Eye movements in children: characteristics in typical and atypical development and assessment in practice

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Abstract

An efficient and coordinated oculomotor control is vital in the classroom environment. It allows pupils to perform rapid, accurate saccades during reading, scanning a page and exploring a scene or the surrounding space. Further this control facilitates accurate smooth pursuits to follow the teacher's movements through a variety of teaching routines, and playground activities such as children running or balls rolling. Hence, eye movement deficits or difficulties have the potential to impact children's development and learning significantly. This review outlines the importance of appropriate eye movement control in children, and describes the typical characteristics of fixational, saccadic and smooth pursuit eye movements, and their development during childhood to achieve adult values. Following this, an introduction to the different eye movement characteristics found in children with learning difficulties is presented, in order to raise optometrists' awareness of the increased risk of eye movement deficits in populations with atypical or different development. The article also describes and discusses the clinical techniques currently available to evaluate fixations, saccades and smooth pursuits in optometric practice, and provides some recommendations to support optometrists when assessing eye movements in children. Finally, the potential contribution of eye-tracking technologies for clinical practice is presented, and their technologies' limitations and current challenges are discussed.

Introduction

A large percentage of learning is done visually; therefore, 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 disorders and/or accommodative deficits, may result in learning difficulties. Eye movement deficits or poor eye movement control can also impair vision and consequently impact on a child's development and learning. For instance, efficient and coordinated eye movement control is essential in the school environment, as it allows children to perform rapid changes of gaze between objects of interest and words during reading, to maintain a stable gaze on an object of interest (ie fixate a picture or word) and to follow moving objects or individuals accurately (ie rolling balls or children running).

The prevalence and characteristics of eye movement difficulties or deficits in children are unknown. Further, eye care professionals are frequently faced with children considered to be at risk of eye movement difficulties, who are mainly referred by educational (eg psychologists) and other healthcare professionals (eg occupational therapists and general practitioners) on the grounds of 'poor tracking', skipping words and losing their place when reading (Barrett 2009). In addition, many children with delayed reading skills or other learning-related difficulties are commonly referred to eye care professionals for binocular vision and/or eye movement assessments.

There are different types of eye movements that account for specific purposes and suit different types of objects, motions and conditions (Leigh and Zee 2015). This article will focus on saccadic, smooth pursuit and fixational eye movements. First, the characteristics and development of these eye movement types will be presented and this will be followed by an introduction to the different characteristics of these in children with certain learning difficulties. Then, this article will describe and discuss the current techniques and methods available to assess eye movements and provide recommendations to improve the examination of eye movements in optometric practice.

Saccades

Saccades are rapid movements of the eyes responsible for shifts of gaze that bring an object of interest into the foveal region. These eye movements allow us to change our gaze point quickly and fixate on new objects of interest. They range in amplitude from very small saccades made while reading to much larger saccades made while we explore a room, a landscape or a scene. The basic characteristics of a typical saccade are as follows: an initial extreme acceleration of the eyes followed by a relatively small deceleration with a slight undershoot and a peak velocity (maximum velocity) that depends on the amplitude of the saccade (Carpenter 1988). The initial acceleration appears to be almost the same for all saccades, independent of their amplitude. In contrast, peak velocity increases with the amplitude of the saccade,

meaning that large saccades have higher peak velocities, and this parameter varies from 30°/second to 800°/second for amplitudes ranging from 0.5° to 40° (Carpenter 1988). Similarly, saccadic duration also increases with amplitude, with durations ranging from 30 to 100 ms for saccadic amplitudes of from 0.5 to 40° (Carpenter 1988).

Currently, the relationship between the duration and the amplitude of saccades, as well as the relationship between the peak velocity and the amplitude of saccades, is well established and systematic. For instance, in typical saccadic functions, a clear linear relationship can be observed if we plot the duration of a series of saccades against their amplitude (Figure 1a). In addition, for typical saccadic functions, if the peak velocity of a number of saccades is plotted against their amplitude, a quasilinear relationship is observed up to saccades of approximately 10–15°. After this value, the peak velocities saturate at approximately 500°/second (Figure 1b). These relationships, known as the saccadic main sequence, were first described in 1975 (Bahill 1975), and are currently an invaluable tool to measure the 'normalcy' of saccades (Ramat et al. 2007). For illustrative purposes, Figure 1 presents typical saccadic main sequence relationships obtained from a typically developing child (black symbols) and also atypical saccadic main sequence relationships obtained from a child with cerebral palsy (blue symbols), which show abnormally slow saccades.

Saccadic performance and quality can also be measured in terms of accuracy. In general, when our eyes are directed to a new object of interest, they do not land exactly in the precise centre of that object (Leigh and Zee 2015). Hence, the eyes usually show some degree of saccadic inaccuracy (dysmetria) that includes undershoots (hypometria) or 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 (Leigh and Zee 2015). Finally, latency, also known as saccadic reaction time, is another well-established and studied saccadic performance parameter. Saccadic latency, which is described as the time between the appearance of a new object of interest in the field of vision and the initiation of the saccade, typically ranges from 150 to 250 ms (Gilchrist 2011).

