

Deficits in achromatic phantom contour perception in poor readers

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Abstract

In a previous study [Sperling, A. J., Lu, Z. L., Manis, F. R., & Seidenberg, M. S. (2003). Selective deficits in magnocellular processing: A “phantom contour” study. *Neuropsychologia*, 41, 1422–1429] we found that dyslexic children were relatively slower in processing achromatic phantom contours. The maximum temporal frequency at which they could identify achromatic phantom contours was correlated with reading ability and orthographic skill in particular. Here we investigated whether similar deficits could be identified in adults. Poor readers were chosen who scored below the 25th percentile on either a standardized test of word identification or nonword pronunciation. Good readers were chosen who scored above the 40th percentile on both reading tasks. We replicated the findings of the child study: poor readers had slower processing in the achromatic version of the task, but not in the chromatic version. Achromatic performance correlated with several measures of reading and reading-related skills, including exception word reading and phonological awareness. We discuss the possibility that the deficits may indicate impairment in noise exclusion that is more readily apparent at higher temporal frequencies.

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1. Introduction

According to the majority of researchers, the fundamental deficit in developmental dyslexia is impaired representation or processing of phonological information (Rayner, Foorman, Perfetti, Pesetsky, & Seidenberg, 2001; Stanovich & Siegel, 1994; Wagner & Torgesen, 1987). Although this concept has gained widespread acceptance, there is less agreement about the underlying cause of these phonological impairments. The search for such a cause has led to renewed interest in the possible contribution of visual processing deficits to the etiology of dyslexia. The possibility has generated considerable debate, because visual processing deficits appear unrelated to the phonological deficits that are prominent in dyslexia and have been the focus of research. Moreover, this research seems a return to earlier, discredited visual deficit theories (Velluntino, 1979).

Nonetheless there is a steadily growing body of evidence that in many cases, dyslexia may be associated with a deficit in

visual processing, particularly sensitivity to luminance contrast and motion perception (Demb, Boynton, & Heeger, 1998; Eden et al., 1996; Lovegrove, Bowling, Badcock, & Blackwood, 1980; see Stein, 2001 for review). Such tasks have been chosen due to evidence of their preferential association with the magnocellular stream (Merigan & Maunsell, 1993; Schiller & Malpeli, 1978).

This research, although suggestive, raises many questions. If there is a visual deficit in at least some dyslexics, is it specific to the magnocellular channel? How would such a deficit create the impairments seen in dyslexic reading? Does this impairment cause reading impairments, or is it a causally unrelated symptom of a more language-specific neurological impairment? Much of the debate has centered on inconsistent findings and questions about the methods used by researchers to identify magnocellular processing. Several studies failed to replicate psychophysical findings of visual magnocellular impairments in dyslexia (e.g., Amitay, Ben-Yehudah, Banai, & Ahissar, 2002; Hayduk, Bruck, & Cavanagh, 1996; Ramus et al., 2003; Vanni, Uusitalo, Kiesila, & Hari, 1997; Williams, Stuart, Castles, & McAnally, 2003) and some researchers have asserted that due to the demanding nature of most psychophysical paradigms and the usual lack of definitive parvocellular control conditions, lower attentional

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vigilance could account for the difference between dyslexic and non-dyslexic participants (Ramus, 2003; Skottun, 2000; Stuart, McAnally, & Castles, 2001). Such an explanation is particularly plausible since attention deficits are frequently co-morbid with dyslexia (Willcutt & Pennington, 2000). Moreover, the effects in some studies were carried by subsets of subjects, suggesting considerable heterogeneity (e.g., Borsting et al., 1996; Demb et al., 1998; Sperling, Lu, Manis, & Seidenberg, 2003). At the same time, both supporting and non-replicating studies vary greatly in the ages of their participants (e.g., children versus adults), in whether their reading abilities (especially phonological abilities) were thoroughly evaluated at the time of testing, and in whether other conditions such as attention deficits had been assessed. Even the criteria by which individuals were identified as dyslexic have varied considerably, with the range of reading delay in these studies spanning as much as 4 years.

In a recent study (Sperling et al., 2003) we investigated the existence of magnocellular impairments in dyslexic children ranging in age from 10 years, 9 months to 13 years, 8 months, using an experimental paradigm that addressed some of the major points of methodological concern. Reading performance of the participants (all of lower-middle to middle socioeconomic status), was assessed with a battery of phonological, orthographic, and cognitive tests. The psychophysical procedures were designed to provide comparable evaluations of magnocellular-type (M) and parvocellular-type (P) processing using an identical task structure, based on a method developed by Rogers-Ramachandran and Ramachandran (1998) to differentiate between components of the visual system that process boundaries and surface features. Their stimuli consisted of two adjacent counter-phase panels of dots. During the experiment, the dots reversed phase polarity. At high reversal frequencies, the phase of individual dots could no longer be determined, but a “phantom contour” could be perceived demarcating the boundary between the panels, which allowed the observer to identify whether the panels were arranged vertically or horizontally.

