Revised title: Beyond the global motion deficit hypothesis of developmental dyslexia: a cross-sectional study of visual, cognitive, and socio-economic factors influencing reading ability in children.

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ABSTRACT

Although primarily conceptualized as a disorder of phonological awareness, developmental dyslexia is often associated with broader problems perceiving and attending to transient or rapidly-moving visual stimuli. However, the extent to which such visual deficits represent the cause or the consequence of dyslexia remains contentious, and very little research has examined the relative contributions of phonological, visual, and other variables to reading performance more broadly. We measured visual sensitivity to global motion (GM) and global form (GF), performance on various language and other cognitive tasks believed to be compromised in dyslexia (phonological awareness, processing speed, and working memory), together with a range of social and demographic variables often omitted in previous research, such as age, gender, non-verbal intelligence, and socio-economic status in an unselected sample ($n = 132$) of children aged 6 – 11.5 yrs from two different primary schools in Edinburgh, UK. We found that: (i) Mean GM sensitivity (but not GF) was significantly lower in poor readers (medium effect size); (ii) GM sensitivity accounted for only 3% of the variance in reading scores; (iii) GM sensitivity deficits were observed in only 16% of poor readers; (iv) the best predictors of reading performance were phonological awareness, non-verbal intelligence, and socio-economic status, suggesting the importance of controlling for these in future studies of vision and reading. These findings suggest that developmental dyslexia is unlikely to represent a single category of neurodevelopmental disorder underpinned by lower-level deficits in visual motion processing.

KEY WORDS
Reading; dyslexia; children; magnocellular; dorsal stream; ventral stream; random dot kinematogram; motion processing; global motion; global form.

1. Introduction

Developmental dyslexia (DD) is defined as difficulties with word recognition, spelling, and decoding, despite adequate intelligence, education, and motivation (International Dyslexia Association, 2007). It affects 10-15% of the English-speaking population and seems to be more prevalent in males (e.g., Rutter et al., 2004). It appears to be heritable, but its genetic basis is not well understood (Grigorenko, 2009; Pernet et al., 2009). Researchers and practitioners often conceptualize dyslexia as a distinct category, made up of poor readers whose intelligence is at an average or above average level, and who demonstrate markedly different patterns of cognitive performance to poor readers of low intelligence – so called "garden-variety poor readers" (Hoskyn & Swanson, 2000; Siegel, 1988; Thomson, 2003); others, however, believe that dyslexia can be better conceptualized according to a continuum of difficulties in language processing, with dyslexic readers representing those at the lower end of the distribution (e.g., Pennington, 2006; Rose, 2009; Shaywitz, et al., 1992; Stuebing et al., 2002). Either way, it is important to have a broadly-agreed threshold that may help identify who might benefit from specialist dyslexia support (Swanson & Hsieh, 2009). However, this is not the case, and the threshold or cut-off point differs considerably between studies and in real-world practice.

While phonological awareness difficulties represent the primary features of dyslexia (Snowling, 2000), many dyslexic individuals demonstrate additional difficulties in (1) phonological representations (related to processing speed and lexical retrieval: e.g., Ramus & Szenkovits, 2008; Wolf & Bowers, 1999); and (2) coding, storing and retrieving these representations (related to short-term or working memory; e.g., Gathercole et al., 2006). Such deficits may relate to the day-to-day difficulties often reported by individuals with dyslexia, such as problems remembering, organizing and sequencing information. However, phonological awareness deficits are not seen in all poor readers (Castles & Coltheart, 1996; Ramus & Ahissar, 2012), and may only account for a small proportion of variance in subsequent reading ability in children (e.g., Wagner et al., 1997). As such, it may be that phonological difficulties do not represent the cause of dyslexia but are secondary to more basic perceptual or cognitive processes underlying the condition.

Perhaps the largest body of research in this area has been directed at exploring the possibility that dyslexia develops as a result of visual processing deficits within the “transient”, “magnocellular” (M) and / or “dorsal” visual processing streams, which are widely believed to be specialized for the perception of brief and / or rapidly-moving stimuli (e.g., Cornelissen et al., 1995; Goodale & Milner, 1992; Gori et al., 2016; Slaghuis & Ryan, 1999; Stein, 2001; Stein & Walsh, 1997; Ungerleider & Mishkin, 1982).

Here, it is important to acknowledge the common misconceptions that the magnocellular (M) and parvocellular (P) pathways at the level of the retina and lateral geniculate nucleus (LGN) map directly onto the dorsal and ventral cortical visual streams, and that these pathways exclusively subserve the perception of “motion” and “form” respectively. Indeed, considerable anatomical, physiological, and psychophysical evidence indicates that (1) inputs originating from M and P pathways interact throughout visual areas of the cortex (e.g., DeYoe & Van Essen, 1988; Maunsell, Nealey & DePriest, 1990; Merigan, Byrne & Maunsell, 1991) (2) there is a large degree of overlap in the spatiotemporal properties of individual M and P neurons in the LGN, and the M and P systems as a whole (Anderson, Drasdo, & Thompson, 1995; Cavanagh & Favreau, 1985; Cropper & Derrington, 1996; Edwards & Badcock, 1996; Nassi, Lyon & Callaway, 2006), indicating that motion perception likely involves the activity of both M and P pathways (for further discussion of these important points, see Skottun, 2015, and Skottun & Skoyles, 2006).

Nonetheless, it is clear that: (1) M cells in the retina and LGN respond optimally to stimuli of lower spatial and higher temporal frequency, and respond to considerably lower luminance contrasts, compared with P cells (Maunsell & Newsome, 1987; Merigan & Maunsell, 1993); (2) neurons in middle temporal visual area (MT/V5) receive a large input from geniculate M cells, via other cortical areas, and typically respond preferentially to the global direction of motion in random-dot stimuli (Milner & Goodale, 1995; Newsome & Pare, 1988; Ungerleider & Mishkin, 1982); and (3) a number of studies indicate that dyslexia is associated with decreased sensitivity to stimuli that correspond to those preferred by the M and dorsal pathways. For example, children and adults identified as having (or at risk of developing) dyslexia demonstrate significantly lower contrast sensitivity for grating stimuli of low spatial and high temporal frequency (e.g., Lovegrove et al., 1980; Martin & Lovegrove, 1987), lower sensitivity to the frequency doubling (FD) illusion (e.g., Kevan & Pammer, 2008; Pammer & Kevan, 2007) and poorer performance in tasks of global motion perception (Boden & Giaschi, 2007; Boets et al., 2011; Cornellisen et al., 1995; Grinter, Maybery, Badcock, 2010; Kevan & Pammer, 2009; Talcott et al., 2000).

However, some evidence remains mixed (Benassi et al., 2010; Johnston et al., 2017; Schulte-Körne & Bruder, 2010). Not all studies report significant motion processing deficits in dyslexia (Boets et al., 2006; Hulslander et al., 2004; Kronbichler, Hutzler, & Wimmer, 2002; Laycock et al., 2006; Skottun & Skoyles, 2006; 2008), and studies which examine the clinical significance of reduced motion sensitivity in dyslexia tend to find that effect sizes are small, and as few as one third of dyslexic individuals exhibit significant deficits (i.e. more than 1 SD below the mean) in visual motion sensitivity (Conlon et al., 2012; Conlon, Sanders, & Wright, 2009; Ramus, Pidgeon, & Frith, 2003; Ramus et al., 2018; Wright & Conlon, 2009).

