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Reading ability of children treated for amblyopia

Laveniya Kugathasan[a], Marita Partanen[b], Violet Chu[a], Christopher Lyons[a], Deborah Giaschi[a,*]

[a] Department of Ophthalmology and Visual Sciences, University of British Columbia, Vancouver, British Columbia, Canada
[b] Department of Educational and Counselling Psychology, and Special Education, University of British Columbia, Vancouver, British Columbia, Canada

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ABSTRACT

Previous studies have reported compromised reading ability in children with amblyopia. Standardized psychoeducational test norms have not been used; therefore, the practical consequences of poor reading ability, such as eligibility for reading supports at school, have not been assessed. Furthermore, several studies have used atypical reading conditions such as monocular or distant viewing. It is also not clear how amblyopia treatment impacts reading ability. Thus, the goal of this study was to use standardized tests to compare binocular reading performance in children treated for amblyopia to that of a large normative sample, as well as to the types of control groups used in previous studies. Children treated for strabismic or anisometropic amblyopia (N = 14) were compared to children treated for strabismus without amblyopia (N = 12) and to children with healthy vision (N = 39). Visual acuity, stereoacuity, interocular suppression, intellectual functioning, oral single-word reading (TOWRE-2), and oral paragraph reading (GORT-5) were assessed. The control group showed significantly higher single-word reading accuracy than the amblyopia and strabismus groups. However, mean performance for all groups was within the average range of the normative sample. While mean scores were in the average range, six children (four amblyopia, two strabismus) performed below average on the single-word reading task; four of these children also showed below average paragraph reading. Reading scores were not correlated with visual acuity in the patient groups. The results raise the possibility that both strabismus and amblyopia can disrupt reading ability, even following successful treatment, to an extent that might benefit from reading supports at school.

1. Introduction

Amblyopia is a developmental visual disorder that is prevalent in 2–4% of the population (Attebo et al., 1998; McKean-Cowdin et al., 2013; Ying et al., 2014). The disorder is defined clinically as poor visual acuity that cannot be immediately corrected by lenses, in an otherwise healthy eye (Wong, 2012). It is most commonly caused by untreated eye misalignment (strabismus), uncorrected refractive error between the eyes (anisometropia), or both conditions (aniso-strabismus). Visual acuity loss, however, is only one of the many deficits caused by amblyopia, and it has the least real-world functional impact because visual acuity is usually normal in the non-amblyopic fellow eye.

Beyond visual acuity, monocular deficits in other aspects of spatial vision, such as contrast sensitivity and spatial integration, have been well established in amblyopia (Levi, 1991). There is also abundant evidence for concurrent deficits in stereopsis (Levi, 2006; McKee, Levi, & Movshon, 2003), motion perception (Aaen-Stockdale, Ledgeway, & Hess, 2007; Buckingham, Watkins, Bansal, & Bamford, 1991; Giaschi, Regan, Kraft, & Hong, 1992; Hayward, Truong, Partanen, & Giaschi, 2011; Hess, Demanins, & Bex, 1997; Ho et al., 2005, 2006; Husk, Farivar, & Hess, 2012; Meier, Sum, & Giaschi, 2016; Simmers, Ledgeway, Hess, & McGraw, 2003), oculomotor control (Chung, Kumar, Li, & Levi, 2015; Ciuffreda, Kenyon, & Stark, 1979; Gonzalez, Wong, Niechwiej-Szwedo, Tarita-Nistor, & Steinbach, 2012), and visuomotor coordination (Gnanaseelan, Gonzalez, & Niechwiej-Szwedo, 2014; Grant & Moseley, 2011; Grant, Suttle, Melmoth, Conway, & Sloper, 2014; Niechwiej-Szwedo et al., 2011; Niechwiej-Szwedo, Goltz, & Wong, 2013; Niechwiej-Szwedo, Goltz, Chandrakumar, & Wong, 2014; O'Connor, Birch, Anderson, Draper, & FSOS Research Group, 2010; Suttle, Melmoth, Finlay, Sloper, & Grant, 2011; Webber, Wood, Gole, & Brown, 2008). These deficits are often independent of the visual acuity deficit, and they frequently occur in the fellow eye (reviewed in Meier and Giaschi (2017)).

Deficits in reading ability in amblyopia have also been reported (reviewed in Webber (2018)), although the evidence is mixed. Two large prospective birth cohort studies found no association between amblyopia and reading ability (Rahi, Cumberland, & Peckham, 2006; Wilson & Welch, 2013). A small study reported a prevalence of 5% for

* Corresponding author at: Department of Ophthalmology and Visual Sciences, University of British Columbia, 4480 Oak Street, Vancouver, BC V6H 3V4, Canada.
E-mail address: giaschi@mail.ubc.ca (D. Giaschi).

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specific reading disability in amblyopia (Koklanis, Georgievski, Brassington, & Bretherton, 2006), which is within the 5–12% range reported for reading disabilities in the general population (Katusic, Colligan, Barbaresi, Schaid, & Jacobsen, 2001). Other studies found slower reading in strabismic (Kanonidou, Gottlob, & Proudlock, 2014; Kanonidou, Proudlock, & Gottlob, 2010; Stifter, Burggasser, Hirmann, Thaler & Radner, 2005a, 2005b), in anisometropic (Buczkowska & Miśkowiak, 2017; Kelly et al., 2017) or in both types of amblyopia (Kelly, Jost, De La Cruz, & Birch, 2015; Repka et al., 2008). Interpretation of this body of literature is complicated due to inconsistencies in the way in which reading was assessed, the comparison group used, and the treatment status of the participants, as reviewed below.

Skilled and efficient reading involves various cognitive and linguistic processes, including an understanding of the auditory and visual components of words as well as meaning of words. Children who are learning to read initially rely on phonological awareness (Stanovich, 1988), which is the ability to detect, manipulate, and think about the sound structure in spoken language. Orthographic skills are also important for reading development and this involves the acquisition of a mental 'dictionary' of words (Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001). Non-word reading tasks are typically used to assess phonological decoding ability, whereas reading or spelling of irregular words are used to assess orthographic skills. Reading fluency is assessed by measures of sentence or paragraph reading, and these can be conducted either aloud or silently. Oral reading fluency tasks typically include measures of reading rate and accuracy. Methods to assess reading comprehension vary, including the use of oral cloze measures (i.e., fill in the missing blank in a sentence) or answering questions about a passage that was read aloud or silently. Most previous studies of reading in amblyopia have assessed only a subset of these components of reading ability. In addition, several studies have assessed monocular reading based on the unilateral visual acuity deficit in amblyopia, but in the real world, reading is a binocular task.

