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Disabled readers suffer from visual and auditory impairments but not from a specific magnocellular deficit

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Summary

The magnocellular theory is a prominent, albeit controversial view asserting that many reading disabled (RD) individuals suffer from a specific impairment within the visual magnocellular pathway. In order to assess the validity of this theory we tested its two basic predictions. The first is that a subpopulation of RD subjects will show impaired performance across a broad range of psychophysical tasks relying on magnocellular functions. The second is that this subpopulation will not be consistently impaired across tasks that do not rely on magnocellular functions. We defined a behavioural criterion for magnocellular function, which incorporates performance in flicker detection, detection of drifting gratings (at low spatial frequencies), speed discrimination and detection of coherent dot motion. We found that some RD subjects (six out of 30) had impaired magnocellular function. Nevertheless, these RD subjects were also consistently impaired on a broad range of other perceptual tasks. The performance of the other subgroup of RD subjects on magnocellular tasks did not differ from that of controls. However, they did show impaired performance in both visual and auditory non-magnocellular tasks requiring fine frequency discriminations. The stimuli used in these tasks were neither modulated in time nor briefly presented. We conclude that some RD subjects have generally impaired perceptual skills. Many RD subjects have more specific perceptual deficits; however, the 'magnocellular' level of description did not capture the nature of the perceptual difficulties in any of the RD individuals assessed by us.

Keywords: coherent motion; contrast sensitivity; magnocellular; reading disability; temporal processing

Abbreviations: 2AFC = two-alternative forced choice; ISI = inter-stimulus interval; JND = just-noticeable difference; LGN = lateral geniculate nucleus; MT = medial temporal area; RD = reading disabled; RDK = random dot kinematogram; SPL = sound pressure level; V1 = primary visual cortex

Introduction

About 5–10% of the population suffers from reading disability (Shaywitz, 1998). The reading difficulties typically persist into adulthood, when these difficulties are characterized by slow and laborious reading and poor spelling (Pennington *et al*., 1990). The aetiology of this impairment is still unclear, despite decades of intensive research. Among the most dominant, but also most controversial theories in recent years is the magnocellular deficit hypothesis (Stein and Walsh, 1997). The proponents of this theory claim that a deficit in the magnocellular visual pathway contributes significantly to the reading difficulties of a large proportion of disabled readers (Stein *et al*., 2000). Its opponents, however, point out that findings of magnocellular processing deficits are not uncontested (Walther-Müller, 1995; Skottun, 2000*a*, *b*) and, furthermore, that no clear account has yet been proposed to explain how a dysfunctional magnocellular system impedes reading acquisition.

The magnocellular pathway originates in the retina and projects to the primary visual cortex (V1) via the magnocellular layers of the lateral geniculate nucleus (LGN). Lesions of the magnocellular layers of the LGN in monkeys result in reduced contrast sensitivity to stimuli with both low spatial frequency and high temporal frequency (Merigan and Maunsell, 1990; Merigan *et al*., 1991). Layers in V1 that receive magnocellular inputs project mainly to the dorsal visual stream, which extends to the parietal lobe. A large

proportion of the inputs to the medial temporal (MT) motion area are magnocellular in origin (Maunsell *et al*., 1990; Watson *et al*., 1993).

Recent research motivated by the proposal of a magnocellular visual deficit has found that disabled readers have reduced contrast sensitivity to transient stimuli of low spatial frequencies (such as drifting gratings or flicker) (Cornelissen, 1993; Borsting *et al*., 1996; Ridder *et al*., 1997), as predicted by this hypothesis. Furthermore, disabled readers were found to have difficulties in motion discriminations such as detection of coherent motion direction in an array of randomly moving dots (Talcott *et al*., 1998; Slaghuis and Ryan, 1999). This type of display preferentially activates area MT in monkeys (Newsome and Pare, 1988; Britten *et al*., 1992) and in humans (Tootell *et al*., 1995). Poor speed discrimination in disabled readers has also been documented (Demb *et al*., 1998*a*). This psychophysical evidence is corroborated by anatomical evidence of reduced cell size in magnocellular layers of the LGN (Livingstone *et al*., 1991), and functional MRI findings of reduced activation to coherent motion in the MT area of disabled readers (Eden *et al*., 1996; Demb *et al*., 1998*b*). This pattern of experimental results appears to support deficient processing in the magnocellular stream.

Yet other studies of reading disabled (RD) populations have not reported a reduction in contrast sensitivity to transient, low spatial frequency stimuli (Gross-Glenn *et al*., 1995; Spinelli *et al*., 1997; Skottun, 2000*a*; see also Ben-Yehudah *et al*., 2001, who demonstrated that deficits in contrast sensitivity at this range were specific to the experimental paradigm); and, conversely, others have reported reduced contrast sensitivity to non-transient stimuli, such as stationary gratings of various spatial frequencies (e.g. Evans *et al*., 1994).

From the mixed body of data it is difficult to conclude whether the visual problems exhibited by disabled readers can be characterized as a 'magnocellular deficit'. First, experimental findings are inconsistent across studies. Secondly, even studies yielding findings consistent with this hypothesis sampled magnocellular functions only anecdotally. In other words, although an impaired magnocellular function should yield poor flicker detection, such poor detection can result from other types of deficits. In order to demonstrate the existence of a functional magnocellular deficit, one should show impaired performance across a variety of magnocellular tasks and also that the performance of other tasks, ones that do not tax magnocellular processing, is not impaired. These could include both visual non-magnocellular tasks and tasks in other modalities. The generalized magnocellular hypothesis does not claim that perception is not impaired in other modalities. Rather, deficient magnocellular processing is considered the visual aspect of a general, pan-sensory impairment in the ability to process brief and rapidly emitted stimuli (Tallal *et al*., 1993; Witton *et al*., 1998; Stein and Talcott, 1999). Thus, failure in tasks that utilize relatively long stimuli and do not require detection or discrimination of briefly presented cues would challenge the magnocellular hypothesis.

In the present study we used four types of tasks to assess magnocellular processing: (i) detection of whole-screen flicker (Ridder *et al*., 1997); (ii) detection of drifting gratings (Borsting *et al*., 1996); (iii) speed discrimination between drifting gratings (Demb *et al*., 1998*a*); and (iv) coherent motion direction detection (Talcott *et al*., 1998). In addition, we tested a non-magnocellular visual task that required discrimination between sequentially presented grating stimuli with different spatial frequencies. Auditory discrimination tasks were also carried out to assess intensity and frequency just-noticeable differences (JNDs). Of these, at least the intensity discrimination task does not require fast temporal processing, and was also used as a control task since it was previously found to be unimpaired in RD subjects (Nicolson *et al*., 1995; Ahissar *et al*., 2000). Preliminary results of this study have been presented in abstract form at a congress held in Essex, UK, in May 2001, entitled 'Sensory bases of reading and language disorders' (summarized in Ramus, 2001).