A number of methodological factors may contribute to the lack of consistency in findings to date (e.g., Johnston et al., 2017; Skottun, 2015). First, not all studies take appropriate account of inconsistencies in the definition of dyslexia, or estimation of "risk" of dyslexia, in selecting the participant sample. Many do not employ adequate control conditions (for example, tasks of spatial vision designed to test the parvocellular and / or ventral cortical visual processing stream), and / or are underpowered to detect significant associations between visual and reading performance due to small sample sizes. Finally, the use of procedures with two patches of stimuli presented concurrently or subsequently may disadvantage children with dyslexia due to their reliance on working memory (Peli & Garcia-Perez, 1997), which is known to be compromised in DD.

Whether functional deficits within the M and / or dorsal visual streams underlie phonological difficulties in dyslexia (Gori et al., 2016; Stein, 2018; Vidyasagar & Pammer, 2010), arise as a consequence of dyslexia (Goswami, 2015), or merely co-exist with reading and writing difficulties in many cases (Ramus, 2003; Vellutino et al., 2004) therefore remains a topic of considerable debate. Arguably the most powerful approach to addressing these difficulties would be to conduct prospective, longitudinal studies of young (preferably pre-reading) children; using large, unselected samples. The small number of studies that have used this approach generally appear to confirm that visual motion processing ability accounts for a unique proportion of the variance in subsequent reading (Boets et al., 2008; Kevan & Pammer, 2009; Talcott et al., 2002): however, effect sizes tend to be small, and studies have so far not taken into account, or attempted to control for, the many variables that are likely to have a significant impact on reading performance such as gender (Katusic et al., 2001; Rutter et al., 2004), non-verbal reasoning (Shaywitz et al., 1990; 1995), and the many social and economic factors that influence individuals' motivation and opportunities to read (Buchmann & Hannum, 2001; Chaney, 2008), which appear to be mediated by factors such as parental literacy and exposure to written and printed language (Hamilton et al., 2016; Mol & Bus 2011; Neuman & Celano, 2001).

In this study, we recruited a large (*n* = 132), unselected sample of children, aged 6 – 11.5 yrs, from two primary schools located in different socioeconomic areas of Edinburgh, UK, in order to avoid sampling bias and the difficulties associated with allocating children to groups on the basis of familial risk of dyslexia. We tested children's sensitivity to global motion (GM) and global form (GF) using dot and line stimuli of 100% luminance contrast in order to target cortical (dorsal and ventral) visual processing streams. We chose these because the evidence for selective deficits at this level of visual processing is stronger than for those at the level of the retina and LGN (Schulte-Körne & Bruder, 2010) and because the measurement of coherence thresholds is more robust to small nonlinearities in the display compared to contrast thresholds, which allowed us to develop our stimuli on portable equipment that we could take into schools for testing. We used single-interval procedures in order to minimize the involvement of working memory, and increase the likelihood that vision tasks predominantly reflected lower-level perceptual mechanisms.

We also measured children's performance on various language and cognitive tasks, including processing speed (rapid automatized naming, or RAN), working memory (digit span), non-verbal intelligence (matrix reasoning and block design sub-tests of Wechsler's Intelligence Scales for Children), and reading (nonsense and speeded reading). We further took account of children's age, gender, and school (as a proxy for socioeconomic background) to develop multiple linear regression models and test their ability to predict reading performance. We also grouped children into "poor" and "typical" readers according to their reading level using established norms to examine between-group differences across this broad range of measures. Overall, we wanted to establish: (1) whether poor readers are significantly less sensitive, on average, to GM (but not GF) stimuli, compared with good readers; (2) whether any differences persist after controlling for age, gender, non-verbal intelligence (NVIQ), and socio-economic status (SES); (3) the contribution of higher-level visual processing (GM and GF) to reading performance, relative to other factors known to be important in developmental dyslexia, such as phonological awareness, NVIQ and SES.

The current research adds to a long-standing debate on whether developmental dyslexia is underpinned by visual deficits in visual motion processing, and whether global motion tasks designed to match the known preferences of the dorsal cortical visual processing stream may be used as reliable indicators of dyslexia. By examining the role of vision within a broader cognitive and social context, and conducting the research under more ecologically-valid conditions, we further hoped to evaluate the real-world importance of vision testing in predicting dyslexia in children.

2. Methods

All work was carried out in accordance with the World Medical Association's Declaration of Helsinki (2013). Children were recruited from two primary schools in Edinburgh, UK. School 1 (*n* = 67) was located within one of the most deprived areas of Scotland according to the Scottish Index of Multiple Deprivation (SIMD; Scottish Neighbourhood Statistics 2014a), while school 2 (*n* = 65) was located within one of the least deprived areas (SNS, 2014b). School 1 had received a rating of "excellent" at the most recent Her Majesty's Inspectorate of Education (HMIE) inspection (2013) and School 2 had been rated as "good" (2011). See Table 1 for more detailed school characteristics.

Table 1.
Socio-economic and school performance for each of the primary school

Indicators	School	
	1	2
SIMD rank (decile)	125 (1)	5688 (9)
Unemployment[a]	33%	5%
Anxiety/depression/psychosis prescription drugs	12%	7%
Free school meals (P1-P3)	65%	10%
Schools' evaluation[b]		
Curriculum	excellent	good
Improvement in performance	very good	good

Note. [a] Unemployment rate for Scottish population estimated for 6.9% (The Scottish Government, 2014) [b] Based on Edinburgh City Council audits (HMIE, 2011; 2013).

Because a representative sample and ecological validity were important in this study, we used affordable, commercially-available and easy-to-use apparatus and procedures, and conducted testing in participants' normal school environment. We were provided with a quiet classroom in which we could test participants individually in each school.

2.1 Design

We used a cross-sectional design to examine whether visual sensitivity to GM stimuli could predict reading performance, taking into account age, gender, school, and various phonological and cognitive skills. In order to control for visual sensitivity more broadly, and the involvement of other, non-dorsal-stream pathways in the GM task, we also tested sensitivity to GF stimuli, which are likely to be mediated predominantly by a parvocellular-biased ventral cortical visual pathway (Maunsell et al., 1990; Zeki, 1993).

In addition, a between-groups, quasi-experimental design was implemented to examine differences in visual and cognitive performance between (a) "poor" and "typical" readers; and (b) genders and schools.

2.2 Participants

132 children, aged between 6 and 11.5 yrs. (mean age = 8.3 years; SD = 1.7; 45% F) with normal or corrected-to-normal vision participated in the study.

2.3. Materials

2.3.1 Visual Sensitivity Testing

All visual stimuli were designed using Psykinematix version 2.0 software (KyberVision Japan LLC) on an Apple MacBook Air laptop computer, with 1.6 GHz dual-core Intel Core i5 with 3MB shared L3 cache.

Stimuli were initially displayed on one of two 17-inch, cathode-ray tube monitors (Dell / Mitsubishi), maintained within each of the two participating schools. Both monitors broke down after several days, so stimuli were subsequently displayed on an Apple MacBook Air 13.3-inch; LED-backlit glossy widescreen display with native resolution of 1440 x 900 pixels and temporal resolution of 60 Hz. One-way multivariate analysis of variance (MANOVA) revealed no statistically significant differences in sensitivity to either global motion or global form between display types [$F(8, 166) = .658$, $p = .728$], so data gathered using all displays were combined.

