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ORIGINAL ARTICLE

L/M Speed-Matching Ratio Predicts Reading in Children

CHRIS CHASE, PhD, ROBERT F. DOUGHERTY, PhD, NICOLA RAY, PhD, SUSAN FOWLER, DBO, PhD, and JOHN STEIN, FRCP

Department of Psychology, Claremont McKenna College, Claremont, California (CC), Department of Psychology, Stanford University, Palo Alto, California (RFD), and Department of Physiology, Anatomy and Genetics, Oxford University, Oxford, United Kingdom (NR, SF, JS)

ABSTRACT

Purpose. Many behavioral studies have found impaired perception of dynamic visual stimuli in dyslexia and several neuroimaging studies have found reduced activation of the human motion area MT+ in dyslexia. These results are often interpreted as a magnocellular (MC) deficit in dyslexia. It has also been claimed that colored filters can help dyslexics to read. One defining feature of the MC-pathway is a greater weight for L-cone input than M-cone input, and at most very weak S-cone input. We measured the subjective speed matches between L-, M-, and S-cone isolating stimuli in good and poor readers.

Methods. Subjects performed a speed-matching task with drifting cone-isolating stimuli to find the point of subjective equality between two drifting patterns. Such a task is known to activate cortical area MT+, presumably via the MC-pathway.

Results. L- to M-cone speed-match ratios were negatively correlated with single-word ($r = -0.46$) and irregular-word reading ($r = -0.56$) but not with non-word reading.

Conclusions. Results suggest that relative L-cone sensitivity within the MC-pathway may limit orthographic reading performance.

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Key Words: reading, visual psychophysics, magnocellular, motion perception

Visual neurological abnormalities associated with dyslexia have been known for some time. Laminar organization and cell size were found to be abnormal in the magnocellular (MC) layers of the lateral geniculate nucleus.[1] Visual cortical neurons in the MC-pathway terminal layer, 4Cα, also appear symmetrical in dyslexics, whereas normally cell size is larger in the left hemisphere.[2] The parvocellular (PC) pathway appears to be normal in dyslexia. These MC-pathway abnormalities may affect motion perception in dyslexics,[3–9] and fMRI has shown reductions in dyslexic cortical activation during motion perception in V1 and MT+.[4,5]

The MC-pathway has adequate spatial frequency and contrast sensitivity for text processing,[10] and color has been found to affect reading performance—possibly through the MC-pathway. Reading performance tends to be better for some dyslexic and normal readers with blue transmitting filters,[11–16] whereas diffuse red light impairs the performance of normal readers.[10] One study found that high-pass yellow filters benefited one group of poor readers, whereas another group preferred low-pass blue filters.[16] Wilkins et al. have reported that individuals who benefit from color while reading prefer very specific hues and saturations.[17] Vidyasagar has proposed that some dyslexics may have an abnormal S-cone input to the MC-pathway and that a yellow filter may improve reading performance by reducing S-cone input.[18]

This pattern of results suggests a possible connection between the MC-pathway, wavelength sensitivity, and reading development. Some poor readers have weak MC-pathway function. Diffuse red light impairs reading performance, but other colors can improve reading. Perhaps some poor readers have abnormal cone photoreceptor inputs to their MC-pathway. MC-pathway signals are dominated by L- and M-cone inputs,[19] but considerable individual variation in L/M-cone ratios have been found.[20–23] Despite these differences, colors appear similar to most individuals because L- and M-cone inputs are scaled to equalize their input to the opponent color channels carried by parvocells.[22,24] This makes it less likely that color variation affects reading through the PC-pathway. However, MC inputs are not scaled as dramatically as PC inputs, and under moderate adapting conditions can continue to reflect individual differences in L/M-cone ratios.[21] In this study we measured the point of subjective equality (PSE) in a speed-matching task using cone-isolating stimuli. This task is expected to activate area MT+,[25–27] and we propose that it is a good psychophysical indicator of relative cone inputs to the MC-pathway. We compared these speed-matching measurements to motion coherence perception and academic performance in a group of children with a wide range of reading abilities.

METHODS

Participants

Forty-seven children (21 female) between the ages of 7 and 15 (mean age = 10.2) were recruited from the clientele of the Dyslexia Research Trust Clinic in Reading, England and from a local Primary School in the neighborhood of the Clinic. Our experimental procedures conformed to the tenets of the Declaration of Helsinki and were approved by the local ethics committee. Written informed consent was obtained from each participant and a parent or legal guardian. All subjects were native British-English speakers and screened for neurological abnormalities using a brief medical history. They also were tested for normal intelligence and normal color and vision perception using the procedures described below.

Psychometric Assessment

The Similarities, Matrices, Single Word Reading and Spelling subtests of the British Abilities Scales II (BAS II)[28] were given to all the children. In addition, they read the Castles and Coltheart irregular and non-word reading lists that were scored for accuracy.[29] Performance on irregular and non-words was converted to Z-scores based on norms established for the Castles and Coltheart word lists,[11] and the BAS II subtests were converted to Z-scores based on the BAS II age norms.