Above an observer’s reversal threshold, the phantom boundary disappeared. Observers had significantly higher (faster) threshold frequencies when low luminance black and white dots were used, than when isoluminant red and green dots were used. According to Rogers-Ramachandran and Ramachandran (1998), the low luminance black and white dots activated fast-acting, boundary-extracting processes that are usually thought to be more characteristic of magnocellular-type processing, whereas the isoluminant red and green dots activated slower, surface- and color-sensitive processes more characteristic of parvocellular-type processing. Other investigations of magnocellular processing have been conducted with variants of phantom contour paradigms, including studies of glaucoma patients (Simpson & Flanagan, 1992) and young children (Barnard, Crewther, & Crewther, 1998).

In order to make our own experiment more interesting for children, our stimuli consisted of four simple shapes, composed of dots in the figure and background (Fig. 1). As in Rogers-Ramachandran and Ramachandran (1998), the only difference between the two versions of our experiment was a shift from low luminance black and white dots in the achromatic version to individually calibrated isoluminant red and green dots in the chromatic version. Thus the methods for assessing performance were comparable in all respects except the critical stimulus properties.

Data analyses revealed that dyslexic children had significantly slower flicker threshold frequencies than non-dyslexic children on the achromatic but not the chromatic version of the task. As expected, nearly all participants had slower flicker frequencies at threshold for the chromatic version than for the achromatic version, as the former activated predominantly slow-acting parvocellular processing. Moreover, achromatic thresholds, and not chromatic, were correlated with basic reading ability (as measured by the Woodcock Word Identification test; Woodcock, McGrew, & Mather, 2001). Of all our reading tests, performance on Orthographic Choice (participants

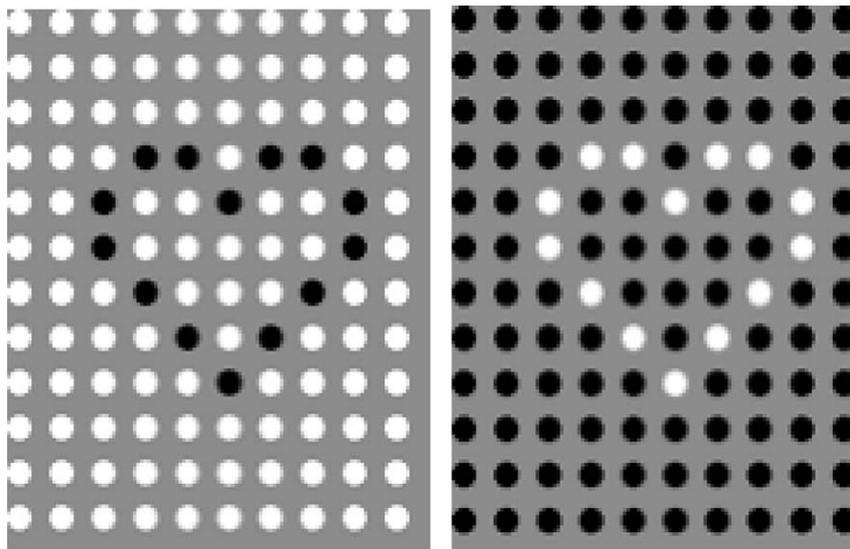


Fig. 1. Counter-phase “heart” dot image used in the achromatic version. The dots were red and green in the chromatic version.

choose between a correctly spelled word, such as RAIN, and a pseudo-homophone such as RANE) was the test most strongly correlated with achromatic threshold. The link between achromatic thresholds and orthographic skill is in line with a recent, growing body of similar evidence (Cornelissen & Hansen, 1998; Cornelissen et al., 1998; Talcott et al., 2000; Witton et al., 1998). An unexpected finding, however, was that those dyslexic children who performed most poorly on the achromatic version had *higher* scores on our test of nonword reading (and therefore better phonological skills) than those dyslexic children who had normal achromatic thresholds ($p < 0.05$). Allowing the interpretation that the achromatic stimuli were mainly processed mainly by the magnocellular pathway, the latter finding casts doubt on the hypothesis that visual magnocellular deficits in dyslexia are part of a pan-sensory deficit in rapid, temporal processing which affects both phonological processing and visual magnocellular perception (Farmer & Klein, 1995; Stein, 2001; Tallal, 1980; Tallal, Miller, & Fitch, 1993). Therefore, our initial findings suggested that the maximum temporal frequency for achromatic phantom contours is related to reading and orthographic skill, with little or no connection to phonological processing.