Stimuli were viewed binocularly at a viewing distance of 60 cm (or 76 cm for the bigger monitors). Participants were seated unrestrained at the correct distance and encouraged to remain still throughout testing. The field of view was set as 27 x 17 deg.

As the study took place at participants' schools, complete control over ambient light levels during testing was not possible. However, overhead lights were turned off, window blinds or curtains closed, and the display screen angled away from windows and protected with a screen shade in order to minimize large changes in ambient lighting.

Global Motion (GM)

The stimulus designed to match the known preferences of the dorsal stream was a random dot kinematogram (RDK) consisting of a patch of 100 white dots (0.1° diameter) on a black background, randomly distributed within a 23° × 17° region in the centre of the display. A variable proportion of the dots moved coherently (signal dots), at a velocity of 4.4 deg/s, either to the left or to the right amongst the remaining randomly moving dots (noise dots). Stimuli were presented as 18-frame sequences, with each frame lasting 16.7 ms. In order to ensure that participants did not track the path of a single signal dot, both the random dots and the dots carrying the coherent signal had a limited lifetime of 50 ms (3 frames) [see figure 1].

Global Form (GF)

The control stimulus, designed to match the known preferences of the ventral cortical processing stream, was a static array of 900 oriented white line segments 0.25° x 0.05° presented within a 23° × 17° patch presented in the centre of the display, on a black background. The target stimulus was a 23° x 11.5° region defined by line segments that were oriented tangential to concentric circles. On each trial the target circle, with a variable percentage of coherently organised line segments were presented randomly to the left or to the right of the centre of the display for 1800 ms (see figure 1). The parameters for this task were based on Kevan and Pammer's (2009) study that used a similar task to control for non-motion higher-level visual processing.

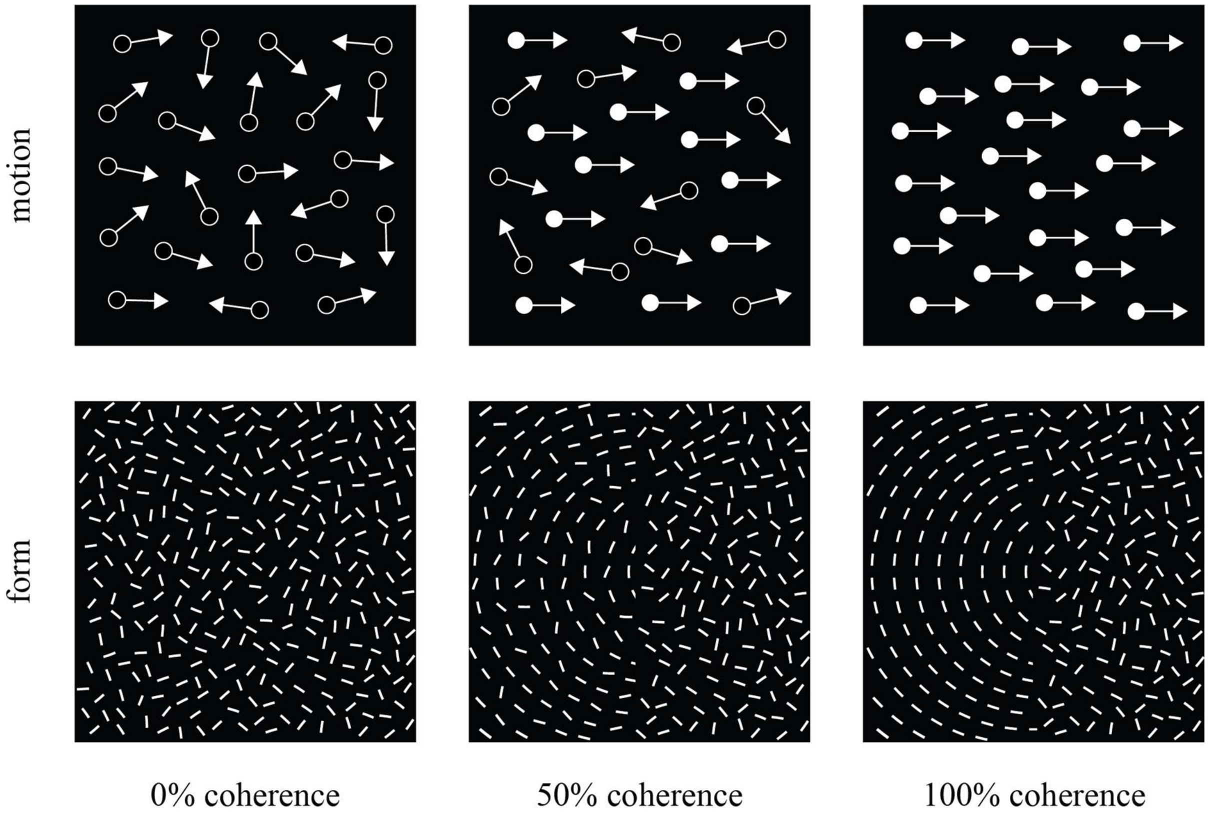

Figure 1. Schematic representation of the stimuli used in Global Motion (GM) task (top) and Global Form (GF) task (bottom), depicting 0, 50, and 100% coherence of motion and form, respectively. Arrows represent the direction of motion of individual dot elements in the GM display.

2.3.2 Cognitive Testing

Each participant completed a range of tasks to examine performance on measures generally believed to be: (1) associated with risk of dyslexia, such as phonological awareness, processing speed (RAN), and working memory (digit span); and (2) independent of risk of dyslexia, such as NVIQ. These tasks were taken from the Dyslexia Early Screening Test (DEST-2: Nicolson & Fawcett, 2004; suitable for children aged 4.5 – 6.5 yrs) and the Dyslexia Screening Test - Junior (DST-J: Fawcett & Nicolson, 2004; suitable for children up to 11.5 yrs). Test-retest reliability of these tests has been reported as excellent, and construct validity of DST-J assessed as high (Fawcett & Nicolson, 2004). At-risk indices from the tests were transformed into *z*-scores in order to allow risk of dyslexia to be considered across the sample as a whole. The age standardisation of the scores was conducted on a larger sample of children (*n* = 457) taking part in a bigger research project.

Matrix reasoning and block design tasks were taken from the Wechsler Intelligence Scales for Children (WISC-4, 2004; WPPSI-IV, 2013); both have been reported to have reliability coefficients of at least .8 in typical and reading-disordered samples (Wechsler, 2004; 2013). Testing and scoring were conducted in accordance with the manuals.

Phonological Awareness (PA) The Rhyme / Alliteration task from the DEST-2 was used as a measure of phonological awareness in the younger group of children. In this task, children were given two words (e.g., *bat cat*) and asked if they rhymed (rhyme task) or asked what was the first sound of a word, e.g., *ball* (alliteration task). Older children were given the Phonemic Segmentation task from the DST-J, where they had to repeat a word without an indicated phoneme, for example: 'say *marmalade*; say it again but without *mar*'.