Visual Assessment

A clinical orthoptist screened all the children for visual anomalies. Vision testing included near and far acuity, ocular motor movement, binocular vision, stereopsis, and color perception.

Ocular motor function was evaluated using an eye-tracking device to record eye movements. Recordings were rated on a three-point scale, where 1 = poor, 2 = below average, and 3 = normal. Pursuit was assessed by observing the subject's ability to follow a moving target horizontally. When pursuit movements are disturbed, instead of smoothly following the moving target, the eyes track by means of a series of fine or gross jerks, known as saccadic intrusions. Saccades were assessed by asking a subject to move her eyes between two stationary targets spaced 40 cm apart. If saccades are accurate the new fixation target is reached in one movement. Saccade errors include hypometric eye movements, where the eyes reach the target in a series of steps, or hypermetric saccades, where the eyes overshoot the target. Fixation stability was assessed by observing the subject's ability to keep both eyes still while looking at a small target at 30 cm. Near point convergence was measured in centimeters with a small spot fixation target, using the RAF near-point rule. Fusional vergence was assessed by asking the subject to follow the target as it moved towards her and to report when the target broke into two images. The examiner also observed when vergence failed when one eye diverged away from the target. Accommodation was assessed as the distance at which the subject reported print blurred and went out of focus (where N5 was normally the print size used). End point nystagmus was assessed by clinical observation.

The cover test assessed binocular single vision and squint. Subjects maintained fixation on a target at 1/3 and 6 m. First one eye was covered, and then the other, and any movement of the uncovered eye to take up fixation was noted, which indicates a manifest squint. However, movement of the covered eye when the cover is removed indicates a latent deviation in the presence of binocular single vision. Stereoacuity was assessed using the TNO test. Color vision was assessed using the Ishihara plates and the L'Anthony D-15 test.

All subjects had distance acuity of 6/9 or better in either eye and could read N5 sized print for near acuity at 30 cm. A few children had mild heterophoria on the cover test, and five children failed the Ishihara and L'Anthony D-15 tests, showing Protan abnormalities. Otherwise, all visual tests were normal.

Visual Psychophysics

Subjects performed motion coherence, form coherence, and speed judgment tasks. Both the motion and speed judgment tasks are known to activate cortical area MT+[26,30] and have been used in used in other studies to assess MC function.[7,9,25,26]

Motion Coherence Threshold. The details of the motion coherence task have been previously described.[7] Children were tested using random dot kinematograms (RDKs) and psychophysical thresholds were measured using a two-alternative, forced-choice (2AFC) procedure. They viewed two panels, side by side, with white dots (90 cd/m^2) presented on a black background. Viewing distance was 57 cm with each panel subtending 10 × 14° of viewing angle. In one panel, a percentage of the dots moved coherently in a horizontal direction that reversed every second. The noncoherent dots in this panel moved in a random (Brownian) motion. In other panel, dots moved randomly. The location of the panel with coherent motion changed randomly on each trial. Subjects viewed both stimulus patches for 2.5 s and were instructed to indicate in which panel the dots were moving together, and to guess when uncertain. They received feedback about their performance on every trial. Several practice trials with 75% coherence were given, and "catch" trials with 75% coherence were spaced throughout the experiment to assure that subjects stayed on task. The percentage of coherently moving dots was adjusted on each trial using a weighted staircase procedure[31] to determine threshold. A correct response was followed by a 1 dB reduction in signal coherence, and an incorrect response by a 3 dB increase in coherence. Motion coherence thresholds were estimated from one staircase series for each subject. Detection threshold was defined as the geometric mean of the last six of eight reversals. Inspection of the catch trials showed that all participants were able to complete this task.

Form Coherence Threshold. Hansen et al. developed the form coherence task as a control measure for comparison to their motion coherence task.[32] Subjects viewed two panels for 2.5 s to detect a global visual pattern embedded in a static display of randomly oriented line segments where one panel has some percentage of the line segments in a collinear arrangement to form a circular pattern in the center of the panel. Subjects were asked to indicate which of the two panels contained the circular pattern. Each panel contained 900 lines of eight pixels each. The circular target had a radius of 80 pixels. As with the motion task, form coherence was defined in terms of the proportion of the elements that contribute to the pattern relative to the randomly-oriented elements. The same procedures as for the motion coherence task, described above, were followed. The difference between the two tasks primarily involves the dynamical verses static nature of the displays. Results from this task were used as a covariate in multiple regression analyses to control for individual biases in the performance of the motion task.