Overall, the basic saccadic dynamics (saccadic duration and peak velocity) are adult-like very early in life (Garbutt et al. 2006), but saccadic accuracy and latency continue to develop during childhood (Garbutt et al. 2006; Gredebäck et al. 2006). Studies have shown that, although saccades are present in infants and young children, they are not accurate; instead, they are hypometric (Garbutt et al. 2006; Gredebäck et al. 2006). Hence, infants and young children generally do not perform a single and accurate saccade, but a series of small saccades. With age, the number of saccades to match the gaze with the object of interest decreases, resulting in more accurate saccades. Latency has also been found to be significantly longer in infants and children compared to adults (Fukushima et al. 2000; Gredebäck et al. 2006). There is some disagreement about the age at which saccadic accuracy and latency reach adult levels, but the literature suggests that saccades in early or mid-childhood

(3–5 years of age) can be found to be as accurate as in adults and that latency continues to decrease until 10–12 years of age.
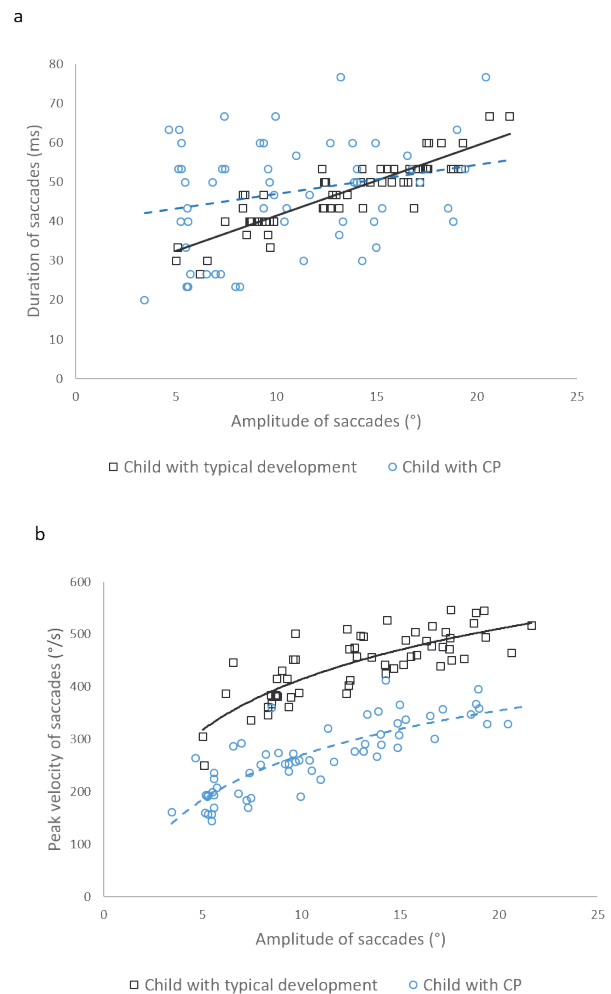
Figure 1. Saccadic main sequence relationships obtained from a typically developing child (black) and a child with cerebral palsy (CP: blue). A typical linear relationship between the duration and amplitude of the saccades (a) and a quasilinear relationship between the peak velocity and the amplitude of saccades (b) are found in typically developing children without oculomotor disorders (black). An abnormal relationship between the duration and the amplitude of saccades (a) and between the peak velocity and the amplitude of saccades (b) can be found in a child with CP (blue) showing an oculomotor disorder.

Smooth pursuit

Smooth pursuit eye movements are responsible for the smooth tracking of slow-moving objects and the maintenance of their moving image on the fovea. Different parameters can be used to evaluate the performance and quality of smooth pursuit eye movements. For instance, velocity gain is described as the eye velocity divided by the target velocity. Ratios close to 1 indicate that the velocity of the eyes accurately matches the velocity of the moving object. In contrast, gains over or below 1 indicate that the eyes lead ahead or lag behind the moving object and, therefore, are not accurate.

The number and amplitude of the saccades performed during smooth pursuit eye movements are also an indicator of the smooth pursuit quality (Ross et al. 1996). Moreover, the saccades performed during 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 the fovea (de Brouwer et al. 2002). The black trace in Figure 2 illustrates the eye movement trace obtained from a typically developing child while smooth pursuing a moving cartoon on a screen; the trace demonstrates the presence of both segments of smooth pursuit as well as saccades. Figure 2 also illustrates the eye movement trace obtained from a child with cerebral palsy (blue trace) who is performing the same task. Obvious differences can be observed between the eye movement traces presented in Figure 2.
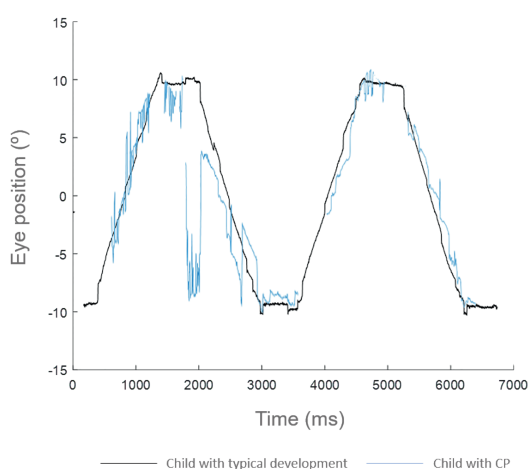
Figure 2. Eye movement trace from a typically developing child (black trace) and a child with cerebral palsy (CP: blue trace) smoothly pursuing an object that moves on a screen left to right and right to left twice. The figure illustrates that typical smooth pursuit is achieved by combining large segments of smooth pursuits with saccades of small amplitude. For the child with CP the figure illustrates an atypical smooth pursuit performance with intermittent smooth pursuit segments and a significant number of saccades of large amplitude. Significant data loss can also be observed in the eye trace of the child with CP (blank segments in the eye trace) that is likely to be due to a poor-quality recording or limited patient cooperation.

It is now generally accepted that young infants are able to pursue moving objects by combining smooth pursuit and saccadic eye movements (Phillips et al. 1997; Pieh et al. 2012). In infancy, smooth pursuit is mainly achieved by a sequence of saccades, but these decrease early in life, at which point pursuit starts to be mainly dominated by smooth pursuit eye movements (Phillips et al. 1997; 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 (Pieh et al. 2012; Rutsche et al. 2006).