Rapid Automatized Naming (RAN). In this task of general processing speed, taken from the DEST-2, participants were asked to name 40 outline drawings as fast as they could. Practice with half of the pictures was given prior to the timed task. Scores were recorded in seconds. This task has been found to be a unique contributor to predicting reading problems that are independent of phonological awareness (Wolf & Bowers, 1999).

Digit Span (DS). This task comprised two tasks: Digit Span Forward (repeating numbers in the same order; 16 items) and Digit Span Backward (repeating in the reverse order than presented by the examiner; 14 items). Younger children below the age of 6 yrs. 6 months were tested only on the first part of the test. This test is designed to measure auditory short-term memory, sequencing skills, attention and concentration and is believed to be compromised in dyslexia (e.g., Wang & Gathercole, 2013).

Block Design (BD). Participants were asked to re-create a design using red-and-white blocks from a previously constructed model and / or a Stimulus Book within a specified time. The task is designed to measure the ability to analyse and synthesise abstract visual stimuli. It involves non-verbal concept formation, visual perception and organisation, simultaneous processing, visual-motor integration, and figure-ground segregation (Wechsler, 2004).

Matrix Reasoning (MR). In this task, participants looked at an incomplete matrix and were asked to select the missing part from a set of response options. This test is designed to measure visual information processing and abstract reasoning (i.e., continuous and discrete pattern completion, classification, analogical reasoning and serial reasoning). The test is seen as a measure of fluid intelligence and general non-verbal intellectual ability (Wechsler, 2004).

Matrix reasoning and block design aged scores were averaged to provide a total score for non-verbal IQ.

2.3.3 Reading Tests (DST-J)

Speeded Reading (SR). The task is also referred to as the one-minute reading task. Children are asked to read aloud a page of individual words as quickly as possible (organised in four rows of 30 words, graded in difficulty from the easiest to the hardest). The score of the test was the number of words correctly read.

Nonsense Reading (NR). In this task, children were asked to read a passage with real and nonsense words. The length of the passage depends on the child's age. Both accuracy and time are considered. For each correctly read real word and nonsense word, one and two points were awarded, respectively. Extra points were added if the passage was read in less than one minute. If a child took more than one minute points were subtracted.

Both tests were standardised for age according to the DST-J manual; the manual also provides 'at risk' indices which were used to categorise children into the groups of poor or typical readers. The readings tests' scores were averaged to provide a total score for overall reading for some of the analyses.

2.4. Procedure

Each study was granted ethical approval by the School of Applied Science's Research Integrity Committee at Edinburgh Napier University, and by the City of Edinburgh Council. Procedures to gain informed consent to participate were developed in accordance with the British Psychological Society's Code of Human Research Ethics (2010), which recommends that informed consent should be collected both from the child and a responsible adult – usually the child's parent or advocate.

In this study, we adopted a three-tiered informed consent protocol. First, head teachers provided informed consent to participate *in loco parentis* on behalf of the pupils. Second, the child's parent or guardian also provided informed consent to participate on an opt-out basis.

Because the main aim of the study was to study an unselected sample, it was essential that the sampling frame was appropriate to achieve these ends. The most common reasons for parents not opting their children in to research are apathy, inertia and lack of motivation rather than active refusal (Ellickson & Hawes, 1989). Further, parents from lower socioeconomic groups are significantly overrepresented in those who do not "opt-in" their children. For these reasons, we used a parental "opt-out" approach to maximize participation and ensure the sample was representative. All parents were sent a letter via their child's teacher which explained the aims and procedures of the study and details of what to do to opt their child out of the study.

Finally, each child was approached in person on a class-by-class basis and invited to take part. The nature of the research was outlined to them in age-appropriate terms, using the children's version of the Participant Information Sheet developed in accordance with the World Health Organization's *Informed Assent for Minors* template. If the child indicated s/he was willing to participate, either alone, or with another adult present, informed consent was indicated by writing their name. None of the children approached were opted out by their parents or guardians, and all children initially agreed to take part in the study: however some did not complete all of the tasks, so the number of participants differed slightly from test to test.

Children were tested over two sessions, each lasting approximately 30 minutes. They were first tested on sub-tests of the WPPSI/WISC and the DEST/DST-J; the order of these was randomised. Then they were followed up with the vision tests and reading tests within one session. The order of tasks was randomized. Children were assured that they could stop or take a break whenever they wished.

2.4.1 Visual Sensitivity Tasks

Discrimination thresholds were measured separately for global motion (GM) and global form (GF) using two-alternative, forced-choice (2-AFC) procedures in conjunction with a three-up, one-down staircase with six reversals, converging to a performance level of 79% correct. The order of the tasks was randomized.

Calculating the average measure from at least two staircase runs for each participant can provide a more reliable estimate of threshold in psychophysical tasks. On the other hand, repeated staircase runs are associated with an increased risk of perceptual learning, fatigue, and distraction (Leek, 2001; Macmillan & Creelman, 1991), the effects of which are likely to be greater in children compared with adults, and in people with dyslexia compared with controls. Indeed, our pilot study (*n* = 30) revealed that children tended to lose motivation and concentration in the GM and GF tasks after 6 reversals. Previous studies have shown that thresholds calculated from a first staircase run are highly correlated with those from subsequent runs, and that thresholds from a single staircase run are statistically equivalent to those averaged over multiple staircase runs (Boets et al., 2011; Kassaliete et al., 2015). In order to maximize the chances of children's participation and enhance the reliability of measures, the threshold coherence (percentage of moving dots, in the GM task, and line segments, in the GF task) was therefore calculated as the mean of a single staircase comprising 6 reversals for each participant.

Global Motion

Children were told that the white dots in the RDK were sheep, seen from a distance, that were running away to the forest (right) or to the barn (left); pictures of both were placed on the screen's sides; they were asked to decide which way most of them were going either by pointing, or indicating verbally (barn or forest); see figure 2.

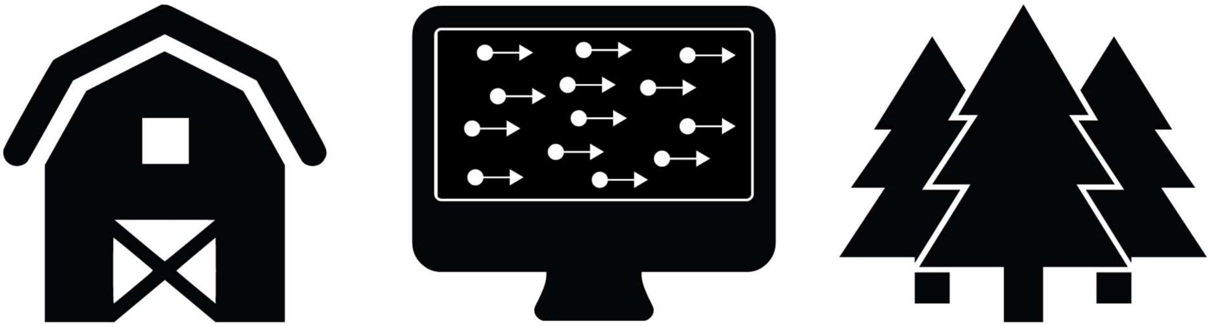

Figure 2. Experimental setup. The visual task (here Global Motion) was presented on a computer screen. To each side of the screen pictures were presented for children to refer to (barn to the left and forest to the right).