Methods

Participants

Thirty RD adults (18 females, 12 males; mean age 21.5 ± 3.6 years) were recruited through educators, parents or clinicians on the basis of psycho-educational diagnoses of reading disability, or by self-report of a history of reading difficulties (students who read advertisments on the university campus). They were asked to refer friends or spouses within the same age group and with a similar educational background as controls [30 normal readers (20 females, 10 males); mean age 21.4 ± 3.3 years)]. The criterion for inclusion in the RD group was a current non-word reading score (see below) of at least 1 SD below the control group average. Both RD and control participants performed within the normal range on the Hebrew version Similarities subtest of the Wechsler Adult Intelligence Scale (WAIS-III) (Wechsler, 1997). Performance on other subtests was not a basis for participant exclusion. All participants were native Hebrew speakers and had normal or corrected-to-normal eyesight, and normal hearing in the range of frequencies tested. All participants gave their informed consent to take part in this study and were paid for their participation. The study was approved by the ethics committee of The Department of Psychology, The Hebrew University of Jerusalem.

Since our population was composed entirely of native Hebrew speakers, one might ask whether our RD test population was comparable to RD subjects speaking other languages. Such concern is alleviated by recent research, which suggests that although the depth of the orthography affects reading performance, the neurocognitive basis of reading disability is universal and does not depend on orthography (Paulesu *et al*., 2001). Thus, we can expect our test population to have psychophysical performance

comparable to that of RD subjects in other languages, as shown previously by Ben-Yehudah *et al*. (2001).

Assessment of reading and cognitive skills

Several reading and cognitive tests were administered to all participants. All tests were administered in Hebrew. The Hebrew script is unique in the sense that it uses both shallow and deep orthography. Reading is taught using pointed script, which is phonetically unambiguous (with a shallow orthography, as in Italian or Finnish), and the points (or diacritics) are quickly dropped in favour of unpointed script which includes consonantal information, but only partial vowel information (deep orthography, as in English). Most texts beyond the first 2 or 3 years of primary school employ unpointed script.

The oral reading tests we administered included both pointed and unpointed script. Pointed script was used for lists of single words (RW-*read*) and single non-words (NW-*read*) since the diacritics are necessary to make them phonetically unambiguous. Both speed and accuracy were measured, and combined into a single score. We also tested reading rate on an academic level passage without diacritics (PASS-*read*), since this is the standard script format for adults. Embedded in context, words can be properly decoded even without diacritics.

Orthographic skills were assessed using a spelling test (SPELL), and speed and accuracy on a word-pseudohomophone discrimination task (ORTH). Phonological awareness was assessed using a spoonerism task (SPOON, swapping the first phoneme in the first word of an orally presented word pair with the first phoneme of the second).

Cognitive skills were assessed using four subtests of the WAIS-III (Wechsler, 1997): Digit Symbol – Coding, Digit Span, Similarities and Block Design.

Stimuli and procedure

(i) Whole-screen flicker (flicker)

Contrast detection thresholds were assessed for a 9.1° × 7.1° flickering screen (square wave, mean luminance 20.7 cd/m^2) using a temporal two-alternative forced choice (2AFC) paradigm (a replication of the study by Ridder *et al*., 1997). Each trial consisted of two 500 ms intervals, demarcated by tones (high for first, low for second) and separated by 500 ms. During one interval the screen flickered, and during the other interval the screen was of uniform mean luminance. Since one of the intervals contained only a uniform mean luminance screen, the tones were essential to indicate when each interval occurred. Participants indicated which interval contained the flickering stimulus. The flicker frequencies used were 5, 10, 15, 20 and 25 Hz, presented in mixed pseudo-random order. Contrast was varied in a two-down/one-up adaptive staircase procedure, converging on the value of 71% correct (Levitt, 1971). Contrast was increased by 1 dB following an incorrect response, and decreased by 1 dB following two consecutive correct responses. Stimulus contrast was defined as $(L_{max} - L_{min})/(L_{max} + L_{min})$, where L_{max} and L_{min} denote stimulus maximum and minimum luminance, respectively (Michelson contrast). Detection thresholds (percentage contrast) were determined as the average of the last 10 reversals. Results were presented in the conventional form of contrast sensitivity (inverse of the detection threshold). Trials in which the target stimulus was of a high contrast (flickering at 15 Hz) were randomly interspersed among the trials containing targets of adaptively changing contrast. They served as 'catch trials' to test for errors that did not stem from the difficulty of the perceptual discriminations. Twenty-eight controls and 25 RD subjects performed this task.

(ii) Drifting gratings (drift)

Contrast detection thresholds were assessed for 0.5 c/° vertical sinusoidal gratings drifting at 10 Hz (20°/s) with a mean luminance of 20.7 cd/m^2 (replication of a study by Borsting *et al*., 1996). The stimulus subtended 12.5° × 9° visual angle at 150 cm viewing distance. The paradigm used was a temporal 2AFC design as described above. Thresholds were determined as the average of the last five reversals in a two-down/one-up staircase procedure. Contrast was increased by 1 dB following an incorrect response, and decreased by 2 dB following two consecutive correct responses. As in the *flicker* task, results were presented as contrast sensitivity. The 0.5 c/° grating was one condition in a task that included five other spatial frequencies (1–12 c/°; for details see Ben-Yehudah *et al*., 2001), presented in mixed pseudo-random order. In addition, this task included trials in which the target stimulus was high contrast (spatial frequency 2 c/°). These 'catch trials' were randomly interspersed among the trials containing targets of adaptively changing contrast, and tested for errors that did not stem from the difficulty of the perceptual discriminations. Twenty-one controls and 20 RD subjects performed this task.

(iii) Speed discrimination (speed)

Speed discrimination thresholds were determined for a 0.4 c/° vertical drifting grating of low mean luminance (5.33 cd/m^2) presented in a 5° radius circular aperture and viewed from a distance of 57 cm (following the design used by Demb *et al*., 1998*a*). Stimulus contrast was varied randomly between 16 and 24%, and interval duration was varied randomly between 360 and 540 ms, replicating the study of Demb *et al*. (1998*a*). A temporal 2AFC paradigm was used. In one interval the gratings drifted at 20.8°/s, and in the other the speed was higher and varied adaptively in a two-down/one-up manner, starting with a speed of 25°/s, using an initial step size of 4% of the baseline speed until four reversals occurred, and 1% thereafter up to a total of 17 reversals. Participants indicated in which interval the grating moved faster. Thresholds were determined by fitting a logistic psychometric function to the

accumulated data. Each participant's threshold was taken as the mean of two assessments. All 30 controls and 30 RD subjects performed this task.

(iv) Coherent motion

Detection of coherent motion direction was assessed in a 7° × 7° random dot kinematogram (RDK) containing 150 high luminance dots (0.07° in diameter) presented on a black background. Two stimulus types were tested: (i) *brief*: a fixed set of dots moved coherently throughout a brief display of 130 ms; (ii) *long*: the dots in the coherent set were re-sampled in each animation frame (10 ms) throughout the long display (900 ms), and consequently observers could not track single dots and had to base their judgement on the global motion signal. For each stimulus type, thresholds were assessed separately for dots moving at 3.5°/s (*slow*) and at 10.6°/s (*fast*). This yielded four experimental conditions (*brief-slow*, *brief-fast*, *long-slow* and *long-fast*). Coherence level was varied adaptively between trials using a two-down/one-up staircase procedure, starting with 25% in the *brief* conditions and 50% in the *long* condition, with an initial step size of 5% for the first two reversals, then 2% for three more reversals and 1% thereafter up to a total of 17 reversals. Thresholds were determined by fitting a logistic psychometric function to the accumulated data. Each participant's threshold was taken as the mean of two or three assessments. All 30 controls and 30 RD subjects performed this task.

