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The effect of contrast on reading speed in dyslexia

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Abstract

Contrast coding has been reported to differ between dyslexic and normal readers. Dyslexic readers require higher levels of contrast to detect sinewave gratings for certain spatiotemporal conditions, and dyslexic readers show faster visual search at low contrast. We investigated whether these differences in early contrast coding generalize to reading performance by measuring reading speed as a function of text contrast for dyslexic children and adults and for age-matched controls. Contrast affected reading performance of dyslexic and normal readers similarly. For both groups, reading speed was relatively constant between 100 and 2% contrast, and decreased rapidly below 2% contrast. This pattern of results held true for both children and adults, for text with and without sentence context, across a range of character sizes, and for reading aloud and reading silently. We conclude that earlier findings of group differences in contrast effects on grating detection or visual search tasks do not generalize to reading.

Keywords: Dyslexia; Contrast; Reading

1. Introduction

Developmental dyslexia[1] is defined as decreased reading ability relative to intelligence in the absence of neurologic disorder, sensory impairment or inadequate schooling (DSM-IV, 1994). Recent research has emphasized the importance of phonological skills in normal reading acquisition (e.g. Bradley & Bryant, 1983; Muter, Hulme, Snowling & Taylor, 1997), and has documented the impairment of these skills in dyslexic readers (e.g. Manis, Custodio & Szeszulski, 1993). In addition, many studies have found visual factors that differentiate dyslexic from normal readers, including sensitivity to contrast, flicker and motion. Contemporary theories of developmental dyslexia suggest that both phonetic and visual etiologies may exist as separate subtypes within the dyslexic population (Lovett, 1987; Castles & Coltheart, 1993; Manis, Seidenberg, Doi, McBride-Chang & Petersen, 1996). The question remains as to whether the visual anomalies can explain the reading deficits.

In this study we address the role of contrast processing in the reading performance of dyslexics. Many dyslexics show contrast sensitivity deficits under various spatiotemporal conditions although there are discrepancies in the literature (Lovegrove, Bowling, Badcock & Blackwood, 1980; Lovegrove, Martin, Bowling, Blackwood, Badcock & Paxton, 1982; Martin & Lovegrove, 1984, 1987; Gross-Glenn, Skottun, Glenn, Kushch, Lingua, Dunbar et al., 1995; Borsting, Ridder, Dudeck, Kelley Matsui & Motoyama, 1996). According to a recent review (Skottun, 2000), the greatest contrast-sensitivity differences between dyslexic and normal readers are found at medium to high spatial frequencies (> 2 c/deg) and at high temporal frequencies (20 Hz).

It is unclear what role contrast sensitivity deficits might play under normal reading conditions. Spatial frequencies above 2 c/deg are important for recognizing letters smaller than 1° (Legge, Pelli, Rubin & Schleske, 1985; Legge, Rubin & Luebker, 1987), but there is no evidence that this character size establishes a boundary between good and poor reading in dyslexia. Fixation durations in reading average about 250 ms (e.g. Rayner

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[1] The terms 'dyslexia' and 'reading disability' are considered here as interchangeable. DSM-IV refers to the condition as 'reading disorder', but notes that it is also referred to as 'dyslexia'.

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& McConkie, 1976) corresponding to a temporal frequency of only 4 Hz, much lower than the temporal frequencies (20 Hz) at which the largest contrast-sensitivity deficit is observed. Also, in most of the studies that revealed contrast-sensitivity deficits, the mean luminance was considerably lower than the recommended 55–138 cd/m^2 for reading in classrooms (Kaufman, 1987). The study that most closely matches the temporal frequency and luminance normally used for reading is that of Martin and Lovegrove (1984), in which sinewave gratings were presented for 350 ms with an illumination of 100 cd/m^2. Their group of dyslexic readers was less sensitive to contrast than normal readers with gratings between 1 and 8 c/deg, but the deficit was small compared with the contrast-sensitivity deficits at a lower illumination condition.