Studies investigating eye movement development in school-age children have reported conflicting results, and therefore the exact age at which smooth pursuit achieves adult values is still unclear. For instance, velocity gain has been shown to increase significantly between 1 and 6 years of age (Rutsche et al. 2006). After this age, smooth pursuit performance parameters are extremely similar to those found in adults (Ingster-Moati et al. 2009; Irving et al. 2011), but some studies report that, even after the age of 6 years, smooth pursuit is not as accurate as in adults (Accardo et al. 1995).

Given the methodological differences found in the studies evaluating the development of smooth pursuit, it is not currently possible to determine the exact age at which smooth pursuit reaches adult levels. Although it is clear that this type of eye movement significantly develops during childhood until the age of 8 years old, the debate still continues about its development and maturation levels after this age. As differences in many smooth pursuit parameters, including gain, are negligible between adults and children older than 8 years of age (Ingster-Moati et al. 2009; Irving et al. 2011), it is reasonable to suggest that smooth pursuit characteristics may reach adult levels soon after that age, during late childhood or early adolescence.

Fixation

Fixation is the active process of maintaining static gaze on a stationary object of interest. During fixation the image of the stationary object is maintained on the fovea, therefore allowing the inspection of such an object with high acuity (Leigh and Zee 2015). Fixation requires not only attention but also the inhibition of inappropriate eye movements such as saccades (Luna and Velanova 2011).

Typically, the quality of fixation is evaluated by assessing the deviations away from the fixation point as well as the number and size of intrusive saccades performed during fixation. It is important to note that our eyes are never still and some eye movements which are imperceptible to the observer, such as drifts, tremors and microsaccades, occur during periods of normal fixation (Martinez-Conde et al. 2004). Microsaccades are very small saccades with amplitudes of less than 1°; drifts are smooth eye movements of slow velocity and tremors are rapid oscillations of the eyes smaller than microsaccades. The review of these eye movements is out of the scope of this article, given that it is not currently possible to evaluate these with the current clinical methods, procedures and tests used in optometric practice. For a comprehensive review, the reader is directed to the paper by Martinez-Conde et al. (2004).

There is limited literature investigating the development of fixation, but it has been proposed that visual fixation is present early in life (Luna and Velanova 2011), and its control and stability improve with age during childhood (Luna and Velanova 2011; Luna et al. 2008). It is generally accepted that, in typically developing children, the number of intrusive saccades as well as the number of saccades towards distractors significantly decrease from 5 to 10–15 years of age (Aring et al. 2007; Ygge et al. 2005). At the same time,

the mean standard deviation of the mean eye position also decreases with age, resulting in a more accurate and stable fixation (Aring et al. 2007; Ygge et al. 2005). Although none of the studies evaluating the development of fixation in children included an adult sample for comparison, the results seem to indicate that most fixation parameters do not change between the ages of 8–10 years. Furthermore, no significant differences are found in any of the fixation parameters in children aged 10–15 years (Ygge et al. 2005), and this indicates that maturation levels have been reached and that adult values have been achieved by this age range.

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 that do not occur as a result of an intelligence impairment (Holland 2011).

Eye movement deficits are more frequently found in children with learning difficulties (Fukushima et al. 2005), and it is suggested that this is a result of a different developmental trajectory or brain dysfunction (Luna et al. 2008; Rommelse et al. 2008). Given that it is not possible to describe eye movement control for each one of the learning-related difficulties known, the following section presents a summary of the current evidence related to eye movement control in child populations with four different learning difficulties: autism, attention deficit-hyperactivity disorder (ADHD), developmental coordination disorder (DCD) and dyslexia. These four specific learning difficulties have been chosen as they are relatively common in the general population, and children with these conditions are likely to attend mainstream optometry practices for their eye examinations.

Autism spectrum disorder

Autism spectrum disorder (ASD) is a group of developmental disorders characterised by difficulties in social interaction and social communication. It encompasses an unusually restricted range of behaviours and interests (Simmons et al. 2009). While the saccadic dynamics (saccadic duration and peak velocity) seem to be intact in children with ASD, it has been proposed that the consistency of their saccadic responses may be impaired (Stanley-Cary et al. 2011). This inconsistency is reflected by the high variability found in most saccadic parameters, but in particular in saccadic accuracy. These findings support the view that children with ASD may experience difficulties with maintaining an appropriate saccadic performance throughout the day or during a specific activity or task.

A recent meta-analysis also suggests that there is no significant difference in latency in visually guided saccades between children and young adults with ASD and control subjects (Johnson et al. 2016). In contrast, smooth pursuit in children and young adults with ASD has been shown to be impaired, with lower gains and a large number of catch-up saccades (Takarae et al. 2004, 2008), suggesting that smooth pursuit in this population is not accurate or well controlled. There is limited available literature addressing the quality of fixation in ASD, but in general, no large differences have been found between children and young adults with and without ASD in the number of intrusive saccades found during fixation. However, some subtle differences that include an increased variability in the amplitude of microsaccades during fixation have been reported in cases of ASD. Overall, these findings suggest that, while the gross control of fixation is intact, there is some evidence to support the presence of subtle difficulties in maintaining fixation in this population (Frey et al. 2013).