Global Form

Children were told that the white line segments in the display were pencils, which had been randomly thrown on a table, and that some magical creatures came to put them in a circular shape but managed to do so only on one side of the table. The creatures were then hiding in the barn or the forest (same reference used to simplify the instructions). Participants were asked to indicate which side of the screen contained the circular pattern by pointing with a finger or indicating verbally (barn or forest).

Responses were communicated to the laptop computer through a three-button computer mouse. BP, who was positioned out of sight of the display screen, controlled the mouse on the child's behalf. No feedback was given. For all the tasks, a practice session preceded the main test trials.

3. Results

Some children did not complete the full set of the vision tests due to loss of interest or fatigue. It was therefore important to investigate whether there was any bias within the missing values before further analysis. Little's MCAR test was conducted to investigate if the missing values found in the data set were missing completely at random. The test was non-significant (χ^2 (19) = 19.5, p = .422) which indicated that the missing data were missing at random. We therefore used a pairwise deletion method to manage missing data because it permits as many cases as possible for each analysis. The Benjamini-Hochberg procedure (1995) was used to control for Type 1 error where appropriate.

Categorizing children into poor and typical reader groups

There is no agreement either in the theoretical literature or in educational practice on what criteria should be used to differentiate individuals as "poor" readers, or those at high risk of DD, from "typical" readers. Here, children were categorised as "poor" or "typical" readers using established screening tests (DEST2 and DST-J) with good psychometric properties and standardized across large samples of children. Children whose age-normed *z*-scores corresponded to the 22nd percentile or less, corresponding to "at risk" or "at high risk" of DD on either the speeded reading or the nonsense reading sub-tasks were classified as "poor" readers (*n* = 31). The remaining children comprised the "typical" readers group (*n* = 101).

Descriptive statistics and group comparisons

Tables below present the means and standard deviations for the visual and cognitive measures according to reading group (table 2), gender (table 3), and school (table 4).

Table 2.
Descriptive statistics and group differences for the visual sensitivity and cognitive measures in poor and typical readers.

Measure	Typical readers		Poor readers		*Sig.*	*d*
	Mean	SD	Mean	SD		
Global Motion	62.340	18.154	70.965	10.974	*	0.58
Global Form	42.849	10.801	48.483	13.226	*	0.47
Phon. Awareness	0.447	0.562	-0.636	1.125	*	1.22
RAN	-0.132	0.727	0.571	1.127	*	0.74
Digit Span	0.156	1.130	-0.354	1.036	*	0.47
NVIQ	9.965	2.726	6.900	1.802	*	1.33
Nonsense reading	3.891	0.313	1.645	1.305	*	2.37
Speeded reading	3.634	0.504	0.839	0.898	*	3.84

Note. * for significance at a level adjusted with Benjaminio-Hochberg correction; *sig.* – statistical significance; *d* – effect size (Cohen's d); poor readers' *N* varies from 24 to 31; typical readers' *N* varies from 90 to 101

Table 3.
Descriptive statistics and group differences for the visual sensitivity and cognitive measures across genders

Measure	Females		Males		*Sig.*
	Mean	SD	Mean	SD	
Global Motion	62.742	16.985	65.429	17.473	ns
Global Form	45.401	11.872	42.856	11.161	ns
Phon. Awareness	0.293	0.794	0.140	0.890	ns
RAN	0.180	0.981	-0.091	0.781	ns
Digit Span	0.119	1.122	-0.016	1.134	ns
NVIQ	9.085	2.730	9.410	2.953	ns
Nonsense reading	3.178	1.368	3.593	0.833	ns
Speeded reading	3.068	1.230	2.904	1.426	ns

Note. * for significance; ns = statistically non-significant; females' *N* varies from 54 to 59; males' *N* varies from 60 to 73

Table 4.
Descriptive statistics and group differences for the visual sensitivity and cognitive measures across schools

Measure	School 1 (low SES)		School 2 (high SES)		*Sig.*	*d*
	Mean	SD	Mean	SD		
Global Motion	62.343	17.844	65.789	16.619	ns	
Global Form	46.738	10.813	41.525	11.641	*	0.46
Phon. Awareness	-0.026	1.076	0.439	0.440	*	0.57
RAN	0.2420	1.040	-0.188	0.621	*	0.50
Digit Span	-0.374	1.144	0.458	0.949	*	0.79
NVIQ	8.144	2.545	10.400	2.701	*	0.86
Nonsense reading	2.966	1.358	3.877	0.625	*	0.96
Speeded reading	2.105	1.327	3.877	0.484	*	1.77

Note. * for significance at a level adjusted with Benjaminio-Hochberg correction; *sig.* – statistical significance; *d* – effect size (Cohen's d); ns = statistically non-significant; school 1 children' *N* varies from 54 to 67; school 2 children' *N* varies from 60 to 65

There was a statistically significant association between SES and reading level [($\chi^2(1) = 29.681, p < .001$] with fewer poor readers in high SES school and more in low SES.

Reading group differences – analyses with controlled variables

Based on the above presented preliminary analyses it can be assumed that age and NVIQ (but not gender) may potentially act as confounding variables leading to invalid conclusions of simple group comparisons. Therefore, two-way analyses of co-variance (ANCOVAs) were run to determine the effect of reading group (typical vs poor readers) and gender (males vs females). DVs were measures of sensitivity to GM and GF stimuli, and the covariates were age (in months) and non-verbal reasoning (combined scaled score of block design and matrix reasoning tests). Socio-economic background associated with the location of the schools the children attended to (low SES vs high SES) could not be included as another IV as there was an insufficient number of cases in some groups (for instance only one child with reading problem in school associated with high SES). Therefore, a separate analysis investigating the impact of SES was conducted and presented in the next section.

The DVs in the ANCOVAs were measures of visual functioning assessed by sensitivity to stimuli preferentially activating the dorsal stream (global motion task) and ventral stream (global form task). The covariates controlled for were age (in months) and NVIQ (combined scaled score of block design and matrix reasoning tests).

Global Motion (GM)

Levene's test for equality of variances was significant (p = .007) which indicated lack of homogeneity of variances. Visual inspection revealed this was likely due to the small number of females in the group of poor readers (n = 9) and the ratio of the largest group variance to the smallest group variance is less than 3, in which case we can accept the assumption of homogeneity of variance Dean, Voss, & Draguljić, 2017). The main effect of reading group was significant [F(1, 107) = 6.791, p = .010; partial η^2 = .060; medium effect size], indicating that those classified as "poor" readers were significantly less sensitive to global motion, on average, than their typically-reading counterparts. There was no main effect of gender [F(1, 107) = .071, p = .791], and no interaction between reading group and gender [F(1, 107) = .001, p = .971].

Global Form (GF)

Shapiro-Wilk tests revealed that data were normally distributed (p > .05) and Levene's test for equality of variances revealed that variance was similar between groups (p = .177). There were no main effects of reading group [F(1, 115) = 2.365, p = .127] or gender [F(1, 115) = 2.492, p = .117] and no significant interaction between reading group and gender [F(1, 115) = .372, p = .543].

Correlations between visual sensitivity and cognitive measures

Correlations between the visual tests, cognitive measures and reading are presented in table 5. Note that GM sensitivity was not correlated with any of the language, cognitive, or reading scores across the sample as a whole. Small but significant correlations were found between GF and both NVIQ and nonsense reading.

