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Psychophysical evidence for a magnocellular pathway deficit in dyslexia

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Abstract

The relationship between reading ability and psychophysical performance was examined to test the hypothesis that dyslexia is associated with a deficit in the magnocellular (M) pathway. Speed discrimination thresholds and contrast detection thresholds were measured under conditions (low mean luminance, low spatial frequency, high temporal frequency) for which psychophysical performance presumably depends on M pathway integrity. Dyslexic subjects had higher psychophysical thresholds than controls in both the speed discrimination and contrast detection tasks, but only the differences in speed thresholds were statistically significant. In addition, there was a strong correlation between individual differences in speed thresholds and reading rates. These results support the hypothesis for an M pathway abnormality in dyslexia, and suggest that motion discrimination may be a more sensitive psychophysical predictor of dyslexia than contrast sensitivity. © 1998 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Developmental dyslexia can be defined as unexpectedly low reading ability relative to IQ that cannot be explained by motivation, learning opportunity, or sensory acuity. There is controversial evidence that an abnormality in the magnocellular (M) visual pathway may play a role in the disorder [1]. The M pathway begins with retinal ganglion cells that project to the M layers of the lateral geniculate nucleus (LGN) and terminates in primary visual cortex [2]. Evidence for an M pathway deficit in dyslexia includes: abnormally small M layer LGN cells [3]; reduced or delayed electrophysiological responses to stimuli processed mainly by the M pathway [3–6]; but see [7,8]; and reduced fMRI responses to stimuli processed mainly by the M pathway [9,10].

These results suggest that dyslexic subjects should perform poorly in visual tasks that require an intact M pathway. Monkeys with M layer LGN lesions have impaired contrast sensitivity for stimuli of lower spatial and higher temporal frequencies, characteristics similar to M cell peak sensitivities [11,12]. M pathway lesioned monkeys are also impaired on motion discrimination tasks consistent with the strong M pathway projection to the motion-sensitive MT/MST cortical brain areas [13–15,12].

Two studies have revealed reduced motion discrimination performance in dyslexia using moving dot stimuli and either a coherent motion detection task or a speed discrimination task [16,9]. The stimuli used in these studies were different than the standard stimuli used in contrast sensitivity studies in dyslexia (sinusoidal gratings), and both paradigms were substantially different from tasks used to demonstrate motion perception impairment in M pathway lesioned monkeys [15,12].

Contrast sensitivity studies have also revealed reduced performance in dyslexia, especially for lower

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spatial and higher temporal frequencies [17–21]. Although some have failed to show contrast sensitivity losses [16,22–24], some of these failures (e.g. [16,22]) might be explained by the use of high rather than low mean luminances because low mean luminances emphasize the M pathway inputs to cortex [25,26].

Our study had two goals. First, contrast sensitivity and motion discrimination performance were compared using the same stimulus and the same subjects in order to test which of these two measures produced larger group differences. Second, in addition to the group analyses, individual differences in psychophysical performance were compared with individual differences in various reading tests to determine the reading skills that are most strongly related to psychophysical measures of M pathway integrity.

2. Methods

2.1. Subjects

Five dyslexic subjects (two females) were solicited from the Stanford Disabilities Resource Center. All were Stanford students (mean age = 22.2, S.D. = 2.9) and were assumed to be of above average intelligence. All had a childhood history of dyslexia, were diagnosed with dyslexia as adults, and received special treatment by the university (e.g. extra time on exams). Five control subjects (two females) were solicited from the Stanford population (mean age = 26.8, S.D. = 6.1). None had a history of reading difficulty. All subjects were right-handed, except one control who was left-handed. Two of the dyslexic subjects (one female) were co-diagnosed with attention deficit disorder and were taking Ritalin, but did not take it prior to testing. None of the other subjects were taking medication or had a neurological or psychiatric illness that would interfere with the study. Subjects were paid or volunteered without pay, all gave informed consent, and all had normal or corrected to normal acuity. Subjects had also participated in a previous fMRI study on vision and dyslexia [10].