Attention deficit-hyperactivity disorder

ADHD is a neurobehavioural disorder characterised by inattention, hyperactivity and impulsivity (American Psychiatric Association 2013). Not surprisingly, eye movement control, in particular saccadic control and saccadic initiation, has been shown to be impaired in children with ADHD. These saccadic deficits seem to reflect the difficulty that these children have in controlling their impulsivity and attention. For instance, children with ADHD can frequently show an increased number of anticipated saccadic responses during a saccadic task, so that saccades are triggered before the stimulus appears or even before the command or instruction is given (Munoz et al. 2003). In addition to the impulsive and anticipated saccadic responses, when the saccades are appropriately elicited, children with ADHD exhibit longer saccadic latencies (Mahone et al. 2009; Munoz et al. 2003). It is still unclear whether smooth pursuit and fixation are impaired in ADHD, but it could be argued that, because of the impulsive nature of the condition, these children could also experience difficulties in suppressing the saccadic system during smooth pursuit and visual fixation, resulting in reduced performance in these eye movement types.

Developmental coordination disorder

Currently, many children with motor impairments that significantly affect their daily life activities and academic achievement are diagnosed with DCD, also known as dyspraxia. DCD is a neurodevelopmental disorder characterised by significant difficulties with the acquisition and execution of motor skills (American Psychiatric Association 2013). Although it is reasonable to suggest that the presence of general motor impairments may also interfere with eye movement control, current research indicates that basic eye movement control is intact in this population. For instance, children with DCD are able to produce fast and accurate saccades (Gonzalez et al. 2016; Sumner et al. 2018) and adequate smooth pursuit eye movements (Robert et al. 2014; Sumner et al. 2018).

However, differences in eye movement control have been found between children with DCD and typically developing children during complex and prolonged eye movement tasks. For instance, saccadic performance has been found to be reduced in children with DCD in tasks where cues were given about the direction and magnitude of the saccade prior to the appearance of the target (Gonzalez et al. 2016). Similarly, although smooth pursuit performance in DCD has been shown to be comparable to that found in typically developing children, during prolonged periods of smooth pursuit children with DCD produce fewer segments of pursuit, resulting in a reduction in the average pursuit duration (Sumner et al. 2018).

Overall, these findings indicate not only deficits in inhibition and anticipation of the saccades but also difficulties with maintaining pursuit performance.

Finally, the only study investigating fixation in children with DCD reported an increased number of intrusive saccades during fixation and a reduced fixation duration, further suggesting difficulties in eye movement inhibition, anticipation and maintenance (Sumner et al. 2018). However, further research is needed to confirm these findings.

Dyslexia

Dyslexia can be defined as a learning difficulty that primarily affects the skills involved in accurate and fluent reading and spelling (Rose 2009). A question of intense debate, the answer to which still remains unclear, is whether there are any differences in eye movement control between children with and without dyslexia. Saccades and fixations during reading have been found to differ between individuals with and without dyslexia. For instance, during reading, individuals with dyslexia produce a greater number of saccades and regressions as well as longer fixation durations than individuals without dyslexia (Bellocchi et al. 2013; Rayner 1985). However, it can be argued that the different eye movement behaviour found during reading in children and adults with dyslexia is likely to reflect a difficulty related to the ability to read and comprehend the text rather than an eye movement deficit.

Surprisingly, there is limited documented research evaluating eye movements in children with dyslexia in non-reading-related conditions. The early studies from Pavlidis (1981) showing eye movement differences between children with and without dyslexia in a sequential eye movement task (ie non-reading task) have been difficult to replicate. Moreover, the inconsistencies in the findings related to oculomotor deficits in children and adults with dyslexia reported over the past decades have allowed this issue to remain unsolved. For instance, there is some evidence to support that there are no differences in eye movement behaviour between children with and without dyslexia during visual tasks that require similar perceptual and motor demands to reading (Hutzler et al. 2006).

In contrast, poor binocular control during fixation (Bucci et al. 2008; Jainta and Kapoula 2011) and poor fixation control during and after saccades (Eden et al. 1994) have been more consistently found in children and adults with dyslexia.

Table 1. Summary of the main oculomotor findings in children with four common learning difficulties

Learning difficulty	Definition	Summary of oculomotor findings		
		Saccades	Smooth pursuit	Fixation
Autism spectrum disorder (ASD)	Group of neurodevelopmental disorders characterised by difficulties in social interaction, social communication and unusually restricted range of behaviours and interests	Basic saccadic control is intact in ASD. However, studies suggest that the consistency of saccadic responses may be impaired, affecting the maintenance of saccadic response	Low smooth pursuit gains and increased number of catch-up saccades during smooth pursuit	Subtle fixation deficits found with an increased number of microsaccades during fixation
Attention deficit-hyperactivity disorder (ADHD)	Neurodevelopmental disorder characterised by inattention, hyperactivity and impulsivity	Deficits in saccadic control and initiation. Increased number of saccadic anticipative responses and longer latencies	It is still unclear whether smooth pursuit and fixation are impaired in ADHD, but it could be argued that, because of the impulsive nature of the condition, difficulties in suppressing the saccadic system during smooth pursuit and visual fixation are possible. Further research is needed	
Developmental coordination disorder (DCD)	Neurodevelopmental disorder characterised by significant difficulties with the acquisition and execution of motor skills	Basic saccadic control is intact. Some studies indicate a possible deficit in the inhibition and anticipation of the saccades	Basic smooth pursuit control is intact. Smooth pursuit performance is reduced for prolonged periods of pursuit	Increased number of intrusive saccades and reduced fixation duration. Recent findings that need to be further investigated
Dyslexia	Neurodevelopmental disorder that primarily affects the skills involved in accurate and fluent reading and spelling	Debate still continues in this field, but overall it can be suggested that the basic saccadic control is intact in this population in non-reading related tasks. Saccadic differences during reading tasks are likely to be secondary to the reading difficulty	Further research is needed to clarify the characteristics of smooth pursuit in individuals with dyslexia	There is some evidence to support the presence of fixation instability in dyslexia resulting from reduced binocular control and coordination

Binocular control or coordination, which can be described as the ability of each eye to fixate simultaneously on the same object or word, has been shown to be poorer in children with dyslexia compared to typically developing children during and after a saccade (Bucci et al. 2008) and also during reading (Jainta and Kapoula 2011). It has been suggested that this reduced binocular coordination could result in fixation instability (poor fixation control) and disparity, and consequently further impact on the reading ability of this population (Jainta and Kapoula 2011). Given the current evidence, it could be suggested that, in order to differentiate eye movement disorders (ie fixation instability or poor binocular coordination) from eye movement differences resulting from a primary problem with reading and comprehension in individuals with dyslexia, the eye movements in this population should be assessed in non-reading conditions.