Despite the numerous studies reporting a contrast sensitivity deficit in dyslexia, it is difficult to establish a direct link between contrast sensitivity and dyslexic reading performance. Contrast-sensitivity deficits are not perfectly correlated with the presence of reading problems: while some studies estimate that these deficits occur in as many as 70% of dyslexics (Lovegrove, Martin & Slaghuis, 1986), other studies fail to find group differences in contrast sensitivity (e.g. Cornelissen, Richardson, Mason, Fowler & Stein, 1995; Walter-Müller, 1995), indicating that the actual incidence may not be this prevalent. Few studies have measured the effect of contrast on reading performance in dyslexia.

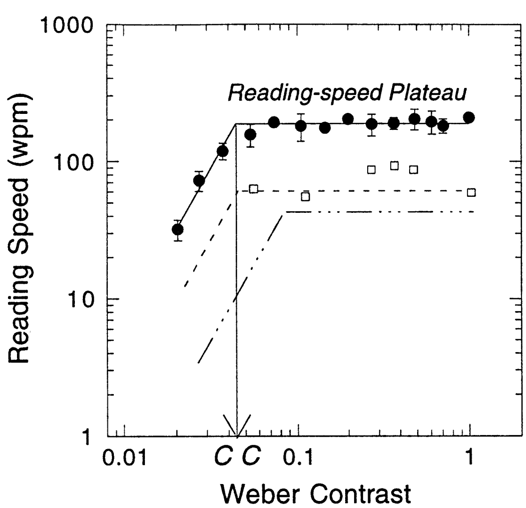

Fig. 1. Sample of reading speed data across contrast for one control participant from Study 1. The data were fit with a two-limb function (solid line). The contrast at the point of intersection of the two limbs is considered the 'critical contrast' (CC). Dashed line with open squares represents the predicted outcome according to the hypothesis of improved performance at intermediate contrast. Hatched line represents the predicted outcome according to the increased contrast threshold hypothesis (i.e. a rightward shift in the reading speed-versus-contrast curve would be expected).

How does reading speed of normal observers depend on contrast? In general, the dependence of reading speed on contrast is described by a curve that decreases gradually (less than a factor of two) over a 10-fold reduction in contrast, then decreases more rapidly at lower contrasts (see Fig. 1). Legge et al. (1987; Legge, Parish, Luebker & Wurm, 1990) observed that the contrast below which reading performance deteriorated rapidly was dependent on print size, but that this dependency is explained by different contrast thresholds that occur with different print sizes. Accordingly, if dyslexic readers have higher contrast thresholds than normal readers, but are otherwise similar in terms of visual processing, their reading-speed-by-contrast curves would be expected to have the normal shape, but be shifted rightward along the contrast axis by a scaling factor equivalent to their threshold elevation factor.

Surprisingly, recent findings indirectly suggest that the speed-versus-contrast curves for dyslexics may be abnormal in shape-showing *improved* performance at low-contrasts. Visual-search times and reading speeds of disabled readers are improved by blurring the text (Williams, Brannan & Lartigue, 1987; Williams & Lecluyse, 1990; but see also Hogben, Pratt, Dedman & Clark, 1996). In a later study Williams, May, Solman and Zhou (1995) report that disabled readers show faster visual search performance at low contrast (38% Weber contrast[2]). The authors argue that the improved rates found with blurry text were due to the contrast reduction that accompanied the blur. According to their argument dyslexic readers should show faster reading speeds somewhere along the plateau of their reading curves as in Fig. 1.

What might account for improved reading performance at low-contrasts? Williams et al. (1995) propose that the mechanism underlying enhanced performance with blurred or low-contrast text involves ameliorating a slow or deficient response of the magnocellular (M) visual pathway (Williams & Lovegrove, 1992; Breitmeyer, 1993), presumably by providing the reader with a stimulus that maximally activates this pathway (e.g. low contrast, high temporal frequency). An alternative explanation for a low contrast improvement in dyslexic reading performance concerns the visual span for reading (i.e. the number of letters recognized during each fixation). There is evidence that dyslexics perceive letters farther into their peripheral visual field (i.e. show a larger visual span than normal) (Geiger & Lettvin, 1987; Goolkasian & King, 1990). Legge, Ahn, Klitz and Luebker (1997) demonstrated that the visual span shrinks when contrast is reduced. Thus, reducing text contrast may act to shrink or 'normalize' the visual

[2] Williams et al. (1995) used the Michelson definition of contrast. Their low-contrast condition was 16% Michelson contrast, which corresponds to 38% Weber contrast for letters.