Rahi et al. (2006) reported age-appropriate word identification and reading comprehension in children with amblyopia, but few details about the standardized tests used are available. Koklanis et al. (2006) used a range of standardized tests and reported that phonological awareness and word decoding were poorer in strabismic amblyopia than in anisometropic amblyopia and also in children with interocular suppression. A control group without amblyopia was not assessed. Wilson and Welch (2013) found no association between amblyopia or recovered amblyopia and binocular word reading assessed with the Burt Word Reading Test that measures reading accuracy only.

Kanonidou et al. (2010) measured monocular and binocular silent paragraph reading using excerpts from a fairy tale that were projected onto a screen that was 1.2 m from the participants. Adults with strabismic amblyopia read more slowly with either eye and binocularly relative to a control group. Comprehension of the paragraphs and phonological decoding measured with a standardized test of irregular-word reading (NART) were similar in both groups. In a subsequent study using excerpts from an encyclopedia and a viewing distance of 2 m, binocular reading became increasingly abnormal with smaller font sizes (Kanonidou et al., 2014). Kelly et al. (2015, 2017) measured binocular silent paragraph reading from a booklet at a habitual reading distance. Children with anisometropic or strabismic amblyopia read more slowly than both children with treated strabismus without amblyopia and control children with normal vision (Kelly et al., 2015). Although strabismus may interfere with reading ability (Lions, Bui-Quoc, Seassau, & Bucci, 2013; Ridha, Sarac, & Erzurum, 2014), this result suggests that amblyopia and not strabismus was the key factor in slow reading. In addition, children with anisometropic amblyopia read more slowly than children with anisometropia without amblyopia and age-matched controls (Kelly et al., 2017). In both studies, the groups did not differ in comprehension on a non-standardized test, although a few children with comprehension accuracy less than 80% were excluded from each group. These four studies were mainly concerned with the mechanisms underlying reading impairment in amblyopia (see Discussion), and measured reading rate and comprehension only.

Stifter, Burggasser, Hirmann, Thaler, and Radner (2005a, 2005b) measured oral sentence reading on a standardized German chart viewed at 25 cm. Monocular reading was slower and reading acuity, defined as the smallest print size that could be read, was poorer in amblyopic eyes relative to fellow eyes in children with microstrabismic amblyopia. Binocular reading was slower and less accurate in children with microstrabismic amblyopia relative to an age-matched control group with normal visual acuity; binocular reading acuity was similar between the groups.

Repka et al. (2008) measured rate, accuracy and comprehension on a commonly used standardized oral paragraph reading test (GORT-4) in children with mild residual amblyopia following treatment. Reading with amblyopic eyes was found to be slightly slower and less accurate compared with fellow eyes, while comprehension was similar in the two eyes. The test was conducted monocularly and used only part of the test, therefore the results could not be compared to those found in the large normative database of the GORT-4. Furthermore, a control group with healthy vision was not tested.

A recent study used a set of standardized Polish oral reading tests with children with anisometropic amblyopia (Buczkowska & Miśkowiak, 2017). The amblyopia group showed poorer single-word reading rate and phonological decoding, as well as sentence comprehension, relative to an age-matched control group.

Amblyopia is typically treated with spectacles and/or surgery to correct the factors that caused it, followed by occlusion of the fellow eye either with an eye patch or less commonly with atropine penalization or Bangerter filters. Clinically, occlusion therapy is considered to be "successful" if visual acuity of the amblyopic eye improves to within normal limits or if equal visual acuity in the two eyes is achieved. In addition to visual acuity, patching has been shown to improve other aspects of spatial vision such as contrast sensitivity and spatial integration (reviewed in Meier and Giaschi (2017)). However, stereopsis (Birch & Wang, 2009; Wallace et al., 2011) and motion perception deficits (Giaschi, Chapman, Meier, Narasimhan, & Regan, 2015) often persist in spite of improved visual acuity in response to patching in prospective studies. In addition, patients treated with patching who have recovered visual acuity may show long-term deficits in visuomotor skills (Grant & Conway, 2015). The effect of amblyopia treatment on reading ability is less clear.

One study reported that for participants whose amblyopia had resolved, defined as an interocular difference favoring the fellow eye of no more than 1 line, the amblyopic eye's reading abilities were similar to those of the fellow eye (Repka et al., 2008). Another study reported that impairment of monocular reading acuity and speed was evident in successfully treated patients with amblyopia who had no persistent visual acuity deficit (Stifter et al., 2005a). Zürcher and Lang (1980) noted that reading capacity was markedly impaired in the amblyopic eye of patients with 'cured' strabismic amblyopia. However, it is not clear how reading capacity was measured, and binocular reading was not impaired.

The National Reading Panel in the United States has suggested that assessment and treatment of reading disabilities should include a focus on phonological awareness, phonics (letter-to-sound correspondence), vocabulary, reading fluency, and reading comprehension (National Institute of Child Health and Human Development, 2000). All areas should be tested in order to identify weaknesses and plan appropriate instruction for a child with reading difficulties. There are many standardized tests that can be used to evaluate these domains (reviewed in Collins, Mudie, Inns, and Repka (2017)).

The functional impact of the reported deficits in reading in amblyopia has not been established. In a laboratory setting, children with amblyopia may perform significantly worse than control children, but this difference may be amplified by recruitment bias if the controls are above-average readers. To understand the reading ability of children treated for amblyopia compared to their peers in a school setting, it is important to use standardized tests to determine: (1) if the control participants are performing within the average range, and (2) if children with amblyopia meet the requirements to potentially require reading supports in school.

The goal of the current study was to assess binocular oral reading ability in children who had completed treatment for amblyopia (anisometropic, strabismic or aniso-strabismic) and in age-matched controls with healthy vision. Because strabismus has been linked to reading problems, we also included a group of children with no history of amblyopia who had been treated for strabismus. We used standardized word and paragraph tests to assess several components of reading, including orthographic skills, phonics, reading fluency, vocabulary and reading comprehension, in all three groups relative to the age-normed scores provided by the tests. While silent reading may be a more realistic task for older readers, oral reading tests are necessary to assess rate and accuracy. We also assessed several different aspects of vision that have been previously linked to reading ability, including visual acuity, stereoacuity, interocular suppression, and global motion perception.

2. Methods

2.1. Participants

The study consisted of three participant groups within the age range of 7–17 years: (1) a control group with healthy vision, (2) a strabismus group without amblyopia, and (3) an amblyopia group. Informed consent was first obtained from the parents or guardians of all children/youth who participated in this research, followed by assent from the participants. This work was carried out in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki).