Table 5.
Spearman's correlations between the visual sensitivity and cognitive measures for the full sample

	2.	3.	4.	5.	6.	7.	8.	9.	10.
1. Global Motion	.145	-.081	.028	-.153	.047	-.201	.088	-.069	-.143
2. Global Form	-	-.078	-.018	.122	-.294*	-.251*	-.248*	-.241	-.271*
3. Phon. Awareness		-	.348*	-.273*	.382*	.034	.404*	.363*	.500*
4. Digit Span			-	-.160	.276*	.106	.297*	.282*	.309*
5. RAN				-	-.401*	-.044	-.341*	-.351*	-.351*
6. NVIQ					-	.188	.452*	.469*	.400*
7. Age						-	.032	.023	.071
8. Reading							-	.981*	.853*
9. Speeded reading								-	.772*
10. Nonsense reading									-

Note. *significant at a level adjusted with Benjamini-Hochberg correction; N= ranges from 111 to 142

Correlations calculated separately for poor and typical readers are presented in tables 6 and 7. Of note, GM sensitivity did not correlate with any other measures in either the "poor" or "typical" reading groups. RAN was significantly correlated with NVIQ in both "poor" and "typical" readers, but only correlated with reading (speeded and nonsense-word) in the "poor" reading group.

Table 6.
Pearson's correlations between the visual sensitivity and cognitive measures for poor readers

	2.	3.	4.	5.	6.	7.	8.	9.	10.
1. Global Motion	-.059	.083	.417	-.410	.306	-.264	-.063	.066	-.157
2. Global Form	-	.185	.003	.254	-.100	-.004	-.217	-.315	-.080
3. Phon. Awareness		-	.583*	-.049	.035	-.041	.307	.264	.274
4. Digit Span			-	-.369	.171	-.198	.243	.393	.137
5. RAN				-	-.583*	.011	-.525*	-.567*	-.380*
6. NVIQ					-	.014	.333	.502*	.106
7. Age						-	.203	.208	.200
8. Reading							-	.816*	.917*
9. Speeded reading								-	.525*
10. Nonsense reading									-

Note. *significant at a level adjusted with Benjamini-Hochberg correction; N= ranges from 24 to 31

Table 7.

Spearman's correlations between the visual sensitivity and cognitive measures for typical readers

	2.	3.	4.	5.	6.	7.	8.	9.	10.
1. Global Motion	.167	-.028	.010	-.186	.114	-.189	.106	.124	.005
2. Global Form	-	-.069	.049	.035	-.258*	-.336*	-.184	-.151	-.268*
3. Phon. Awareness		-	.284*	-.221*	.228*	.055	.079	.009	.264*
4. Digit Span			-	-.036	.206	.200	.217*	.179	.242*
5. RAN				-	-.276*	-.061	-.137	-.124	-.131
6. NVIQ					-	.248*	.174	.189	.060
7. Age						-	.055	.054	.111
8. Reading							-	.964*	.609*
9. Speeded reading								-	.396*
10. Nonsense reading									-

Note. *significant at a level adjusted with Benjamini-Hochberg correction; N= ranges from 87 to 101

Figure 3 presents scatter dot graphs of reading scores by global form and global motion thresholds.

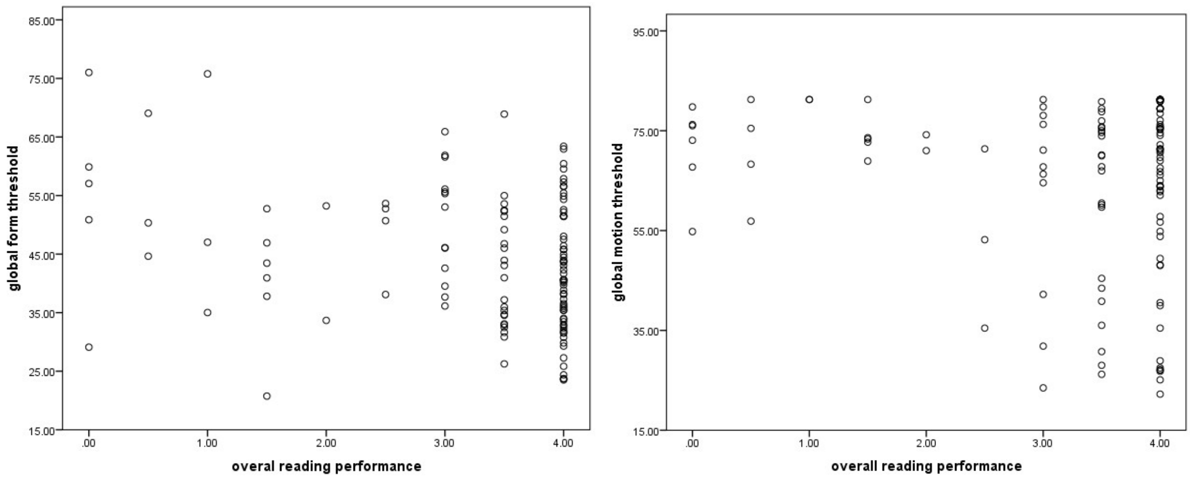

Figure 3. Scatter dot graphs of overall reading performance (age-scaled and averaged scores of speeded and nonsense reading) by global form (left) and global motion (right) thresholds.

Predicting reading

Hierarchical multiple regressions were run to determine if the addition of visual and phonological measures improved the prediction of overall reading over and above age, NVIQ and SES alone (all inserted in the first step; enter method: see table 8). The first model of age, SES and NVIQ was statistically significant [R^2 = .378, $F(3, 100) = 20.279$, $p < .001$] and explained 38% of the variance in reading. Further models were created using stepwise methods. Simple linear regressions revealed that SES and NVIQ on their own explained 33% [$F(1, 130)$ = 65.682, $p < .001$] and 22% [$F(1, 129) = 36.962$, $p < .001$] of the variance in reading, respectively. Age and gender did not explain any unique variance in reading.

The addition of phonological awareness to the prediction of reading (Model 2) led to a statistically significant increase in R^2 of .136, $F(4, 99) = 26.212$, $p < .001$. The addition of RAN to the prediction of reading (Model 3) also led to a statistically significant increase in R^2 of .032, $F(5, 98) = 23.639$, $p < .001$. The addition of GM sensitivity to the prediction of reading (Model 4) also led to a statistically significant increase in R^2 of .030, $F(6, 97) = 22.047$, $p < .001$ additionally explaining 3% of variance of reading. The full model containing all these variables (Model 4) could explain 57.7% of variance in reading.

Table 8.
Hierarchical multiple regression predicting overall reading scores

	Reading							
	Model 1		Model 2		Model 3		Model 4	
Variable	B	β	B	β	B	β	B	β
Constant	1.879**		2.114**		2.239**		3.073**	
Age	-.005	-.099	-.003	-.047	-.001	-.018	-.003	-.057
School	.466**	.449	.415**	.399	.391**	.377	.425**	.409
NVIQ	.113**	.308	.053	.145	.029	.079	.031	.085
PA			.513**	.412	.468**	.376	.417**	.336
RAN					-.234*	-.205	-.261*	-.228
GM							-.011*	-.184
R^2	.378		.514		.547		.577	
F	20.279**		26.212**		23.639**		22.047**	
ΔR^2	.378		.136		.032		.032	
ΔF	20.279**		27.742**		6.998*		6.933*	

Note. Age in months; PA – Phonological awareness; Non-verbal IQ; GM-global motion
*significant at <.05; **significant at <.001

Further investigation explored the performance profile of "poor" readers – specifically, the proportions of poor readers displaying one or more perceptual or cognitive deficits (i.e. at least one standard deviation below the mean for their age). Table 9 presents the proportion of participants showing weaknesses in the areas measured in the current study and figure 3 presents the overlap of different deficits in poor readers.