PSE Speed Matching Task. Subjects performed a speed-matching task with drifting cone-isolating stimuli to find the PSE between two drifting patterns. The speed of an L-cone isolating standard was adjusted to match the speed of test stimuli that varied across five different contrast levels and three different cone-isolating hues. The 2AFC trials were presented using an interleaved staircase procedure.[25] The standard and test stimuli were drifting radial sinusoidal gratings with a spatial frequency of 0.5 c/deg and were presented on a gray background of 35 cd/m^2. They appeared at the same time and to the left and right of a small fixation target, centered at six degrees eccentricity. The positions were randomized so that the test grating could appear on either the left or right. The subject's task was to decide which grating was moving faster. The standard grating was an L-cone isolating stimulus with a fixed 2.5% cone-contrast and whose drift speed was adjusted by the staircase procedure. The three hues of test gratings (L-, M-, and S-cone isolating) moved at a fixed speed of 4.2 Hz (8.4° per second) and were presented at five different fixed cone-contrast levels. Stimulus contrast was temporally windowed by a 500 ms Gaussian envelope (full-width, half-maximum). Viewing distance was 52 cm with each grating subtending eight degrees of visual angle. For L-cone stimuli, contrast was 10, 5, 1, 0.75, and 0.5%; for M-cone stimuli, contrast was 15, 7.5, 5, 2.5, and 1%; and for S-cone stimuli, contrast was 80, 40, 20, 10, and 5%. Each cone-isolating test stimulus was run in a separate trial block in a counterbalanced order. Within a block, all five contrast levels were interleaved.

The PSE between the speeds of the standard and test gratings was determined using a 1 up, 1 down staircase procedure. The starting speed of the standard was randomly selected. The initial step-size was 1.6 Hz. After the first two reversals, the step-size was cut in half, then halved again after the third reversal, and finally reduced to 0.2 Hz after the fourth reversal, where it was held constant for the rest of the procedure. To avoid fatigue in the children, the staircase stopped when all contrast levels had reached at least sixteen trials or eight reversals. This resulted in an average block duration of 90 trials. The median speed of the last four reversals was used to estimate the PSE for each cone-contrast level and the standard deviation was used to estimate the reliability of each PSE value.

Stimuli were presented on a HP A4331D monitor controlled by an ATI Radeon Mobility 7500 video card with 10-bit DAC resolution. The monitor was calibrated for intensity and wavelength[33,34] using an Ocean Optics USB2000 spectroradiometer. The speed judgment experiment and calibration procedures were written in MatLab using the Psychophysics Toolbox extensions.[35,36] Cone absorptions were estimated from Stockman fundamentals.[37]

To assess calibration and quantization error, we measured the spectra for each cone-isolating stimulus at several cone contrasts and then computed the cone excitations using the Stockman fundamentals and intensity functions of the monitor obtained during calibration. The maximum cone-contrasts that could be achieved with the monitor's gamut remained stable throughout the experiment and were 19.5, 22.3, and 85.9% for the L-, M-, and S-cone isolating hues, respectively. The estimated splatter from other cones caused by quantization error was <5% for L- and M-cone conditions and under 1% for the S-cone condition; that is, for an L-cone isolating stimulus of 2.5% contrast, the estimated M- and S-cone contrasts were <0.125%.

Other sources of error that we did not measure include chromatic aberration (which should be minimized by the low spatial frequency of our stimuli), individual variability in cone absorption, and macular pigment variance across subjects. Golz and MacLeod estimated the uncertainty of cone-contrast CRT measures due to individual variability in these factors.[38] For M-cone isolating hues, on average biological variability introduces 2.4% L-cone contrast, and for L-cone isolating hues the M-cone splatter is 1.9%. Together with our calibration measures, these data suggest that the relative contrast of our cone-isolating hues varied by no more than 5%.

The relationship between speed judgment and cone-contrast was fit with a sigmoid function using a maximum likelihood procedure.[25] The function used was $P = (C^x/[C^x + S^x]) \times M$, where P is the perceived speed, C is the stimulus contrast, M is the maximum speed (upper asymptote), x is the slope, and S is the semisaturation value of the curve (i.e., the shift of the function along the cone-contrast axis). For each hue, the semisaturation value represents the relative position of the speed-contrast function along the test-hue cone-contrast axis. The slope represents the gain in perceived speed as test contrast increases. The maximum speed represents a perceptual ceiling in speed judgment.

Curve-fits for each subject were constrained to use the same slope and maximum speed values for all three cone-contrast functions. Functions varied between cone conditions only by the semisaturation parameter. For each subject, preliminary fits were made with all three parameters free to vary. Values for maximum speed and slope were then fixed to their respective averages computed across all three color conditions, and a final curve fit was made in which only the semisaturation parameter (S) was free to vary. In this study, we concentrated our analysis on the semisaturation values, but we also examined the slope and maximum speed values using the preliminary curve fits after they were fixed for each subject.

Validity Check of PSE Task. This PSE task has not been used with children before. Although participants were given an opportunity to practice, due to time constraints data were collected in a single 20- to 30-min testing session, and multiple measurements could not be made. Consequently, these data required careful screening to assure that the children successfully completed the task; including results from children who were simply guessing would add considerable noise to the data.

The validity of the curve fits for the PSE task was evaluated for each subject. We calculated the χ^2 goodness of fit (weighted for the variance of each of the five data points) for the sigmoid function fit to each of the three hues. Fourteen children had a χ^2 p value of

≤0.01, indicating a poor fit, and were thus excluded from the analysis. Visual inspection of these data suggests that these children were not responding in a consistent manner. We also visually inspected all the data and excluded an additional three subjects who had adequate χ^2 fits but whose speed-match functions were nonmonotonic.

