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Visual search efficiency and functional visual cortical size in children with and without dyslexia

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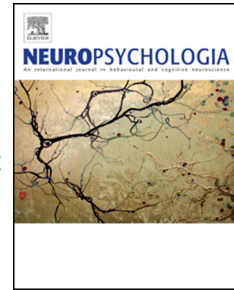
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1 **Neuropsychologia Research Report**

2

3 **Title**

4 Visual search efficiency and functional visual cortical size in children with and without dyslexia

5

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54

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56

57 **Abstract**

58 Dyslexia is characterised by poor reading ability. Its aetiology is probably multifactorial, with
59 abnormal visual processing playing an important role. Among adults with normal reading ability,
60 there is a larger representation of central visual field in the primary visual cortex (V1) in those with
61 more efficient visuospatial attention. In this study, we tested the hypothesis that poor reading ability
62 in school-aged children (17 children with dyslexia, 14 control children with normal reading ability) is
63 associated with deficits in visuospatial attention using a visual search task. We corroborated the
64 psychophysical findings with neuroimaging, by measuring the functional size of V1 in response to a
65 central 12° visual stimulus. Consistent with other literature, visual search was impaired and less
66 efficient in the dyslexic children, particularly with more distractor elements in the search array
67 ($p=0.04$). We also found atypical interhemispheric asymmetry in functional V1 size in the dyslexia
68 group ($p=0.02$). Reading impaired children showed poorer visual search efficiency ($p=0.01$), needing
69 more time per unit distractor (higher ms/item). Reading ability was also correlated with V1 size
70 asymmetry ($p=0.03$), such that poorer readers showed less left hemisphere bias relative to the right
71 hemisphere. Our findings support the view that dyslexic children have abnormal visuospatial
72 attention and interhemispheric V1 asymmetry, relative to chronological age-matched peers, and
73 that these factors may contribute to inter-individual variation in reading performance in children.

74

75 **Keywords (max 6 words)**

76 Dyslexia, visual search, visual cortex, magnetic resonance imaging, reading, attention

77

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79 1. Introduction

80 Dyslexia is a developmental learning disorder affecting 5-12% of children (Peterson & Pennington,
81 2012). It is characterised by significant and persistent reading difficulty despite sufficient cognitive
82 abilities and education, such that reading performance (word reading accuracy, reading fluency and
83 reading comprehension) is markedly below that expected for chronological age (WHO, 2018). Albeit
84 one of the most common learning disabilities, the aetiology of dyslexia is not yet fully understood.
85 Altered brain structure and function have been reported to be contributing factors (Galaburda,
86 2005; Norton, Beach, & Gabrieli, 2015; Ramus, Altarelli, Jednorog, Zhao, & Scotto di Covella, 2018)
87 and familial risks have also been identified (Debska, et al., 2016; Gialluisi, et al., 2020; Hosseini, et al.,
88 2013; Paracchini, Scerri, & Monaco, 2007). There have been decades of evidence in favour of
89 sensory processing deficits, including at early subcortical levels (e.g. (Boets, Vandermosten,
90 Cornelissen, Wouters, & Ghesquiere, 2011; Diaz, Hintz, Kiebel, & von Kriegstein, 2012; Giraldo-Chica,
91 Hegarty, & Schneider, 2015; Giraldo-Chica & Schneider, 2018; Gori, Cecchini, Bigoni, Molteni, &
92 Facchetti, 2014; Gori, Seitz, Ronconi, Franceschini, & Facchetti, 2016; Livingstone, Rosen, Drislane, &
93 Galaburda, 1991; Lovegrove, Bowling, Badcock, & Blackwood, 1980; Muller-Axt, Anwander, & von
94 Kriegstein, 2017). However, most studies, especially neuroimaging and electroencephalographic
95 studies, have focussed on the cerebral cortical networks involved either in phonological or higher
96 language level processes (e.g. Diehl, et al., 2014; Norton, et al., 2015; Power, Colling, Mead, Barnes,
97 & Goswami, 2016; Price, 2012; Sun, Lee, & Kirby, 2010; Vandermosten, Boets, Wouters, &
98 Ghesquiere, 2012)

99
100 Here, we were interested in early visual sensory processing in dyslexia as a potential precursor to
101 higher order brain differences in language and visual word form areas associated with reading
102 (Dehaene & Cohen, 2011). When learning to read, our visual system must be trained to scan the text
103 in a sequential manner to be able to integrate the information into words and sentences. Of the two
104 major afferent streams of visual processing between the retina and primary visual cortex (V1), the

105 parvocellular-ventral stream possesses the neural architecture for fine spatial resolution and object
106 recognition, whereas the magnocellular-dorsal stream provides temporal and positional information.
107 It has been proposed that during reading, an ‘attentional spotlight’ is deployed from the
108 magnocellular dominated dorsal cortical areas, sequentially highlighting the letters of the text. This
109 effectively gates the parvocellular information passing through V1 (Vidyasagar, 1999, 2004, 2005), so
110 that only one or two letters of text are processed by ventral stream structures at any one time. A
111 defect in the magnocellular-dorsal pathway, as has been demonstrated previously in dyslexia
112 (Cicchini, Marino, Mascheretti, Perani, & Morrone, 2015; Gori, et al., 2014; Gori, et al., 2016; Kevan
113 & Pammer, 2008; Stein, 2019; Stein & Walsh, 1997), could plausibly contribute to impaired reading
114 by altering visuospatial attention. Indeed, there is growing evidence that from longitudinal studies
115 that suggest a causal link between visuospatial attention deficits and reading difficulties (Bertoni,
116 Franceschini, Ronconi, Gori, & Facoetti, 2019; Carroll, Solity, & Shapiro, 2016; Franceschini, Gori,
117 Ruffino, Pedrolli, & Facoetti, 2012; Valdois, Roulin, & Line Bosse, 2019).

118
119 Visuospatial attention can be measured using a visual search task (Treisman & Gelade, 1980), which
120 assesses the ability to find a target hidden amongst a field of distractors. Visual search is slower in
121 dyslexic children (Casco & Prunetti, 1996; Iles, Walsh, & Richardson, 2000; Vidyasagar & Pammer,
122 1999); however, it is not clear whether slower response times arise from processing delays related
123 not to visual search *per se* but to signal transmission speed. Hence, in this study, we looked for
124 evidence of non-search delays in processing in dyslexic children by modelling visual search
125 performance with a linear regression to quantify slope as the primary indicator of task performance
126 (i.e. search efficiency, ms/item), as well as quantify the intercept to represent non-search processes
127 (Dickinson, Haley, Bowden, & Badcock, 2018).

128
129 Furthermore, as the number of distractors in a search array increases (set size = target plus number
130 of distractors), the time taken to find the target increases. People with more ‘efficient’ visuospatial

131 attention require less time to successfully execute the task as it becomes more difficult (i.e. lower
132 ms/item slope of the approximately linear function between response time and increasing set size).
133 Since print and text are a commonly encountered instances of a cluttered visual scene, the brain
134 likely uses the same neural circuitry and attentional mechanisms for reading that are used for
135 serially searching for a target amongst visual clutter (Vidyasagar, 2004, 2005; Vidyasagar & Pammer,
136 2010). Indeed, faster readers show faster response times in visual search tasks among both young
137 (Casco, Tressoldi, & Dellantonio, 1998; Verghese, Kolbe, Anderson, Egan, & Vidyasagar, 2014;
138 Vidyasagar & Pammer, 1999) and adult (Casco, et al., 1998; Verghese, et al., 2014; Vidyasagar &
139 Pammer, 1999) populations. Additionally, in adults with normal reading ability, more efficient visual
140 search performance (i.e. lower ms/item visual search slope) correlates with a larger representation
141 of the central visual field in primary visual cortex, V1 (Verghese, et al., 2014). Thus, the
142 psychophysical evidence for a relationship between visual search and reading ability is supported by
143 neuroimaging findings, at least in adults. Efficient serial visual search is critical for efficient reading,
144 and a better understanding of visual search under-performance and its relationship to functional V1
145 size may provide insight into atypical visual processing mechanisms in dyslexia.

146

147 The focus of our study was to consider the reading ability and visual performance of children of
148 reading-age, as this is the age-group where abilities diverge and problems manifest in school
149 performance. Given that visual search is particularly impaired in dyslexic children when there are
150 more distractor elements in the search array (Vidyasagar & Pammer, 1999), we expected that visual
151 search performance would be impaired in the dyslexic children (i.e. higher ms/item visual search
152 slope) relative to normal-reading children. In addition to grouping the data into 'dyslexic' versus
153 'non-dyslexic' readers, since reading ability is a continuous variable in the population, we also
154 considered the entire spectrum of visual performance in our participants. We therefore
155 hypothesized, similar to that reported in normal reading adults (Verghese, et al., 2014), that there
156 would be a relationship between visuospatial attention and the size of functional central field

157 representation on left V1 (measured using retinotopic mapping of V1 by magnetic resonance
158 imaging, MRI) in a cohort of children with varying reading ability.