Our initial study employed the phantom contour paradigm to evaluate achromatic and chromatic phantom contour processing in dyslexia. We therefore asked whether the findings would be replicated in a different population, adult good and poor readers. Replication is especially important given the history of non-replications in the literature on visual impairments, and because of the need for further research to understand the cause of the deficits found in dyslexic children. We therefore conducted the phantom contour experiment with adults, using the same paradigm as before, and employing a battery of reading and cognitive tests to evaluate both phonological and orthographic processing.

2. Methods

2.1. Participants

Fifty-nine participants were recruited from the University of Southern California; all were students at the university. They were recruited through advertisements that specified fluency in English, and either normal reading abilities or a history of reading problems. Informed consent was obtained from all participants, and participants received course credit or a small payment for their participation. Testing procedures were approved by the University's Internal Review Board.

2.2. Reading and cognitive tests

2.2.1. Standardized reading and cognitive tests

All reading and cognitive tests were run under photopic conditions in a dedicated room at USC. In order to evaluate reading ability, we administered the Letter-Word Identification and Word Attack tests of the Woodcock–Johnson Tests of Achievement—III (Mather & Woodcock, 2001a). The first assesses word identification skill (single word reading) and the second phonological decoding (reading nonwords). Non-verbal and verbal cognitive ability were evaluated with, respectively, Spatial Relations (a non-verbal test of visual-spatial thinking) and the Verbal Comprehension composite (Picture Vocabulary, Synonyms, Antonyms, Analogies) tests of the Woodcock–Johnson Tests of Cognitive Abilities—III (Mather & Woodcock, 2001b). In order to be classified as poor readers, participants had to score below the 25th percentile on either Word Identification or Word Attack, with standardized scores of at least 85 on both

the Spatial Relations and Verbal Comprehension tests (within a standard deviation of the national mean). The 25th percentile cut-off corresponds to a standard score of 90. The criteria were chosen to focus on the core reading deficits associated with poor reading and dyslexia—that is, phonological decoding and word recognition (Stanovich & Siegel, 1994; Wagner & Torgesen, 1987). Although some studies use word identification measures as the sole criterion for defining reading problems and/or dyslexia in adults, we used nonword pronunciation as well because evidence suggests that compensated dyslexic adults can attain normal levels of performance in terms of accuracy of word recognition, but perform poorly as a group on tests of nonsense word reading (Bruck, 1990; Pennington & Lefly, 2001). Adult poor readers who enter university may be even more likely to have been able to compensate for the word reading impairment. All participants were queried about their reading history. Twenty-seven participants met the criteria for the poor reader group, and many stated that they had a childhood history of reading problems. Although our criteria closely follow those used to identify individuals as dyslexic, not all individuals reported childhood reading problems, and not all showed severe deficits in word or nonword reading, or discrepancies between reading and cognitive ability scores, as is typically seen in cases of uncompensated dyslexia. Hence, we decided to refer to this group using the less specific label of *poor* readers rather than *dyslexic* readers. Good readers needed to score above the 40th percentile on both Word Identification and Word Attack, and at least 85 on the cognitive ability tests. Thirty-two participants met these criteria.

2.2.2. Additional reading tests

In addition to the standardized tests, we administered several tests to further evaluate phonological and orthographic processing. For phonological processing, we created an adult version of a two-alternative forced-choice paradigm called Phonological Choice (developed for children and adolescents by Olson, Forsburg, Wise, & Rack, 1994), consisting of 60 trials. Participants had to choose which of two nonwords was a pseudo-homophone for a real word (e.g., PHUMBLE versus TEMBLE). The words remained on the screen until participants made their decision, and participants were instructed to choose as quickly as they could without making mistakes. For orthographic skill, we included Exception Word reading (70 items along a gradient of increasing orthographic complexity and decreasing frequency, with a presentation format similar to that of Word Identification: e.g., eye...depot...anemone), as well as an adult version of the Orthographic Choice test, which requires participants to decide which of two printed stimuli, a word or a pseudo-homophone (e.g., RAIN versus RANE) was a correctly spelled word (60 trials). A Homonym Choice test, in which participants first read a question and then selected which of two homophones answered the question (e.g., “which has 7 days? WEEK versus WEAK), was also used (60 trials). Participants were instructed to respond as quickly as possible without making mistakes. Owing to procedural changes, Homonym Choice and Phonological Choice were added to the reading battery in the second semester of testing. As a result, we collected data for the latter two tasks from 19 of the good readers and 17 of the poor readers, or approximately 60% of the sample. Responses for all three Choice tests were recorded via a button box, modified to record reaction time within ± 2 ms. All Choice tests, as well as the phantom contour paradigm, were programmed using Matlab 5.2, with Psychtoolbox extensions (Brainard, 1997).