Table 1
Reading, IQ and additional measures for each of the participants in Study 1[a]

	Group	Age	Reading (ORQ)	Ability (FSIQ)	Spelling subtype	ADD (z-score)	Visual Acuity (near)	Contrast range with significantly faster reading (%)
R1	RD	11.8	52	83	Dysphoneidesia	2.23		
R2	RD	11.5	73	104	Dyseidesia	0.94	−0.06	
R3	RD	11.9	76	98	Dysphoneidesia	−0.40	−0.08	
R4	RD	12.1	67	78	None	−1.33		
R5	RD	11.3	82	100	Dyseidesia	0.18		
R6	RD	14.4	76	88	Dyseidesia	−1.15	0.06	36[b]
R7	RD	11.1	91	108	Dyseidesia	−0.51		
C1	CON	12.5	121	122	None	−0.43	0.02	36[c]
C2	CON	13.3	97	97	None	−1.06	0.04	10–27[b]
C3	CON	12.5	112	119	None	−0.07	0.06	10–27[b]
C4	CON	12.5	112	114	None	−0.17	−0.06	36[c]
C5	CON	12.3	118	114	None	−0.41	0.02	36[b], 10–27[c]

[a] Measures include: oral reading quotients (GORT-3, Wiederholt & Bryant, 1992); full-scale intelligence quotients (K-BIT, Kaufman & Kaufman, 1990); log-MAR visual acuity (Lighthouse Visual Acuity); subtype classifications of dysphonetic and dyseidetic spelling patterns (Dyslexia determination test, Griffin & Walton, 1981); and z-scores from an attention deficit checklist (the ADHD Rating Scale, DuPaul, 1991), where a z-score above $+1.5$ is considered clinically significant. Contrast ranges that supported significantly faster reading are reported for the sentence[b] and random word[c] conditions.

span in dyslexia. In this way, dyslexic readers would be forced to read using only their foveal visual field, reducing confusions between peripheral and foveal vision, and thereby improve their reading performance (Geiger, Lettvin & Fahle, 1994).

In our study we measured reading speed of dyslexic and normal readers as a function of contrast. We sought to determine if dyslexics have reading-versus-contrast curves of normal shape but with a rightward shift, or if the curves show improved reading at a range of reduced contrasts. Answering these questions is important in helping to determine if dyslexics exhibit normal visual processing of contrast in reading. The results are also of substantial practical importance for the design of reading materials for dyslexic readers.

2. General method

2.1. Participants

Seventeen dyslexic participants were identified through disability offices of colleges and grade schools in the Minneapolis, MN vicinity and were assessed with the following diagnostic instruments of reading and general ability: The Gray oral reading test (GORT-3) oral reading quotient (a composite score for reading rate, accuracy and comprehension of passages) and the Kaufman brief intelligence test (K-BIT) full scale IQ. Controls were assessed with the same tests. Additional characteristics of our participants are presented in Tables 1–3. Participants, or their parents, indicated that they had no history of visual, hearing or neurological problems.

The dyslexic and control groups were defined according to a discrepancy between actual and predicted achievement (Heath & Kush, 1991), where an IQ-achievement regression is used to predict achievement (Reynolds, 1984). Members of the dyslexic group all had reading scores at least 1 SD below the predicted score[3], and controls were all within 0.5 SD of the predicted score.