159

160 **2. Materials and Methods**

161 **2.1 Participants**

162 The study was approved by the Monash University Human Research Ethics Committee and complied
163 with the tenets of the Declaration of Helsinki. Written informed consent was obtained from all
164 participants and their guardians. We aimed to recruit a minimum of 23 participants based on a
165 power analysis (power of 80% for detecting a moderate correlation at alpha of 0.05) of data from a
166 previous study (Verghese, et al., 2014) that reported a moderate ($r = -0.56$) correlation between
167 overall visual search performance and functional V1 size in adults with normal reading abilities.
168 Thirty-two children (18 dyslexic, 14 controls) aged 9-11 years were consecutively recruited into the
169 study in response to advertisements circulated at Monash University, The University of Melbourne,
170 local schools, and online community support groups. The narrow age range was chosen to minimize
171 significant developmental variation in brain structural measures such as intracranial, whole brain,
172 grey matter and white matter volume (Mills, et al., 2016).

173

174 Participant screening, reading and intellectual aptitude, and visual search tests were conducted at
175 the first visit (no more than 1.5 hours, with regular breaks in between tests). The MRI brain scan (1
176 hour visit) was conducted within three months of the first visit. Participants were screened by an
177 optometrist to ensure the following inclusion criteria: best corrected visual acuity at least 6/9.5
178 (logMAR), refractive error within ± 5.00 DS, normal ocular health, normal binocular vision on
179 screening tests for accommodation, convergence and stereopsis, no history of attention deficit
180 hyperactivity disorder or Asperger's syndrome. Grouping of children into normal vs dyslexic was
181 determined based on parent/guardian report of a diagnosis of dyslexia or normal reading ability, and
182 confirmed at the first test visit by administration of the Dyslexia Determination Test (Griffin &

183 Walton, 1981). The Dyslexia Determination Test is a validated screening test (Simmons, 1984) that
184 looks for any dyslexic pattern in relation to reading, writing and spelling, and characterises the
185 dyslexia into dyseidesia, dysphonesia or a combination of both.

186

187 To quantify reading ability, the reading subtests ('Word Reading', 'Reading Comprehension',
188 'Pseudoword decoding') of the WIAT-II (Wechsler Individual Achievement Test, Australian
189 Standardised Edition, 2nd Edition) were administered at each participant's current school year level
190 (Year 4, 5, or 6). Raw scores for each subtest were weighted, converted into standard scores and
191 summed to obtain a composite standard score for reading ability, herein referred to as the 'reading
192 ability score'. Intellectual aptitude (intelligence quotient, IQ) was assessed using the Kaufman Brief
193 Intelligence Test (KBIT, 2nd edition), which includes both verbal ('Verbal Knowledge' and 'Riddles'
194 subtests, which were read out loud by the investigators) and non-verbal ('Matrices' subtest) IQ
195 measures. The KBIT test of IQ was chosen for its brevity over a full-scale IQ measure in order to
196 remove any confound of reading ability that may impact on a written IQ test, and to minimise
197 possible fatigue effects from the battery of tests. Age-dependent standard scores for verbal IQ, non-
198 verbal IQ and the overall IQ composite score are shown in Table 1.

199

200 Given that dyslexia is defined by poor reading ability despite normal cognitive ability, one dyslexic
201 child's data was removed from analysis due to a below average IQ < 78 (i.e. more than 1.5 standard
202 deviations below average IQ composite score of 100), leaving 14 control (mean age 10 years 6
203 months, 8 females and 6 males) and 17 dyslexic participants (mean age 10 years 9 months, 9 females
204 and 8 males) for which visual search performance was assessed. In addition, one control participant
205 withdrew from the study after the first visit, one dyslexic participant could not complete the brain
206 scan due to claustrophobia, and MRI data from 1 control and 2 dyslexic participants were discarded
207 due to excessive movement artefacts. Thus, the final subset of children (total n=24) with visual

208 search data and acceptable MRI data included 11 control (mean age 10 years 5 months, 6 females)
 209 and 13 dyslexic participants (mean age 10 years 11 months, 6 females).

210

211 **Table 1.** Participant demographics (mean \pm standard deviation, range) and outcomes of the reading
 212 and intelligence tests (median \pm interquartile range, range). Group data were compared (*p*-values)
 213 using *t*-tests, or Mann-Whitney rank sum tests where data were not normally distributed.

	Controls	Dyslexic	<i>p</i> -value
Age (months)	126 \pm 9 (110 – 138)	129 \pm 12 (108 – 143)	$t_{29} = 0.78, p = 0.44$
Reading ability score	108 \pm 26 (92 – 130)	83 \pm 15 (53 – 98)	Mann Whitney U=5, $p < 0.0001$
IQ composite score	114 \pm 12 (86 – 122)	102 \pm 20 (84 – 118)	Mann Whitney U=50.5, $p = 0.04$
IQ verbal score	107 \pm 13 (93 – 127)	101 \pm 18 (83 – 116)	Mann Whitney U=64.5, $p = 0.15$
IQ non-verbal score	110 \pm 19 (82 – 130)	104 \pm 24 (70 – 117)	Mann Whitney U=64.0, $p = 0.14$

214

215 **2.2 Visual search task**

216 Participants viewed the stimuli binocularly in a darkened room with the appropriate refractive
 217 correction for the working distance. Stimuli were generated (Visage VSG2/5, Cambridge Research
 218 Systems, Kent, UK) and displayed on a gamma-corrected 21-inch CRT monitor (EIZO Flexscan F980,
 219 800 \times 600 pixel resolution, 100 Hz frame rate). The display subtended 12° \times 16° at a working distance
 220 of 137 cm. This distance was chosen so that the visual search display was comparable to the vertical
 221 angular subtense of the display for the MRI scans (12°).

222

223 We used the approach of Verghese, et al., (2014) to quantify visuospatial attention based on two
 224 visual search tasks: (1) a simple *feature* search that is stimulus-driven (pre-attentive, pop-out target)
 225 and shows flat search rates (close to 0 ms/item), and (2) a serial *conjunction* search that requires
 226 top-down visuospatial attention and typically shows a linearly increasing search rate (approximately
 227 5-20 ms/item). Examples of the two visual search tasks are shown in Figure 1A. The target was

228 always a small ($0.50^\circ \times 0.12^\circ$), vertical white bar (CIE chromaticity coordinates: $x = 0.3$, $y = 0.3$;
229 luminance: 25 cd/m^2), against a background of uniform grey (luminance: 18 cd/m^2). The distractors
230 were the same colour and luminance ($x = 0.3$, $y = 0.3$; luminance: 25 cd/m^2) as the target. For the
231 feature search task, only one type of distractor was present – small horizontal white bars ($0.12^\circ \times$
232 0.50°). For the conjunction search task, small horizontal white bars ($0.12^\circ \times 0.50^\circ$) and large vertical
233 white bars ($0.98^\circ \times 0.24^\circ$) were presented. Set size included the target (if present) and the number of
234 distractors.

235

236 On each trial, 16, 32 or 64 items ('set size') were presented. Set size was randomly interleaved to
237 minimise the effects of fatigue or learning. The target was present in half of the trials. An auditory
238 cue occurred at the onset of each presentation and also when a response was made by button press
239 (CB6 response box, Cambridge Research Systems, Kent, UK). Participants were instructed to indicate
240 as quickly and as accurately as possible whether the target was present or absent in each trial. No
241 feedback was provided. Participants were free to make eye movements and the display remained on
242 the screen until a response was recorded. Trials were separated by 3-second intervals of blank
243 screen, with two extra 6-second rest intervals to allow two short breaks during each test run. After
244 at least one practice run to familiarise participants with the task, participants completed one feature
245 search test (3 runs of 10 trials = 30 trials) and two conjunction search tests (2×3 runs of 20 trials =
246 120 trials) in approximately 30 minutes, with breaks as required.