2.3. Phantom contour paradigm

The task was run with the lights turned off to eliminate ambient luminance as much as possible. The basic experimental set-up and procedures were similar to those used in the child study (Sperling et al., 2003), with a few modifications. The experiment was again run on a Macintosh G4 computer with a Radius Thunder color graphics card installed to allow greater color resolution (10 bits per gun). Stimuli were displayed on an Apple Multiple Scan 720 monitor, with a resolution of 640×480 pixels. In both the achromatic and chromatic conditions, the background was a uniform gray (13.7 cd/m^2 —a change from 12.7 cd/m^2 in the child study) and the dots were of a uniform cone contrast (9%) in DKL color space (Derrington, Krauskopf, & Lennie, 1984). The low luminance of the background gray level was chosen to minimize contrast and luminance, so as to maximize magnocellular response (Demb et al., 1998). The original four shapes were used (heart, fish, boat, and rocket). Participants sat 54 cm away from the monitor. Individual dots subtended an area of approximately

0.58° × 0.58° visual angle, and the entire image subtended 12.4° × 10.4° visual angle.

A handful of children had nearly reached ceiling performance in the child study, so to prevent potential ceiling effects we raised the monitor refresh rate from 60 Hz to 75 Hz, increasing the maximum reversal rate. To prevent identification based on the first and/or last frame, on every trial, a brief mask preceded and followed the presentation of the target shape. The mask consisted of a random assortment of phase-reversing dots. Each trial followed the same presentation: mask (five phase reversals); shape (six reversals); mask (five reversals). Every session began at a relatively slow rate of 7.5 reversals per second. Participants verbally reported which shape they saw and the experimenter pressed one of four coded keys, followed by auditory feedback. A two-up/one-down staircase was used to estimate the threshold frame rate (frequency): after two consecutive correct trials, the duration of each image frame would decrease by one screen refresh, and after every single incorrect trial, the duration of each image frame increased by one screen refresh, creating successive frequencies of, approximately, 7.5 Hz, 9.4 Hz, 12.5 Hz, 18.8 Hz, and 37.5 Hz. The staircase enabled a determination of the reversal rate at which participants could perform the task at 70.7% correct (Levitt, 1971). Although the staircase procedure was used in data collection, the thresholds were estimated via an interpolating procedure. Specifically, Weibull functions (Weibull, 1951) were fit to the psychometric functions using a maximum likelihood procedure; thresholds were then calculated from the Weibull functions. The method interpolated the data measured at all the frequencies used in the experimental setup and allowed good estimates of thresholds between those frequencies.

The achromatic version had 60 trials, and all participants completed it first. In order to ensure isoluminance for each participant, the chromatic version consisted of a “minimum performance” calibration (Lu & Sperling, 2001). During the calibration procedure, participants ran four to five blocks of 32 trials. The experimenter added luminance to the red dots while subtracting an equal amount of luminance from the green dots – or the reverse – producing luminance contrast that ranged from –4% to +4%. Each block of calibration trials was performed with a different amount of luminance added/subtracted, and these values were presented in varying orders to each participant. The experimenter then determined the isoluminance point for each individual by selecting the luminance level at minimum performance. Participants then re-ran the staircase procedure at this calibrated level (one block of 40 trials), and the overall threshold frequency was computed using both the calibration trial and the “new” staircase trials, again discarding the first three staircase reversals. Data from the non-isoluminant calibration trials were removed from further analyses.¹

3. Results

3.1. Reading and cognitive test scores

Table 1 shows the reading and cognitive scores for the good and poor readers. Exception Word scores represent the mean number of correctly pronounced words out of 70. Scores on the Phonological Choice, Orthographic Choice and Homonym Choice tasks were converted to d' values (Green & Swets, 1966) in the following manner: correctly choosing the target when it appeared on the left side of the screen was considered a hit, whereas incorrectly choosing the foil when it appeared on the left side of the screen was considered a false alarm. The d' values

¹ Performance of the achromatic task prior to the chromatic task was unlikely to result in practice effects for the latter, because while the P channel responds to isoluminant flicker, the M channel is much more highly sensitive at the luminance and contrast levels chosen. During calibration, it might appear that participants performed many more trials of the chromatic version than the achromatic version. However, most of the calibration trials were achromatic trials because the achromatic system is much more sensitive and most of the calibration stimuli were not completely isoluminant.

Table 1
Reading and cognitive scores (means and standard deviations)

	Good readers; <i>N</i> = 32	Poor readers; <i>N</i> = 27
Age (years; months)	21; 5 (3; 2)	20; 8 (1; 6)
WJ – III tests of achievement – standard scores		
Letter-word ID	108 (7.5) ^b	94 (6.4)
Word attack	103 (6.2) ^b	84 (4.3)
WJ – III tests of cognitive abilities – standard scores		
Verbal comprehension	104 (9.5) ^a	97 (7.5)
Spatial relations	109 (10.6) ^a	102 (8.8)
Additional tests		
Phonological choice (d')	3.6 (0.5) ^b	2.6 (0.7)
Orthography Composite (d')	3.4 (0.4) ^a	2.8 (0.4)
Exception words (<i>f</i> 70)	63 (2.7) ^b	57 (3.4)

^a $p < 0.01$.