RESULTS

The results for the PSE task are based on data from 25 children, 11 girls and 14 boys (mean age = 10.5; range = 7.10 to 15.6). As described above, data from 17 children were excluded because of poor performance on this task. An additional five children were excluded for color perception deficiencies. Data from all participants (n = 47) were included in analyses that did not involve the PSE task.

L/M Ratio Estimates

Fig. 1 shows the PSE for one subject as a function of the target cone-contrast. The most striking feature is the sharp increase in perceived speed with increased contrast.[39] Also, the S-cone stimulus requires a much higher contrast to achieve a similar perceived speed.[25] In fact, for a wide range of contrasts, S-cone stimuli appear to move very slowly or even not at all.[40] The presence of the contrast effect on perceived speed and the shifted S-cone function in all the datasets that survived our data screening provided a validity check on the compliance of the children in performing this subjective matching task. However, the fact that about one-third of the datasets did not survive the data quality check suggests that some children may require additional training to successfully complete this task.

While the basic pattern of the speed-matching data shown in Fig. 1 is consistent across subjects, the specific semisaturation values varied considerably across subjects. To remove some of this variance that is due to differences in speed-contrast sensitivity, stimulus sensitivity, and consistent subject biases in the matching task, we computed the L/M and L/S speed-match ratios for each subject from the semisaturation values of the three hues. We express this measure as a proportion of L-cone (%L) using the formula: (100/L-cone semisaturation value)/(1/L-cone semisaturation value + 1/[M- or S-]cone semisaturation value).[20] The mean %L for L/M was 56.4% (SD = 15.5) with a range from 23.2 to 87.5%. The mean %L for L/S was 91.7% (SD = 4.4) with a range from 81.4 to 99.5%.

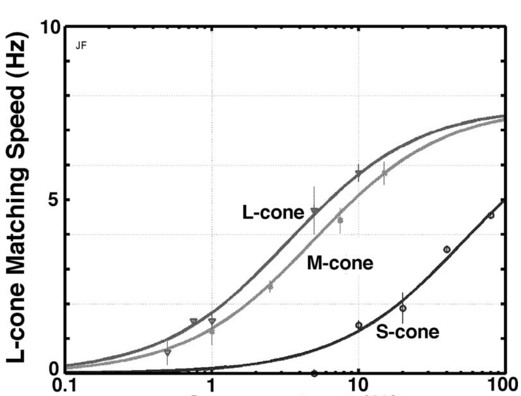

FIGURE 1.
Speed matches (PSE) between an L-cone standard and L, M, and S-cone isolating test stimuli for subject JF. Contrasts for the test stimuli, moving at 4.2 Hz, are shown on the x axis. The speed of the 2.5% contrast L-cone standard needed to achieve a speed match is shown on the y axis. Measured values are indicated by the points and the lines indicate the function-fits to the data. The semisaturation values are 3.4, 5.0, and 53.0% for the L-, M-, and S-cone contrast functions, respectively. Error bars indicate ±1 SEM.

Cone-Isolating Speed Matches and Academic Performance

Using data from the 25 children who were able to complete the PSE task, correlations were performed to determine whether L/M and L/S speed-match ratios were related to academic skills. The S-cone data showed no significant effects with any of our behavioral measures. The rest of our analysis concentrated on the L/M speed-match ratios. Multiple regressions were computed using the BAS II Matrices subtest as a covariate. Academic scores were based on age norms, so age was not included as a covariate. Matrices scores were entered first into the regression followed by the L/M speed-match ratio. Results are presented in Table 1. The L/M speed-match ratio produced strong correlations with single-word reading (p = 0.004) and irregular-words (p = 0.01), but non-word reading was not correlated. After controlling for IQ, the L/M speed-match ratio accounted for 21% of the variance for word reading, 28% of the variance for irregular words, and 12% of variance for non-words. Spearman rank correlations produced the same pattern of results as the multiple regressions ($\rho = -0.42$, p = 0.04; irregular-word $\rho = -0.45$, p = 0.04; non-word $\rho = -0.24$, p = 0.28), suggesting these results were not cause by the undue influence of outliers. Figs. 2 and 3 show a linear scatter plot between the L/M speed-match ratio, single-word, and irregular-word reading, respectively.

Academic Performance and Motion Coherence

Using the whole sample (n = 47), a multiple regression analysis was performed with BAS II Matrices and the form coherence tasks as covariates, motion coherence sensitivity as the independent variable, and single-word reading as the dependent variable. Results showed that motion coherence sensitivity and single-word reading performance were positively correlated (standard coefficient = 0.31, p = 0.05). A Spearman rank correlation also was significant ($\rho = 0.31$, p = 0.04). Correlations with other academic measures were not significant. Fig. 4 presents a linear scatter plot between motion coherence and single-word reading.

Cone-Isolating Speed-Matching and Motion Coherence

A multiple regression analysis also was performed with motion coherence sensitivity and the L/M speed-match ratio with BAS II Matrices and the form coherence task included as covariates. The L/M speed-match ratio was not significantly correlated with the motion coherence threshold.