2.2. Stimuli

2.2.1. Text

Oral reading speed was measured with single sentences and random word sequences presented in the format used for the *MNREAD* acuity chart (Mansfield, Legge & Bane, 1996). Each sentence had 60 characters, including spaces, printed onto three lines (see Fig. 2). Words were high frequency, with a majority ranking in the top 600 most frequent words (Zeno, Ivens, Millard and Duvvuri, 1995) (see Appendix A). Random word sequences were matched with the sentences for word length and word frequency. The stimuli were printed as dark letters on white background cards. Characters were printed using the *Times-Roman* font, with an x-height of 14 mm. In the experiments, character size was adjusted by changing viewing distance. Mean letter-to-letter spacing (i.e. the horizontal width of the

[3] Note that while this discrepancy criterion may identify 16% of the population, it selects a similar sample of individuals identified with a lag in grade equivalent scores (on average, our participants read more than four levels below grade). We used a discrepancy criterion because there are problems with interpretation of grade equivalent scores. Estimates of the incidence of dyslexia range from 5 to 15% of the population.

Table 2
Oral reading and full-scale intelligence quotients for the participants in Study 2[a]

	Group	Age	Reading (ORQ)	Ability (FSIQ)	Spelling subtype	ADD (z-score)	Visual acuity (near)	Visual acuity (far)	Pelli–Robson	Listening comp. (age)	Contrast range with significantly faster reading (%)
R8	RD	23.0	91	103		−0.69	−0.06	−0.26	1.95	29.6	
R9	RD	25.0	82	109		0.92	−0.16	−0.04	1.80	21.0	36[c, e], 14–19[c, e]
R10	RD	12.3	82	101	None	0.43					36[b, d]
R11	RD	23.5	79	108	Dyseidesia	−0.59	−0.04	−0.26	2.10	15.5	
R12	RD	20.0	88	106	Dyseidesia	0.82	−0.18	−0.16	2.10	29.0	36[c, e]
R13	RD	24.2	82	102	Dysphoneidesia	0.53	−0.18	−0.28	1.95	15.5	
C6	CON	21.0	121	120		−0.69	−0.16	−0.24	1.95		36[c, e], 14–19[b, c, e]
C7	CON	22.0	130	104		−0.17	−0.08	−0.04	1.95		14–19[b, c, e]
C8	CON	18.0	121	114		−0.66	−0.20	−0.06	1.95		
C9	CON	28.0	121	118		−0.76	−0.06	−0.08	1.95		
C10	CON	21.0	109	112		−0.66	−0.14	−0.10	1.95		36[b, c, d], 19–27[b, c, d]

[a] Additional measures include subtype classifications of dysphonetic and dyseidetic spelling patterns (DDT), attention deficit z-scores (the ADHD Rating Scale), near and far visual acuity (Lighthouse Visual Acuity), log contrast sensitivity (Pelli–Robson contrast sensitivity letter chart, Pelli, Robson & Wilkins, 1988), and age level scores from the listening comprehension subtest of the Woodcock–Johnson psycho-educational battery, revised-tests of cognitive ability (Woodcock & Johnson, 1990). Contrast ranges that supported significantly faster reading are reported for the sentence[b] and random word[c] conditions, and for 0.2°[d], 0.8°[e], and 2.0°[f] conditions.

Table 3
Oral reading and full-scale intelligence quotients for the participants in Study 3[a]

	Group	Age	Reading (ORQ)	Ability (FSIQ)	Spelling subtype	ADD (z-score)	Visual acuity (near)	Visual acuity (far)	Pelli–Robson	Listening comp. (age)	Contrast range with significantly faster reading (%)
R10	RD	12.3	82	101	None	0.43					36[b]
R11	RD	23.5	79	108	Dyseidesia	−0.59	−0.04	−0.26	2.10	15.5	
R12	RD	20.0	88	106	Dyseidesia	0.82	−0.18	−0.16	2.10	29.0	
R14	RD	18.7	79	94	Dysphonesia	−0.13	−0.07	−0.04	1.95		48–70[b, c]
R15	RD	20.6	97	108	None	0.90	−0.04	−0.08	1.65	29.0	
R16	RD	32.0	88	110	Dysphoneidesia	−0.50	−0.18	−0.26	1.65	26.0	14–19[b]
R17	RD	50.0	97	112	None	0.33	0.06	−0.08	1.80		36[b], 14–19[b]
C11	CON	20.0	109	103		0.03	0.00	−0.14	1.65		36[b], 14–19[b]
C12	CON	20.4	133	124		−0.17	−0.04	−0.20	1.80		14–19[b] 48–70[c]
C13	CON	21.5	118	109		−0.31	−0.07	−0.26	1.95		36[b], 14–19[b]
C14	CON	26.6	103	114		−0.87	−0.13	−0.16	1.80		