^b $p < 0.001$.

were calculated according to the following formula:

$$d' = Z\text{-score (hits)} - Z\text{-score (false alarms)}$$

Values for the Orthographic and Homonym Choice tests were combined to provide an Orthographic Composite score.

Poor readers were significantly worse than good readers on tests of general reading ability, phonological processing, and orthographic skill (p -values for t tests were all < 0.01). Response latencies were not correlated with accuracy for any of the computer-based choice tasks ($p > 0.10$). All poor readers met the cognitive ability criteria; however, they were significantly worse than the good readers on Verbal Comprehension and Spatial Relations ($p < 0.01$). The degree to which Verbal ability scores can be considered independent from reading experience, however, has been called into question (the Matthew effect: Stanovich, 1986, 1993). Although there was a difference between the groups on Spatial Relations, the poor reader group's mean on Spatial Relations was higher than the national norm, and scores on this test were not correlated with either of the phantom contour scores ($p > 0.05$).

3.2. Performance on phantom contour task

In light of the exponential spacing of the flicker frequencies in the task, logarithmic transformations of the frequencies were used for the following analyses. The overall main effect of version (achromatic versus chromatic) was significant, $F(1, 56) = 354.0$, $p < 0.0001$. Both groups had higher average threshold frequencies in the achromatic version than in the chromatic version. The overall main effect of reading group was not significant, $F(1, 56) = 2.64$, $p > 0.05$, nor was the interaction of reading group and version significant, $F(1, 56) = 2.76$, $p > 0.05$. The simple main effect of reading group on threshold frequency in the achromatic version was significant, $F(1, 57) = 5.87$, $p < 0.02$ (see Fig. 2). Poor readers had significantly slower threshold frequencies than good readers on this task (good readers: 25.2 Hz; poor readers: 22.1 Hz). The effect size of the group difference was medium (Cohen's $d = 0.61$). The simple main effect of reading group on average threshold frequency in the chromatic ver-

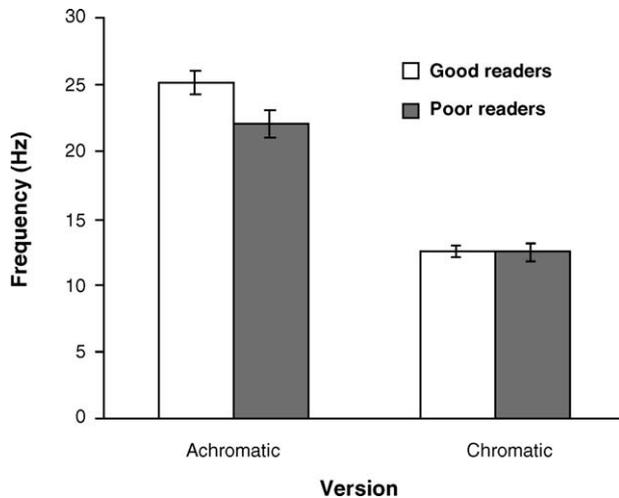


Fig. 2. Achromatic and chromatic thresholds for good readers and poor readers.

sion was not significant, $F(1, 56) = 0.15, p > 0.70$ (good readers: 12.5 Hz; poor readers: 12.4).

3.3. Relationships between reading scores and visual processing

Table 2 provides Pearson correlation coefficients for the entire sample, as well as the separate reading groups. Collapsed across groups, threshold frequency in the achromatic version correlated significantly with Word Identification score, $r(59) = 0.37, p < 0.01$, replicating the finding of the Sperling et al. (2003) study, and with a measure related to orthographic skill, Exception Word Reading, $r(59) = 0.51, p < 0.001$. Unlike the child study, however, achromatic threshold frequency was not correlated with the orthographic composite scores, $r(34) = 0.29, p < 0.10$, though it is worth noting that approximately 15 people performed at or near ceiling on Orthographic Choice and 7 on Homonym Choice. Achromatic threshold frequency was not correlated with response latency on the Orthographic Choice, Homonym Choice or Phonological Choice tasks ($p > 0.05$). Achromatic threshold frequency was corre-

lated with Word Attack score, a measure of phonological processing, $r(59) = 0.38, p < 0.01$, although not significantly with Phonological Choice ($p > 0.05$). In addition, achromatic threshold frequency was correlated with the measure of verbal ability (Verbal Comprehension) $r(59) = 0.45, p < 0.001$. The results all point toward a relationship between achromatic task performance and general reading and/or verbal ability. Chromatic threshold frequency (but not achromatic threshold frequency) was weakly correlated with Spatial Relations, $r(58) = 0.27, p < 0.05$, and more strongly with achromatic threshold frequency, $r(58) = 0.36, p < 0.01$, the latter of which probably reflects largely common method variance.