TABLE 1.
Multiple regression coefficients with BAS II matrices and L/M ratios as the covariates and academic scores as the dependent measures

Test	Covariate	Standard coefficient	R^2	Change in R^2	t value	p value
Single-word reading	Matrices Z	0.50	0.26		3.24	0.004
	L/M ratio	−0.46	0.47	0.21	−2.94	0.008
Irregular-word reading	Matrices Z	0.08	0.04		0.41	0.69
	L/M ratio	−0.54	0.32	0.28	−2.79	0.01
Non-word reading	Matrices Z	0.14	0.02		0.35	0.73
	L/M ratio	−0.40	0.14	0.12	−1.57	0.13

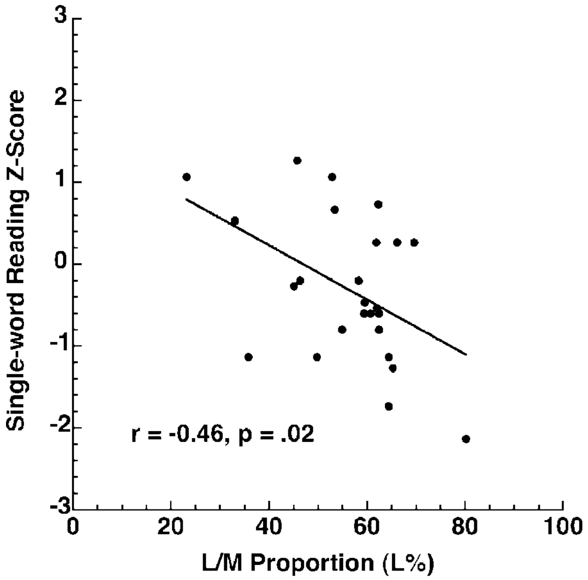

FIGURE 2.
Correlation plot between the L/M speed-match ratio (%L) and BAS II single-word reading z-score.

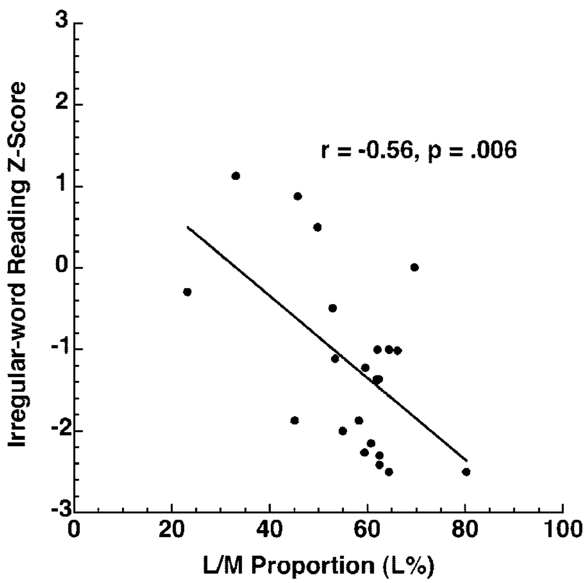

FIGURE 3.
Correlation plot between the L/M speed-match ratio (%L) and Castles and Coltheart irregular-word reading z-score.

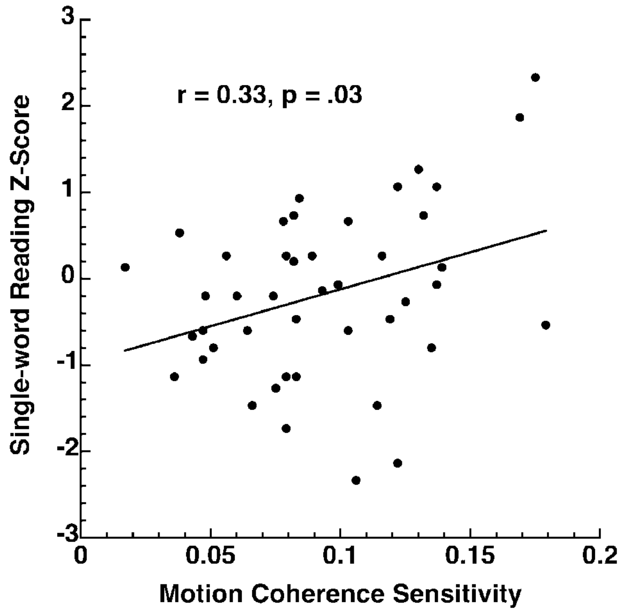

FIGURE 4.
Correlation plot between motion coherence sensitivity and BAS II single-word reading z-score.

DISCUSSION

L/M Speed-Match Ratio and Reading

L/M speed-match ratios estimated from our PSE task were negatively correlated with single-word and irregular-word reading. Those with the higher L/M speed-match ratios tended to be the poorer readers. This result is new and requires further study to replicate and explore different factors that could be associated with L/M speed-match variation. Some possibilities include a difference in L/M cone numbers in the retina, cone absorption, differences in chromatic adaptation mechanisms, or other postreceptor mechanisms.

L/M speed-match ratios were strongly correlated with irregular but not non-word reading. Previous studies have reported that visual abnormalities thought to involve a MC-deficit correlated most specifically with orthographic reading skills, whereas phonological skills were more closely related to auditory processing.[8,41–43] Our results further support this pattern, as non-word reading relies heavily on phonological processing skills.