(v) Spatial frequency discrimination (spatial)

Spatial frequency discrimination thresholds were determined for horizontal sinusoidal gratings. A temporal 2AFC paradigm was used. One interval contained the reference frequency and the other the test frequency, which varied adaptively between trials. Each stimulus was presented for 250 ms, and the inter-stimulus interval (ISI) was 500 ms. This task included two reference frequencies, low (0.6 c/°) and intermediate (4 c/°), presented in separate blocks. Grating contrast was constant at 20%. The test frequency was randomly selected in each trial to be either higher or lower than the reference frequency, and was varied adaptively in a two-down/one-up staircase manner, starting with 75% of the reference frequency. The initial step size was 10%, with the step size halved every three reversals (to a minimum of 1%), up to a total of 15 reversals. Discrimination thresholds (presented as percentage of the baseline frequency) were calculated as the average of the last 10 reversals. Reported thresholds are the mean thresholds over two assessments. Twenty-one controls and 19 RD subjects performed this task.

(vi) Auditory discriminations

All tasks used a 2AFC procedure with the adaptive parameter changing in a two-down/one-up staircase manner and a fixed reference stimulus.

*(a) Intensity discrimination (*intensity*).* Two intervals containing 1 kHz, 100 ms tones were presented. The reference tone was at a 30 dB sound pressure level (SPL), and the test tone changed adaptively in a two-down/one-up staircase manner, starting with a 40 dB SPL and using an initial step size of 1 dB, which was reduced to 0.5 dB after three reversals. The assessment was terminated after either 12 reversals or 60 trials had elapsed. Thresholds were calculated as the average of the last eight reversals. The ISI was 900 ms. Participants had to indicate which tone was louder. Twenty-eight controls and 27 RD subjects performed this task.

*(b) Frequency discrimination (*frequency*).* Two 65-dB SPL pure tone intervals were presented with an ISI of 1 s. The reference frequency was 1 kHz and the test frequency changed adaptively from 1.2 kHz in a two-down/one-up staircase, using an initial step size of 30 Hz, which was reduced to 5 Hz after three reversals. The assessment was terminated after either 13 reversals or 70 trials had elapsed. Thresholds were calculated as the average of the last six reversals. Participants had to indicate which tone was higher. Frequency discrimination was assessed for both 50 ms (*brief*) and 250 ms (*long*) tone durations. All 30 controls and 29 of the RD subjects performed this task.

Apparatus

All visual psychophysical tests were administered in a dark room and began only after participants had been seated in it for a few minutes. Stimuli were presented on a Trinitron Multiscan II Monitor (43.2 cm diagonal) with a frame rate of 100 Hz, using a VSG graphics card (VSG software version 5.02; Cambridge Research Systems Ltd, Rochester, UK). Contrast sensitivity was assessed using Psycho (version 2.00), a commercial program designed by Cambridge Research Systems to assess contrast sensitivity using the VSG card (this graphics card uses 12 bits per pixel, allowing for luminance resolution of 4096 levels). Other visual stimuli were generated with custom programs. Psychoacoustic tests were conducted in a sound-attenuating chamber using a TDT System II signal generator (Tucker-Davis Technologies Inc, Gainsville, FL, USA). Auditory stimuli were presented diotically through Sennheiser HD-265 linear headphones (Sennheiser, Old Lyme, CT, USA).

Results

Reading and cognitive skills

Table 1 summarizes the performance of control and RD participants on the reading and cognitive tests. The RD and control group means differed significantly with respect to all reading measures. Consistent with results from the literature (Pennington *et al*., 1990; Gottardo *et al*., 1997; Rack, 1997), RD subjects were also significantly impaired on the Digit

Table 1 *Reading, language and cognitive tests for control and RD participants*

Variable (units)	Subjects		*P* value (*t*-test)
	Control [mean (SD)]	Reading disabled [mean (SD)]	
NW-*read* (*Z*-score*)	0.0 (1.1)	–6.0 (3.1)	<0.001
RW-*read* (*Z*-score*)	0.0 (1.1)	–6.2 (3.5)	<0.001
PASS-*read* (words/minute)	130 (17)	83 (22)	<0.001
SPELL (errors/24)	0.5 (1.3)	6.1 (5.0)	<0.001
ORTH (*Z*-score*)	0.0 (0.9)	–11.7 (15.4)	<0.001
SPOON (errors/20)	1.6 (1.7)	7.8 (5.8)	<0.001
WAIS-III subtests (scaled scores)			
Digit Symbol - Coding	11.6 (3.2)	8.7 (2.1)	<0.001
Digit Span	10.2 (2.7)	7.4 (2.1)	<0.001
Similarities	14.0 (2.4)	13.1 (2.6)	0.18
Block Design	12.6 (3.1)	11.9 (3.1)	0.37

NW-*read* = non-word reading; RW-*read* = real word reading; PASS-*read* = oral passage reading rate; SPELL = spelling; ORTH = orthographic word-pseudohomophone discrimination; SPOON = spoonerism; WAIS-III = Wechsler Adult Intelligence Scale (III).
*Composite of the speed and accuracy *Z*-scores, computed in relation to the control group averages (which are, by definition, 0.0).

Span (verbal memory) and Digit Symbol-Coding (visual-motor coordination) subtests of the WAIS-III, but not on the Block Design (visual decomposition) and Similarities (verbal reasoning) subtests.

Psychophysical measures

Table 2 lists the mean group thresholds for all the psychophysical tasks, along with the significance of the statistical tests. The RD group was significantly impaired in detecting whole-screen flicker (5–25 Hz) and in discriminating the speed of drifting gratings. They were even more impaired in discriminating between spatial frequencies (centred around both 0.6 and 4 c/°), although the stimuli did not modulate in time and were not brief (250 ms duration). RD performance on other magnocellular tasks, including detection of drifting gratings and one condition of coherent motion, was only marginally impaired. Their auditory performance was impaired on the frequency discrimination task but not on the intensity discrimination task, consistent with previous reports (e.g. Ahissar *et al*., 2000). Overall, the RD group did not show a pattern of results indicative of a specific magnocellular deficit. Their performance was somewhat poorer on most psychophysical tasks measured, but poorer performance was neither specific to magnocellular-related tasks nor confined to the visual modality; therefore, based on these results, we cannot conclude that disabled readers as a group show a specific magnocellular impairment.

A subgroup with a magnocellular deficit?