[a] Additional measures include subtype classifications (DDT), attention deficit z-scores (the ADHD rating scale), near and far visual acuity (Lighthouse Visual Acuity), log contrast sensitivity (Pelli–Robson Contrast sensitivity letter chart), and age scores for Listening Comprehension (Woodcock–Johnson psycho-educational battery, revised-tests of cognitive ability). Contrast ranges that supported significantly faster reading are reported for reading aloud[b] and reading silently[c].

Fig. 2. Examples of sentence and random word stimuli at three contrast levels.

white space between adjacent letters) within words was 9% (SD = 0.6%) of the mean letter width.

Passages used for silent reading were approximately 300 characters long (mean = 298, SD = 14.3), printed onto 10–11 lines. They were taken from children's stories intended for second to fourth grade levels, with words of the same high frequencies as the test sentences described in the previous paragraph (see Appendix A). The passages were printed on cards with dark letters on white background, using the *Times-Roman* font with an x-height of 7.5 mm.

2.3. Contrast and luminance

The contrast for each sentence was set by the dot density used to print the letters (see Appendix B). Seventeen levels of contrast were used, ranging from 1 to 100% in approximately 0.15 log unit steps. We used the Weber definition of contrast: $(L_B - L_T)/L_B$, where L_B and L_T are the background and text luminances. The cards were illuminated with a projector so that L_B was 100 cd/m^2 $\pm 10\%$ (verified prior to each experimental session).

2.4. Data analysis

For each observer in each condition we measured reading speed (in words/min) as a function of text contrast. These reading-speed versus contrast data were subsequently analyzed as follows:

1. For each participant, reading speed was plotted against contrast in log–log coordinates. The geometric mean of two or three repeat measures was taken to be the reading speed estimate for each contrast level. Least-squares regression was used to fit these data with a two-limbed function: a flat portion characterized the approximately constant reading speeds at high to medium contrasts, and a sloped portion characterized the rapid decrease in reading speed at low contrasts. The two-limbed function was a good fit for each individual's data. The intersection of the lines provided an estimate of the 'critical contrast' — the lowest contrast level that supported reading close to maximum reading speed. We refer to the reading speeds for contrasts greater than the critical contrast as the *reading-speed plateau* (see Fig. 1).

We compared the critical contrasts between dyslexic and control groups using analysis of variance. This comparison tested the prediction that dyslexic readers have a higher contrast threshold for reading (i.e. a rightward shift in the reading speed-versus-contrast curve), as might be predicted based on their reported higher contrast thresholds for grating stimuli.

2. We compared the dyslexic and control groups' performance on the reading speed plateau in a separate repeated-measures analysis of variance. The analysis tested the hypothesis that dyslexic readers show improved reading at reduced contrast levels (i.e. an abnormal shape of the reading speed-versus-contrast curve), as predicted by the improved visual search rates found by Williams et al. (1995).

We also addressed the possibility that pooling across subjects in the ANOVA could conceal either a subset of dyslexic readers who have better performance at low contrast, or a pattern where each individual dyslexic reader has a unique contrast level that supports improved reading performance. To test these possibilities, we performed two further analyses that searched in each individual's reading speed data for a range of contrasts that support significantly faster reading.

3. *Comparison at 36% contrast*. Williams et al. (1995) found improved visual search performance at 38% Weber contrast. Therefore, we first examined whether each individual read faster with the nearest contrast at which we tested (36%).

4. *Comparison across all contrast ranges*. We performed an exhaustive set of statistical comparisons of reading speeds within a selected contrast range with speeds outside that range. For each comparison, the mean reading speed for contrasts (c_i) in a range between a and b ($a < c_i < b$) was compared to the mean reading speed across contrasts outside the range ($c_i < a$ and $c_i > b$). These comparisons were performed for a and b set to each pairwise combination of contrasts greater than the critical contrast and less than 100% contrast.