Analyses of the two reading groups further clarify the nature of the correlations. The correlation between achromatic threshold frequency and Exception Word Reading was driven chiefly by the poor reader group, $r(27) = 0.42, p < 0.05$, as was the correlation with Word Identification, although this was marginal, $r(27) = 0.31, p = 0.12$. The correlation with Verbal Comprehension was driven more by the good reader group, $r(32) = 0.36, p < 0.05$, although there was a marginal correlation among the poor readers as well, $r(27) = 0.35, p < 0.08$.

In light of our previous findings that processing in the achromatic task was strongly correlated with orthographic ability in children (Sperling et al., 2003), we examined the relationship between adult achromatic threshold frequency and the orthographic skills required for Exception Word Reading. We also examined the relationship between achromatic processing and Word Attack scores, to determine whether achromatic processing was related to the severity of phonological decoding deficits in poor reading and dyslexia. A series of hierarchical regressions was conducted on the entire sample. Although the correlations make it clear that achromatic frequency is related to Exception Word Reading, it was also related to Word Attack and Verbal Comprehension. Hence, it was important to determine whether the relationship with Exception Word Reading was distinct from verbal ability and phonological decoding skill. In the first set of regressions, Word Identification and Verbal Comprehension were entered together on the first step, and accounted for 63% of the variance in Exception Word Reading, $F(2, 57) = 52.5$,

Table 2
Correlations between threshold frequencies (log) and reading/cognitive scores

	Good readers		Poor readers		Combined sample	
	Achromatic	Chromatic	Achromatic	Chromatic	Achromatic	Chromatic
Chromatic	0.22		0.44*		0.36**	
LWID	0.060	0.004	0.31	0.10	0.33**	0.073
Wd. attack	0.021	0.26	-0.056	0.34	0.26*	0.18
Verbal	0.36*	-0.070	0.35	0.34	0.41***	0.13
Spatial	0.14	0.43*	-0.099	0.14	0.14	0.27*
Ph. choice	-0.037	-0.080	0.17	-0.15	0.31	-0.15
Orth comp	-0.27	-0.21	0.037	0.17	0.21	0.20
Excepts	0.13	0.22	0.42*	0.23	0.42***	0.20

LWID: Letter-Word Identification; Wd. attack: Word Attack; Verbal: Verbal Comprehension; Spatial: Spatial Relations; Ph. choice: Phonological Choice; Orth comp: Orthographic Composite; Excepts: Exception Word Reading.

* $p < 0.05$.

** $p < 0.01$.

*** $p < 0.001$.

$p < 0.001$. Achromatic threshold frequency was added on the second step, increasing the total variance explained to 68%, $F(3, 56) = 38.4$, $p < 0.001$. The variance accounted for by achromatic threshold frequency when both Word Identification and Verbal Comprehension had been controlled was thus 5%, $t(56) = 2.03$, $p < 0.05$. Achromatic threshold frequency also accounted for variance in Exception Word Reading when Word Attack was substituted for Word Identification in the first step of the regression, although this was marginal $t(56) = 1.87$, $p = 0.07$.

Additional regressions were conducted with Word Attack or Word Identification as the dependent measures. Although achromatic threshold frequency was correlated with Word Attack and Word Identification (see Table 2), it did not account for variance in Word Attack independent of Verbal Comprehension, nor for variance in Word Identification independent of Verbal Comprehension. Thus the reading task to which achromatic threshold frequency was most strongly and uniquely related was Exception Word Reading.

4. Discussion

4.1. Similarities and differences between adults and children

In this study we analyzed how reading skills related to the kinds of visual processing engaged by the phantom contour task. The results replicated the main findings we observed in children age 10–14 (Sperling et al., 2003). Although both good and poor readers had faster flicker thresholds with low luminance achromatic dots than with isoluminant chromatic dots, poor readers had slower flicker thresholds than good readers on the achromatic version, and not the chromatic version.

The analysis of how such visual processing relates to particular reading skills differed somewhat in this study from the findings in the child study, in which achromatic threshold frequency was moderately positively correlated with Orthographic Choice scores, but negatively correlated with Nonword Reading, a measure of phonological processing (Sperling et al., 2003). In the current study, achromatic threshold frequency was correlated with both Exception Word Reading scores and Word Attack scores, but with neither Orthographic/Homonym Choice scores nor Phonological Choice Scores. In addition, in adults, achromatic threshold frequency was correlated with Verbal Comprehension. It appears that magnocellular processing was more related to general reading skill in the adult sample than in the child sample.