Although RD subjects as a group do not show the pattern of visual impairments expected from a magnocellular deficit, such a pattern may characterize a subgroup of the RDs. Since the RD group is heterogeneous with respect to their perceptual performance, the group averages above may have concealed specific magnocellular deficits. In order to characterize an overall parameter of magnocellular performance for each participant individually, we computed a composite magnocellular *Z*-score in the following way. We first computed *Z*-scores (distance in SDs from the population mean) for the thresholds measured on four tasks commonly believed to depend on magnocellular sensitivity: detection of whole-screen flicker (*flicker*; averaged across the various temporal frequencies tested), detection of drifting gratings (*drift*), speed discrimination of drifting gratings (*speed*), and thresholds for coherent motion detection of fast dot motion (*brief-fast* and *long-fast*; although we measured coherence detection for both slow and fast dot motion, fast motion detection is a more sensitive measure of magnocellular function). We then averaged the four *Z*-scores, and divided the resulting measure by its standard deviation over the entire population in order to normalize this composite *Z*-score. The distributions of the magnocellular *Z*-scores for the control and RD populations are shown in Fig. 1. At the lower end of the magnocellular performance distribution there are six RD subjects whom we classified as 'RD-poor' with respect to magnocellular task performance, and one control participant. All other RD participants were classified as 'RD-good'. INP, the one control participant with a low magnocellular *Z*-score, was excluded from further statistical analysis [leaving 29 participants in the control (C) group; INP's data are presented in Figs 2, 3 and 5].

We then examined whether RD-poor participants (whose magnocellular *Z*-score was very low) were consistently poor in all the above magnocellular tasks but had no consistent difficulties on visual tasks that are not specifically magnocellular-related, or in auditory tasks unrelated to fast processing.

Table 2. *Psychophysical task performance [means (SEM)] for control and RD participants*

	Subjects		Statistical significance
	Control [mean (SEM)]	Reading disabled [mean (SEM)]	
Visual tasks			
Contrast sensitivity			
Flicker (Hz)			
5	126 (10)	111 (11)	
10	167 (14)	142 (18)	
15	153 (11)	122 (15)	0.006*
20	106 (6)	93 (9)	
25	80 (5)	66 (6)	
Drift	567 (28)	480 (32)	0.062**
Speed discrimination (JND)			
Speed	13.3% (1.3)	18.7% (2.0)	0.035**
Coherent motion (% coherence)			
Brief-slow	11.8% (2.2)	15.3% (2.0)	0.134**
Brief-fast	3.8% (0.6)	5.5% (1.2)	0.134**
Long-slow	12.6% (1.0)	15.1% (1.7)	0.236**
Long-fast	6.2% (0.4)	8.6% (0.9)	0.071**
Spatial frequency discrimination (JND)			
Spatial			
0.6 c/°	9.5% (0.9)	22.4% (3.3)	0.004†
4 c/°	14.5% (1.9)	23.1% (3.8)	
Auditory tasks (JND)			
Frequency			
50 ms tones	2.5% (0.5)	9.5% (2.6)	0.019†
250 ms tones	1.7% (0.5)	10.8% (3.9)	
Intensity	3.2 dB (0.4)	3.9 dB (0.5)	0.610**

See Methods for abbreviations and a description of the tasks. **P*-value of the group effect in a group (control versus RD) by temporal flicker frequency ANOVA. The interaction term was not significant. ***P*-value for the Kolmogorov–Smirnov two-sample test. †*P*-value of the group effect in a repeated measures ANOVA for group (control versus RD) by condition. The effect of condition and the interaction term were not significant at $P < 0.05$.

Figure 2 shows the mean contrast sensitivity of the three groups (C, RD-good and RD-poor) for drifting grating detection (Fig. 2A, *drift*) and whole screen flicker detection (Fig. 2B, *flicker*). The RD-poor subgroup was indeed significantly impaired on both tasks. A one-way ANOVA (analysis of variance) showed a significant effect of group in the *drift* task [$F(2,38) = 6.19$, $P = 0.005$]. A *post hoc* test (Scheffé's method) showed that while the RD-good subgroup did not differ from the control group, the RD-poor subgroup did. The RD-poor subgroup was also more impaired in the *flicker* task at all tested temporal frequencies. A group by temporal flicker frequency ANOVA showed a significant group effect [$F(2,49) = 5.74$, $P = 0.006$], but a non-significant interaction [$F(8,196) = 1.60$, $P = 0.13$].

The RD-poor subgroup was also more impaired in all tasks involving motion, while the RD-good did not differ from the control group. Figure 3A shows the performance of the three groups on the *speed* task [significant group effect: $F(2,56) = 40.0$; $P < 0.001$]. Figure 3B and C shows the performance in the coherent motion detection tasks, for *brief* and *long* display durations, respectively. One-way ANOVAs showed highly significant group effects in all but the *brief-slow* condition, in which the effect fell just short of significance [*brief-slow*: $F(2,56) = 3.10$, $P = 0.053$; *brief-fast*: $F(2,56) = 18.6$, $P < 0.001$; *long-slow*: $F(2,56) = 9.54$, $P < 0.001$; *long-fast*: $F(2,56) = 16.3$, $P < 0.001$].

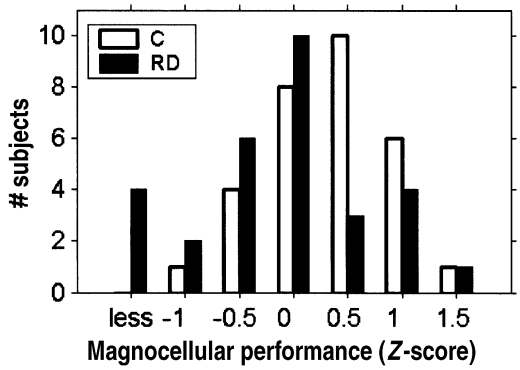

Fig. 1 Distribution of magnocellular *Z*-scores. The controls (C, white bars) are normally distributed, but the reading disabled (RD, black bars) distribution has a few participants at the lower end of the tail with very poor magnocellular performance. Numbers on the *x*-axis denote bin centres (centre of the interval over which subjects are summed).

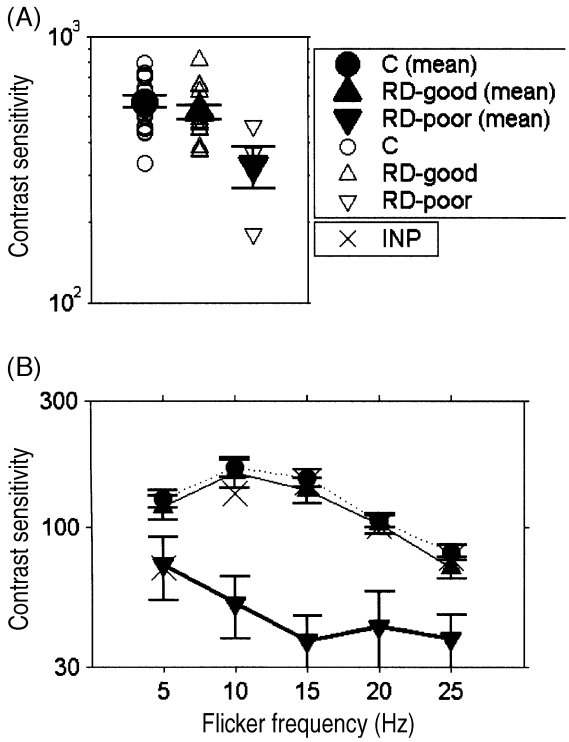

Fig. 2 Contrast sensitivity for transient stimuli. Mean (±SEM) contrast sensitivity thresholds of controls (C, filled circles) and the two RD subgroups (RD-good, filled triangles; RD-poor, filled inverted triangles). (**A**) *Drift:* detection of 10 Hz (20°/s) drifting gratings (0.5 c/°). Open symbols denote individual thresholds (C, circles; RD-good, triangles; RD-poor, inverted triangles). (**B**) *Flicker:* whole-screen flicker detection. A black cross denotes control participant INP, who had a very low magnocellular *Z*-score. In both tasks the RD-poor subgroup had significantly lower contrast sensitivity compared with the controls and the RD-good subgroup; the means of the controls and the RD-good subgroup did not differ significantly.