247

248 **2.3 Visual search data analysis**

249 Visual search response time (in seconds) and accuracy (% correct) data were collected. To address
250 our hypotheses, only correct target-present trials were analysed because target-present trials better
251 represent the visuospatial attentional effect, and because target-present performance has been
252 shown to correlate with functional V1 size (Verghese, et al., 2014). For each individual, a linear
253 model was fit to the median response time data as a function of set size (number of elements in the

254 visual search array) using Microsoft Excel (Microsoft, Redmond, WA, USA) and a least squares
255 method. From the linear regression, we obtained a measure of slope (i.e. search efficiency) and y-
256 intercept (i.e. non-search visual processing) for the feature and conjunction search tasks. To quantify
257 overall visual search performance, a single measure of slope (ms/item) was calculated as the
258 difference in slope between the feature and conjunction search tasks as per previous work
259 (Verghese, et al., 2014), where a lower ms/item visual search slope indicates better (i.e. more
260 efficient) visual search performance.

261

262 **2.4 Brain imaging**

263 Participants underwent training and familiarisation with the scanning environment in a mock MRI
264 scanner prior to the test session. For the data collection, a Siemens 3T Skyra MRI scanner with a 32-
265 channel receiver head coil was used. For structural imaging, a T1-weighted MPRAGE sequence
266 (repetition time = 2300 ms, echo time = 2.07 ms, inversion time = 900 ms, flip angle = 9, slice
267 thickness = 1 mm, in-plane voxel dimensions = 1 x 1 mm) was used for anatomical co-registration
268 purposes. Functional brain images were then acquired using a gradient-echo planar imaging
269 sequence (repetition time = 1500 ms, echo time = 30 ms, flip angle = 50, slice thickness = 2.3 mm, in-
270 plane voxel dimensions = 2.32 x 2.32 mm aligned orthogonal to the calcarine sulcus).

271

272 The conventional stimuli for phase-encoded retinotopic mapping (12° diameter, high-contrast
273 drifting checkerboard expanding ring to map eccentricity and rotating wedge to map polar angle)
274 were presented using PsychToolbox (Brainard, 1997) and Matlab (Version R2011b, Mathworks,
275 Natick, MA, United States), obtained from the VISTA lab retinotopy toolbox online (Stanford Vision
276 and Imaging Group, Stanford University; available from:
277 <http://white.stanford.edu/newIm/index.php/Software>). The stimuli were displayed using an LCD
278 projector (maximum brightness = 1500 lumens, resolution = 1024 x 768 pixels, frame rate = 60 Hz)
279 onto a back-projection screen positioned at 155 cm from the eye plane. To maintain fixation during

280 scanning, participants were instructed to press a button when the central fixation spot changed
281 colour (red to green and vice-versa). Eye and head movements were continuously monitored in real-
282 time by the investigators via an integrated Eyelink 1000 system (SR Research Ltd., Ottawa, Ontario,
283 Canada).

284

285 **2.5 Brain imaging data analysis**

286 The anatomical T1-weighted images were averaged and analysed using the FreeSurfer (Fischl, 2012)
287 software package (Version 5.1.0: <https://surfer.nmr.mgh.harvard.edu/>) according to a standard
288 processing pipeline (Dale, Fischl, & Sereno, 1999). In brief, the anatomical images were automatically
289 segmented into grey and white matter using custom software, and any segmentation errors were
290 manually corrected. Grey matter was subsequently grown from the segmented white matter to form
291 a 3-4mm layer covering the white matter surface, and the cortical surface was reconstructed in 3D at
292 the white/grey matter boundary. The data was pre-processed to remove linear trends from the
293 functional MRI time series (without spatial smoothing) and correct for motion (applied between
294 sessions and within individual scans).

295

296 Phase-encoded retinotopic mapping (Sereno, et al., 1995) of V1 of the right and left hemispheres
297 was conducted on a flattened representation of the cortical surface in Freesurfer. Pseudo-colour
298 phase maps were used to visualize the retinotopic maps. The V1 region of interest was manually
299 delineated on the inflated cortical surface by two independent graders (authors BNN and SKC), one
300 of whom was blinded to the participants' group (author SKC). In a pilot analysis of half of the MRI
301 data (n=12), the intra-class correlation coefficients for the left and right functional V1 size were 0.92
302 and 0.95, respectively, indicating excellent internal consistency between graders (Cronbach's α left
303 V1 = 0.94, right V1 = 0.97). For the final dataset analysis, functional V1 size measurements obtained
304 by grader 1 (author BNN) were taken. A ratio of inter-hemispheric asymmetry (left/right V1 size) was

305 calculated, where a ratio of less than 1 indicates a bias towards having a larger representation of
306 right V1 relative to the left V1.

307

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308 **2.6 Statistical analysis**

309 Statistical analysis was conducted using SPSS Version 26.0 (IBM Corp., Armonk, NY, USA). A
310 Kolmogorov-Smirnov test was used to assess data normality. To compare group demographic
311 features and functional brain imaging outcomes, t-tests or Mann Whitney rank sum tests were used
312 for normally or non-normally distributed data, respectively. A repeated-measures analysis of
313 variance (RM-ANOVA) was used to assess group differences in visual search performance, where the
314 between-factor was group and the within-factors were set size and search task. Spearman rank
315 correlational analysis was conducted to assess relationships between non-normally distributed
316 measures, otherwise Pearson correlations were calculated. A $p < 0.05$ was considered statistically
317 significant.

318

319 **3. Results**

320 **3.1 Participants**

321 The control and dyslexic groups were not different in age ($t_{29}=0.78$, $p=0.44$) nor in the proportion of
322 females to males (chi square test of proportions: $p=0.82$). As expected, the dyslexic children had
323 significantly lower reading ability scores on the WIAT-II test (i.e. standardised according to current
324 school year level; Table 1; $p<0.001$). While we were careful to exclude any participants with below
325 average IQ composite score, our normal-reading control group had higher mean IQ (Table 1; $p=0.04$)
326 with similar range (controls: 86 – 122, dyslexic: 84 – 118). There was no difference between dyslexia
327 and control participants in group mean non-verbal IQ (Table 1; $p=0.14$) nor verbal IQ (Table 1;
328 $p=0.15$). Overall IQ composite score was predictive of reading ability (Spearman $r = 0.44$, $p=0.02$).
329 The association between IQ composite score and reading ability appeared to be linked to verbal IQ
330 (Spearman $r = 0.35$, $p = 0.07$) rather than non-verbal IQ (Spearman $r = 0.28$, $p = 0.15$), but these
331 correlations did not reach conventional statistical significance.

332

333

334 **3.2 Visual search**

335 There were no differences in accuracy (% correct) across all target present visual search tasks
336 between control and dyslexic participants (Table 2; $p > 0.05$ for all comparisons); hence, all visual
337 search data was considered reliable and included in the analysis. Figure 1B plots the time taken to
338 correctly detect the target within a field of distractors as a function of set size. While there was no
339 overall group difference in response time (RM-ANOVA main effect of group: $F(1,29)=2.91$, $p=0.10$),
340 there was a three-way interaction between group, search task and set size ($F(2,58)=3.37$, $p=0.04$).
341 Feature search response times were similar between groups across all set sizes (RM-ANOVA main
342 effect of group: $F(1,29)=0.49$, $p=0.49$; set size x group interaction: $F(2, 58)=0.23$, $p=0.80$). On the
343 other hand, there was a trend consistent with existing literature that conjunction search response
344 times across all set sizes were slower in the dyslexic children (RM-ANOVA main effect of group:
345 $F(1,29)=3.96$, $p=0.06$), with the delay being most prominent with increased number of distractors
346 (set size x group interaction: $F(2, 58)=3.48$, $p=0.04$).

347
348 When we considered individual performance in terms of slope (search efficiency), the dyslexic group
349 were less efficient than the control group for the conjunction search task only (Figure 1C middle
350 panel; group x search task interaction: $F(1,29)=5.43$, $p=0.03$). This translated to poorer overall visual
351 search performance (poorer visuospatial attention) in the dyslexic children, i.e. the difference
352 between feature and conjunction search slopes (Figure 1C, right panel; $t_{29}=2.33$, $p=0.03$). To
353 determine whether the conjunction search delays observed in the dyslexic children might be related
354 to a delay in non-search processing, we tested whether the intercepts of the individual linear fits
355 differed between groups. Both control and dyslexic groups showed similar intercepts for the
356 conjunction search task (control: 1.4 ± 0.5 seconds, dyslexic: 1.6 ± 0.5 seconds; $t_{29}=0.91$, $p=0.37$),
357 suggesting no difference in signal processing or motor activity that might contribute to an overall
358 delay in visual search response times.

359 **Table 2.** Percent (%) accuracy of target present visual search performance (median, range). Group
 360 data were compared (*p*-values) using Mann-Whitney rank sum tests as data were not normally
 361 distributed.