The development of orthographic knowledge begins in children with a letter-by-letter processing strategy that evolves into to a more holistic method where whole words or spelling patterns are recognized on sight.[44] To read irregular words requires a holistic approach that directly accesses lexical knowledge of the whole word, since such words have unusual pronunciations (e.g., "yacht") that preclude a letter-by-letter decoding. Conversely, non-words have no lexical representation and must be pronounced using letter-by-letter phonological knowledge.[29]

Taken in conjunction with previous work that shows that the MC-pathway is important for identifying the global shape of letters and words,[45] our results suggest that the L/M speed-match ratio in the MC-pathway may play a role in access to the holistic orthographic representation but not phonetic letter-by-letter reading. Low spatial frequencies carried by the MC-pathway dominate early visual information processing and define the global shape of objects.[46] Chase proposed a model of reading in which the MC-pathway provides a low spatial frequency pattern that can be used for orthographic identification.[45] If there is sufficient information, words can be identified holistically on the basis of the MC-pathway alone; however, orthographic analysis may need the slower PC pathway to provide more details, particularly for letter-by-letter analysis.

L/M Speed-Match Ratio and Motion Coherence

Motion coherence sensitivity was positively correlated with single-word reading. This result replicates many other studies[5–9,47] and adds further support for a role of the MC-pathway in text processing. The L/M speed-match ratio, however, did not correlate with motion coherence, suggesting that these measures may reflect different MC functions. The role of the MC-pathway in text processing is not well understood. Several different functions have been proposed, including visual attention,[18,48] letter position encoding,[49] and global text features.[45] In one study, letter position encoding correlated with motion coherence sensitivity,[49] and so the L/M speed-match ratio may not affect the encoding of letter position but still correlate with the development of orthographic knowledge in other ways as described above. Further research is needed to sort out the different factors involved in text processing and the MC-pathway.

Speed Judgment and Reading Ability

About one third of the children in this study were unable to complete the speed judgment task successfully with the training given. The children who were excluded were not different in age or IQ from those who successfully completed the task, but a study by Wilmer et al. with adult dyslexics suggests another possible explanation why so many had difficulty performing this task.[47] They identified two different dyslexic visual processing deficits—motion coherence detection and speed judgment. Perhaps some the children in our sample had difficulty learning to perform the speed judgment task because they were dyslexic. Using a 1 SD discrepancy between IQ and reading performance as a criteria for dyslexia, 60% of the whole sample ($n = 47$) could be diagnosed as reading impaired. The portion probably was so high because many participants were recruited from a dyslexic clinic. Further research is needed to explore this idea, providing more training or a different speed judgment task so that valid data can be obtained.

L/M Balance and Reading

The negative correlation we found between the L/M speed-match ratios and reading performance suggests several possibilities about reading and color. A report that shows reading improves for some individuals with yellow or blue filters[16] implies that text processing in the MC pathway may need a balanced L- and M-cone input. The imbalance could occur within the MC-pathway or be induced through interference from the blue-yellow color opponent channel in the PC-pathway. The use of yellow or blue filters could balance the L- and M-cone input in the PC channel, thus reducing interference or directly balance L- and M-cone input in the MC-pathway.[50,51] Another alternative is that the PC-pathway is primarily responsible for these correlations between reading and L/M speed-match ratios. This interpretation is less likely considering that the stimuli used in the speed-matching task are known to activate MT[25,26] and that the dominant signal in MT is derived from the MC pathway. However, color-opponent input from the PC-pathway to MT has been found,[52] so this interpretation cannot be ruled out completely. Vidyasagar's[18] hypothesis that abnormal S-cone input to the MC-pathway may impair reading development was not supported by these results as the S-cone speed-match ratios did not correlate with reading performance.

Why would L/M speed-match ratios predict reading performance? The focal characteristics of the accommodation response are affected by longitudinal chromatic aberration.[53–57] When the L/M-cone contrast ratio of the stimulus is high, the mean accommodation level decreases, biasing the response towards far.[55,56] Variation in L/M ratio sensitivity may affect a child's accommodation response and interfere with text perception. Ray et al.[16] found a high proportion (39%) of disabled readers had poor accommodation. The use of yellow filters significantly improved their accommodation, perhaps by balancing L- and M-cone input,[50,51] and reading performance also improved more in those who used yellow filters than a placebo. Further research is needed to explore LCA, the balance of L- and M-cone input, accommodation, and reading development.