The clinical examination of eye movements

Current literature indicates that children and young adults with learning difficulties and disabilities are more likely to have different eye movement characteristics and/or development (Table 1). Hence, it is important that optometrists are aware of these and consequently assess eye movements in children with atypical development and learning skills. The following section summarises and discusses the most widely used and established tests, protocols and methods to evaluate eye movements in clinical practice.

Observational tests

Leigh and Zee (2015) suggest that the best approach to examine saccades with observational tests is to use two targets and instruct patients to alternate their fixation between the targets, with the targets located at least 50 cm away from the patients (Figure 3). Saccades can be examined in both horizontal and vertical directions. The examiner should observe not only spontaneous saccades towards the two targets but also saccades that are in response to visual or auditory targets and also saccades in response to a command. During this test, the examiner should observe the saccadic eye movements and make judgements about latency, velocity, trajectory, accuracy and conjugacy of the saccades based on simple observation.

Figure 3. Saccadic eye movement assessment using a simple observational test in a typically developing 8-year-old child.

While saccadic eye movements are not frequently assessed in optometric practice, smooth pursuit eye movements receive more attention as they can be assessed during the motility test of a routine eye examination. The evaluation of smooth pursuit generally consists of holding a pen torch at 1 metre (Leigh and Zee 2015) or 50 cm (Evans 2007) from the patient's eyes and asking the patient to follow the pen torch light with the eyes, keeping the head still (Figure 4), while the pen torch light is moved slowly from the centre to the periphery (Evans 2007; Leigh and Zee 2015). The examiner should assess smooth pursuit eye movements in the horizontal, vertical and diagonal directions, and look for corrective saccades that indicate inappropriate gains. For instance, catch-up saccades indicate low-pursuit gains, and back-up saccades indicate high-pursuit gains, both suggesting poor pursuit accuracy and precision. Another available technique to examine smooth pursuit in clinical practice is the diagnostic H (Scott et al. 1995). To perform the procedure, a pen torch is held about 50–60 cm away from the patient and moved following an H-shaped pattern.

Figure 4. Smooth pursuit eye movement assessment using a simple observational test in a typically developing 12-year-old child.

The optokinetic nystagmus (OKN) is an involuntary response of the eyes to a moving stimulus. This response consists of alternating sequences of smooth pursuit where the eyes follow the moving stimulus (slow phases) and saccades that move the eyes in the opposite direction (fast phases). Using an OKN rotating drum, the characteristics of reflexive saccades and smooth pursuit eye movements can be assessed, and this assessment may be of particular use in infants, young children and individuals in whom cooperation is reduced. Abnormal, poor or absent OKN responses can indicate neurological and/or developmental conditions (eg delayed visual maturation, cerebral visual impairment or ocular motor apraxia) where a referral is essential. This event is rarely found in mainstream optometric practice and therefore is out of the scope of this review. For a comprehensive clinical review on OKN, which will be not presented and discussed here, the reader is directed to the paper by Harris (2013).

Fixation tests in clinical practice are used to evaluate the ability of the patient to maintain steady fixation on an object (Scheiman and Rouse 2005; Scheiman and Wick 2014). Fixation and its stability are assessed by asking the patient to fixate on a target and, therefore, this evaluation can be easily performed during a cover test (at distance and/or at near) or when measuring the near point of convergence or accommodation (near-fixation stability). The examiner should make judgements on how stable the eyes are and look for the presence of intrusive saccades. Next, the eyes

should be occluded one at a time to see if any abnormalities develop in response to occlusion, such as latent nystagmus (Leigh and Zee 2015). All patients except very young, inattentive, hyperactive or anxious patients should be able to maintain a stable fixation with no observable movement of the eyes for 10 seconds (Scheiman and Wick 2014).

Standardised rating systems and assessment protocols have also been developed to improve the observational evaluation of eye movements. For instance, the Southern California College of Optometry (SCCO) oculomotor test offers two quick and simple routines for testing saccades and smooth pursuits together with a simple rating scale (Barber 1995). The saccadic routine proposes the evaluation of this eye movement type only in the horizontal meridian. The targets should have a printed letter with a size corresponding to a visual acuity of approximately 6/24. In the SCCO test, the targets are situated approximately 40 cm away from the patient's eyes, separated from each other by approximately 20 cm and placed equidistantly to the patient's left and right. The examiner instructs the patient to alternate the gaze from one target to the other 10 times while keeping the head still.

During the test, the examiner should look for saccadic inaccuracies, and ratings are given 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; and 1 if the patient cannot perform the task or if latency is abnormally increased (Barber 1995).

The SCCO approach for testing smooth pursuit eye movements follows the same rating principle and target characteristics. The protocol involves placing the target 40 cm away from the patient's eyes and moving it left–right–left and up–down–up, and then following the same pattern in the two diagonal orientations. The target should be moved a total of 20 cm in a smooth manner: 20 cm in 2 seconds (Barber 1995). The patient is instructed to follow the target with the eyes and keep the head still. 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 protocol proposes to examine both saccades and smooth pursuits in monocular and binocular conditions. Any head movements that cannot be controlled by the patient are recorded as a test failure, as the patients are asked to keep their heads steady during the task.