Search task	Set size	Controls	Dyslexic	<i>p</i> -value
Feature	16	100 (80 – 100)	100 (80 – 100)	Mann Whitney U=100.5, <i>p</i> =0.21
Feature	32	100 (80 – 100)	100 (80 – 100)	Mann Whitney U=109, <i>p</i> =0.44
Feature	64	100 (80 – 100)	100 (80 – 100)	Mann Whitney U=106.5, <i>p</i> =0.39
Conjunction	16	95 (85 – 100)	95 (75 – 100)	Mann Whitney U=103.5, <i>p</i> =0.51
Conjunction	32	95 (85 – 100)	90 (75 – 100)	Mann Whitney U=85.5, <i>p</i> =0.17
Conjunction	64	90 (70 – 100)	90 (65 – 100)	Mann Whitney U=117.5, <i>p</i> =0.95

362

363 **3.3 Functional primary visual cortical size**

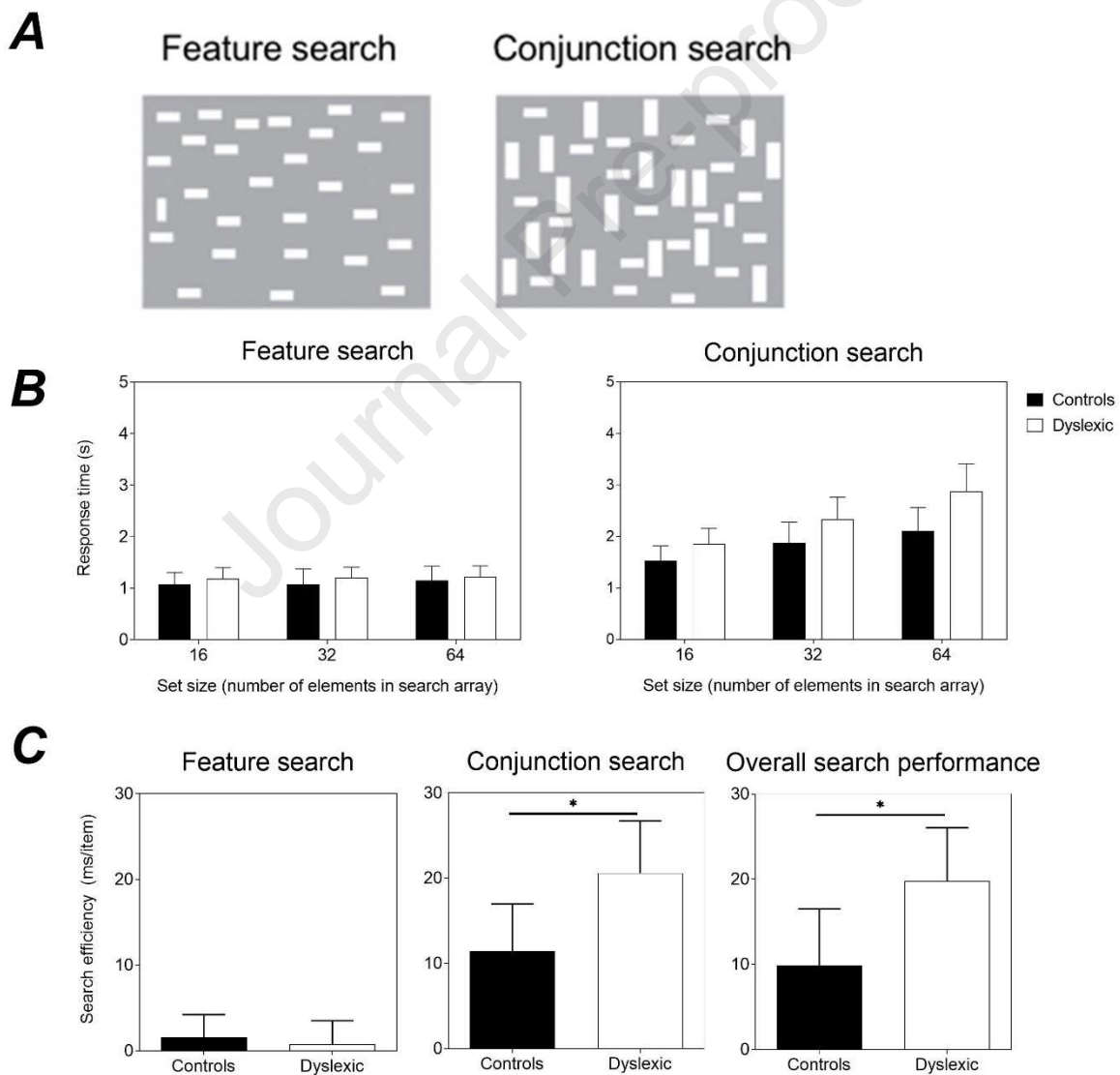
364 Despite having similar total functional V1 size (Figure 2A; sum of left and right hemispheres; $t_{22}=0.82$,
 365 $p=0.42$), dyslexic and control participants showed different right and left hemispheric functional V1
 366 size (group x hemisphere interaction: $F(1,22)=6.99$, $p=0.02$). Dyslexic children demonstrated a right
 367 hemisphere bias (Figure 2B; ratio <1 indicates larger representation of the visual stimulus in right V1
 368 relative to left V1), whereas normal reading children showed close to 1:1 ratio in functional V1 size
 369 between the right and left hemispheres (Figure 2B; group difference in V1 asymmetry: $t_{22}=2.22$,
 370 $p=0.04$).

371

372 To confirm that any group differences in functional brain measures were not influenced by
 373 differences in structural brain size, we determined that the dyslexic and normal-reading children
 374 showed similar intracranial volume (mean \pm standard deviation; control: 1457 ± 160 cm³, dyslexic:
 375 1455 ± 151 cm³; $t_{22}=0.02$, $p=0.98$), total cortical grey matter volume (control: 588 ± 60 cm³, dyslexic:
 376 582 ± 50 cm³; $t_{22}=0.25$, $p=0.81$) and total cortical white matter volume (control: 434 ± 62 cm³,
 377 dyslexic: 435 ± 51 cm³; $t_{22}=0.04$, $p=0.97$).

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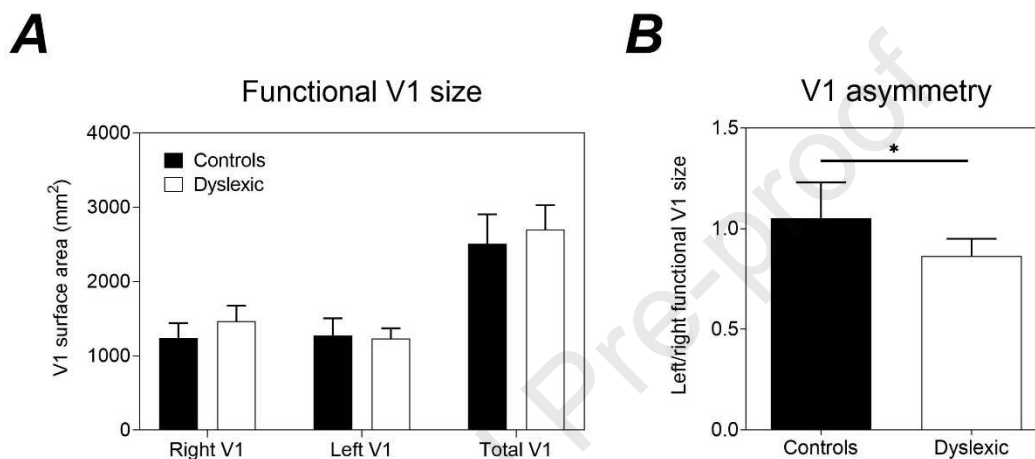
379 **Figure 1. (A)** Schematic illustration of the visual stimuli used for the feature search and conjunction
 380 search tasks. The target for the visual search task is the smaller vertical bar. **(B)** Feature and
 381 conjunction visual search response time (s) as a function of set size for the control (n=14) and dyslexic
 382 (n=17) groups. **(C)** Visual search efficiency (ms/item slope) for the control (n=14) and dyslexic (n=17)
 383 groups for the feature (left panel) and conjunction (middle panel) search tasks. Overall visual search
 384 performance (right panel) was the difference between feature and conjunction search slopes. Higher
 385 search efficiency slopes imply less efficient visual search performance. For all panels, group means
 386 and 95% confidence intervals of the mean are plotted.



387

388

389 **Figure 2. (A)** Functional size of right and left hemispheres of primary visual cortex (V1) from
 390 retinotopic mapping in controls (n=11) and dyslexic (n=13) groups. Total V1 size was defined as the
 391 sum of the left and right hemispheres. **(B)** Functional V1 size asymmetry, defined as the ratio
 392 between left and right hemisphere functional V1 sizes. A ratio less than 1 indicates a larger right V1
 393 size relative to the left V1. For all panels, group means and 95% confidence intervals of the mean are
 394 plotted.