2.1.1. Control group

For the control group, we recruited 49 participants who had been schooled and were fluent in English, and reported no visual, auditory, developmental or cognitive impairments, from the community around BC Children's Hospital. Inclusion in the study required: (1) best-corrected monocular visual acuity in each eye of at least 0.2 logMAR or better, measured from 6 m on the Regan high-contrast letter chart (Regan, 1988) and from 30 cm on the University of Waterloo Near Vision card (Cho & Woo, 2004) with credit given to each letter correctly read, (2) stereoacuity better than or equal to 60 arcsec on the Randot Preschool Stereoacuity Test (Birch et al., 2008; Stereo Optical Co., Inc., Chicago, IL), (3) intellectual functioning at or above the 16th percentile, as described below, and (4) reading performance at or above the 16th percentile on all five reading measures, as described below. Three participants were excluded due to poor vision, four due to below average performance on the intellectual functioning tasks, and three due to below average performance on the reading tasks. Data from a total of 39 control participants were included in the data analysis (*M* age = 12.11, *SD* = 2.92, *range* = 7.15–17.28, 21 females).

2.1.2. Patient groups

We recruited 15 participants with treated amblyopia and 12 participants with treated strabismus, and no developmental, cognitive or additional visual disorders (although one child was born at 31 weeks gestation; see Table 2), from the Ophthalmology Clinic at BC Children's Hospital. The initial pre-treatment diagnosis of amblyopia or strabismus was made by a pediatric ophthalmologist. Amblyopia was typically defined as a minimum two-line difference in Snellen acuity (0.2 logMAR specified as whole-line acuity) between the eyes, with a best-corrected visual acuity of 0.2 logMAR or worse in the amblyopic eye and within the normal range for age in the fellow eye. The upper limit for normal visual acuity was 0.5 logMAR for ages younger than 3 years, 0.4 logMAR for age 3 years, 0.2 logMAR for ages 4–6 years, and 0.1 logMAR for ages 7 and older (Drover et al., 2008; Pan et al., 2009). A participant was considered to have anisometropic amblyopia if their visual acuity loss was accompanied by a spherical equivalent difference between the eyes ≥1 diopter or an astigmatic difference ≥1.5 diopter in the absence of any ocular manifest deviation (Weakley, 2001). The amblyopia subtype was considered to be strabismic if it occurred in the presence of either a heterotropia at distance and/or near or a history of strabismus surgery (Pediatric Eye Diseases Investigator Group, 2003). Aniso-strabismic amblyopia was diagnosed if the participant met criteria for both anisometropic and strabismic amblyopia. Participants in the strabismus group met the above criteria for strabismus, but had no history of amblyopia.

One participant with amblyopia was excluded from analysis due to below average performance on the intellectual functioning tasks described below. Clinical characteristics of the 14 amblyopia participants (*M* age = 11.10, *SD* = 2.87, *range* = 7.41–16.35, 7 females) and the 12 strabismus participants (*M* age = 12.52, *SD* = 2.72, *range* = 8.70–16.49, 5 females) are listed in Tables 1 and 2, respectively. Five participants were classified with anisometropic amblyopia,[1] six with strabismic amblyopia, and three with aniso-strabismic amblyopia. At the time of study participation, participants were at least 3 years older than their diagnosis age. Most participants in the amblyopia group had completed occlusion therapy at the time of participation in the current study, but two participants were nearing the end of treatment; some participants still showed a 2-line difference in visual acuity following treatment, but others with a good treatment outcome no longer showed this difference (see Table 1, post-treatment Test Visit). The strabismus group comprised two participants with infantile esotropia, five with accommodative esotropia, and five with intermittent exotropia.

2.2. Testing protocol

During a 90-minute session, participants completed tests of near and distance visual acuity and stereoacuity, as described above in Section 2.1.1, and interocular suppression, intellectual functioning, and reading ability, as described in the next sections. Participants were given breaks as needed to minimize fatigue. Both cognitive and reading tests were standardized tests that provided norms according to the participant's age; this ensured a comparison between participant groups and population data. The cognitive and reading tasks also show evidence of adequate validity and reliability (Torgesen, Wagner, & Rashotte, 2012; Wiederholt & Bryant, 2012; Woodcock, McGrew, & Mather, 2001, 2007). Near visual acuity was measured because the cognitive and reading tasks were performed at near; distance visual acuity was measured for comparison with previous studies and with diagnostic information in the patient groups.

2.2.1. Interocular suppression evaluation

Interocular suppression was measured with a dichoptic global motion task (Hess, Mansouri, & Thompson, 2010a, 2010b) that we previously adapted for use with children (Narasimhan, Harrison, & Giaschi, 2012). The stimulus was generated using a Macintosh Pro Quad-Core Intel Xeon computer. Participants discriminated the left/right direction of random dot kinematograms while wearing eMagin Z800 3D visor virtual reality goggles. The kinematograms consisted of 100 white dots moving at a speed of 4.4°/s on a homogenous mid-grey background. The number of coherent signal dots and random motion noise dots was adjusted with a staircase procedure to first determine a binocular motion coherence threshold. Next, interocular suppression was measured by determining the contrast level at which the noise dots

[1] Participant A2 showed only a 1-line difference in visual acuity when first seen in our clinic, but they had a history of amblyopia, met the definition for anisometropia, and received occlusion therapy for amblyopia.

Table 1
Clinical history of participants with amblyopia.

ID	Diagnosis	Diagnosis Information (pre-treatment)				Recent Clinical Assessment (post-treatment)				Test Visit (post-treatment)				
		Amblyopic Eye	Age (years)	Distance Visual Acuity (logMAR)		Optical Correction	Deviation (Prism Diopters)		Treatment Type	Age (years)	Distance Visual Acuity (logMAR)		Stereoacuity (arc sec)	Treatment Status
				OD	OS		Near	Distance			OD	OS		
A1	A	Left	4.87	+0.3	+0.6	OD: −3.75 OS: −1.50–2.25 × 165	Orthotropic	Orthotropic	Patching	8.86	−0.025	+0.025	40	C
A2	A	Right	4.39	+0.3	+0.2	OD: +2.50 OS: +0.50 + 0.25 × 90	Orthotropic	Orthotropic	Patching	10.48	+0.338	+0.050	100	C
A3	A	Left	Not available	Not available	Not available	OD: +0.75 OS: +3.25	Orthotropic	Orthotropic	Patching	12.34	−0.138	−0.038	40	C
A4*	A	Left	4.42	0.0	+0.6	OD: +1.00 + 1.00 × 90 OS: plano + 4.25 × 85	Orthotropic	Orthotropic	Glasses	14.08	−0.088	+0.213	40	C
A5*	A	Left	3.18	0.0	+1.0	OD: −0.25 + 0.75 × 80 OS: +1.75 + 2.50 × 95	Orthotropic	Orthotropic	Patching	10.00	−0.088	+0.125	100	C
A6	A + S (accommodative esotropia)	Left	2.99	0.0	+0.6	OD: +0.75 + 1.00 × 20 OS: +3.25 + 2.25 × 135	6	6–8	Patching & Atropine	12.97	0.000	+0.413	800	C
A7	A + S (accommodative esotropia)	Right	3.43	+0.6	+0.2	OD: +4.25 + 1.00 × 83 OS: +2.50 + 0.50 × 93	Orthotropic (with glasses)	Orthotropic (with glasses)	Patching	8.13	+0.200	−0.088	100	C
A8	A + S (congenital exotropia)	Right	1.52	+0.4	0.0	OD: +6.75 + 1.00 × 60 OS: +5.00 + 0.75 × 130	2	6	Patching & Surgery	16.35	+0.013	−0.063	800	C
A9	S (esotropia)	Right	4.95	+0.3	0.0	OD: +4.75 + 3.00 × 100 OS: +4.25 + 3.00 × 100	5	2–5	Patching & Surgery	8.88	+0.288	+0.013	> 800	P
A10	S (accommodative esotropia)	Left	6.15	+0.2	+0.5	OD: +4.50 + 3.50 × 80 OS: +5.25 + 3.50 × 90	2–3	0	Patching	15.44	−0.075	+0.350	400	C
A11*	S (accommodative esotropia)	Left	5.49	+0.1	+0.3	OD: +5.75 + 1.50 × 95 OS: +6.00 + 2.50 × 70	4	4	Patching	12.58	−0.025	+0.200	400	C
A12	S (accommodative esotropia)	Left	5.02	0.0	+0.5	OD: +1.00 OS: +1.00	0	18	Patching	8.08	−0.025	+0.313	> 800	P
A13*	S (partially accommodative esotropia)	Left	4.31	0.0	+0.2	OD: +2.25 + 1.00 × 95 OS: +2.75 + 0.75 × 100	14	6	Patching, Atropine, & Surgery	9.86	0.000	+0.088	> 800	C
A14	S (infantile esotropia)	Left	0.84	+0.5	+0.7	None	2	4–6	Patching & Surgery	7.41	+0.13	+0.213	> 800	C

