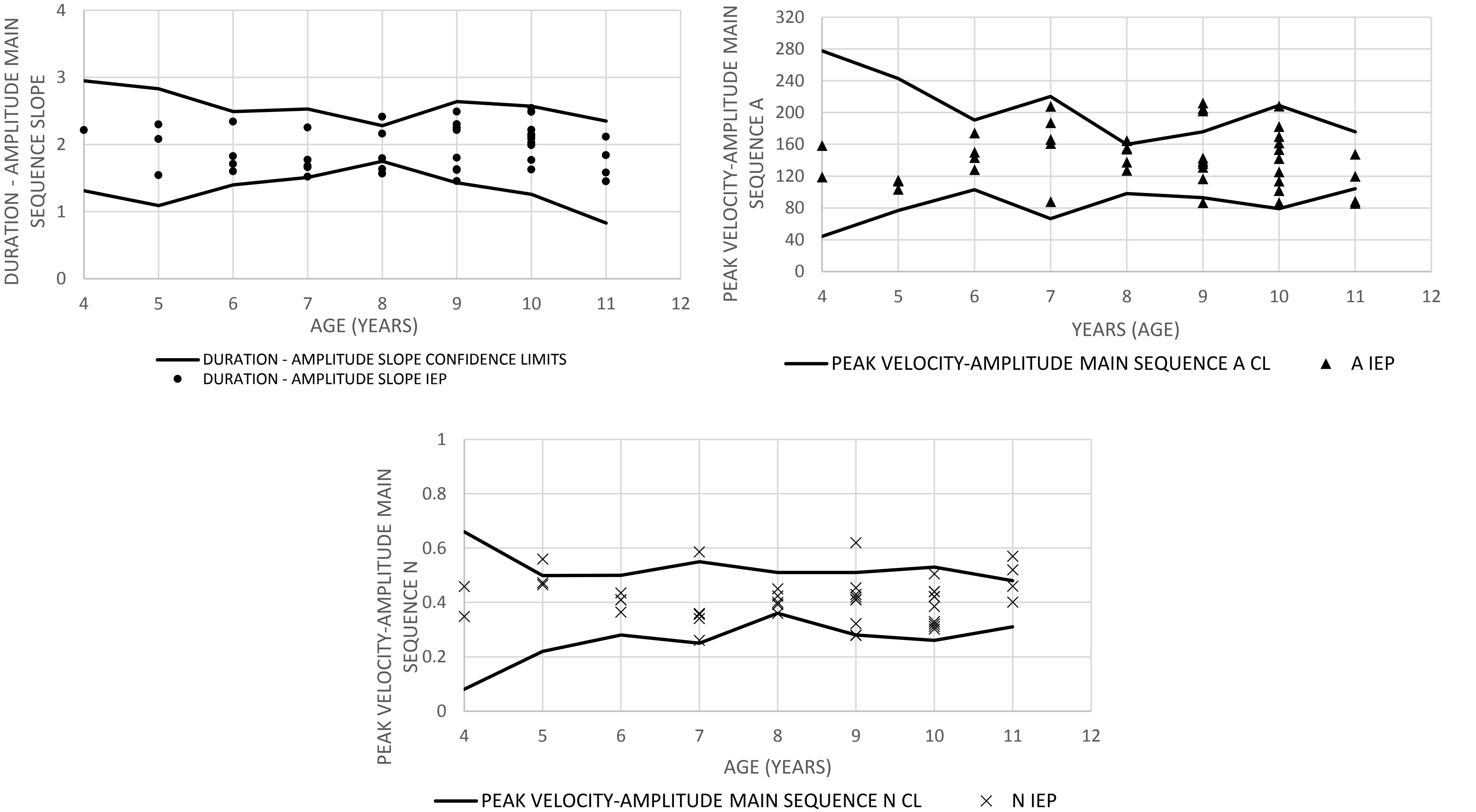


Figure 2. Slope (S) (top left), A coefficient (top right), n coefficient (bottom) for each participant with an IEP for the horizontal saccadic main sequences superimposed on the eye movement norms (95% confidence limits (CL)) produced from the eye movements in children with no IEP.