2.2. Reading tests

Subjects were administered five reading measures: the Wide Range Achievement Test (WRAT 3) reading and spelling tests that require subjects to read or spell words of increasing levels of difficulty (e.g. cat to synecdoche); the word attack subtest of the Woodcock–Johnson educational battery that requires subjects to sound out nonsense word letter strings (e.g. raff, monglustamer); and the Nelson–Denny reading rate and comprehension measures that require subjects to answer questions about a series of paragraphs (similar to the SAT or GRE exams). After the first minute of the Nelson–Denny test, subjects were asked to mark the line they were reading to measure reading rate (words per minute). For all tests, percentile scores were derived for each subject by looking up raw scores in tables that accompanied the tests.

2.3. Psychophysical methods

Psychophysical performance was measured for contrast detection and speed discrimination. The stimuli and tasks were patterned after monkey studies (cited above) that showed reduced performance following M pathway lesions. In addition, we used a low mean luminance to emphasize M pathway inputs to cortex [25,26].

Speed discrimination thresholds were measured using a two-interval forced choice, double (three-down one-up) staircase procedure. Stimuli, displayed on a Radius high-resolution, monochrome monitor driven by a 10-bit Radius frame buffer card, were moving 0.4 cyc/deg sine-wave gratings at low mean luminance (5 cd/m^2) windowed in a 5° circular aperture. On each trial, subjects viewed two stimuli in succession, each preceded by an auditory beep with a 250 ms interstimulus interval. One of the stimuli on each trial was a baseline stimulus moving at 20.8 deg/s. The other was a test stimulus with a variable speed always above 20.8 deg/s. The subjects' task was to report which of the two stimuli moved faster, with feedback after each trial. The initial speed increment was large (20% of the baseline speed) so that subjects would understand the task. The initial downward step was large (12% of the baseline speed); thereafter the step size was 2%.

Following previous studies, stimulus (Michelson) contrast and duration were randomized to force subjects to base their responses only on stimulus speed [27,12], and subjects were informed of this. Contrast was varied randomly between 16 and 24% (average of 20% contrast $\pm$ 20%) so subjects could not use apparent contrast cues, and stimulus duration was varied randomly (average of 450 ms $\pm$ 20%) so subjects could not count the number of cycles as they moved past.

After 50 trials, the subject's responses were compiled (percent correct versus test speed), fit with a Weibull function using a maximum likelihood procedure [28], and a threshold was determined (at 79% correct performance). Typically, a subject's threshold would decrease with practice at the task. Each subject completed between four and ten repeats of the staircase procedure until their performance appeared to asymptote three times in a row. We computed each subject's threshold as the mean of the last three measurements (as a Weber fraction, or percent increase over the baseline speed).

Contrast detection thresholds were measured using a similar procedure. One interval on each trial included a