Note: Subtypes: A = anisometropic amblyopia, A + S = aniso-strabismic amblyopia, S = strabismic amblyopia. OD = right eye, OS = left eye. Treatment status: C = completed treatment, P = occlusion still in progress. orthotropic = no measurable deviation.

* Participant scored below the 16th percentile on at least one reading measure.

Table 2
Clinical history of participants with strabismus.

ID	Diagnosis	Diagnosis Information (pre-treatment)				Recent Clinical Assessment (post-treatment)				Test Visit (post-treatment)			
		Affected Eye	Age (years)	Distance Visual Acuity (logMAR)		Optical Correction	Deviation (Prism Diopters)		Surgery?	Age (years)	Distance Visual Acuity (logMAR)		Stereoacuity (arc sec)
				OD	OS		Near	Distance			OD	OS	
S1	accommodative esotropia	Right	3.56	+0.1	+0.1	OD: +4.25 OS: +5.00	30	18	No	9.48	+0.200	+0.038	> 800
S2[+]	accommodative esotropia	Right	5.92	0.0	0.0	OD: +3.50 + 0.25 × 90 OS: +2.25 + 0.75 × 80	10	0	No	13.79	−0.125	−0.175	40
S3[*]	accommodative esotropia	Left	3.20	+0.1	+0.1	OD: +3.00 + 1.50 × 135 OS: +2.75	6	8	Yes	9.46	+0.100	+0.038	> 800
S4	accommodative esotropia	Left	2.84	0.0-	+0.1	OD: +2.25 + 0.75 × 100 OS: +2.25 + 0.75 × 110	16	6	No	8.70	+0.038	+0.100	800
S5	partially accommodative esotropia	Right	2.83	0.0	+0.1	OD: +3.25 + 1.25 × 40 OS: +3.75 + 1.75 × 160	4	4	No	14.72	−0.088	−0.075	> 800
S6	infantile esotropia	Right	2.38	+0.3	+0.3	OD: +0.75 + 1.50 × 95 OS: +1.00 + 0.50 × 90	30	20	Yes	13.83	−0.150	+0.150	> 800
S7	infantile esotropia	Right	0.41	+0.3	+0.2	None	8	6	Yes	8.79	−0.063	+0.050	> 800
S8	intermittent exotropia	Right	3.58	+0.1	0.0	OD: −4.25 + 1.00 × 15 OS: −5.00 + 1.00 × 75	12	25	Yes	14.07	−0.050	+0.063	60
S9	intermittent exotropia	Left	6.36	0.0	0.0	None	12	20	No	14.87	−0.175	−0.163	40
S10	intermittent exotropia	Right	3.15	+0.2	+0.2	OD: −6.50 + 1.75 × 115 OS: −6.50 + 2.25 × 115	35	50–60	Yes	16.49	+0.050	−0.100	60
S11[*]	intermittent exotropia	Left	6.62	0.0	0.0	None	4	20	No	14.04	−0.050	+0.050	40
S12	intermittent exotropia	Right	5.16	0.0	0.0	None	12	20	No	12.01	+0.175	+0.138	40

Note: Subtypes: OD = right eye, OS = left eye.
[*] Participant scored below the 16th percentile on at least one reading measure.
[+] Participant was born prematurely at 31 weeks gestation without retinopathy of prematurity.

interfered with direction discrimination of the signal dots under dichoptic viewing. Coherence was set at the threshold level determined in the first step; signal dots were presented to the amblyopic/worse eye at 100% contrast. Noise dots were presented to the fellow/better eye with increasing contrast according to a staircase procedure to determine a dichoptic contrast interference threshold. Greater procedural detail can be found in Narasimhan et al. (2012).

All but the first 12 participants tested also completed a second interocular suppression task that used competing eye charts presented to each eye. This task has been validated in children (Birch et al., 2016), and in people with amblyopia (Kwon, Wiecek, Dakin, & Bex, 2015). The stimuli were generated using a Macintosh G4 computer and presented on a ViewSonic Graphic series G225f CRT monitor with a refresh rate of 120 Hz. Dichoptic presentation was achieved through liquid crystal shutter glasses (RealD Crystal Eyes 4s) synchronized to the computer. Each line of the eye charts contained five letters, and at each position the identity of the letter and its contrast varied independently for each eye. Participants were instructed to name the letters from left to right. A balance point was obtained, ranging from 0.5 (equally balanced) to 1.0 (complete suppression), based on the relative amount of contrast presented to each eye for the participant to report seeing 50% of the letters in each eye.

2.2.2. *Intellectual functioning screening*

Intellectual functioning screening consisted of two standardized subtests from the Woodcock-Johnson® III Tests of Cognitive Abilities (WJ III COG; Woodcock et al., 2001, 2007). The Verbal Comprehension Test included four sections that tested knowledge about language development in the English language, including vocabulary, understanding of verbal relationships, and verbal reasoning. The Concept Formation Test evaluated the fluid reasoning and executive processing capabilities of the participant, by having them identify and apply rules underlying patterns. Each participant's raw score was transformed into a standard score (M = 100, SD = 15) based on their chronological age; this was conducted in the WJ III COG software. Participants from any of the three participant groups were excluded from the analyses if they obtained a standard score below 85 (i.e., the 16th percentile, which is 1 standard deviation below the normative mean) on either subtest as it suggests possible impairment in intellectual functioning.