The Northeastern State University College of Optometry (NSUCO) oculomotor test is a more comprehensive standardised direct observational eye movement test that includes standardised instructions, a scoring system, a detailed description of the target to use and normative data (Maples et al. 1992). To conduct the test appropriately, the patient should stand in front of the examiner and be presented with one target for testing smooth pursuit or two targets for testing saccades. The targets should consist of small (approximately 0.5 cm) reflective or coloured spheres mounted on a stick. When conducting this test with children, it is recommended to replace the stick-mounted coloured spheres with small toys (Maples et al. 1992).

The NSUCO oculomotor test should be conducted binocularly, and no instructions should be given to the patient about whether the head or body needs to be kept still during the test. Saccades are only tested in the horizontal meridian, and the targets are placed no more than 40 cm away from the patient's eyes and no more than 10 cm either side of the patient's midline (20 cm between targets).

The patient is asked to look from one target to another on command. This is repeated until the patient makes five round trips or 10 saccades from one target to another. For the smooth pursuit assessment, a rotational motion is performed with the target in both clockwise and anticlockwise directions, and the patient is instructed to follow the target as it is moved. Two clockwise rotations and two anticlockwise rotations are made, and a horizontal sweep through the midline of the body is made when switching from the clockwise to anticlockwise motion. The rotational path of the target should not be more than 20 cm in diameter (Maples et al. 1992). The examiner evaluates the eye movement performance in both tasks following the scoring criteria presented in Tables 2 and 3. Finally, the results obtained can be compared to the published normative values (Maples et al. 1992).

Table 2. Northeastern State University College of Optometry (NSUCO) scoring criteria for the examination of saccadic eye movements (Maples et al. 1992)

Ability (points)	Observation
1	Completes fewer 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 once or more
2	Moderate over- or undershooting noted once or more
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/body movement (points)	**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 the time)
4	Slight movement of the head or body (<50% of the time)
5	No movement of head or body

Table 3. Northeastern State University College of Optometry (NSUCO) scoring criteria for the examination of smooth pursuit eye movements (Maples et al. 1992)

Ability (points)	Observation
1	Cannot complete half-rotation in either clockwise or anticlockwise 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 fewer 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 is needed when doing pursuits?**
1	No attempt to follow the target or requires greater than 10 refixations
2	Refixations 5–10 times
3	Refixations 3–4 times
4	Refixations twice or less
5	No refixations
Head/body movements (points)	**Can the patient accomplish the pursuit 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 the time)
4	Slight movements of the head or body (<50% of time)
5	No movement of the head or body

The main concerns and criticisms of observational tests for the evaluation of eye movements are related to the subjectivity of these tests and their arguable repeatability. First, the assessment of eye movements using any observational method is still subjective, even when standardised systems are used. In addition, it is reasonable to suggest that these tests assess gross eye movement control and abilities, and that only relatively obvious eye movement deficits can be identified. Second, little is known about the repeatability of observational tests for the evaluation of eye movements. While it is reasonable to suggest that the results obtained using standardised rating systems and protocols such as the SCCO and the NSUCO are more repeatable than those obtained without these standardised methods, there are no published studies that have investigated this issue. The authors of the NSUCO test conducted several early studies after its development and proposed that this test has high interrater and test–retest repeatability (Maples and Ficklin 1991) and, therefore, provides repeatable and consistent results. However, these findings should be further validated by independent researchers.

Another important element to be considered by optometrists when assessing eye movements using observational tests is the target of choice. This is particularly important when testing children. Eye movement performance has been found to be improved in children when using cartoon pictures compared to traditional stimuli (Irving et al. 2011). In addition, more attention-grabbing and dynamic targets have been suggested to improve eye movement performance even in young adult populations (Vinuela-Navarro et al. 2017). Hence, interesting and attention-grabbing targets should be used when testing eye movements, in particular in children, to ensure that the patient's attention is maintained.