We used a non-parametric bootstrap method, described in Appendix C (see Efron & Tibshirani, 1993) for these tests. This resampling method did not require us to make assumptions about the underlying distribution of reading speeds. After the appropriate Bonferroni correction (see Appendix C), this method had sufficient power to find significant differences in reading speed of 15% on average[4].

3. Study 1: oral reading with and without context

We measured reading speed as a function of text contrast in dyslexic children and age-matched controls. We collected reading speed data using short sentences and random word sequences. The random sequences eliminated the effects of sentence context, which might elevate reading speed to ceiling performance across a range of contrasts for dyslexics[5], and therefore mask small abnormalities in their reading-versus-contrast curves.

[4] The power of our statistical test depends on the variance in each individual's reading speed measurements. A significant variation in reading speed from the maximum speed (determined from the two-limbed fit) is determined taking into consideration the variance about the maximum speed in an individual's data. For Analysis 3 a variation of 22% was considered significant for the dyslexic group on average, and a variation of 13% for the control group on average. For Analysis 4, these averages were 17 and 8% for the groups, respectively.

[5] Potentially, for all readers context could enable rapid reading even when the text is close to contrast threshold. Context may be especially beneficial for dyslexic readers, given that low-achieving readers show the greatest improvements when visually degraded text is presented within a predictable context (Perfetti & Roth, 1981; Simpson, Lorsbach & Whitehouse, 1983).

3.1. Method

3.1.1. Participants

Measurements were collected from seven dyslexic and five control students (see Table 1).

3.1.2. Procedure

At the viewing distance of 1 m the characters subtended 0.8°. At the start of each block of trials, participants were given a practice trial with a high contrast sentence in order to familiarize them with the experimental set-up and procedure. Prior to each trial the test sentence was occluded with a blank card. This card was removed at the start of the trial and the participant read the sentence as quickly as possible. The reading time (measured from the moment that the blank card was removed until the participant finished uttering the last word in the sentence) was recorded using a stopwatch. Any words that were missed or read incorrectly were noted on a scoresheet. Reading speed was calculated as the number of words read correctly divided by the time taken.

Four trials were given for each contrast level: two sentences and two random word sequences. Different texts were used for each contrast level, but all participants read the same text for a given contrast level. Trials were presented in blocks of sentences and random word sequences, with the order of contrast level randomized within each block. The presentation order of sentence and word sequence blocks was randomized between participants.

3.2. Results

1. The ANOVA for critical contrast showed no difference between the dyslexic and control groups ($P > 0.5$), suggesting that there is no difference in contrast sensitivity for reading, at least for 0.8° characters at 1 m distance.

2. The ANOVA for plateau reading speeds showed that the dyslexic group had slower reading speeds than the control group ($P = 0.01$), but there was no significant effect of contrast in either group for either the sentence or random word conditions (see Fig. 3). This suggests that dyslexic readers did not demonstrate improved reading at low or intermediate contrasts.

3. Testing individuals' data for faster reading speed at 36% contrast revealed that three controls showed significantly faster reading (two with random words and one with sentences). The improvement in reading speed was between 7 and 28%. One dyslexic reader also showed significant improvement (12%) at this contrast for sentences (see the last column of Table 1).

4. Testing individuals' data for faster reading speeds at any contrast range showed that no dyslexic participants had a range of contrast that supported faster