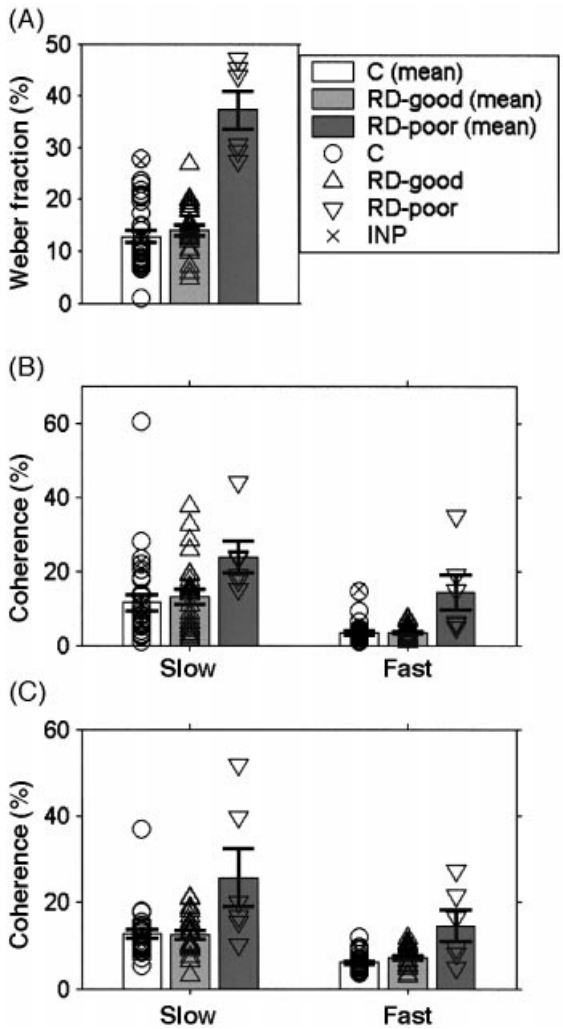

Fig. 3 Sensitivity to motion. Performance (mean ± SEM) of the controls (C, white bars), RD-good (light grey bars) and RD-poor (dark grey bars) subgroups on motion tasks. Open symbols denote individual participants (C, circles; RD-good, triangles; RD-poor, inverted triangles; control participant INP is denoted by a black cross). (**A**) *Speed*: speed discrimination thresholds of sequentially presented drifting gratings (0.4 c/°, ~20°/s). Thresholds are expressed as JNDs. (**B**) *Brief*: coherent motion direction detection thresholds expressed as proportion of dots moving coherently in the display. The display was presented for 130 ms and the set of coherent dots was constant (dots had a fixed trajectory throughout the display). Group means are shown for both slow (*brief-slow*, 3.5°/s) and fast (*brief-fast*, 10.6°/s) dot motion. (**C**) *Long*: coherent motion direction detection thresholds using a long presentation (900 ms) and randomly re-sampled coherent dot set, for slow (*long-slow*, 3.5°/s) and fast dot motion (*long-fast*, 10.6°/s). The RD-poor subgroup had significantly poorer speed discrimination and higher motion direction detection thresholds compared with both other groups in all but the *brief-slow* condition. Control and RD-good group means did not differ significantly.

It is clear from this analysis that the participants in the RD-poor subgroup have consistent difficulties in all tasks tapping magnocellular processing compared with other RD subjects, who do not exhibit such difficulties. None of the individual participants in the RD-poor subgroup performed well on any magnocellular task. INP, the control participant with a magnocellular *Z*-score in the RD-poor range had consistent difficulties in all motion tasks, which gave rise to the low *Z*-score.

Having established that the performance of all the individuals in the RD-poor subgroup was impaired on all magnocellular tasks, we then examined whether their performance was unimpaired on non-magnocellular tasks. To answer this question, two types of tasks were further administered: a non-magnocellular visual task to test processing within the same modality (spatial frequency discrimination) and two different auditory tasks (intensity and frequency discrimination). Figure 4 shows group means and individual participant performance on the spatial frequency discrimination task (*spatial*) for low (centred on 0.6 c/°) and intermediate (centred on 4 c/°) frequencies. Participants viewed two static, sequentially presented sinusoidal gratings, and were asked to indicate which one was denser (higher spatial frequency). Neither stimulus duration (250 ms) nor the interstimulus interval (500 ms) was brief.

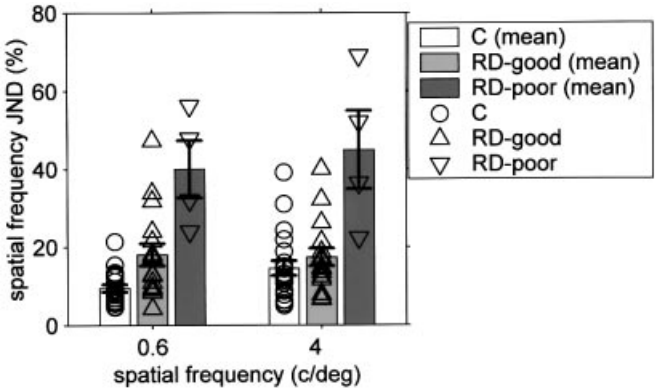

Fig. 4 Spatial frequency discrimination (*spatial*). Discrimination between the spatial frequencies of two static, sequentially presented gratings (centred on 0.6 c/° and 4 c/°). Thresholds are expressed as the spatial frequency JND. The RD-poor subgroup (dark grey bars) had significantly poorer spatial frequency discrimination compared with both the controls (white bars) and the RD-good subgroup (light grey bars). Means of controls and RD-good were equal on the 4 c/° condition, but not on the 0.6 c/° condition. Open symbols denote individual participants (C, circles; RD-good, triangles; RD-poor, inverted triangles; INP did not perform this task).

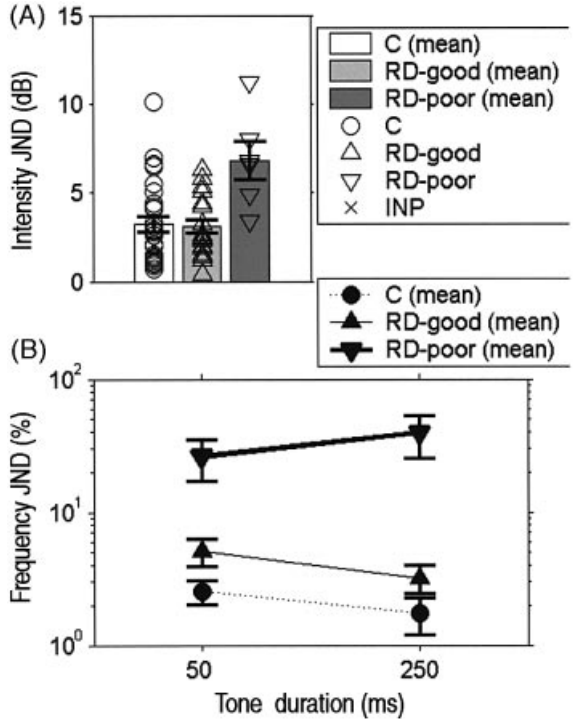

Fig. 5 Auditory discrimination. (**A**) *Intensity*: intensity discrimination of tones with a 30-dB reference. The RD-poor subgroup (dark grey bars) had significantly higher intensity JNDs compared with both the controls (white bars) and the RD-good subgroup (light grey bars), which did not differ. Open symbols denote individual participants (C, circles; RD-good, triangles; RD-poor, inverted triangles; control participant INP is denoted by a black cross). (**B**) *Frequency*: frequency discrimination of pure tones with a 1 kHz reference for 50 ms (*brief*) and 250 ms (*long*) tones. The RD-poor subgroup (inverted triangles) had significantly higher frequency JNDs compared with both the controls (circles) and the RD-good subgroup (triangles). Whereas the performance of controls and RD-good improved for the longer tone duration, the RD-poor performance deteriorated.