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REFERENCES

1. Livingstone MS, Rosen GD, Drislane FW, Galaburda AM. Physiological and anatomical evidence for a magnocellular defect in developmental dyslexia. Proc Natl Acad Sci U S A 1991;88:7943–7.
2. Jenner AR, Rosen GD, Galaburda AM. Neuronal asymmetries in primary visual cortex of dyslexic and nondyslexic brains. Ann Neurol 1999;46:189–96.
3. Cornelissen P, Richardson A, Mason A, Fowler S, Stein J. Contrast sensitivity and coherent motion detection measured at photopic luminance levels in dyslexics and controls. Vision Res 1995;35: 1483–94.
4. Demb JB, Boynton GM, Heeger DJ. Functional magnetic resonance

imaging of early visual pathways in dyslexia. J Neurosci 1998;18: 6939–51.
5. Eden GF, VanMeter JW, Rumsey JM, Maisog JM, Woods RP, Zeffiro TA. Abnormal processing of visual motion in dyslexia revealed by functional brain imaging. Nature 1996;382:66–9.
6. Slaghuis WL, Ryan JF. Spatio-temporal contrast sensitivity, coherent motion, and visible persistence in developmental dyslexia. Vision Res 1999;39:651–68.
7. Talcott JB, Hansen PC, Assoku EL, Stein JF. Visual motion sensitivity in dyslexia: evidence for temporal and energy integration deficits. Neuropsychologia 2000;38:935–43.
8. Talcott JB, Witton C, Hebb GS, Stoodley CJ, Westwood EA, France SJ, Hansen PC, Stein JF. On the relationship between dynamic visual and auditory processing and literacy skills; results from a large primary-school study. Dyslexia 2002;8:204–25.
9. Demb JB, Boynton GM, Best M, Heeger DJ. Psychophysical evidence for a magnocellular pathway deficit in dyslexia. Vision Res 1998;38:1555–9.
10. Chase C, Ashourzadeh A, Kelly C, Monfette S, Kinsey K. Can the magnocellular pathway read? Evidence from studies of color. Vision Res 2003;43:1211–22.
11. Edwards VT, Hogben JH. New norms for comparing children's lexical and nonlexical reading: a further look at subtyping dyslexia. Aust J Psychol 1999;51:37–49.
12. Iovino I, Fletcher JM, Breitmeyer BG, Foorman BR. Colored overlays for visual perceptual deficits in children with reading disability and attention deficit/hyperactivity disorder: are they differentially effective? J Clin Exp Neuropsychol 1998;20:791–806.
13. Solan HA. Influence of varying luminance and wavelength on comprehension and reading efficiency: a brief review of three studies. J Optom Vision Dev 1998;29:98–103.
14. Solman RT, Cho HS, Dain SJ. Colour-mediated grouping effects in good and disabled readers. Ophthalmic Physiol Opt 1991;11:320–7.
15. Williams MC, Lecluyse K, Rock-Faucheux A. Effective interventions for reading disability. J Am Optom Assoc 1992;63:411–7.
16. Ray NJ, Fowler S, Stein JF. Yellow filters can improve magnocellular function: motion sensitivity, convergence, accommodation, and reading. Ann N Y Acad Sci 2005;1039:283–93.
17. Wilkins A, Sihra N, Smith IN. How precise do precision tints have to be and how many are necessary? Ophthalmic Physiol Opt 2005;25: 269–76.
18. Vidyasagar TR. Attentional gating in primary visual cortex: a physiological basis for dyslexia. Perception 2005;34:903–11.
19. Chatterjee S, Callaway EM. S cone contributions to the magnocellular visual pathway in macaque monkey. Neuron 2002;35:1135–46.
20. Carroll J, Neitz J, Neitz M. Estimates of L:M cone ratio from ERG flicker photometry and genetics. J Vis 2002;2:531–42.
21. Kremers J, Scholl HP, Knau H, Berendschot TT, Usui T, Sharpe LT. L/M cone ratios in human trichromats assessed by psychophysics, electroretinography, and retinal densitometry. J Opt Soc Am A Opt Image Sci Vis 2000;17:517–26.
22. Neitz J, Carroll J, Yamauchi Y, Neitz M, Williams DR. Color perception is mediated by a plastic neural mechanism that is adjustable in adults. Neuron 2002;35:783–92.
23. Roorda A, Williams DR. The arrangement of the three cone classes in the living human eye. Nature 1999;397:520–2.
24. Brainard DH, Roorda A, Yamauchi Y, Calderone JB, Metha A, Neitz M, Neitz J, Williams DR, Jacobs GH. Functional consequences of the relative numbers of L and M cones. J Opt Soc Am A Opt Image Sci Vis 2000;17:607–14.
25. Dougherty RF, Press WA, Wandell BA. Perceived speed of colored stimuli. Neuron 1999;24:893–9.
26. Wandell BA, Poirson AB, Newsome WT, Baseler HA, Boynton GM, Huk A, Gandhi S, Sharpe LT. Color signals in human motion-selective cortex. Neuron 1999;24:901–9.
27. Seidemann E, Poirson AB, Wandell BA, Newsome WT. Color signals in area MT of the macaque monkey. Neuron 1999;24:911–7.
28. Elliott C, Smith P, McCulloch K. British Ability Scales. 2nd ed. Chiswick, England: NFER-Nelson; 1985.
29. Castles A, Coltheart M. Varieties of developmental dyslexia. Cognition 1993;47:149–80.
30. Newsome WT, Pare EB. A selective impairment of motion perception following lesions of the middle temporal visual area (MT). J Neurosci 1988;8:2201–11.
31. Kaernbach C. Simple adaptive testing with the weighted up-down method. Percept Psychophys 1991;49:227–9.
32. Hansen PC, Stein JF, Orde SR, Winter JL, Talcott JB. Are dyslexics' visual deficits limited to measures of dorsal stream function? Neuroreport 2001;12:1527–30.
33. Brainard DH, Pelli DG, Robson T. Display characterization. In: Hornak JP, ed. Encyclopedia of Imaging Science and Technology. New York: Wiley; 2002:172–88.
34. Wandell BA. Foundations of Vision. Sunderland, MA: Sinauer Associates; 1995.
35. Brainard DH. The psychophysics toolbox. Spat Vis 1997;10:433–6.
36. Pelli DG. The VideoToolbox software for visual psychophysics: transforming numbers into movies. Spat Vis 1997;10:437–42.
37. Stockman A, MacLeod DI, Johnson NE. Spectral sensitivities of the human cones. J Opt Soc Am A Opt Image Sci Vis 1993;10: 2491–521.
38. Golz J, MacLeod DI. Colorimetry for CRT displays. J Opt Soc Am A Opt Image Sci Vis 2003;20:769–81.
39. Stone LS, Thompson P. Human speed perception is contrast dependent. Vision Res 1992;32:1535–49.
40. Cavanagh P, Tyler CW, Favreau OE. Perceived velocity of moving chromatic gratings. J Opt Soc Am A Opt Image Sci Vis 1984;1: 893–9.
41. Sperling AJ, Lu Z, Manis FR, Seidenberg MS. Selective magnocellular deficits in dyslexia: a "phantom contour" study. Neuropsychologia 2003;41:1422–9.
42. Talcott JB, Witton C, McLean MF, Hansen PC, Rees A, Green GG, Stein JF. Dynamic sensory sensitivity and children's word decoding skills. Proc Natl Acad Sci U S A 2000;97:2952–7.
43. Witton C, Talcott JB, Hansen PC, Richardson AJ, Griffiths TD, Rees A, Stein JF, Green GG. Sensitivity to dynamic auditory and visual stimuli predicts nonword reading ability in both dyslexic and normal readers. Curr Biol 1998;8:791–7.
44. Corcos E, Willows DM. The processing of orthographic information. In: Willows DM, Kruk RS, Corcos E, eds. Visual Processes in Reading and Reading Disabilities. Hillsdale, NJ: Erlbaum; 1993:163–90.
45. Chase CH. A visual deficit model of developmental dyslexia. In: Chase CH, Rosen GD, Sherman GF, eds. Developmental Dyslexia: Neural, Cognitive, and Genetic Mechanisms. Baltimore, MD: York Press; 1996:127–56.
46. Hughes HC, Nozawa G, Kitterle F. Global precedence, spatial frequency channels, and the statistics of natural images. J Cognit Neurosci 1996;8:197–230.
47. Wilmer JB, Richardson AJ, Chen Y, Stein JF. Two visual motion processing deficits in developmental dyslexia associated with different reading skills deficits. J Cogn Neurosci 2004;16:528–40.
48. Pammer K, Hansen P, Holliday I, Cornelissen P. Attentional shifting and the role of the dorsal pathway in visual word recognition. Neuropsychologia 2006;44:2926–36.
49. Cornelissen PL, Hansen PC, Gilchrist I, Cormack F, Essex J, Frankish C. Coherent motion detection and letter position encoding. Vision Res 1998;38:2181–91.