396 3.4 Relationship between measures

397 Given the continuum of reading ability (range of standardised scores: 53 to 130) amongst our study
 398 participants, we considered the correlation between our visual outcome measures and reading
 399 ability across the entire cohort (n=24). Reading impaired children showed poorer overall visual
 400 search performance (Figure 3A; Pearson $r=-0.44$, $R^2=0.19$, $p=0.01$), needing more time per unit
 401 distractor (i.e. higher ms/item search efficiency). Reading ability was also correlated with V1 size
 402 asymmetry (Figure 3B; Pearson $r=0.45$, $R^2=0.21$, $p=0.03$), such that poorer readers showed less left
 403 hemisphere bias relative to the right hemisphere.

404

405 While we hypothesized that better visuospatial attention (i.e. lower ms/item search efficiency)
 406 would predict greater central visual field representation in the left V1 hemisphere relative to the
 407 right hemisphere (i.e. V1 asymmetry > 1.0), we did not find a statistically significant correlation

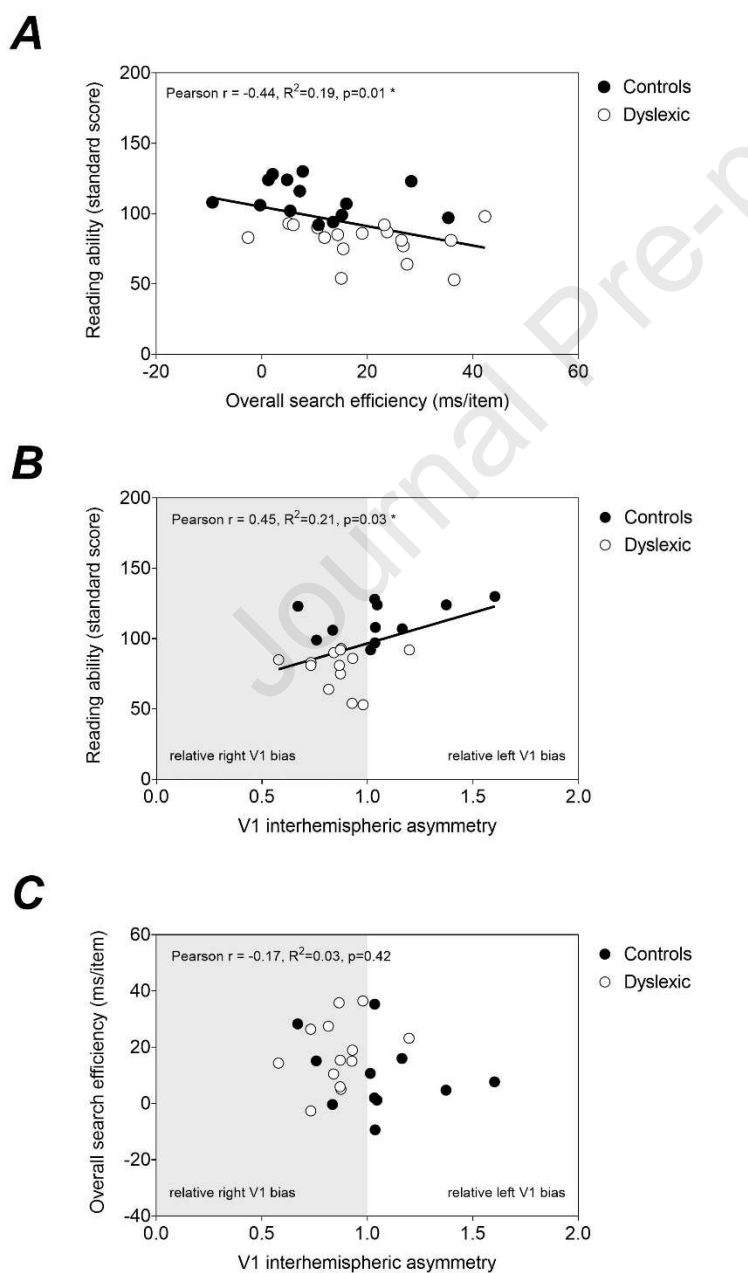
408 between these visual outcome measures (Figure 3C; Pearson $r=-0.17$, $R^2=0.03$, $p=0.42$). Previous
409 work in a normal-reading adult population (Verghese, et al., 2014) reported right and left V1 size
410 separately and not as a relative ratio; that study found a correlation between visuospatial attention
411 (i.e. lower ms/item search efficiency) and left V1 size only. Our analysis did not yield the same results
412 in children when we considered the left V1 functional size alone (Pearson $r=0.21$, $R^2=0.04$, $p=0.31$)
413 and the right V1 functional size alone (Pearson $r=0.33$, $R^2=0.11$, $p=0.12$).

414

415 Because reading ability was related to IQ, we analysed whether IQ would also be correlated with
416 overall visual search efficiency and V1 functional size asymmetry. Similar in direction to reading
417 ability scores, children with higher overall IQ showed more efficient visual search with lower
418 ms/item slopes (Spearman $r=-0.41$, $p=0.03$). We also analysed whether the total activation of V1
419 would correlate with the measured visual search efficiency or with the non-search related
420 processing time, which is the intercept of the visual search function. We found that total activation
421 of V1 (sum of right and left hemisphere functional V1 size) was not correlated with overall visual
422 search efficiency (Pearson $r = 0.30$, $R^2 = 0.09$, $p = 0.15$), whereas the correlation between total V1
423 size and non-search related processing time did not reach statistical significance (i.e. intercept of the
424 visual search function for target present trials; Pearson $r = 0.37$, $R^2 = 0.14$, $p = 0.07$).

425

426 **Figure 3.** Relationship between visual search performance, reading ability and functional visual
 427 cortical size. (B) Reading ability vs overall visual search efficiency, where a lower ms/item slope
 428 indicates better (more efficient) visuospatial attention. (B) Reading ability vs V1 functional size
 429 interhemispheric asymmetry, where an asymmetry < 1.0 indicates a relative right V1 bias (shaded
 430 area) and an asymmetry > 1.0 indicates a relative left V1 bias. (C) V1 functional size interhemispheric
 431 asymmetry (ratio) vs overall visual search efficiency (ms/item). Pearson correlational analysis results
 432 are shown, with asterisks and solid regression lines denoting statistical significance at $p < 0.05$.



433

434

435 4. Discussion

436 This study aimed to investigate overall visual search efficiency in dyslexic and normal-reading
437 children and look for a neurophysiological correlate of impaired visuospatial attention in the
438 functional size of primary visual cortex. First, we confirmed that dyslexic children have poorer visual
439 search efficiency by demonstrating that the dyslexic group showed impaired conjunction search
440 performance in an attention-dependent visuospatial task, but similar feature search performance in
441 a pre-attentive visuospatial task. Thus, regardless of reading ability, children of similar age (9-11
442 years) have similar visual search response times when the object of interest 'pops out'. Our study
443 builds on previous reports of impaired visual search performance in dyslexia (Casco & Prunetti, 1996;
444 Iles, et al., 2000; Vidyasagar & Pammer, 1999) by showing that slower visual search in the dyslexic
445 children, as the task became more complicated with additional distractors (i.e. higher ms/item
446 search slope), was not attributed to an overall increase in non-search related processing time (i.e.
447 intercept of the visual search function). Hence, we consider our findings as supportive of an inherent
448 problem of visuospatial attention in dyslexia (Vidyasagar, 2004; Vidyasagar & Pammer, 2010).

449
450 Consistent with other work demonstrating visuospatial attentional deficits in poorer reading children
451 (Facoetti, Paganoni, Turatto, Marzola, & Mascetti, 2000), we show that poorer visual search
452 efficiency measured is correlated with reading ability in children, measured using a standardised
453 academic achievement test (WIAT-II). A previous study in normal-reading adults demonstrated that
454 poorer visual search efficiency was correlated with slower reading speed, i.e. the time required to
455 read standardised comprehension passages at a self-determined pace (Verghese, et al., 2014). Here,
456 we did not report reading speed because there was no single standardised comprehension passage
457 suitable for all our participants at different school levels (ranged from Years 4 to 6). Furthermore, it
458 became apparent in some dyslexic children that reading speed would have been artificially low
459 because they skipped parts of text due to their reading difficulty. Rather, the WIAT-II test was
460 chosen as our primary reading outcome measure as it encompassed a wide range of reading-related

461 skills (including phonological skills, reading comprehension, and phonetic decoding skills), and not
462 just reading speed alone.