2.2.3. *Reading evaluation*

Reading ability was evaluated using two different individually-administered, norm-referenced standardized oral reading tests. The Test of Word Reading Efficiency Second Edition (TOWRE-2; Torgesen et al., 2012) evaluates single-word reading ability, specifically measuring the speed and accuracy of two different word-reading skills. The Sight Word Efficiency task consists of a list of real words that increase in difficulty and it examines the ability to recognize familiar words in a fluent and efficient manner. The Phonemic Decoding Efficiency task consists of a list of pronounceable nonwords using English language rules; it examines the ability to decode and blend sounds to identify a novel word. For each task, the participant is instructed to read aloud as many words as possible in 45 s. The number of words read correctly was converted into a standard score (M = 100, SD = 15) based on the participant's age; this was calculated from the TOWRE-2 manual.

The Gray Oral Reading Tests Fifth Edition (GORT-5; Wiederholt & Bryant, 2012) evaluates paragraph reading ability, specifically measuring rate, accuracy, and comprehension. Fluency, which is a composite measure of rate and accuracy, was not calculated because our focus was on component reading abilities. The test consists of 16 passages of increasing difficulty and each passage is followed by five verbally-presented comprehension questions. The starting passage is

Table 3
Summary statistics for the vision measures – mean (standard deviation).

Vision Variable	Control Group	Strabismic Group	Amblyopia Group	F statistic	*p*-value	Effect size (*f*)
Distance VA – AE (logMAR)	−0.09 (0.07)	+0.02 (0.12)	+0.20 (0.14)	F(2, 62) = 43.116	< .001	1.04 (large)
Distance VA – FE (logMAR)	−0.13 (0.05)	−0.02 (0.11)	−0.03 (0.07)	F(2, 62) = 16.852	< .001	0.65 (large)
Near VA – AE (logMAR)	−0.04 (0.07)	+0.06 (0.17)	+0.21 (0.20)	F(2, 62) = 20.909	< .001	0.70 (large)
Near VA – FE (logMAR)	−0.06 (0.06)	−0.03 (0.07)	+0.02 (0.12)	F(2, 62) = 5.683	.005	0.39 (medium)
Stereoacuity (arc sec)	40 (0)	757 (774)	659 (668)	F(2, 62) = 17.362	< .001	0.68 (large)
Motion Suppression (%)	84 (18)	66 (26)	68 (26)	F(2, 56) = 4.603	.014	0.36 (medium)
Letter Suppression	0.58 (0.06)	0.73 (0.17)	0.77 (0.14)	F(2, 50) = 16.141	< .001	0.68 (large)
Global Motion (% coherence)	18 (16)	26 (26)	33 (32)	F(2, 59) = 2.394	.100	0.25 (medium)

Note: AE = amblyopic eye, FE = fellow eye.

determined by the child's grade at school. The time taken to read each passage aloud and the number of words pronounced correctly when reading the passage are recorded. The GORT-5 provides results in scaled scores ($M = 10$, $SD = 3$); this is calculated from the GORT-5 manual based on the participant's age.

The GORT-5 paragraphs are printed in an age-appropriate font size that decreases with the difficulty of the paragraph. The smallest font used during the reading evaluation was 12 pt (logMAR: 0.70, Snellen acuity: 20/100 at a typical reading distance of 35 cm). The words on the TOWRE-2 task are printed in a larger font size (19 pt).

Reading scores below the 16th percentile (1 standard deviation [SD] below the mean) were considered to be "below average" as this is the cutoff that is commonly used in educational research (Allor, 2002; Catts, Nielsen, Bridges, & Liu, 2016; Cohen-Mimran & Sapir, 2007). The DSM-5 considers 1 SD to be a "lenient" threshold, as long as learning difficulties are supported by converging evidence from clinical assessment, academic history, school reports or test scores.

2.3. Data analysis

One-way ANOVA was used to test for group differences on the measures of Age, Verbal Comprehension, Concept Formation, Distance Visual Acuity (VA), Near VA, Stereoacuity, Global Motion Coherence, Motion Suppression, and Letter Suppression. Effect size was indexed by Cohen's f for each ANOVA. This was followed up with Games-Howell post-hoc tests because homogeneity of variance was violated for most variables. For the monocular measures, the amblyopic, strabismic or eye with lowest visual acuity were grouped together (labelled AE), and the fellow or eye with best visual acuity were grouped together (labelled FE). For analysis, a score of 1600 arcsec was assigned to participants in the amblyopia and strabismus groups for whom stereoacuity was not measurable on the Randot Preschool test.

Multiple linear regression was used to model the contribution of the vision variables to each of the five reading measures (TOWRE-2 [Sight Word Efficiency, Phonemic Decoding Efficiency], GORT-5 [Rate, Accuracy, Comprehension]). None of the models was significant (F values ranged from 1.052 to 1.658); therefore, no covariates were used in the one-way ANOVAs for each of the reading measures. These were followed by Scheffé comparisons due to the flexibility of defining all simple and complex contrasts with this method. A correct basal was not obtained for one control participant on the GORT-5 and therefore a standardized score could not be calculated; this resulted in 38 controls included for the GORT-5 analyses.

Correlation analyses among the vision and reading measures were conducted for the full group of participants and for the amblyopia plus strabismus groups.

3. Results

The three groups did not differ in age, $F(2, 62) = 0.900$, $p = .412$. Furthermore, age was accounted for in the standardized scores on the reading tests, and the standard deviation of the reading scores in our sample were similar to the published norms for the tests; therefore, age was not considered in the subsequent analyses. The groups showed similar Verbal Comprehension standard scores, $F(2, 62) = 0.249$, $p = .781$, $f = 0.09$ (control group [$M = 107.05$, $SD = 10.65$]; strabismus group [$M = 109.00$, $SD = 9.80$]; amblyopia group [$M = 106.29$, $SD = 8.91$]), and Concept Formation standard scores, $F(2, 61) = 0.245$, $p = .783$, $f = 0.09$ (control group [$M = 109.89$, $SD = 9.68$]; strabismus group [$M = 112.08$, $SD = 9.00$]; amblyopia group [$M = 109.64$, $SD = 12.11$]). Therefore, the intellectual functioning measures were not considered further.

3.1. Vision

A significant main effect of group was found for all of the dependent vision variables except Global Motion Coherence (Table 3).

Post-hoc comparisons showed that distance VA of the worse/affected eye was significantly better in the control group than in the amblyopia group ($p < .001$) and the strabismus group ($p = .028$), and better in the strabismus than the amblyopia group ($p = .005$). Distance VA of the better/fellow eye was significantly better in the control group than in the amblyopia group ($p < .001$) and in the strabismus group ($p = .016$); the amblyopia and strabismus groups did not differ ($p = .956$). Near VA of the worse/affected eye was significantly better in the control group than in the amblyopia group ($p = .001$). There were no other significant group differences, and no post-hoc comparisons of near VA of the better/fellow eye reached significance (all p's $> .05$).