Thus, this task does not tax magnocellular activity. A repeated measures ANOVA revealed a significant group effect [$F(2,37) = 20.96$, $P < 0.001$], a marginal effect of spatial frequency [$F(1,37) = 3.04$, $P = 0.09$] and no interaction between the two factors [$F(2,37) = 2.04$, $P = 0.15$]. The RD-poor subgroup was the poorest in performing this task in both low and intermediate spatial frequencies (Scheffé's method; $P < 0.001$, the means for the RD-poor subgroup differed significantly from both other group means).

Contrary to the magnocellular tasks described above, where there was no difference between the control and RD-good group means, in this task there appeared to be a group difference, at least when the spatial frequency was 0.6 c/°. To test whether the RD-good had higher discrimination thresholds, we performed a second ANOVA, including only the RD-good and control groups. We found a significant group effect [$F(1,34) = 5.28$, $P = 0.028$], and a marginal interaction between group and spatial frequency [$F(1,34) = 3.66$, $P = 0.064$]. The effect of spatial frequency was no longer significant [$F(1,34) = 2.02$, $P = 0.16$]. Figure 4 shows that this interaction results from the poorer performance of the RD-good subgroup, compared with the controls, on the low spatial frequency condition. Thus, RD-good individuals do suffer from visual deficits. However, these deficits were revealed only when a non-magnocellular task requiring memory for non-transient spatial attributes was administered.

Results of the auditory tasks are shown in Fig. 5. The RD-poor subgroup had higher JNDs for intensity discrimination as well as pure tone frequency discrimination for both brief- and long-tone durations. A one-way ANOVA followed by a *post hoc* test showed that the RD-poor subgroup had higher intensity discrimination thresholds than the other groups [Fig. 5A; $F(2,55) = 11.3$, $P < 0.001$]. A repeated measures ANOVA showed that the same was true for frequency discrimination (Fig. 5B). A significant group effect was observed [$F(2,51) = 30.0$, $P < 0.001$], with the RD-poor group being significantly poorer than both other groups (Scheffé's method, $P < 0.001$). There was also a significant effect of duration [$F(1,51) = 7.39$, $P = 0.009$]. Whereas the controls and RD-good subgroup improved when tone duration was extended, the RD-poor subgroup performed worse for longer tones than for shorter ones, giving rise to a significant interaction [$F(2,51) = 9.52$; $P < 0.001$]. This latter finding is inconsistent with a specific deficit in processing brief stimuli. If RD-poor participants indeed suffered from such a deficit, one would expect that extending the stimulus duration would improve their performance. Yet, while both the control and RD-good participants benefited from prolonging tone duration, the RD-poor subgroup did not. Taken together with their impaired intensity discrimination, their deficits in performing psychophysical, visual and auditory tasks are

broad and not limited to brief stimuli or to tasks relying on accurate temporal processing.

Interestingly, when the ANOVA was performed using only the RD-good subgroup and the control group, a significant group effect was still observed [$F(1,46) = 5.6$, $P = 0.022$]. There was also a marginal effect for tone duration [$F(1,46) = 3.54$, $P = 0.066$], but no interaction between group and duration [$F(1,46) = 0.60$, $P = 0.44$]. Thus, RD subjects whose performance in magnocellular tasks was well within the normal range have both auditory and visual perceptual deficits. Their deficits are similar in both modalities, and in neither modality are they specific to brief stimuli. They were revealed when spatial (visual) or tonal (auditory) frequency discriminations were required.

Having found that a subgroup of RD subjects had such broad impairments in psychophysical tasks, we asked whether these deficits resulted from genuine perceptual difficulties, or from difficulties introduced by the demands of the psychophysical paradigms we used. For example, subjects in the RD-poor group may be impaired in their ability to map a decision (e.g. motion direction) to a correct motor response (e.g. left/right button press). Their errors may also stem from a difficulty in temporal order judgement (Peli and Garcia-Perez, 1997), or even from general inattention so that they do not carefully attend to all stimuli (Stuart *et al.*, 2001). All these alternatives imply that the deficits exhibited by RD-poor participants should not be specific to difficult perceptual discriminations. Thus, a larger number of errors (compared with the control group) should also be observed on easy trials. The contrast detection tasks included control conditions that allowed for a direct assessment of this prediction. Easy trials (catch trials) were interspersed with the difficult ones throughout the assessment (see Methods for details). We thus examined whether RD-poor participants had a larger number of errors in the catch trials (100 catch trials per participant). In the four conditions of the coherent motion detection task, we examined their performance on the first 10 easy trials of each assessment. This analysis showed that only one RD-poor participant had a larger number of errors in the 2AFC tasks we tested, but not when left/right discriminations were required. For this participant, impaired temporal order judgement may underlie the consistently impaired psychophysical performance (as suggested by Peli and Garcia-Perez, 1997). The other five RD-poor participants did not show a tendency for a larger number of errors in the easy trials. Thus, the broadly impaired psychophysical performance of at least five of the six RD-poor participants cannot be accounted for by the general structure of the psychophysical paradigm. They seem to have genuine perceptual deficits, although these deficits are very broad and are not limited to magnocellular tasks.

We then inquired whether reading and other cognitive tasks (subtests of WAIS-III) are also poorer in this subgroup of RD subjects (RD-poor) compared with the other RD subjects (RD-good). A two-tailed *t*-test shows that the reading and spelling scores of the RD-poor and RD-good subgroups did not differ ($P > 0.3$ for all comparisons). The non-verbal intelligence of the RD-poor subgroup, as measured by Block Design (mean ± standard deviation = 10.7 ± 1.9), was similar to the general population mean (10.0 ± 1.5), but lower than that of the RD-good subgroup (12.2 ± 3.3). Their verbal memory, measured by Digit Span, was somewhat poorer than that of the RD-good subgroup (6.2 ± 1.6 compared with 7.7 ± 2.1), but not significantly so (both scores are substantially lower than those of the controls; see Table 1). The most prominent impairment characterizing the RD-poor subgroup was their very poor performance on the Digit Symbol - Coding subtest (5.8 ± 1.0 in RD-poor versus 9.2 ± 1.9 in RD-good; $P < 0.001$). Participants in this test received a table in which each digit (1–9) was mapped onto a novel simple symbol. They then received a list of digits and were required to write the appropriate symbol next to each digit. This mapping is not based on phonology. Throughout most of the test, the eyes should move quickly and accurately from the mapping table to the test table and vice versa. This test is considered a measure of visual-motor coordination (Kaufman, 1990).