Table 9

Percentages of children showing deficits in cognitive and visual abilities

Measure	Reading Group	
	poor (%) *n* = 24-31	typical (%) *n* = 90-101
Phonological awareness	54	12
RAN	31	17
Digit Span	29	14
NVIQ	23	10
Global Form	20	14
Global Motion	16	9

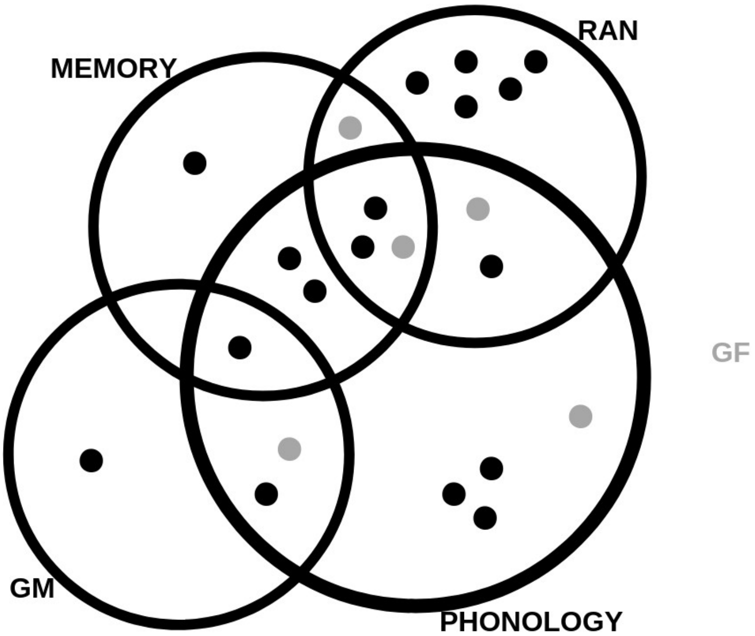

Figure 4. The perceptual and cognitive profiles of children deemed "poor" readers (n = 22) on the basis of their performance on the DEST-2 / DST-J. Circles represent areas of weakness, defined either as 'at risk' quotient (for cognitive tests), or a score of 1SD or below the sample mean for the GM and GF tests. Each dot represents a single child. Note that the majority of children demonstrated a weakness in more than one area. Note that only one poor reader showed a deficit in GM only, and none showed a deficit in GF only. The numbers of children displaying significantly reduced visual sensitivity for GM and GF stimuli were four (16%) and five (20%), respectively. GM = global motion; GF = global form (in grey); RAN = random automatized naming (test of processing speed).

5. Discussion

The aim of this study was to examine: (1) whether visual sensitivity to global motion (but not global form) is reduced in children classified as poor readers; (2) the extent to which any deficits in GM task can predict reading performance, taking into account some of the many other variables known to influence reading; (3) the nature and variability of visual and cognitive difficulties in poorly-reading children.

Vision

We found that children classified as “poor” readers were significantly less sensitive to global motion (GM), on average, compared to typical readers, with a medium effect size (partial $\eta^2 = .060$; Cohen’s $d = 0.58$). This difference remained significant after controlling for the effects of age, NVIQ, and the socio-economic status of schools’ catchment areas. These findings are consistent with those of a number of previous studies (e.g., Boden & Giaschi, 2007; Boets et al., 2011; Cornellisen et al., 1995; Grinter et al., 2010; Kevan & Pammer, 2009; Talcott et al., 2000) which report moderate between-group differences in performance on visual processing tasks requiring integration across space and time typically associated with the dorsal visual processing stream.

However, GM sensitivity was not correlated with either speeded or nonsense-word reading performance, and added only 3% to the model explaining variance in reading, compared with SES (together with NVIQ explaining 38%), phonological awareness (14%), and RAN (3%). Finally, only 16% of “poor” readers showed significant deficits in global motion sensitivity, while 9% of “typical” readers also displayed significantly low GM sensitivity. These results suggest that although GM sensitivity may be lower, on average, in “poor” compared with “typical” readers, tasks of the type carried out here are unlikely to be useful in differentiating between individual children at low and high risk of dyslexia, or in advancing theory of the causes of dyslexia.

Poor readers were also significantly less sensitive to GF compared to typical readers. However, this difference disappeared after controlling for age, NVIQ, and school SES, which indicates that some or all of these variables may play a role in the relationship between global form sensitivity and reading. This finding clarifies the issue of confounding variables that are likely to affect reading by providing evidence that motion, but not form, processing is affected in poor readers even when their intelligence, SES and gender is controlled for.

We found no effects of gender, NVIQ, or socio-economic background on visual sensitivity to either GM or GF in our sample of children. There has been little research directed at the effects of demographic and social variables on visual sensitivity to global motion or global form. The few studies that have addressed at least some of these have reported that NVIQ is negatively associated with GM sensitivity but not with GF (Johnston et al., 2016; Melnick et al., 2013), and that NVIQ and gender together account for a significant proportion of the variance in GM but not GF sensitivity. However, research in this area is limited, and has been conducted exclusively in adults. Of note, GF sensitivity significantly (but weakly) correlated with NVIQ and nonsense word reading in our sub-sample of typical but not poor readers. This may suggest that GF sensitivity develops independently from NVIQ in children at risk of dyslexia. Furthermore, the lack of association between NVIQ and GM sensitivity across the sample, and the lack of any effects of gender in our study could reflect differences in how poor reading manifests in children compared with adults: this could be investigated in future research.

We found no correlations between GM and GF performance for either typical or poor readers. This could indicate that the two tasks reflect the activities of separate functional visual streams in line with classical theories of parallel cortical visual processing (e.g. Milner & Goodale, 1995). Recent evidence, however, suggests there may be some interactions between the mechanisms underlying GM and GF processing in both adults (Johnston et al. 2016) and children (Braddick et al., 2017). Braddick et al. (2016; 2017), for example, found that coherent motion and coherent form tasks were moderately correlated with each other in a sample of typical young children. Differences between their results and ours may be due, at least in part, to the stimuli and tasks used. The GM and GF tasks in Braddick et al.'s studies were designed to be analogous: both required participants to detect a form-defined target in noise, which likely required both segmentation and integration of spatial and / or temporal cues. Our stimuli were not designed to be analogous: our GM task using RDKs likely relies primarily on the integration of local motion signals, while our GF task would require both segmentation and integration of local cues across space. Further research could compare performance on motion-based segmentation tasks with that on comparable form-based tasks (created by spatially superimposing the individual RDK frames, for example; an approach taken by Simmers, Ledgeway, & Hess 2005) in order to investigate whether the first is impaired in children at risk of dyslexia.