Appendix I: Eye movement values for children referred with suspected eye movement difficulties who have eye movements within their age-matched norms

RESULTS FROM THE EYE MOVEMENT RECORDING FOR PARTICIPANT P01 (11 YO)

SMOOTH PURSUIT					
VELOCITY GAIN	POSITION GAIN	PROPORTION OF SP	NUMBER OF SACCADES	MEAN AMPLITUDE SACCADES	NUMBER OF MICROSACC.
HORIZONTAL 6°/S					
0.88	0.81	0.84	2	1.23	19
HORIZONTAL 12°/S					
0.89	0.71	0.87	8	1.59	1
VERTICAL 6°/S					
0.73	0.85	0.65	29	1.37	20
VERTICAL 12°/S					
0.78	0.81	0.82	6	1.29	4

Table 1. Summary table showing the saccadic parameters obtained from participant P05. All parameters were within the corresponding age-matched norms.

HORIZONTAL SACCADES					
SLOPE	INTERCEPT	Q RATIO	A	n	GAIN
1.80	25.78	1.66	136.1	0.45	0.97/0.97/ 0.94/0.96
VERTICAL SACCADES (UP)					
2.15	16.75	1.94	245.97	0.33	GAIN VERTICAL
VERTICAL SACCADES (DOWN)					1.01/1/0.99
1.78	13.75	1.60	292.41	0.12	

Table 2. Summary table showing the saccadic parameters obtained from participant P01. All parameters were within the corresponding age-matched norms.

VISUAL FIXATION			
HORIZONTAL MEP	VERTICAL MEP	HORIZONTAL SD OF MEP	VERTICAL SD OF MEP
0.36	1.85	0.14	0.37

MEAN NUMBER OF SACCADES	MEAN AMPLITUDE OF SACCADES	MEAN NUMBER OF MICROSACCADES
0	-	9

Table 3. Summary table showing the fixation parameters obtained from participant P01. All parameters were within the corresponding age-matched norms.

RESULTS FROM THE EYE MOVEMENT RECORDING FOR PARTICIPANT P04 (9 YEARS OLD)

SMOOTH PURSUIT					
VELOCITY GAIN	POSITION GAIN	PROPORTION OF SP	NUMBER OF SACCADES	MEAN AMPLITUDE SACCADES	NUMBER OF MICROSACC.
HORIZONTAL 6º/S					
0.92	0.82	0.87	7	2.4	9
HORIZONTAL 12º/S					
0.98	0.98	0.89	5	5.4	4
VERTICAL 6º/S					
0.80	0.77	0.54	17	3.75	17
VERTICAL 12º/S					
0.69	0.76	0.52	10	3.77	21

Table 4. Summary table showing the smooth pursuit parameters obtained from participant P04. All parameters were within the corresponding age-matched norms.

SACCADES					
HORIZONTAL SACCADES					
SLOPE	INTERCEPT	Q RATIO	A	n	GAIN
1.75	24.13	1.63	176	0.33	0.99/1/ 0.94/0.95
VERTICAL SACCADES (UP)					
2.67	21.1	1.88	221.67	0.26	GAIN VERTICAL
					1.17/0.98/0.87
VERTICAL SACCADES (DOWN)					
2.32	16.8	1.87	145.12	0.49	

Table 5. Summary table showing the saccadic parameters obtained from participant P04. All parameters were within the corresponding age-matched norms.

VISUAL FIXATION			
HORIZONTAL MEP	VERTICAL MEP	HORIZONTAL SD OF MEP	VERTICAL SD OF MEP
2.28	1.20	1.93	0.71
MEAN NUMBER OF SACCADES	MEAN AMPLITUDE OF SACCADES	MEAN NUMBER OF MICROSACCADES	
1	1.2	36	

Table 6. Summary table showing the fixation parameters obtained from participant P04. All parameters were within the corresponding age-matched norms.