For the binocular vision measures, stereoacuity was significantly better in the control group than in the amblyopia ($p = .011$) and strabismus groups ($p = .021$); the amblyopia and strabismus groups did not differ ($p = .937$). Although a significant main effect of group was found for motion suppression, as quantified by a contrast interference threshold, no post-hoc pairwise comparisons reached significance (all p's $> .05$). For letter suppression, expressed as a contrast balance ratio, the control group had significantly less suppression compared to the amblyopia group ($p = .003$) and the strabismus group, although the latter difference did not reach significance ($p = .058$). The amblyopia and strabismus groups did not differ ($p = .835$).

3.2. Single-word reading

Group means and individual scores on the TOWRE-2 tasks are shown in Fig. 1. There was a significant main effect of group for Sight Word Efficiency, $F(2, 62) = 4.590$, $p = .014$, $f = 0.36$ (Fig. 1A). Post-hoc follow-ups using Scheffé's method revealed that the control group performed significantly better than the average of the amblyopia and strabismus groups ($p < .05$). The amblyopia and strabismus groups demonstrated similar performance ($p = .998$). The effect of group approached significance for Phonemic Decoding Efficiency, $F(2, 62) = 2.698$, $p = .075$, $f = 0.28$ (Fig. 1B). Note our sample size provided adequate power ($\beta = 0.80$) to detect a medium effect size of $f = 0.39$ ($\alpha = 0.05$). Removal of the child born prematurely did not

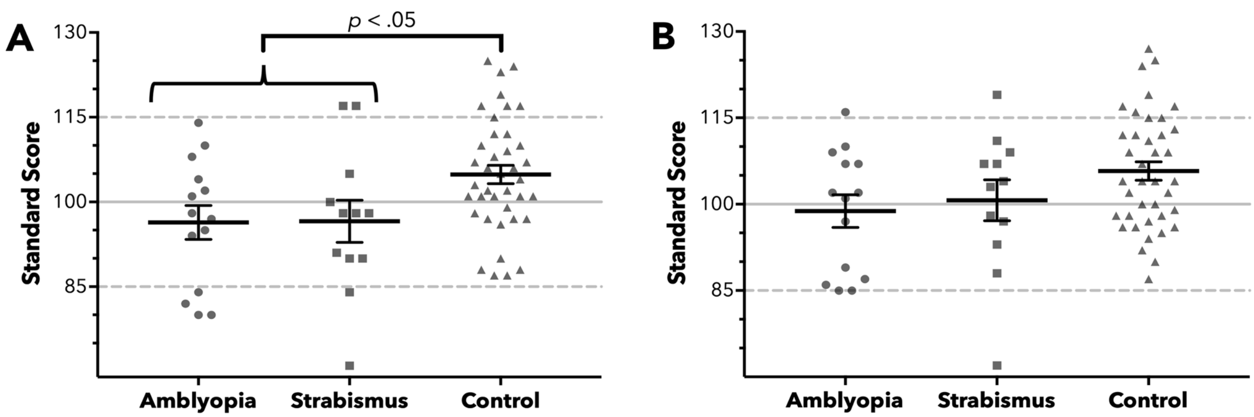

Fig. 1. Mean standard scores for Sight Word Efficiency (A) and Phonemic Decoding efficiency (B) on the TOWRE-2 Reading Test. The solid lines show the normed mean (100); the dotted lines show one standard above (115) and one standard deviation below (85) the mean. Error bars indicate standard error.

change the pattern of results. Importantly, the mean performance of all three groups was within the normed average range (± 1 standard deviation) for each task.

When the performance of individual participants was examined, four participants in the amblyopia group (2 anisometropia, 2 strabismus) and two in the strabismus group (1 intermittent exotropia, 1 accommodative esotropia) performed below the average range (16th percentile, standard score of 85) on the Sight Word Efficiency task. These individuals are marked with an asterisk in Tables 1 and 2. One of these participants (S3) also showed below average performance on the Phonemic Decoding Efficiency task. This participant and A11 were receiving reading supports at school.

Chi-square analysis indicated that the number of participants scoring below the 16th percentile was not significantly higher than would be expected based on this criterion for the amblyopia (4/14; $\chi^2 = 0.84$, $p = .36$), strabismus (2/12; $\chi^2 = 0.00$, $p \geq .99$) or control group (3/49; $\chi^2 = 2.56$, $p = .11$).

3.3. Paragraph reading

Group means and individual scores on the GORT-5 measures are shown in Fig. 2. No significant group differences were observed for GORT-5 rate ($F(2, 61) = 0.300$, $p = .742$, $f = 0.09$), accuracy ($F(2, 61) = 2.125$, $p = .128$, $f = 0.21$) or comprehension ($F(2, 61) = 1.252$, $p = .293$, $f = 0.19$), although the amblyopia group mean was lower than that of the other groups on all three measures. Removal of the child born prematurely did not change the pattern of results. The mean performance of all three groups was within the normed average range for all three measures.

When the performance of individual participants was examined, four of the participants who performed below average on the TOWRE-2 tasks also performed below average on at least one GORT-5 measure. S3 scored below average on all three measures, A4 and A5 on accuracy and comprehension, and A13 on comprehension only. An additional four participants (A7, A12, A14, S2) had received reading supports at school, but performed within the average range on all reading measures.

3.4. Correlations

In the full set of participants, distance visual acuity of the worse eye showed a weak but significant correlation with scores from TOWRE-2 Sight Word Efficiency ($r = -0.315$, $p = .011$) and GORT-5 Accuracy ($r = -0.262$, $p = .036$). The interocular difference in distance visual acuity (fellow/best eye – amblyopic/worse eye) was significantly correlated with TOWRE-2 Sight Word Efficiency ($r = -0.280$, $p = .024$) and GORT-5 Accuracy ($r = 0.255$, $p = .042$). The interocular difference in near visual acuity was correlated with GORT-5 Accuracy ($r = -0.268$, $p = .032$). None of these correlations was significant in the amblyopia plus strabismus groups ($p > .05$). All four of the children in the amblyopia group with poor reading skills had improved visual acuity following occlusion therapy; two no longer met the clinical definition for amblyopia and two were still mildly amblyopic.

Stereoacuity, Motion Suppression, and Letter Suppression were not significantly correlated with any of the reading measures in the full set of participants or in the patient groups (all p’s $> .05$). Four of the six participants with poor reading skills also had poor stereoacuity (Tables 1 and 2). All six showed interocular suppression that was at least one standard deviation higher than the mean for the control group on at least one of the two suppression tasks. Global Motion Coherence was significantly correlated with TOWRE-2 Phonemic Decoding ($r = -0.294$, $p = .02$) and GORT-5 Rate ($r = -0.311$, $p = .015$).