463

464 We *a priori* predicted a relationship between overall visual search efficiency and functional V1 size as
465 a neurophysiological correlate of visual behavioural performance in our cohort of children, as
466 previously established in normal-reading adults (Verghese, et al., 2014). If visual search performance
467 and functional V1 size are both measures of primary visual cortical function, then we might expect
468 the two should be correlated. While the prediction was not true in our dataset, reading ability was
469 correlated with both visual search efficiency (poorer readers had higher ms/item search slopes) and
470 functional V1 size asymmetry (poorer readers had lower left/right hemispheric asymmetry,
471 suggesting a relative right V1 bias), suggesting at least one commonality (possibly related to reading
472 and/or cognitive ability) underlying visual search efficiency and functional V1 size. The major
473 difference is that in this study, we studied children, some with 'pathological' poor reading ability (i.e.
474 dyslexia), and not adults with self-reported normal reading ability (i.e. university students)
475 (Verghese, et al., 2014).

476

477 We found altered left/right V1 interhemispheric asymmetry (see Figure 2B) in dyslexic children
478 relative to normal reading children, and interpret this as a relative bias towards right hemisphere
479 representation of visual information in dyslexia. A future consideration is to examine how normal
480 childhood development and reading experience, over a longitudinal study, impacts on visuospatial
481 attentional efficiency and functional visual cortical size. Perhaps as children develop from their pre-
482 school to school-age years, there is an initial bias towards right hemisphere representation which
483 becomes less apparent as they improve their reading skills, although this could not be explored in
484 this study given the narrow age range of participants (9-11 years). Interestingly, interhemispheric
485 size asymmetry in volume of the lateral geniculate nucleus (LGN) has been reported in young adults
486 with dyslexia (Giraldo-Chica, et al., 2015), suggesting an under-development of the left hemisphere

487 (akin to the presumed under-development of left functional V1 seen in our dyslexic children) with
488 impaired reading ability. The functional significance of left/right LGN and V1 asymmetry in the
489 dyslexia literature is still unknown, but does suggest a developmental imbalance in the left and right
490 hemispheres that appears to be associated with reading ability. Learning to read is known to alter
491 the connectivity between cortex and thalamus even in adult illiterates (Skeide, et al., 2017) and thus
492 it is possible that the interhemispheric asymmetry seen in normally reading adults (Verghese et al.,
493 2014) and the difference in this measure between adult and paediatric cohorts are the gradual
494 results of decades of literacy.

495

496 From our data, it is not possible to disentangle whether the group differences observed in visual
497 search efficiency and functional V1 size asymmetry reflect the underlying aetiology of dyslexia, or
498 the reduced cumulative reading experience that naturally accompanies a reading difficulty. Normally
499 reading children read, on average, a few hundred times more words in a year than dyslexic children
500 (Anderson, Wilson, & Fielding, 1988), which could underlie some of the structural changes observed
501 in brain connectivity between areas normally involved in reading and language comprehension
502 (Romeo, et al., 2018; Yeatman, Dougherty, Myall, Wandell, & Feldman, 2012). This conflates the
503 traditional dilemma of correlation vs causation that has long bedevilled the pursuit of finding a
504 causal deficit in dyslexia (Goswami, 2015). Nevertheless, there is growing interest in remediation
505 techniques that seek to enhance visuospatial attention, global visual scene perception, and dorsal
506 stream motion discrimination and therefore improve reading such as action video games
507 (Franceschini, et al., 2013), perceptual training (Franceschini, Bertoni, Ganesini, Gori, & Facchetti,
508 2017; Lawton, 2016) and transcranial current application (Costanzo, et al., 2019). Whether causally
509 related to reading or not, the deficits in dyslexic visual function observed here using psychophysical
510 and neuroimaging methods are likely to be useful in studying the cognitive and neural changes
511 caused by such remediation procedures (see review by (Vidyasagar, 2019).

512

513 While we did not formally explore reading habits in this study, we can speculate about the possible
514 role of reading in at least partially shaping visual cortical function in children, given more recent
515 evidence for poorer right/left hemifield visual search performance in bidirectional relative to
516 unidirectional readers (Kermani, Verghese, & Vidyasagar, 2018). Bidirectional adult readers, who
517 have presumably split their cumulative lifetime reading experience between two languages that
518 require left-to-right and right-to-left visuospatial attention (for example, English and Farsi
519 respectively), may have a relative disadvantage when visual search is restricted to the left or right
520 hemifield. In light of this, and the fact that reading in English involves left-to-right attention, it is
521 possible that dyslexia disrupts the typical balanced (or possibly more left-biased) hemispheric
522 symmetry in functional V1 size. Indeed, brain imaging studies find lateralized abnormalities, many of
523 which are left hemispheric, of a range of neural networks in dyslexia (see reviews by Kershner, 2019;
524 Paracchini, Diaz, & Stein, 2016) and that left hemispheric function is disrupted in pre-reading
525 children with a family history of dyslexia, before formal diagnosis of dyslexia is possible (Raschle,
526 Chang, & Gaab, 2011; Raschle, Zuk, & Gaab, 2012). These results, however, do not solve the ‘chicken
527 or egg’ problem but may shed light on a mechanism of interhemispheric asymmetry underlying the
528 association observed longitudinally between pre-reading visuospatial attention (at a kindergarten
529 level) and future reading acquisition skills later in childhood (Franceschini, et al., 2012). Alternatively,
530 a future approach to dissociate between cause and consequence of dyslexia is to compare groups of
531 children who are not chronologically age-matched, but ‘ability-matched’ (Goswami, 2015). Because
532 dyslexic children read far fewer words than typical readers of the same age (Anderson, et al., 1988),
533 it is plausible that differences in visual performance and cortical function relate to overall reading
534 experience (Vidyasagar, 2014). Indeed, years of reading experience has been shown to largely
535 account for grey and white matter volume differences between dyslexic and non-dyslexic children
536 (Krafnick, Flowers, Luetje, Napoliello, & Eden, 2014), but is yet to be explored for the left/right
537 asymmetry we observe here.
538

539 While we focused on measuring reading ability as the main outcome of interest, we also
540 encountered inter-individual variation in cognitive ability in our dyslexic and normal-reading
541 children. IQ was predictive of reading ability, as has been reported before (e.g. Kevan & Pammer,
542 2009; Snowling, Hulme, & Nation, 2020). We also found that poorer IQ was associated with poorer
543 visual search efficiency, which suggests that general task demands may account for differences in
544 visuospatial attention between normal-reading and dyslexic children. It is possible that the
545 differences observed in this study between dyslexic and normal-reading children, and the
546 correlations observed between measures, may be associated with IQ rather than specific to dyslexia.
547 IQ was allowed to vary freely within our consecutively recruited cohort and not matched between
548 the normal-reading and dyslexic groups. We admit the possibility that the higher IQ in our control
549 group may also have been a result of inherent selection bias of our university-based research study,
550 as the normal-reading children were mostly children of university professional and academic staff
551 (with some control participants being siblings or friends/acquaintances of the dyslexic children).
552 Future work could interrogate whether the visual deficits we report in the dyslexic children are an
553 epiphenomenon of cognitive deficit, by controlling for IQ in a multivariate regression analysis with a
554 larger sample population. In particular, while the correlation between verbal IQ and reading ability
555 did not reach statistical significance here, it is known that the vastly reduced amount of reading
556 done by dyslexic children (Anderson, et al., 1988) has a negative effect on verbal and phonemic skills
557 (e.g. see Huettig, Lachmann, Reis, & Petersson, 2018; Snowling, et al., 2020). However, we believe
558 that it is difficult to disentangle the relative contributions of dyslexia and IQ, given that IQ and
559 reading ability are inextricably linked.

560

561 In summary, inter-individual variation in children's reading ability is associated with two visual
562 functional measures, namely visual search efficiency and functional size of V1. We confirm that
563 dyslexia and poorer reading ability is associated with poorer visual search efficiency (higher ms/item
564 search slopes). We also demonstrate, for the first time, functional asymmetry between the left and

565 right hemispheres of V1 in dyslexic children relative to normal-reading children, such that there
566 appears to be a relative right V1 bias. While reading ability was correlated with visual search
567 efficiency and functional V1 asymmetry separately, these two measures of visual cortical function
568 were not correlated with each other. We surmise that, by adulthood, the reduced reading
569 accumulated by people with dyslexia (or even those at the lower end of the 'normal-reading'
570 spectrum) is associated with both reduced visuospatial attention as well as a bias away from the left
571 hemisphere in terms of functional V1 size. Our findings highlight the importance of considering the
572 laterality of functional measures in dyslexia, and the possibility that independent cortical networks
573 responsible for visuospatial attention and functional V1 size both contribute to impaired reading
574 ability in dyslexic children.