It is difficult to explain differences between the child and adult results, as the participants involved differed in several respects. First, the children were selected from a broader population (all elementary school readers) than the adults (students at a university). Possibly, the adults were better at compensating for a reading difficulty than the average poor reader (who may not attend college). Second, it is likely that individuals with more severe reading deficits were included in the child sample. Third, and perhaps most importantly, there may be genuine developmental changes in the relationships of reading measures to each other and to measures of visual processing over time, so that a

processing deficit may initially have a more narrow effect that eventually broadens in impact. Taken together, these differences in the samples make it possible that areas of reading dysfunction (e.g., orthographic and phonological skill) may have been more distinct in the child sample than the adult sample.

4.2. Magnocellular versus perceptual integration deficits

The experimental paradigm does not allow one to follow the exact progress of percepts within the magnocellular or parvocellular streams. Evidence concerning the types of stimuli that activate magnocellular and parvocellular processing mechanisms, however, suggests the achromatic version favors M-type processing and the chromatic version favors P-type processing. Given that the only difference between the two versions of the task was a switch from black and white dots to red and green dots (achromatic to chromatic displays), our task allowed for a well-controlled and equal evaluation and comparison of visual processing under both achromatic and chromatic conditions.

Fig. 3 illustrates two alternative explanations of our results. According to both alternatives, the signal is first processed by the M or P channel, depending on the nature of the stimulus, which then passes information to a higher cortical area that identifies the shape, leading to a decision. Fig. 3a depicts normal conditions, in which parvocellular processing is slower than magnocellular processing. One interpretation of the relationship between magnocellular processing deficits and poor/dyslexic reading is illustrated in Fig. 3b. Here the locus of the deficit is the M channel itself. Either inefficient or impaired magnocellular processing results in compromised signals getting passed to higher cortical areas, which must then make a decision based on imprecise perceptual information. Thus, in poor readers, the magnocellular channel is impaired, which leads to their poor performance on the achromatic version of the task. This alternative is not fully satisfactory, however, because it does not explain why there would be a connection to reading ability (and by extension, dyslexia).

A second alternative is illustrated in Fig. 3c. By design, the phantom contour task requires individuals to detect the borders of a shape in a perceptually noisy environment. If identification is based on noisy input, the required integration of borders necessary for proper shape recognition could be adversely affected by the degree to which an individual has difficulty recognizing the relevant signal and discarding the irrelevant noise. Given that the achromatic version has the potential to reach faster frequencies at threshold whereas the chromatic version is naturally restricted to slower frequencies, the limiting stage in the chromatic version is parvocellular processing, while the limiting stage in the achromatic version is shape identification. Shape detection would be susceptible to the cumulative effects of noisy input and poor noise exclusion. In the chromatic version, people likely cannot perform substantially worse than they already do. The group difference would then only be detectable in the achromatic version, where there is greater potential for variability across individuals. Thus, the locus of the deficit could be in a stage of processing involving noise exclusion, rather than the magnocellular channel itself. Many previous results