Table 3. *Correlations between magnocellular performance and reading and cognitive measures*

	Subjects	
	Control	Reading disabled
NW-*read*	0.051 (0.79)	0.112 (0.55)
PASS-*read*	0.153 (0.43)	0.104 (0.58)
ORTH	–0.037 (0.85)	–0.060 (0.77)
WAIS-III subtests		
Digit Symbol - Coding	0.341 (0.070)	–0.570 (0.002)*
Digit Span	0.063 (0.75)	–0.525 (0.003)*
Similarities	–0.050 (0.80)	0.287 (0.13)
Block Design	–0.372 (0.047)*	0.521 (0.004)*

NW-*read* = non-word reading; PASS-*read* = oral passage reading rate; ORTH = orthographic word-pseudohomophone discrimination; WAIS-III = Wechsler Adult Intelligence Scale (III). Spearman rank correlations between the magnocellular *Z*-score and reading and cognitive skills within the control group and the RD group are shown. The correlation coefficient is indicated with the significance level (two-tailed) in parentheses. *Significant correlations ($P < 0.05$).

What does the magnocellular Z-score indicate?

Since a magnocellular deficit does not appear to capture the essence of the visual impairments of any of our RD participants, should the magnocellular *Z*-score be considered a useful indicator of specific skills rather than a descriptor of the deficits of specific individuals? The correlations between the magnocellular *Z*-score and reading and cognitive skills in the control and RD populations should clarify this issue. Table 3 presents the Spearman rank correlation coefficients between the magnocellular *Z*-score and certain reading and

cognitive measures. We used rank correlations to ensure that the outliers (four RD-poor participants with the lowest magnocellular *Z*-score) would not dominate the results.

Both in the control and in the RD group, the magnocellular *Z*-score was not significantly correlated with phonological decoding (reading non-words, NW-*read*) or with orthographic skills (ORTH). However, the magnocellular *Z*-score was significantly correlated with cognitive measures such as the Block Design subtest of the WAIS-III. Digit Symbol-Coding and the magnocellular *Z*-score were also significantly correlated in RD subjects and marginally correlated in controls. Furthermore, this subtest was the only parameter for which the magnocellular *Z*-score made a unique contribution to its variance, after the variance accounted for by Block Design had been removed (17.4%, $P = 0.001$, in the entire population; and 21.4%, $P = 0.002$, in the RD population). Thus, while the magnocellular *Z*-score is not a predictor of reading skills, it is correlated with performance in a task requiring fine visual-motor coordination.

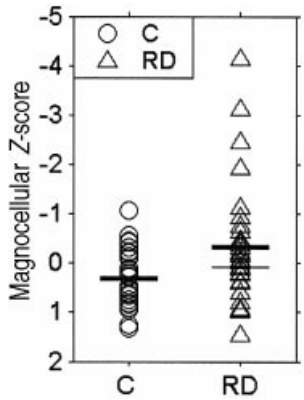

Fig. 6 Magnocellular performance. Individual magnocellular *Z*-scores in the control and RD groups. The thick horizontal lines demarcate group means for the controls and the entire RD group, and the thin horizontal line demarcates the RD group mean after removing the four outlying data points.

Discussion

Summary of results

RD subjects, as a group, showed perceptual deficits in both visual and auditory tasks. However, their pattern of impairments was inconsistent with a magnocellular deficit or a specific deficit in processing brief stimuli. From the perspective of performance on magnocellular tasks, RD subjects could be divided into participants whose performance was worse than that of the controls (six of 30), and those whose performance was within the range of the controls (excluding INP, whose *Z*-score was an outlier in the control group). The former (RD-poor) participants had difficulties in all the visual and auditory psychophysical tasks we examined; thus, their deficit was very broad. The performance of the RD-good subgroup was the same as that of the controls on all the magnocellular tasks measured. They did, however, show visual and auditory perceptual difficulties on tasks unrelated to magnocellular functions.

Relation to previous studies assessing the magnocellular hypothesis

The present study is part of a growing body of evidence reporting results that do not conform to the predictions of the magnocellular hypothesis. In fact, hardly any finding in support of a magnocellular deficit has remained uncontested. For example, Livingstone *et al*. (1991) found that the visual-evoked responses of dyslexics to low-contrast, flickering checkerboards were significantly reduced compared with controls; however, Victor *et al*. (1993), who tried to replicate their results, found no difference between dyslexics' and controls' evoked responses. Similarly, Eden *et al*. (1996), and subsequently Demb *et al*. (1998*b*), who conducted fMRI studies, found that dyslexics' activation of the motion-specific MT area was lacking or reduced, respectively; yet Vanni *et al*. (1997), who conducted a magneto-encephalography (MEG) study, found no group difference in the magnitude of the activation (although there was a tendency for longer latencies in dyslexics). The number of behavioural studies that have assessed contrast sensitivity in dyslexics and found results that are inconsistent with a specific magnocellular deficit, is in fact larger than the number of studies that have found the expected pattern of difficulties (see Skottun, 2000*a*, *b* for a recent review).

This study is thus not the first to question the magnocellular hypothesis for the RD population as a group. It is, however, the first to test the limits of this hypothesis by examining whether there is a subgroup whose perceptual impairments are best characterized by a magnocellular deficit. We found no such subgroup.

Previous reports of magnocellular deficits in disabled readers implicitly treated the RD subjects as a homogeneous group with respect to their psychophysical performance. Group means were compared between RD subjects and controls, and significant differences were found in several studies (e.g. Ridder *et al*., 1997; Demb *et al*., 1998*a*; Witton *et al*., 1998; Slaghuis and Ryan, 1999). When single-subject data are presented, the typical distribution shows a substantial overlap between groups, with few RD 'outliers' (Talcott *et al*., 1998; Hill *et al*., 1999). Usually, the significant group effect observed in these studies was the result of the consistently poor performance of these few RD outliers. A similar distribution was found in our study, as demonstrated in Fig. 6, in which the magnocellular *Z*-scores from Fig. 1 are shown as individual data points. Four data points are clearly outliers (corresponding to the left-most column of Fig. 1; the four poorest RD-poor participants). Removing these data points from the analysis eliminates the significance of the group effect. But should these outliers be removed from the analysis? A crucial criterion is whether they represent

individuals with a specific magnocellular deficit. We clearly show that these RD outliers are individuals whose performance is poor on a broad range of psychophysical tasks.

In our study, classifying RD subjects on the basis of across-the-board magnocellular deficits yielded across-the-board perceptual and/or sensory-motor deficits that are not specific to brief stimuli. This conclusion is corroborated further by a recent study in the auditory domain (Amitay *et al*., 2002), in which we reported a similar pattern of results. A subgroup of RD subjects performed poorly on a broad range of standard psychoacoustic tasks designed to probe temporal processing with widely varying time constants. Their deficits were not confined to tasks probing phoneme-rate processing, but spanned the entire range of time constants, from hundreds of microseconds to several seconds.