50. Stromeyer CF 3rd, Gowdy PD, Chaparro A, Kladakis S, Willen JD, Kronauer RE. Colour adaptation modifies the temporal properties of the long- and middle-wave cone signals in the human luminance mechanism. J Physiol 2000;526(Pt 1):177–94.
51. Stromeyer CF 3rd, Chaparro A, Tolias AS, Kronauer RE. Colour adaptation modifies the long-wave versus middle-wave cone weights and temporal phases in human luminance (but not red-green) mechanism. J Physiol 1997;499(Pt 1):227–54.
52. Barberini CL, Cohen MR, Wandell BA, Newsome WT. Cone signal interactions in direction-selective neurons in the middle temporal visual area (MT). J Vis 2005;5:603–21.
53. Kruger PB, Mathews S, Aggarwala KR, Yager D, Kruger ES. Accommodation responds to changing contrast of long, middle and short spectral-waveband components of the retinal image. Vision Res 1995;35:2415–29.
54. Lee JH, Stark LR, Cohen S, Kruger PB. Accommodation to static chromatic simulations of blurred retinal images. Ophthalmic Physiol Opt 1999;19:223–35.
55. Stark LR, Lee RS, Kruger PB, Rucker FJ, Ying Fan H. Accommodation to simulations of defocus and chromatic aberration in the presence of chromatic misalignment. Vision Res 2002;42:1485–98.
56. Rucker FJ, Kruger PB. Accommodation responses to stimuli in cone contrast space. Vision Res 2004;44:2931–44.
57. Rucker FJ, Kruger PB. Cone contributions to signals for accommodation and the relationship to refractive error. Vision Res 2006;46:3079–89.

Chris Chase
Claremont McKenna College
850 Columbia Avenue
Claremont, California 91711
e-mail: chris.chase@claremontmckenna.edu