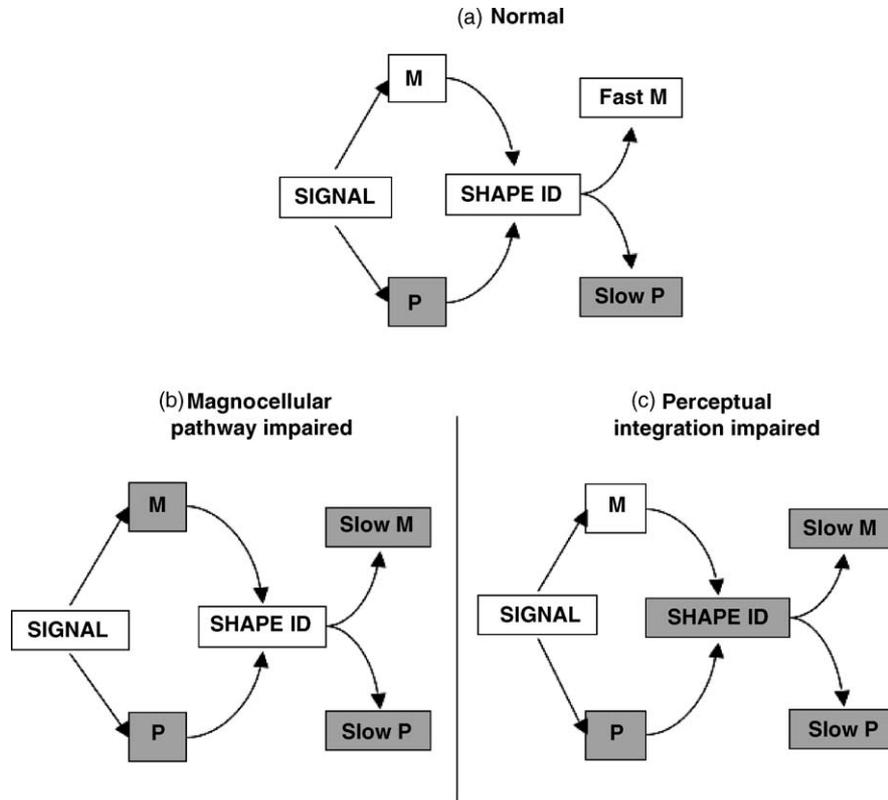


Fig. 3. (a)–(c) Models of the potential loci of the achromatic phantom contour perception deficits. Deficit/slower processing is represented by shading. 3(a) depicts normal visual processing, with P (parvocellular) processing naturally slower than M (magnocellular) processing. In (b), the classic magnocellular theory, there is a deficit in the M stream. As a result, the M processing is selectively slower. In the alternative model in (c), the deficit is considered to be primarily in perceptual integration/shape recognition, which occurs in higher cortical areas (represented here as “Shape ID”). Although the P stream is considered, even under normal conditions, “impaired” relative to the M stream, since the P stream signal is already approaching floor performance, only the M stream signal is noticeably affected by the deficit in shape recognition.

can be re-interpreted in terms of the noise level of the task, rather than whether the task involved predominantly the magnocellular or parvocellular channel. This hypothesis predicts that with noisy stimuli in a parvocellular processing task, we would identify deficits in parvocellular-type processing. That is exactly what we found in a recent contrast sensitivity study in children (Sperling et al., 2005): deficits in both magnocellular and parvocellular processing only in the presence of high external noise.

4.3. Variable influences on reading and language skills

Whether directly or indirectly, the deficit responsible for poor achromatic threshold frequency appears tied to deficits in the encoding of letters and letter patterns (orthographic skill). One answer to the second question above, why achromatic threshold frequency was also correlated with a measure of phonological processing in adults, but not in children, is based on the normal manner in which children learn to read. Could deficits that impair the ability to categorize letters or appreciate sequential redundancies have increasing effects on phonological representations over time? Harm and Seidenberg simulated this possibility as part of a larger analysis of their connectionist reading model (Harm & Seidenberg, 1999), based in part on the concept that the relationship between segmental phonological representa-

tion and reading experience is reciprocal (Morais, Alegria, & Content, 1987). They cited evidence from literacy studies that the development of segmental phonological representations is, in part, the result of learning to read an alphabetic orthography, because illiterate individuals cannot segment spoken words into phonemes as well as literate individuals (Morais, Bertelson, Cary, & Alegria, 1986), if at all. Segmental phonological representations tend not to develop fully in the absence of detailed orthographic information. Thus, deficits that affect the processing or representation of orthographic information could, over time, have a negative impact on phonological skill. The resulting relationship between the visual deficit and phonological skill might not be detectable until adulthood. The idea that age could partly account for variable influences of perceptual processing on reading and language skills is in line with a recent study by Wright and Zecker (2004). The authors suggested that neurological development may be at first delayed and then halted after the onset of puberty in children with learning problems, and the influence of puberty may not be the same for all cognitive and linguistic skills. Thus, a given deficit – in this case, noise exclusion – may have an impact on different tasks at different points in development.

Noise exclusion deficits could potentially also impair phonological processing, and subsequently, other aspects of reading, through the mechanisms of speech perception. Dyslexic chil-

dren and other poor readers, particularly those with language impairments, appear to have difficulty perceiving phoneme categories in infancy (Leppänen et al., 2002), as well as at later ages (Brady, Shankweiler, & Vann, 1983; Joanisse, Manis, Keating, & Seidenberg, 2000; Tallal et al., 1993). The process of forming perceptual categories for phonemes, broadly speaking, involves discrimination of signal from noise – that is, recognizing salient similarities and differences between phonemes. Deficits in noise exclusion could thus result in weaker phoneme boundaries and/or non-optimal perceptual templates for phonemes. Within Harm and Seidenberg's (1999) simulation, phonological deficits of this type had a cascading effect on both word and nonword reading, and when the phonological deficits were severe, the effect extended to exception word reading.

The main finding to stress in the current study is that in an equal evaluation of achromatic and chromatic versions of the phantom contour paradigm, adult poor readers, like the dyslexic children in the previous study, were impaired on the achromatic version. Although adult poor readers do perform better than dyslexic children, they exhibited a deficit relative to age-matched, non-impaired adults. Perceptual processing deficits may exert a dynamic influence in the etiology of poor reading and dyslexia, impacting the reciprocal links that build between orthography, phonology and general language ability.

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