Performance on 'magnocellular tasks' in our general (control) and RD populations was not correlated with any reading measure, and did not account for independent variance in orthographic skills. The latter result differs from previous studies reporting that coherent motion detection (used as a measure of magnocellular function) accounted for a significant, albeit small, proportion of the variance in orthographically related skills of unscreened populations of children (Talcott *et al*., 2000) and adults (Cornelissen *et al*., 1998). On the other hand, the magnocellular *Z*-score was correlated with performance on a task requiring visual-motor coordination (the Digit Symbol - Coding subtest of the WAIS). This correlation may reflect the contribution of magnocellular projections to activity in the parietal cortex. Both animal (Carey, 2000) and human (van Donkelaar *et al*., 2000) studies suggest that structures in the parietal cortex are involved in the control of visually guided movements. Yet, while magnocellular projections may be related to eye–hand coordination, we did not find individuals with specifically impaired magnocellular function.

Classification of RD subjects according to perceptual performance

Our RD population was not homogeneous. We classified our RD participants on the basis of magnocellular task performance. Participants in the first subgroup, RD-poor, had severe difficulties with magnocellular tasks, but were also found to be deficient in a broad range of other perceptual tasks. Could their deficits be attributed to a general difficulty with psychophysical tasks? If such were the case, we would expect these individuals not only to have higher thresholds, but also to be poorer on the easier trials of the psychophysical assessments. However, they had no significant difficulties on trials where the stimuli were easy to detect or discriminate. Thus, we can rule out such a general account, but since their deficits were so comprehensive, it is difficult to provide a more specific account of their origin.

The second subgroup, RD-good, had no difficulty on any magnocellular task. This subgroup consisted of participants with two distinct perceptual profiles. The perceptual performance of many participants in this subgroup was the same as that of the controls. Others had difficulty in discriminating auditory and visual spatial frequencies. The next three subsections are devoted to discussing possible reasons for these more specific deficits.

Impaired perceptual memory?

A large number of RD-good participants have difficulties in tasks requiring auditory (tonal) and visual (spatial) frequency discriminations. Both tasks require a temporal forced choice decision, and are thus 'retain-and-compare' paradigms. As recent findings suggest, a paradigm that requires comparisons between sequentially presented stimuli is particularly difficult for RD subjects (Ben-Yehudah *et al*., 2001). Ben-Yehudah and colleagues compared contrast detection when the stimuli to be compared were presented either sequentially or simultaneously. The performance of RD subjects was similar to that of controls when the stimuli were presented simultaneously, but was poorer than that of controls on the sequential presentation condition. Although RD subjects were impaired on the temporal forced-choice detection tasks administered in the former study, the magnitude of the deficit was minor compared with the deficit found with the frequency discrimination tasks in the current study. Successful discrimination requires participants to accurately retain the parameters of the first stimulus and to compare it with the second. The fact that RD subjects find the discrimination tasks more difficult may stem from the importance of the comparison when discrimination is required. The inability to retain and compare precludes performance of such tasks. On the other hand, in detection tasks, participants are asked whether the stimulus was presented in the first or the second interval. A comparison of the two intervals allows for a more accurate judgement, but since one interval contains only a uniform mean-luminance screen ('no stimulus'), the ability to accurately retain and compare is not crucial. Thus, discrimination tasks are more sensitive to a dysfunction of retain-and-compare mechanisms. The simplest explanation for such a dysfunction is a deficit in perceptual memory.

An attentional deficit?

Poor performance on retain-and-compare tasks can be attributed to an attentional deficit, rather than a deficit in perceptual memory. This interpretation is consistent with the considerable comorbidity of reading disability and attentional disorders (Sheppard *et al*., 1999).

One aspect of an attentional deficit may be a difficulty in sustaining a high level of vigilance over the long trials characterizing temporal forced-choice (retain-and-compare), as opposed to spatial forced-choice paradigms. Although it is hard to refute this alternative, the pattern of results in our study does not seem to support it. If vigilance decays over time, one would expect that it could be recovered with the

onset of an auditory cue. Such a cue was presented to demarcate the two intervals within each trial of our visual contrast detection tasks (*flicker* and *drift*), since one of them contained no stimulus. At least on these tasks we would not expect RD subjects to show a behavioural deficit. However, this was not the case. RD-good participants were not impaired on temporal forced-choice magnocellular tasks, whether the trial intervals were cued (drifting gratings or whole-screen flicker) or not (speed discrimination). Auditory cues did not seem to influence the performance of RD-poor participants either. They were poor on these tasks whether the intervals were cued or not. Thus, the auditory cues did not appear to influence the performance of either subgroup. Taken together, these findings indicate that a generalized difficulty in sustaining attention does not fully account for the pattern of observed deficits.

A parietal deficit?

Vidyasagar (2001) and Hari and Renvall (2001) suggested that dyslexics suffer from an attentional deficit specific to a parietal-lobe dysfunction. Vidyasagar and Pammer (1999) found that dyslexics were impaired on a search task that required shifting attention between items in the visual field, but not on a parallel search that did not require attentional shifts. Hari *et al*. (2001) found that when dyslexics were asked to make temporal order judgements, they tended to perceive the stimulus in the right hemifield as appearing first. They interpreted their findings as reflecting a left 'mini-neglect' stemming from a minor right parietal deficit. This proposition is corroborated by studies showing that dyslexics exhibit a set of phenomena characteristic of left hemineglect patients (Stein and Walsh, 1997; Hari *et al*., 1999).

Previous studies equated such a parietal-related attentional deficit with an underlying magnocellular deficit (e.g. Vidyasagar, 2001). However, physiological and anatomical studies show that the correspondence between the subcortical (magnocellular versus parvocellular) and cortical (dorsal versus ventral) pathways is only partial (e.g. Merigan and Maunsell, 1993). The findings of the current study are inconsistent with a primarily magnocellular deficit, but consistent with a parietal deficit. For example, a recent imaging study suggests that sequential spatial frequency discrimination, similar to the task found to be most difficult for RD subjects in our study, activates parietal areas (Greenlee *et al*., 2000). Similarly, attention to auditory frequency activates regions in the right parietal cortex (Zatorre *et al*., 1999). Thus, whereas a general attentional deficit does not seem to underlie the impaired performance on retain-and-compare tasks, a specific parietal lobe deficit might.

Conclusion

Taken together, our study and others indicate that the magnocellular hypothesis should be revised substantially. The majority of RD subjects are not impaired on magnocellular tasks. The performance of only a small proportion of RD subjects in our study (classified as RD-poor) was consistently poor on tasks tapping magnocellular function. However, their performance was also poor on all other perceptual tasks administered. Thus, 'magnocellular deficit' does not provide a good characterization of the perceptual impairment of any RD in our test group.

Despite this, our findings are consistent with some aspects of the magnocellular hypothesis. First, some RD subjects (a proportion of the RD-good subgroup) do have pan-sensory perceptual deficits, whose nature seems similar across modalities. Secondly, the temporal structure of incoming stimuli appears to play a crucial role in the extent to which a deficit is revealed. Accumulating evidence suggests that rather than the rate of change within stimuli, it is the interval introduced between the stimuli that proves to be the greater difficulty for a substantial proportion of disabled readers.

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