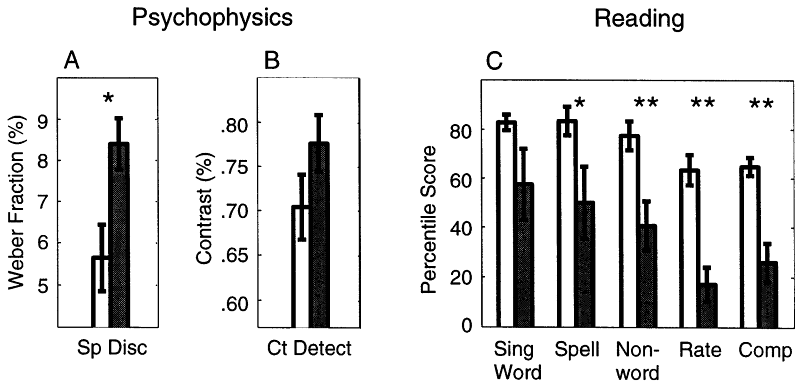

Fig. 1. Group performance on psychophysical and reading tasks (control group = white bars; dyslexic group = gray bars). A. Speed discrimination performance for a moving sine-wave grating at 20% contrast. The Weber fraction is the percent increase over the baseline speed of 20.8 deg/s. Control group: mean = 5.6%, S.D. = 1.8. Dyslexic group: mean = 8.4%, S.D. = 1.4. B. Contrast detection performance for a moving sine-wave grating. Control group: mean = 0.70%, S.D. = 0.08. Dyslexic group: mean = 0.78%, S.D. = 0.07. C. Performance (percentile scores) in the five reading tests. Abbreviations: Sp Disc, speed discrimination; Ct Detect, contrast detection; Sing Word, single word reading subtest of the WRAT3; Spell, spelling subtest of the WRAT3; Non-word, non-word pronunciation ('Word Attack') subtest of the Woodcock–Johnson psychoeducational battery; Rate, reading rate subscore of the Nelson–Denny reading test; Comp, comprehension subscore of the Nelson–Denny reading test. All graphs show group means plus/minus 1 standard error of the mean. There are statistically significant group differences on many of the measures (* $P < 0.05$, ** $P < 0.01$).

stimulus (the target) and the other interval was blank. The task was to report the interval that included the target. Stimuli were the same as those used in the speed discrimination experiment (0.4 cyc/deg sine-wave gratings moving at 20.8 deg/s, mean luminance = 5 cd/m^2), except that they were windowed by smooth functions in both space and time to avoid sharp edges and temporal transients that might have aided detection. Specifically, the outer thirds of the stimuli were multiplied by a half period of a raised cosine function so that the stimuli gradually faded into the equal mean luminance gray background. Likewise, the first and last third of each 375 ms stimulus interval were multiplied by raised cosines. In initial trials, the target contrast was 2%. The initial staircase step size was 6 dB or 1% contrast; the step size for remaining trials was 2 dB or 0.17% contrast. Each subject completed three measurements, except one who required an additional initial practice run. Thresholds were fairly constant across these three measurements, so none of the subjects required any additional practice. We computed each subject's threshold as the mean of the three measurements (in percent contrast).

Correlations between reading ability and psychophysical performance were tested for statistical significance using a one-tailed statistic to test the hypothesis that better performance on the psychophysical measures (i.e. lower thresholds) would be correlated with better reading ability. We also tested for the possibility that one subject might be an outlier, making an otherwise strong correlation appear weak or vise versa. To test for this possibility, we removed one subject at a time and re-calculated the correlations with the remaining nine subjects.

3. Results

As a group, control subjects scored higher on all reading tests, as expected (Fig. 1C). This was statistically significant (one-tailed, df = 8) for four out of five tests: spelling ($t = 2.11$, $P < 0.05$), non-word reading ($t = 3.17$, $P < 0.01$), reading rate ($t = 5.01$, $P < 0.005$), and comprehension ($t = 4.56$, $P < 0.005$). Single word reading was only slightly better in controls than dyslexics ($t = 1.70$, $P < 0.10$).

Speed discrimination thresholds are presented in Fig. 1A. Control subject thresholds were similar to previous reports (e.g. [29,27]), but speed thresholds were significantly elevated/worse in the dyslexic group ($t(8) = 2.72$, $P < 0.02$, one-tailed). Contrast detection thresholds are presented in Fig. 1B. The dyslexic groups' thresholds were only slightly higher than those of the control group ($t(8) = 1.48$, $P < 0.10$, one-tailed).

Correlations between individual differences in psychophysical performance and reading measurements are presented in the first two rows of Table 1. The strongest relationship, plotted in Fig. 2, was between speed thresholds and reading rate ($r = -0.84$, $P < 0.005$, one-tailed). None of the correlations between contrast thresholds and the five reading measures were statistically significant. In addition, the correlation between the two (speed and contrast) psychophysical thresholds was significant ($P < 0.025$, one-tailed).