In agreement with this finding, toys or fixation sticks with highly detailed pictures or small holographic changing pictures are recommended to assess eye movements using observational methods. Alternatively, light-based stimuli, such as stimuli with flashing lights that change colour, are also extremely useful. Independent of the stimuli used, it is recommended that in order to increase the child's attention and engagement during the test, the optometrist asks questions about details of the target used.
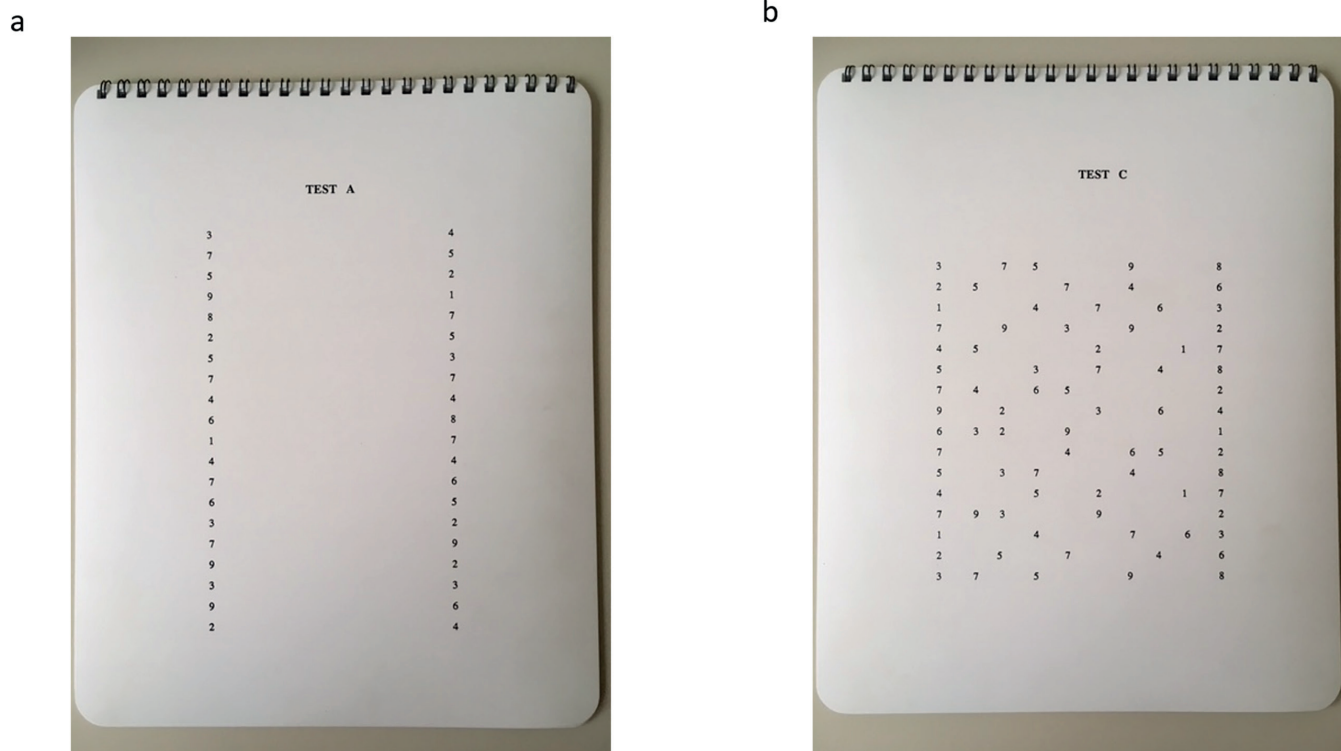
Visual–verbal tests

Visual–verbal tests have been suggested to provide an objective and quantitative examination of eye movements during a simulated reading task that involves reading a series of numbers. 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. There are several commercially available visual–verbal tests, but the developmental eye movement (DEM) test (Garzia et al. 1990) is perhaps the most widely recognised and used and, therefore, the only one described in this article.

The DEM consists of two sections: horizontal and vertical. The vertical subset, which is performed first, contains two tests with a total of 80 numbers arranged vertically (Figure 5a). The horizontal section, which follows, also has 80 numbers but these are horizontally arranged in a random spatial array simulating a reading task (Figure 5b).

Similar to other visual–verbal tests, in the DEM test, the patient is instructed to read the numbers aloud as quickly as possible, trying to keep the head steady, and without finger pointing. The examiner records the time taken by the patient to conduct each section of the test and the errors made. At the end, the total time is transformed to a value called 'adjusted time' that takes into account the number of addition errors (added numbers while reading the numbers aloud) and omission errors (skipped numbers while reading the numbers aloud).

Finally, the ratio, which is suggested to be the measure that allows the examiners to differentiate between the automaticity of naming the numbers and saccadic dysfunction, is calculated by dividing the adjusted horizontal time by the vertical time (Garzia et al. 1990). According to the developers of this test, high ratios with a high horizontal time but normal vertical time point to difficulties in the horizontal subtest only, and consequently suggest a horizontal saccadic deficiency (Garzia et al. 1990). In contrast, if both the horizontal and vertical times are increased,

Figure 5. The developmental eye movement test is a visual–verbal test designed to evaluate saccades objectively and quantitatively during a simulated task that involves reading a series of numbers. The test consists of vertical (a) and horizontal (b) sections.

the developers of the test suggest that the patient has a difficulty with the automaticity of naming numbers but not a saccadic deficiency (Garzia et al. 1990). The test provides tables with normative values for children aged 6–13 years, so that the ratio of any child examined can be then compared with the normative values (Garzia et al. 1990).

Of particular concern is the issue of test–retest variability and the possible learning effect found in the DEM test. Although the developers suggest that the test has good intrasubject test–retest reliability (Garzia et al. 1990), other authors report that not all values obtained are consistently repeatable. Moreover, the final ratio has been shown to be the least repeatable value (Rouse et al. 2004), and this finding is of significant relevance given that this parameter is used to make a diagnosis. Similarly, the validity of the DEM test for effectively identifying saccadic difficulties has been questioned, as the DEM scores and ratios seem to be poorly correlated with saccadic measurements obtained from eye movement recordings (Ayton et al. 2009) but highly correlated with reading abilities (Medland et al. 2010).

Overall, the use of visual–verbal tests such as the DEM test is not recommended by the author in the evaluation of saccadic function for two main reasons. First, it has been suggested that the results of these tests correlate well with reading performance, but not with eye movement parameters obtained with eye trackers, suggesting that they do not provide a measure of real saccadic performance. Second, these tests involve a reading task and difficulties or deficits found in eye movements during reading may reflect difficulties in non-visual aspects involved in the reading process. Hence, it could be argued that these tests may fail to differentiate between deficits in saccadic control and deficits in processing, speech and decoding. In other words, below-average scores in these tests may not indicate eye movement difficulties; therefore, these tests should be used with caution, and optometrists should be aware of their limitations.

The potential of eye tracking for clinical practice

It is important to note that some of the eye movement differences found in children with learning difficulties can potentially be undetectable during an optometric examination. A smooth pursuit deficit with abnormally low or high pursuit gain will be difficult to recognise by direct observation unless obvious intrusive saccades are observed. Similarly, saccadic difficulties will only be recognisable using observational tests when saccades are significantly slower than average or when these are largely hypermetric or hypometric. Eye trackers are the only available tools that allow us to assess eye movements objectively and quantitatively. For instance, all the findings previously described in this article regarding the characteristics of eye movements in children with learning difficulties were obtained using eye-tracking devices.