575

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584

585 **5. References**

- 586 Anderson, R. C., Wilson, P. T., & Fielding, L. G. (1988). Growth in reading and how children spend
587 their time outside of school. *Read Res Quart*, *23*, 285-303.
- 588 Bertoni, S., Franceschini, S., Ronconi, L., Gori, S., & Facoetti, A. (2019). Is excessive visual crowding
589 causally linked to developmental dyslexia? *Neuropsychologia*, *130*, 107-117.
- 590 Boets, B., Vandermosten, M., Cornelissen, P., Wouters, J., & Ghesquiere, P. (2011). Coherent motion
591 sensitivity and reading development in the transition from prereading to reading stage. *Child*
592 *Dev*, *82*, 854-869.
- 593 Brainard, D. H. (1997). The Psychophysics Toolbox. *Spat Vis*, *10*, 433-436.
- 594 Carroll, J. M., Solity, J., & Shapiro, L. R. (2016). Predicting dyslexia using prereading skills: the role of
595 sensorimotor and cognitive abilities. *J Child Psychol Psychiatry*, *57*, 750-758.
- 596 Casco, C., & Prunetti, E. (1996). Visual search of good and poor readers: effects with targets having
597 single and combined features. *Perceptual and motor skills*, *82*, 1155-1167.
- 598 Casco, C., Tressoldi, P. E., & Dellantonio, A. (1998). Visual selective attention and reading efficiency
599 are related in children. *Cortex; a journal devoted to the study of the nervous system and*
600 *behavior*, *34*, 531-546.
- 601 Cicchini, G. M., Marino, C., Mascheretti, S., Perani, D., & Morrone, M. C. (2015). Strong motion
602 deficits in dyslexia associated with DCDC2 gene alteration. *J Neurosci*, *35*, 8059-8064.
- 603 Costanzo, F., Rossi, S., Varuzza, C., Varvara, P., Vicari, S., & Menghini, D. (2019). Long-lasting
604 improvement following tDCS treatment combined with a training for reading in children and
605 adolescents with dyslexia. *Neuropsychologia*, *130*, 38-43.
- 606 Dale, A. M., Fischl, B., & Sereno, M. I. (1999). Cortical surface-based analysis. I. Segmentation and
607 surface reconstruction. *Neuroimage*, *9*, 179-194.
- 608 Debska, A., Luniewska, M., Chyl, K., Banaszkiwicz, A., Zelechowska, A., Wypych, M., Marchewka, A.,
609 Pugh, K. R., & Jednorog, K. (2016). Neural basis of phonological awareness in beginning
610 readers with familial risk of dyslexia-Results from shallow orthography. *Neuroimage*, *132*,
611 406-416.
- 612 Dehaene, S., & Cohen, L. (2011). The unique role of the visual word form area in reading. *Trends*
613 *Cogn Sci*, *15*, 254-262.
- 614 Diaz, B., Hintz, F., Kiebel, S. J., & von Kriegstein, K. (2012). Dysfunction of the auditory thalamus in
615 developmental dyslexia. *Proc Natl Acad Sci U S A*, *109*, 13841-13846.
- 616 Dickinson, J. E., Haley, K., Bowden, V. K., & Badcock, D. R. (2018). Visual search reveals a critical
617 component to shape. *J Vis*, *18*, 2.
- 618 Diehl, J. J., Frost, S. J., Sherman, G., Mencl, W. E., Kurian, A., Molfese, P., Landi, N., Preston, J.,
619 Soldan, A., Fulbright, R. K., Rueckl, J. G., Seidenberg, M. S., Hoeft, F., & Pugh, K. R. (2014).
620 Neural correlates of language and non-language visuospatial processing in adolescents with
621 reading disability. *Neuroimage*, *101*, 653-666.

- 622 Facoetti, A., Paganoni, P., Turatto, M., Marzola, V., & Mascetti, G. G. (2000). Visual-spatial attention
623 in developmental dyslexia. *Cortex*, *36*, 109-123.
- 624 Fischl, B. (2012). FreeSurfer. *Neuroimage*, *62*, 774-781.
- 625 Franceschini, S., Bertoni, S., Giancesini, T., Gori, S., & Facoetti, A. (2017). A different vision of dyslexia:
626 Local precedence on global perception. *Sci Rep*, *7*, 17462.
- 627 Franceschini, S., Gori, S., Ruffino, M., Pedrolli, K., & Facoetti, A. (2012). A causal link between visual
628 spatial attention and reading acquisition. *Current biology : CB*, *22*, 814-819.
- 629 Franceschini, S., Gori, S., Ruffino, M., Viola, S., Molteni, M., & Facoetti, A. (2013). Action video games
630 make dyslexic children read better. *Curr Biol*, *23*, 462-466.
- 631 Galaburda, A. M. (2005). Dyslexia--a molecular disorder of neuronal migration: the 2004 Norman
632 Geschwind Memorial Lecture. *Ann Dyslexia*, *55*, 151-165.
- 633 Gialluisi, A., Andlauer, T. F. M., Mirza-Schreiber, N., Moll, K., Becker, J., Hoffmann, P., Ludwig, K. U.,
634 Czamara, D., Pourcain, B. S., Honbolygo, F., Toth, D., Csepe, V., Huguet, G., Chaix, Y.,
635 Iannuzzi, S., Demonet, J. F., Morris, A. P., Hulslander, J., Willcutt, E. G., DeFries, J. C., Olson,
636 R. K., Smith, S. D., Pennington, B. F., Vaessen, A., Maurer, U., Lytinen, H., Peyrard-Janvid,
637 M., Leppanen, P. H. T., Brandeis, D., Bonte, M., Stein, J. F., Talcott, J. B., Fauchereau, F.,
638 Wilcke, A., Kirsten, H., Muller, B., Francks, C., Bourgeron, T., Monaco, A. P., Ramus, F.,
639 Landerl, K., Kere, J., Scerri, T. S., Paracchini, S., Fisher, S. E., Schumacher, J., Nothen, M. M.,
640 Muller-Myhsok, B., & Schulte-Korne, G. (2020). Genome-wide association study reveals new
641 insights into the heritability and genetic correlates of developmental dyslexia. *Mol*
642 *Psychiatry*. *Mol Psychiatry*, doi: 10.1038/s41380-020-00898-x. Online ahead of print.
- 643 Giraldo-Chica, M., Hegarty, J. P., 2nd, & Schneider, K. A. (2015). Morphological differences in the
644 lateral geniculate nucleus associated with dyslexia. *Neuroimage Clin*, *7*, 830-836.
- 645 Giraldo-Chica, M., & Schneider, K. A. (2018). Hemispheric asymmetries in the orientation and
646 location of the lateral geniculate nucleus in dyslexia. *Dyslexia*, *24*, 197-203.
- 647 Gori, S., Cecchini, P., Bigoni, A., Molteni, M., & Facoetti, A. (2014). Magnocellular-dorsal pathway and
648 sub-lexical route in developmental dyslexia. *Front Hum Neurosci*, *8*, 460.
- 649 Gori, S., Seitz, A. R., Ronconi, L., Franceschini, S., & Facoetti, A. (2016). Multiple Causal Links Between
650 Magnocellular-Dorsal Pathway Deficit and Developmental Dyslexia. *Cerebral cortex*, *26*,
651 4356-4369.
- 652 Goswami, U. (2015). Sensory theories of developmental dyslexia: three challenges for research. *Nat*
653 *Rev Neurosci*, *16*, 43-54.
- 654 Griffin, J. R., & Walton, H. N. (1981). Dyslexia Determination Test. In. Los Angeles, California:
655 Instructional Materials and Equipment Distributors.
- 656 Hosseini, S. M., Black, J. M., Soriano, T., Bugescu, N., Martinez, R., Raman, M. M., Kesler, S. R., &
657 Hoeft, F. (2013). Topological properties of large-scale structural brain networks in children
658 with familial risk for reading difficulties. *Neuroimage*, *71*, 260-274.