RESULTS FROM THE EYE MOVEMENT RECORDING FOR PARTICIPANT P05 (9 YEARS OLD)

SMOOTH PURSUIT					
VELOCITY GAIN	POSITION GAIN	PROPORTION OF SP	NUMBER OF SACCADES	MEAN AMPLITUDE SACCADES	NUMBER OF MICROSACC.
HORIZONTAL 6º/S					
0.89	0.92	0.93	5	2.4	5
HORIZONTAL 12º/S					
0.86	0.81	0.82	10	4.87	1
VERTICAL 6º/S					
0.71	0.70	0.49	45	2.16	39
VERTICAL 12º/S					
0.61	0.72	0.53	18	2.64	3

Table 7. Summary table showing the smooth pursuit parameters obtained from participant P05. All parameters were within the corresponding age-matched norms.

<table>
<tr><th colspan="6">HORIZONTAL SACCADES</th></tr>
<tr><td>SLOPE</td><td>INTERCEPT</td><td>Q RATIO</td><td>A</td><td>n</td><td>GAIN</td></tr>
<tr><td>2.14</td><td>25.2</td><td>1.68</td><td>176</td><td>0.32</td><td>1/0.94/ 0.95/0.95</td></tr>
<tr><td colspan="6">VERTICAL SACCADES (UP)</td></tr>
<tr><td>2.88</td><td>23.88</td><td>1.81</td><td>176.72</td><td>0.29</td><td>GAIN VERTICAL</td></tr>
<tr><td colspan="5">VERTICAL SACCADES (DOWN)</td><td rowspan="2">1.01/0.99/0.98</td></tr>
<tr><td>2.23</td><td>27.37</td><td>1.91</td><td>153.66</td><td>0.38</td></tr>
</table>

Table 8. Summary table showing the saccadic parameters obtained from participant P05. All parameters were within the corresponding age-matched norms.

<table>
<tr><th colspan="4">VISUAL FIXATION</th></tr>
<tr><td>HORIZONTAL MEP</td><td>VERTICAL MEP</td><td>HORIZONTAL SD OF MEP</td><td>VERTICAL SD OF MEP</td></tr>
<tr><td>-0.58</td><td>1.21</td><td>0.2</td><td>0.23</td></tr>
</table>

MEAN NUMBER OF SACCADES	MEAN AMPLITUDE OF SACCADES	MEAN NUMBER OF MICROSACCADES
1	2.42	7

Table 9. Summary table showing the fixation parameters obtained from participant P05. All parameters were within the corresponding age-matched norms.

RESULTS FROM THE EYE MOVEMENT RECORDING FOR PARTICIPANT P09 (10 YEARS OLD)

SMOOTH PURSUIT					
VELOCITY GAIN	POSITION GAIN	PROP OF SP	NUMBER OF SACCADES	MEAN AMPLITUDE SACCADES	NUMBER OF MICROSACC.
HORIZONTAL 6º/S					
0.82	0.70	0.66	4	1.21	9
HORIZONTAL 12º/S					
0.75	0.64	0.71	9	1.51	3
VERTICAL 6º/S					
0.76	0.68	0.64	6	1.4	24
VERTICAL 12º/S					
0.55	0.52	0.50	14	2.14	9

Table 10. Summary table showing the smooth pursuit parameters obtained from participant P09. All parameters were within the corresponding age-matched norms.

HORIZONTAL SACCADES					
SLOPE	INTERCEPT	Q RATIO	A	n	GAIN
2.55	24.05	1.64	154.6	0.40	0.93/0.96/
VERTICAL SACCADES (UP)					
3.2	20.88	2.16	136.08	0.47	GAIN VERTICAL
					1.05/0.95/0.9
VERTICAL SACCADES (DOWN)					
2.03	24.27	1.77	163.67	0.31	

Table 11. Summary table showing the saccadic parameters obtained from participant P09. All parameters were within the corresponding age-matched norms.

VISUAL FIXATION			
HORIZONTAL MEP	VERTICAL MEP	HORIZONTAL SD OF MEP	VERTICAL SD OF MEP
-2.03	2.1	4.7	2.43

MEAN NUMBER OF SACCADES	MEAN AMPLITUDE OF SACCADES	MEAN NUMBER OF MICROSACCADES
0	-	5

Table 12. Summary table showing the fixation parameters obtained from participant P09. All parameters were within the corresponding age-matched norms.