Although the use of eye trackers has historically been limited to research, these devices have the potential to be an extremely powerful tool for clinicians, ideally in the near future. Besides the steady subsequent improvement reached in terms of spatial and temporal resolution and accuracy, the most clinically relevant advance in eye tracking is perhaps the recent achievement of highly accurate and non-invasive photo- and video-based eye tracking. Briefly, the principle behind these is to use a light source, generally infrared, to illuminate the eyes and capture with cameras the reflection of the light source in the cornea (first reflection, ie Purkinje I image) and the pupil. Then, the vector formed by the angle between these reflections is calculated and used to determine the observer's gaze position (Duchowski 2007).

Eye trackers can be used to record any type of eye movements in a wide variety of conditions, such as eye movements during reading, scene exploration and a saccadic task (stimuli appearing at different screen locations). However, for the successful introduction of these technologies into clinical practice, several issues need to be addressed. First, a standardised protocol for recording eye movements containing a battery of eye movement tests should be agreed, and the related guidelines should be published and made available to clinicians. Second, normative values for eye movements using this protocol or a similar one should be published to facilitate the diagnosis of eye movement deficits. Third, the development of more user- and clinic-friendly software and eye tracker controllers that allow clinicians with limited programming experience to record and analyse the recordings is needed. Overall, if a more clinically oriented approach is achieved in the coming years as more clinicians become interested in the field, it is likely that eye trackers will be more frequently found in clinics, or at least in specialist clinics, as their performance continues to improve and as prices continue to decrease.

Conclusions

Optometrists, in particular those often working with children, should be aware of the increased risk of eye movement deficits in children with learning-related difficulties and disabilities and, therefore, should be familiar with the current clinical tests and protocols available to assess eye movements. When assessing eye movements in children, optometrists should use interesting and attention-grabbing targets, consistent recording methods or standardised scoring systems, and avoid visual–verbal tests (eg DEM). Although the use of eye trackers has historically been limited to research, the advent of non-invasive eye tracking allows for the potential of its introduction into clinical practice in the near future.

This article has addressed the development and clinical assessment of eye movements but not the treatment of eye movement deficits or disorders. It is important to note that there is a range of unconventional therapies and treatments used to treat eye movement disorders such as exercise programmes, dietary supplements and sensory processing training that may be relevant to clinical practice. Although a number of studies have reported improvements in oculomotor control and convergence in response to these treatments, the considerable methodological limitations of many of these studies need to be taken into account. Given that a

large majority of management approaches in the field of eye movement disorders do not possess a solid evidence base and thus cannot be advocated at this stage, it is recommended that optometrists take a conservative approach to the management of any eye movement deficit or disorder identified. Prior to the provision of any treatment, children with suspected eye movement disorders who are found to have a below-average or atypical eye movement performance during clinical tests should be referred to a specialist accordingly.

● Summary

This review describes the typical characteristics and development of fixational, saccadic and smooth-pursuit eye movements in children. It outlines the different eye movement characteristics found in children with learning difficulties, in order to raise optometrists' awareness of the increased risk of eye movement deficits in populations with atypical or different development. Finally, the current techniques available to evaluate fixations, saccades and smooth pursuits, including observational tests and eye tracking, are described and discussed, and recommendations are provided to support optometrists when assessing eye movements in children.

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CET multiple choice questions

This article has been approved for one non-interactive point under the GOC's Enhanced CET Scheme. The reference and relevant competencies are stated at the head of the article. To gain your point visit the College's website www.college-optometrists.org/oip and complete the multiple choice questions online. The deadline for completion is 31 December 2019. Please note that the answers that you will find online are not presented in the same order as in the questions below, to comply with GOC requirements.

1. The saccadic main sequence can be used to measure and describe the normalcy of saccades using:

- The relationship between the latency of the saccades and their amplitude

- The relationship between the dysmetria of the saccades and their amplitude

- The relationship between the duration and peak velocity of the saccades and their amplitude

- The relationship between the mean velocity of the saccades and their amplitude

2. What does the term 'saccadic dysmetria' mean?

- That saccades are slow

- That saccades are fast

- That saccades are inaccurate

- That saccades take longer to initiate

3. A smooth pursuit velocity gain of 0.6 indicates that:

- The smooth pursuit is achieved by a series of saccades

- The velocity of the eyes is higher than the velocity of the moving target

- The velocity of the eyes is lower than the velocity of the moving target

- The velocity of the eyes accurately matches the velocity of the moving target

4. Which of the following statements about the development of smooth pursuit is correct?

- Smooth pursuit eye movements achieve adult levels in early childhood

- In early infancy smooth pursuit is mainly achieved by a combination of saccades and short segments of smooth pursuit

- Smooth pursuit velocity gain remains the same between 1 and 6 years of age

- Smooth pursuit develops slowly in the first year of life

5. Which of the following statements is false about eye movements in dyslexia?

- Abnormal eye movements are potentially the cause of dyslexia and reading difficulties

- Saccades and fixations during reading are different between children with and without dyslexia

- It is still unclear whether or not eye movements during non-related reading tasks are different between children with and without dyslexia

- Recent studies suggest that individuals with dyslexia may have poor binocular control and coordination

6. Which children are at risk of eye movement deficits?

- All children

- Only children with dyslexia

- Only children with learning disabilities

- Children with learning difficulties and disabilities

● **CPD exercise**

After reading this article, can you identify areas in which your knowledge of eye movements in children has been enhanced?

How do you feel you can use this knowledge to offer better patient advice?

Are there any areas you still feel you need to study and how might you do this?

Which areas outlined in this article would you benefit from reading in more depth, and why?