Taken together, these findings indicate that if present, the selectivity of any functional visual deficits in DD is unlikely to be straightforward, and the mechanisms underlying them should be further explored.

Cognition

In line with the phonological deficit theory of DD, we found that phonological awareness was significantly lower in "poor" compared with "typical" readers, with a very large effect size (Cohen's $d = 1.22$). Phonological awareness correlated moderately with reading performance in typical readers and added unique variance to our regression model. Poor phonological awareness was found in around 50% of poor readers, representing the single most common difficulty in the "poor" reading group. However, nonsense word reading in poor readers was not correlated with phonological awareness but moderately correlated with processing speed (RAN) indicating that phonological awareness may not be seen causal in dyslexia as well as providing evidence for double deficit hypothesis of dyslexia (Wolf & Bowers, 1999).

We also found significant reductions in performance on RAN and working memory (digit span) in the "poor" compared with "typical" reading group. Effect sizes were large and small (Cohen's $d = 0.74$; $d = 0.47$), respectively. Processing speed also explained a significant proportion of variance in reading. Working memory measure did not contribute to the model, most likely due to its significant associations with PA, RAN and NVIQ. These findings support existing theories that processing, accessing and storing phonological representations are key difficulties in dyslexia (e.g., Johnson et al., 2010; Wagner & Torgesen, 1987).

NVIQ turned out to play an important role in reading: it could distinguish between poor and typical readers (very large effect size: Cohen's $d = 1.33$), correlated with phonological awareness (in typical readers), and with RAN (in all children), and with single word reading (in poor readers), and on its own it could explain 22% of the variance in reading. Nonetheless, the role of IQ in reading, and in DD specifically, remains controversial. To date, there is no strong evidence supporting the validity and usefulness of the reading-IQ discrepancy classification in differentiating between dyslexia and so-called "garden-variety poor readers" (Carroll, Solity, & Shapiro, 2016; Felton & Wood, 1992; Fletcher et al., 1992; Hoskyn & Swanson, 2000; Stanovich & Siegel, 1994; Stuebing et al., 2002): nonetheless, future studies could further elucidate the nature and role of NVIQ in reading.

Demographic and Social Factors

One of the strongest predictors of reading was the school children went to: school explained a large (33%) and significant unique variance in reading scores, and children from the school associated with the top decile of multiple deprivation (SIMD) were significantly more likely to fall into the "poor" reader group compared with those from the school in the lowest SIMD decile. These findings are in line with the many studies that highlight the relationship between SES and reading in children (e.g., Buchmann & Hannum, 2001; Chaney, 2008; Hamilton et al., 2016; Mol & Bus 2011; Neuman & Celano, 2001), and suggest that controlling for SES is vital in studies of dylexia – especially when samples are small, and participants are selected on the basis of risk of (rather than confirmed) dyslexia.

We found no effects of gender on any of the measures (vision, reading, phonological awareness, NVIQ) employed in this study, and even though proportionally more boys were classed as "poor" readers than girls (29% vs. 17%), the difference was not statistically significant. Although not in line with research that reports poorer reading and writing and a greater prevalence of reading difficulties in males (e.g., Berninger et al., 2008; Finnucci & Childs, 1981; Katusic et al., 2001; Miles, Haslum, Wheeler, 1998; Rutter et al., 2004), our findings do corroborate those of previous epidemiological studies that measure reading performance (e.g., Shaywitz et al., 1990; 1996; Wadsworth et al., 1992) rather than proxy measures (such as teacher reports), which are more prone to bias.

To the best of our knowledge, no study has examined the effects of gender on global motion sensitivity in young children. Several studies of adolescents, adults, and older adults suggest that males may be more sensitive to GM, on average, than females (Billino, Bremmer, & Gegenfurtner, 2008; Hutchinson et al., 2012; Murray et al., 2018; Snowden & Kavanagh, 2006): our results indicate that such gender differences, if present, may not develop until later in childhood. Other explanations for our results could be that the girls in our study were more advantaged by the longer stimulus durations in the GM task (e.g., Maeda & Yoon, 2013; Voyer, 2011). Further studies are needed to verify and evaluate the effects of gender on GM sensitivity in children.

As the participants in our study were not limited to pre-reading children, we cannot rule out the possibility that lower GM sensitivity is a consequence, rather than a proximal cause of reading difficulties (e.g., Goswami, 2014; Olulade, Napoliello, Eden, 2013; Szwed et al., 2012). However, by testing young, primary-aged children, rather than adolescents or adults, we believed the likelihood that any reductions in visual sensitivity could arise as a result of problems with reading was limited.

Because we used an unselected sample, membership of groups was determined on the basis of reading performance. Given the difficulties associated with establishing risk of dyslexia in young children, and that there is no consensus about whether DD represents a separate diagnostic category, or the lower end of a broad continuum of reading performance, we thought this was reasonable. However, the extent of concordance between our "poor readers" and DD is unknown: at least some of these children could have been classified as so-called "garden-variety poor readers" whose poorer reading performance could be accounted for by other, more generalized, intellectual disabilities.

In order to promote wide participation and enhance the ecological validity of the study, we used stimuli and procedures that would maximise children's engagement in the vision tasks, including presenting stimuli on a laptop at children's schools, using large step sizes in the threshold staircase, and calculating a single mean threshold of only six reversals. These may have inflated the variability in measures within each group, and therefore reduced the size and the significance of the between-group effects.

Conclusion

Scientific efforts to understand the causes and trajectories of neurodevelopmental disorders such as developmental dyslexia have generally focused on the highly controlled study of a small number of key variables, such as phonological awareness, or visual sensitivity to stimuli believed to be processed predominantly by the magnocellular or dorsal cortical pathway. This approach is high in internal validity, which is essential for elucidating the potential mechanisms underpinning DD, but low in external validity and limited in its clinical significance: studies which examine the relative contributions of larger numbers of variables, take account of real-world challenges of research with children, and focus on how we can best identify and treat this common and debilitating problem, therefore have an important place in the broader evidence base.

By examining the role of visual sensitivity to global motion alongside the many other cognitive, social, and demographic variables known to play a role in DD in an unselected sample of young children, we have shown that GM sensitivity is generally a weak predictor of reading performance overall, and that the best predictors of reading performance in children are socioeconomic status and phonological awareness. We find very little evidence to support the thesis that developmental dyslexia represents a single, specific category of poor readers which can be explained by a deficit in a visual pathway (or pathways) that underlies the perception of global motion. For this reason, it is unlikely that GM tasks on their own will ever prove a sensitive or reliable indicator of risk of dyslexia in children. Our results are more consistent with the prevailing idea that DD encompasses a range of profiles related to a range of possible risk factors, symptoms, and underlying brain mechanisms (e.g., Elliott & Grigorenko, 2014; McGrath et al., 2011; Pennington, et al., 2006; 2012; Willcutt et al., 2010). Future research should focus on the developmental trajectories of larger numbers of young children using prospective, longitudinal designs and mixed methods in order to elucidate the potentially many causes and consequences of poor reading most broadly.

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Declaration of Conflicting Interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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Contributors

BP – research design, stimuli design, data collection, data analysis, writing up
AW – idea for the project, theoretical conceptualisation of the paper, research design, ethics application, data collection, data analysis, writing up.

Both authors have approved the final article.

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