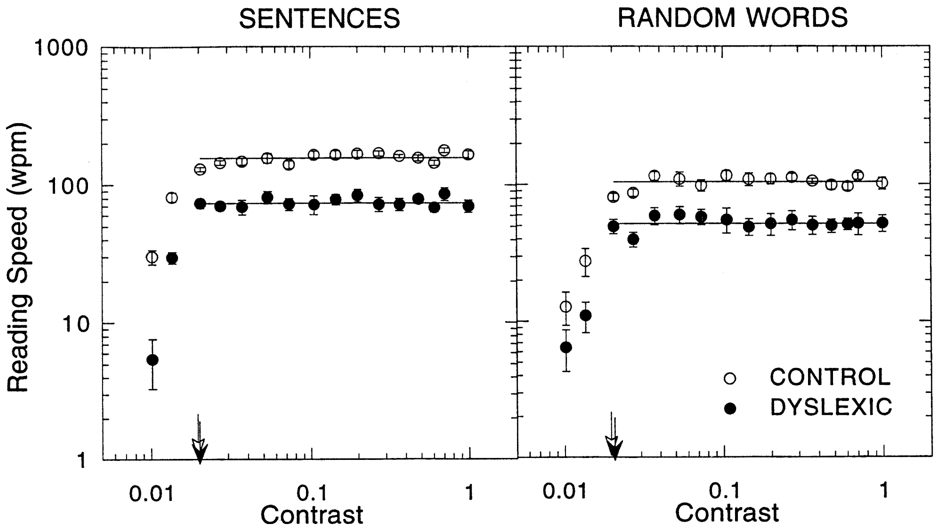

Fig. 3. Group mean data for sentences and random word strings from Study 1. For each group critical contrast in both context conditions was around 2% contrast (S.E. = 0.1%) and did not differ significantly ($F_{group}(1,10) = 0.3$, $P > 0.5$). Group mean critical contrasts are indicated with arrows (filled, dyslexic; open, control). For reading above critical contrast, only the main effect for groups was significant ($F(1,10) = 9.75$, $P = 0.01$), with an overall slower reading speed for dyslexic readers (53.54 words/min) versus controls (127.76 words/min).

reading. Three controls (two with sentences, one with random words) showed a significant reading-speed improvement of 6–10% (listed in Table 1).

These results show that for reading aloud with and without context with 0.8° characters, we find little support for the hypothesis that reading performance in children with dyslexia improves at low or intermediate contrasts. Only one dyslexic, compared with five controls, read significantly faster at low contrast, but this effect was of small magnitude.

4. Study 2: character size

Legge et al. (1987) showed that sinewave grating contrast sensitivity can be related to print size in reading by assuming that 2 cycles/character is critical for letter recognition. If the contrast sensitivity of dyslexic readers differs from that of normal readers at a circumscribed range of spatial frequencies (e.g. 1–8 c/deg, Martin & Lovegrove, 1984), then we would expect abnormalities in curves of reading-speed-versus-contrast at a corresponding range of print sizes (from 2 to 0.25°). In Study 1 we tested with 0.8° characters, in the middle of this range. Here we tested across the range of character sizes from 2 to 0.2°, including a character size similar to that of Williams et al.'s (1995) visual search task (0.3°).

4.1. Method

4.1.1. Participants

We tested 11 adults: six dyslexic and five control, and one dyslexic child (see Table 2). Four observers, two dyslexic and two control, were tested with three character sizes: 2.0, 0.8 and 0.2° (corresponding to 1, 2.5 and 10 c/deg gratings). Seven additional observers, one dyslexic child, three dyslexic adults, and three control adults, were tested at a single character size of either 0.8, 0.3 or 0.2° (corresponding to 2.5, 6.7 and 10 c/deg gratings).

4.1.2. Procedure

Four viewing distances were used: 40, 100, 265 and 400 cm, to subtend character sizes of 2.0, 0.8. 0.3 and 0.2°. Prior to each block of trials, participants were given a high-contrast practice trial. Participants were instructed to read each sentence aloud as quickly as possible. Reading times and errors were recorded as in Study 1, and reading speeds were calculated as the number of words read correctly divided by the time taken.

Trials were presented in blocks of sentences and random word sequences. The order of print-size testing was counterbalanced across the participants who read at multiple print sizes. The presentation order of sentences and random word blocks was randomized between participants. As in Study 1, different texts were used for each contrast level, but all participants read the same text for a given contrast level.