4. Discussion

Our main finding is that 4 out of the 14 (29%) participants with amblyopia and 2 out of the 12 (17%) participants with strabismus showed below average binocular oral reading performance. The main component of reading disrupted was single-word accuracy, although phonemic decoding, as well as paragraph rate, accuracy and comprehension were also affected in some children.

4.1. Components of reading

No previous study has assessed this set of component English reading skills and evaluated them using standardized scores. Studies that reported no association between amblyopia and reading, tested only one or two components of reading (Rahi et al., 2006; Wilson & Welch, 2013). Only single-word accuracy was significantly different between our patient and control groups (although the study may have been underpowered to detect group differences for the reading tasks that showed small effect sizes); thus, it seems important to assess a range of skills. Deficits in accuracy for sentence reading have been reported previously (Repka et al., 2008; Stifter et al., 2005b). Other studies used silent reading with a non-standardized test that could not be used to assess reading accuracy (Kanonidou et al., 2010, 2014; Kelly et al., 2015, 2017).

Several previous studies reported slower reading in amblyopia (Buczkowska & Miśkowiak, 2017; Repka et al., 2008; Stifter et al., 2005a, 2005b). Our results appear to be inconsistent with this finding because we did not observe deficits in reading rate on the GORT-5 in any of the participants with amblyopia. However, the TOWRE-2 is a speeded reading test that does not directly assess reading rate, but for which the instructions are to read as quickly as possible. Deficits in

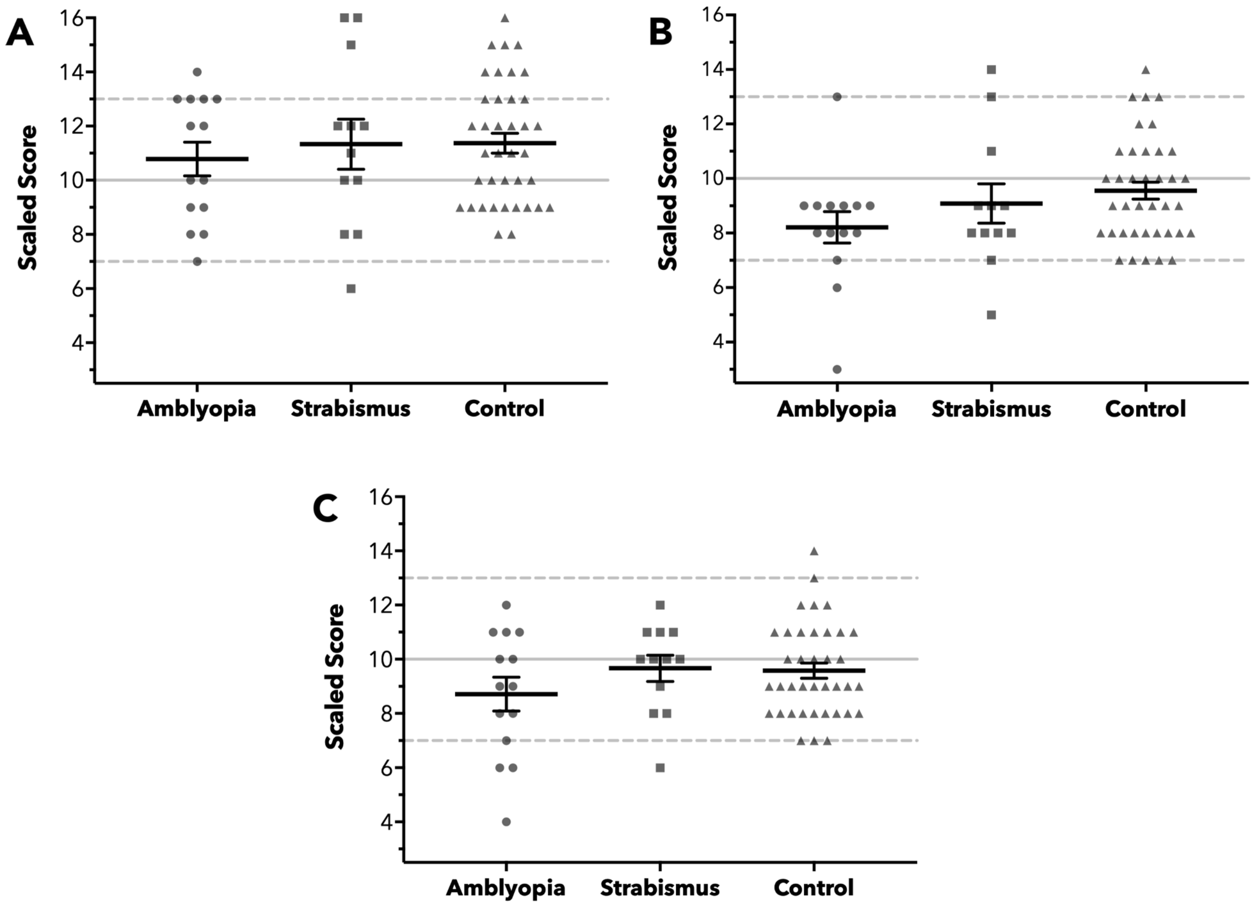

Fig. 2. Mean scaled scores for rate (A), accuracy (B), and comprehension (C) on the GORT-5 Paragraph Reading Test. The solid lines show the normed mean (10); the dotted lines show one standard above (13) and one standard deviation below (7) the mean. Error bars indicate standard error.

reading accuracy in our study may have emerged because the participants were pushed to read more quickly than their comfortable rate. In addition, similar instructions for the GORT-5 may have encouraged rapid reading at the expense of both accuracy and comprehension for select participants in our study. However, we still might expect to see slower oral paragraph reading in the amblyopia group relative to the control group. Another potential explanation could be the use of scaled scores in the GORT-5 which provide a coarser range of scores than the standard scores used on the TOWRE-2 (compare Figs. 1 and 2).

A recent study involving Polish readers identified deficits in phonological decoding in children with anisometropic amblyopia (Buczkowska & Miśkowiak, 2017). An earlier study reported that phonological awareness and word decoding were poorer in strabismic amblyopia than in anisometropic amblyopia, but a control group was not assessed (Koklanis et al., 2006). However, phonological decoding was found to be within the normal range on a standardized test in adults with strabismic amblyopia (Kanonidou et al., 2010, 2014). The group difference in word decoding was not significant in our sample, and we found a decoding deficit in only one child with strabismus.

Most studies, including ours, have found no group deficit in reading comprehension (Kanonidou et al., 2010, 2014; Kelly et al., 2015, 2017; Repka et al., 2008). A previous report of disrupted reading comprehension in amblyopia required participants to break a string of words into two meaningful sentences (Buczkowska & Miśkowiak, 2017), but this is not a typical task for measuring comprehension. Comprehension on a standard reading task was below average in four of our participants with below average reading accuracy.