With one subject removed from the overall group, the correlation between speed thresholds and non-word reading reached significance ($P < 0.05$). With a different subject removed, the correlation between speed thresholds and reading comprehension reached significance ($P < 0.05$). With a third or fourth subject re-

Table 1
Correlations between reading and psychophysical performance

	Ct Detect	Sing Word	Spell	Non-word	Rate	Comp
Sp Disc	0.67[a]	−0.02	−0.08	−0.45[c]	−0.84[b]	−0.42[c]
Ct Detect	–	0.21	0.02	−0.37	−0.50[c]	−0.26
Sing Word	–	–	0.77[b]	0.80[b]	0.33	0.77[b]
Spell	–	–	–	0.75[b]	0.28	0.68[a]
Non-word	–	–	–	–	0.64[a]	0.90[b]
Rate	–	–	–	–	–	0.74[b]

Many of the reading tests and psychophysical measurements were significantly correlated ([a] $P<0.05$, [b] $P<0.01$; [c] $P<0.05$ with one subject removed). Abbreviations are the same as Fig. 1.

moved, the correlation between contrast threshold and reading rate was significant ($P<0.05$). Thus, there was no single subject that consistently drove the correlations down.

Correlations between the reading measures are presented in the bottom four rows of Table 1. Most of the pairs of tests were correlated with one another. Notable exceptions are the correlations between reading rate and both single word reading and spelling. Even when removing single subjects from the group, these correlations did not achieve the liberal one-tailed threshold.

4. Discussion

We found that performance in a motion discrimination task was a better indicator of dyslexia than performance in a contrast detection task. Two previous studies have also demonstrated deficits in motion discrimination performance in dyslexia, in both adults and children [9,16]. On the other hand, previous studies of contrast sensitivity differences in dyslexia have been less consistent (e.g. [19,24]), and the current study showed only a trend towards a group difference. While the correlation between individual differences on the motion discrimination and contrast detection tasks suggest that they may be tapping the same underlying deficit, the motion task may be a more reliable indicator, especially with smaller samples and thus less statistical power. Future studies that require a psychophysical assay for M pathway integrity in dyslexia (e.g. examining subtypes of dyslexia; [30]) should therefore include motion discrimination in addition to contrast detection.

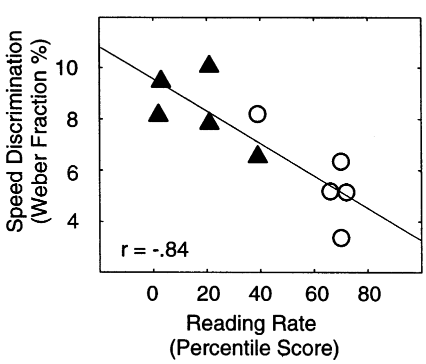

Fig. 2. Individual differences in speed discrimination thresholds are strongly correlated with individual differences in reading rate ($r=-0.84$, $P<0.005$). Solid line is a regression line through the data, open circles represent control subjects, filled triangles represent dyslexic subjects.

Our second main result was a strong correlation between individual differences in motion discrimination performance and reading rate. Many bright, motivated dyslexic university students compensate for reading difficulties by bringing other cognitive abilities to the task, but they appear to do so at the cost of reading slowly [31]. Dyslexic subjects in the present study took regular classes but required extra time on course testing due to their slow reading. A study of compensated dyslexics found that reading speed was still affected, even when all or most other reading skills were normal [32]. Thus, reading rate may be the most sensitive marker of dyslexia in adults with a childhood history of dyslexia and some level of compensation in adulthood. It also appears to be the reading ability that is most strongly related to psychophysical measures of M pathway integrity.

The correlation between individual differences in motion discrimination and reading rate is driven, at least in part, by the significant group differences in both of these capabilities. However, the correlation across all subjects will be enhanced if there is some level of correlation within each group. The scatter plot in Fig. 2 follows this trend but the correlations within each group are not statistically significant by themselves, given the small sample size. It may be possible with a larger sample, and thus more statistical power, to demonstrate a significant correlation separately within either the dyslexic or control groups.

Dyslexia may represent readers in the lower tail of a normal distribution of reading ability [33]. When viewing reading skills on a such continuum, it makes more sense to use the correlational analysis to examine patterns between individual differences in visual performance and specific reading abilities, and disregard group classifications based on often controversial diagnostic procedures.

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