- 659 Huettig, F., Lachmann, T., Reis, A., & Petersson, K. M. (2018). Distinguishing cause from effect –
660 many deficits associated with developmental dyslexia may be a consequence of reduced and
661 suboptimal reading experience. *Language, Cognition and Neuroscience*, 33.
- 662 Iles, J., Walsh, V., & Richardson, A. (2000). Visual search performance in dyslexia. *Dyslexia*, 6, 163-
663 177.
- 664 Kermani, M., Verghese, A., & Vidyasagar, T. R. (2018). Attentional asymmetry between visual
665 hemifields is related to habitual direction of reading and its implications for debate on cause
666 and effects of dyslexia. *Dyslexia*, 24, 33-43.
- 667 Kershner, J. R. (2019). Neurobiological systems in dyslexia. *Trends Neurosci Educ*, 14, 11-24.
- 668 Kevan, A., & Pammer, K. (2008). Making the link between dorsal stream sensitivity and reading.
669 *Neuroreport*, 19, 467-470.
- 670 Kevan, A., & Pammer, K. (2009). Predicting early reading skills from pre-reading measures of dorsal
671 stream functioning. *Neuropsychologia*, 47, 3174-3181.
- 672 Krafnick, A. J., Flowers, D. L., Luetje, M. M., Napoliello, E. M., & Eden, G. F. (2014). An investigation
673 into the origin of anatomical differences in dyslexia. *J Neurosci*, 34, 901-908.
- 674 Lawton, T. (2016). Improving Dorsal Stream Function in Dyslexics by Training Figure/Ground Motion
675 Discrimination Improves Attention, Reading Fluency, and Working Memory. *Front Hum*
676 *Neurosci*, 10, 397.
- 677 Livingstone, M. S., Rosen, G. D., Drislane, F. W., & Galaburda, A. M. (1991). Physiological and
678 anatomical evidence for a magnocellular defect in developmental dyslexia. *Proc Natl Acad*
679 *Sci U S A*, 88, 7943-7947.
- 680 Lovegrove, W. J., Bowling, A., Badcock, D., & Blackwood, M. (1980). Specific reading disability:
681 differences in contrast sensitivity as a function of spatial frequency. *Science*, 210, 439-440.
- 682 Mills, K. L., Goddings, A. L., Herting, M. M., Meuwese, R., Blakemore, S. J., Crone, E. A., Dahl, R. E.,
683 Guroglu, B., Raznahan, A., Sowell, E. R., & Tamnes, C. K. (2016). Structural brain
684 development between childhood and adulthood: Convergence across four longitudinal
685 samples. *Neuroimage*, 141, 273-281.
- 686 Muller-Axt, C., Anwender, A., & von Kriegstein, K. (2017). Altered Structural Connectivity of the Left
687 Visual Thalamus in Developmental Dyslexia. *Curr Biol*, 27, 3692-3698 e3694.
- 688 Norton, E. S., Beach, S. D., & Gabrieli, J. D. (2015). Neurobiology of dyslexia. *Curr Opin Neurobiol*, 30,
689 73-78.
- 690 Paracchini, S., Diaz, R., & Stein, J. (2016). Advances in Dyslexia Genetics-New Insights Into the Role of
691 Brain Asymmetries. *Adv Genet*, 96, 53-97.
- 692 Paracchini, S., Scerri, T., & Monaco, A. P. (2007). The genetic lexicon of dyslexia. *Annu Rev Genomics*
693 *Hum Genet*, 8, 57-79.
- 694 Peterson, R. L., & Pennington, B. F. (2012). Developmental dyslexia. *Lancet*, 379, 1997-2007.

- 695 Power, A. J., Colling, L. J., Mead, N., Barnes, L., & Goswami, U. (2016). Neural encoding of the speech
696 envelope by children with developmental dyslexia. *Brain Lang*, *160*, 1-10.
- 697 Price, C. J. (2012). A review and synthesis of the first 20 years of PET and fMRI studies of heard
698 speech, spoken language and reading. *Neuroimage*, *62*, 816-847.
- 699 Ramus, F., Altarelli, I., Jednorog, K., Zhao, J., & Scotto di Covella, L. (2018). Neuroanatomy of
700 developmental dyslexia: Pitfalls and promise. *Neurosci Biobehav Rev*, *84*, 434-452.
- 701 Raschle, N. M., Chang, M., & Gaab, N. (2011). Structural brain alterations associated with dyslexia
702 predate reading onset. *Neuroimage*, *57*, 742-749.
- 703 Raschle, N. M., Zuk, J., & Gaab, N. (2012). Functional characteristics of developmental dyslexia in
704 left-hemispheric posterior brain regions predate reading onset. *Proc Natl Acad Sci U S A*,
705 *109*, 2156-2161.
- 706 Romeo, R. R., Segaran, J., Leonard, J. A., Robinson, S. T., West, M. R., Mackey, A. P., Yendiki, A.,
707 Rowe, M. L., & Gabrieli, J. D. E. (2018). Language Exposure Relates to Structural Neural
708 Connectivity in Childhood. *J Neurosci*, *38*, 7870-7877.
- 709 Sereno, M. I., Dale, A. M., Reppas, J. B., Kwong, K. K., Belliveau, J. W., Brady, T. J., Rosen, B. R., &
710 Tootell, R. B. (1995). Borders of multiple visual areas in humans revealed by functional
711 magnetic resonance imaging. *Science*, *268*, 889-893.
- 712 Simmons, W. A. R. (1984). *A validity study of the Dyslexia Determination Test (Griffin & Walton,*
713 *1981)*. University of British Columbia.
- 714 Skeide, M. A., Kumar, U., Mishra, R. K., Tripathi, V. N., Guleria, A., Singh, J. P., Eisner, F., & Huettig, F.
715 (2017). Learning to read alters cortico-subcortical cross-talk in the visual system of illiterates.
716 *Sci Adv*, *3*, e1602612.
- 717 Snowling, M. J., Hulme, C., & Nation, K. (2020). Defining and understanding dyslexia: past, present
718 and future. *Oxf Rev Educ*, *46*, 501-513.
- 719 Stein, J. (2019). The current status of the magnocellular theory of developmental dyslexia.
720 *Neuropsychologia*, *130*, 66-77.
- 721 Stein, J., & Walsh, V. (1997). To see but not to read; the magnocellular theory of dyslexia. *Trends*
722 *Neurosci*, *20*, 147-152.
- 723 Sun, Y. F., Lee, J. S., & Kirby, R. (2010). Brain imaging findings in dyslexia. *Pediatr Neonatol*, *51*, 89-96.
- 724 Treisman, A. M., & Gelade, G. (1980). A feature-integration theory of attention. *Cogn Psychol*, *12*, 97-
725 136.
- 726 Valdois, S., Roulin, J. L., & Line Bosse, M. (2019). Visual attention modulates reading acquisition.
727 *Vision Res*, *165*, 152-161.
- 728 Vandermosten, M., Boets, B., Wouters, J., & Ghesquiere, P. (2012). A qualitative and quantitative
729 review of diffusion tensor imaging studies in reading and dyslexia. *Neurosci Biobehav Rev*,
730 *36*, 1532-1552.

- 731 Verghese, A., Kolbe, S. C., Anderson, A. J., Egan, G. F., & Vidyasagar, T. R. (2014). Functional size of
732 human visual area V1: a neural correlate of top-down attention. *Neuroimage*, *93 Pt 1*, 47-52.
- 733 Vidyasagar, T. R. (1999). A neuronal model of attentional spotlight: parietal guiding the temporal.
734 *Brain Res Brain Res Rev*, *30*, 66-76.
- 735 Vidyasagar, T. R. (2004). Neural underpinnings of dyslexia as a disorder of visuo-spatial attention.
736 *Clin Exp Optom*, *87*, 4-10.
- 737 Vidyasagar, T. R. (2005). Attentional gating in primary visual cortex: a physiological basis for dyslexia.
738 *Perception*, *34*, 903-911.
- 739 Vidyasagar, T. R. (2014). Eyeing visual pathways in dyslexia. *Science*, *345*, 524.
- 740 Vidyasagar, T. R. (2019). Visual attention and neural oscillations in reading and dyslexia: Are they
741 possible targets for remediation? *Neuropsychologia*, *130*, 59-65.
- 742 Vidyasagar, T. R., & Pammer, K. (1999). Impaired visual search in dyslexia relates to the role of the
743 magnocellular pathway in attention. *Neuroreport*, *10*, 1283-1287.
- 744 Vidyasagar, T. R., & Pammer, K. (2010). Dyslexia: a deficit in visuo-spatial attention, not in
745 phonological processing. *Trends in cognitive sciences*, *14*, 57-63.
- 746 WHO. (2018). International Classification of Diseases for Mortality and Morbidity Statistics (ICD-11).
747 In. Geneva: World Health Organisation.
- 748 Yeatman, J. D., Dougherty, R. F., Myall, N. J., Wandell, B. A., & Feldman, H. M. (2012). Tract profiles
749 of white matter properties: automating fiber-tract quantification. *PLoS One*, *7*, e49790.
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Highlights

- 1) Visual search efficiency correlates with reading ability in children
- 2) Left/right visual cortical size asymmetry relates to reading ability in children
- 3) Our findings suggest a deficit in visuospatial attention in dyslexia

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