4.2. Comparison groups

Although we observed some differences in reading ability between the patient and control groups, the mean performance of all three groups on all five reading measures was within the average range. Previous studies were not designed to assess this possibility, but our findings suggest that it is not sufficient to only compare amblyopia and control groups because this may overestimate the functional impact of amblyopia on reading. Similarly, the practical importance of monocular reading deficits (Repka et al., 2008; Stifter et al., 2005a; Zürcher & Lang, 1980) has yet to be determined.

Reading ability was similar in our amblyopia and strabismus groups on the TOWRE-2 single-word tests. Kelly et al. (2015) also tested a comparison group of children with treated strabismus and found silent paragraph reading ability that was similar to that of an age-matched control group. The discrepant findings with our study could be due to the reading task; our strabismus group was similar to the controls on the oral paragraph test, although one child had below average performance. In addition, our strabismus group included exotropia and esotropia with no history of amblyopia, while in the earlier study, all participants had small angle esotropia and 15 of 23 had been successfully treated for amblyopia. The poor readers in our strabismus group had poor stereoacuity and/or abnormal interocular suppression, while Kelly et al. (2015) recruited strabismus participants for whom both eyes were working together. A previous study reported a link between poor reading and interocular suppression in strabismic amblyopia (Koklanis et al., 2006), thus disrupted reading may be linked to disrupted binocularity as suggested for children with reading difficulties without amblyopia (Niechwiej-Szwedo, Alramis, & Christian, 2017).

4.3. Mechanisms of reading disruption in amblyopia

Our study was not designed to investigate the mechanisms underlying disrupted reading in amblyopia. However, we can probably rule our poor visual acuity as the main causal factor. None of our five measures of reading ability was correlated with visual acuity or with the interocular difference in visual acuity in the participants with amblyopia or strabismus. This is consistent with the results of most previous studies (Buczkowska & Miśkowiak, 2017; Kanonidou et al., 2014; Kelly et al., 2015). In addition, our reading tasks were performed binocularly with sufficiently large font size. The smallest font (0.70 logMAR) was larger than the smallest font that should be resolvable by our participant with the worst near visual acuity in their amblyopic eye (0.56 logMAR). Furthermore, this participant with the poorest monocular visual acuity exhibited average reading ability.

Several other mechanisms for disrupted reading in amblyopia have been proposed, including crowding, central suppression scotomas and oculomotor dysfunction. Crowding is the negative effect of nearby contours on object recognition. Levi, Song, and Pelli (2007) concluded that crowding, not visual acuity, limits reading performance in amblyopia. The critical letter spacing for reading a stream of words was found to be the same as the critical spacing for identifying a crowded letter in both the central and the peripheral retina in adults with amblyopia. Kanonidou et al. (2010) observed more regressive saccades and longer fixation durations during silent paragraph reading in adults with strabismic amblyopia. It was suggested that these abnormal eye movement patterns were adaptation strategies to compensate for increased crowding and the presence of suppression scotomas. A subsequent study by the same researchers (Kanonidou et al., 2014), found normal binocular reading speeds for larger fonts, but more saccades per line (both forward and regressive) relative to a control group. These abnormal eye movements were not consistent with a crowding explanation.

Kelly and colleagues found that slower silent paragraph reading in children with strabismic (Kelly et al., 2015) or anisometropic amblyopia (Kelly et al., 2015, 2017) was associated with increased forward saccades relative to age-matched control groups. The increase in saccades was attributed to suppression scotomas or to fixation instability. Slow reading in anisometropic amblyopia was shown to be related to fixation instability of the fellow eye (Kelly et al., 2017).

The deficits we observed in single-word reading and interocular suppression in children with amblyopia or strabismus are consistent with the previously proposed mechanisms of fixation instability and suppression scotomas. We cannot rule out crowding as a contributing factor (Song, Levi, & Pelli, 2014), although the TOWRE-2 font is larger and more widely spaced than that of the GORT-5 for which fewer deficits were seen. Abnormal saccadic eye movements should not be a factor in single-word reading. Further experimentation is required to confirm the mechanisms responsible for our results.

4.4. Relationship to learning disabilities

The incidence of reading deficits we observed in children with amblyopia (29%) or strabismus (17%) was higher than that observed in our control group before exclusions (7%), and higher than the prevalence of learning disabilities specific to reading in the general population (5–12%; Katusic et al., 2001). However, the incidence of reading deficits in all three groups did not differ from expectations based on our 16th percentile criterion. It is unclear, therefore, whether the reading deficits we observed were due to the visual developmental disorder or to a learning disability. Most of the children with poor reading skills exhibited a visual disorder before they were of reading age. In addition, verbal comprehension was within the average range for all participants, but children with reading difficulties often show poor performance on vocabulary tasks (Ricketts, Nation, & Bishop, 2007; Rose & Rouhani, 2012). Taken together it is possible that the reading deficits we observed were due to the visual developmental disorders, but further studies, including longitudinal investigations, are needed to answer this question.

4.5. Clinical implications

The success of amblyopia treatment is evaluated in terms of visual acuity improvement, but emerging evidence suggests that deficits in other aspects of vision, such as motion perception, may not improve following standard occlusion therapy (Giaschi et al., 2015). These patching resistant deficits may contribute to amblyopia recurrence and to long-term problems in everyday activities. It is therefore important to identify deficits in amblyopia that fail to improve following occlusion therapy to facilitate the development of alternate treatment approaches (Birch, Jost, Wang, Kelly, & Giaschi, 2018; Webber, Wood, & Thompson, 2016). The correlation we observed between motion perception and reading is related to this issue and requires further study.

Previous results on reading ability in successfully treated amblyopia have been mixed (Repka et al., 2008; Stifter et al., 2005a; Zürcher & Lang, 1980). All of the participants in our amblyopia group had received treatment, reading ability was not correlated with the degree of residual amblyopia (as quantified by the interocular difference in visual acuity), and the children with reading deficits had either no or mild residual amblyopia. A prospective study on the effects of treatment on reading ability seems warranted.

Children with developmental visual disorders who are reading at a level below the 16th percentile may benefit from reading supports at school. Specific adaptations such as providing texts with decreased crowding or increasing time for activities involving reading may be useful (Birch & Kelly, 2017). Further research will be necessary to identify remediation strategies based on the mechanisms underlying poor reading for individual children.

5. Conclusions

Some children with disrupted visual development due to amblyopia or strabismus show below average oral reading ability on standardized psychoeducational tests in spite of good treatment outcomes. Future research should explore the benefit of reading supports in school for such individuals. However, the use of small cohort control groups and non-standardized tests in previous studies may have overestimated the functional impact of amblyopia on reading ability.

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