4.2. Results

1. The ANOVA for critical contrast showed no difference between the dyslexic and control groups at any character size ($P > 0.5$) (see Fig. 4). This suggests that, across character sizes corresponding to the range of spatial frequencies for which some dyslexics show con-

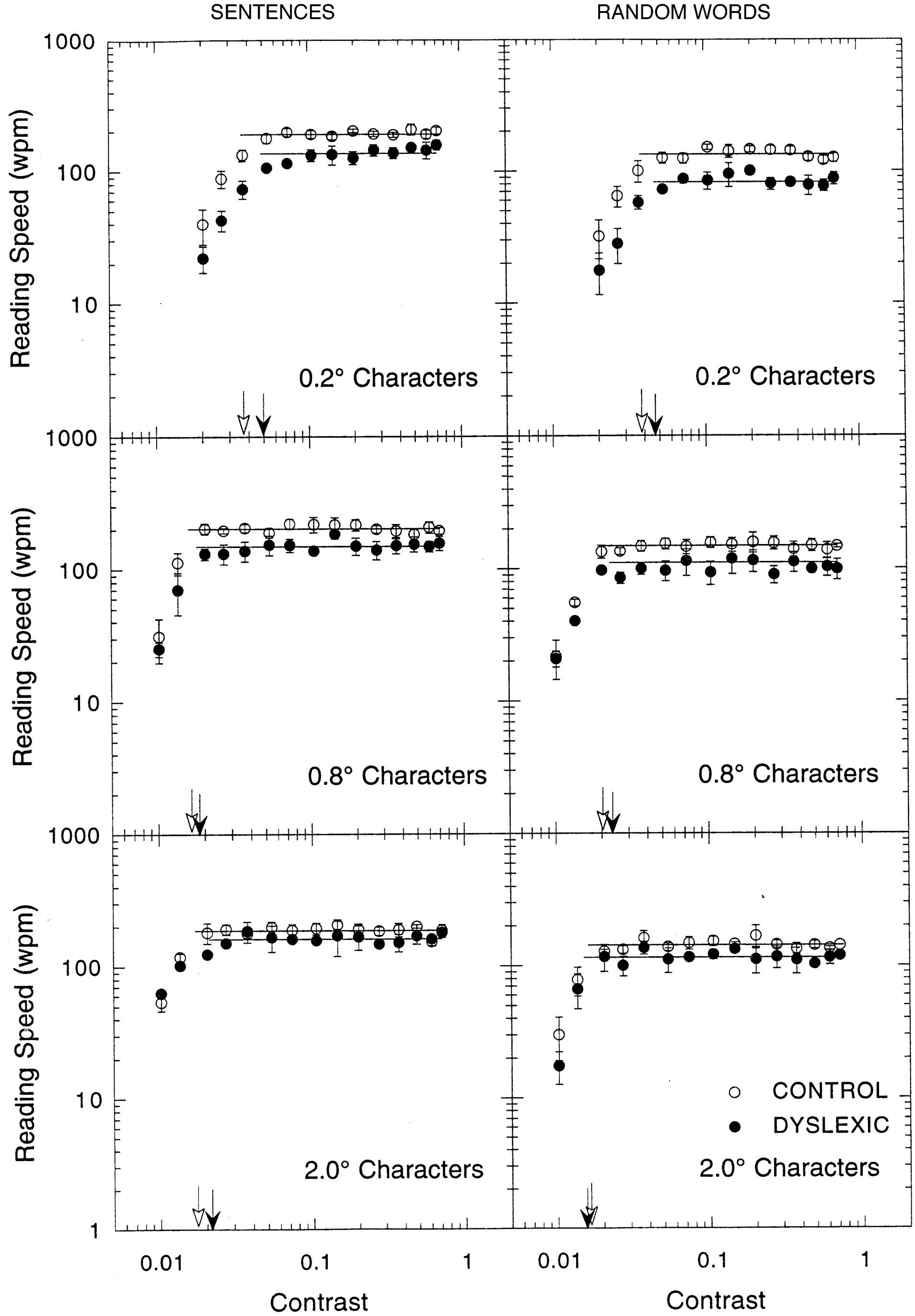

Fig. 4. Group mean data for three character sizes from Study 2. For dyslexic readers, critical contrasts were 0.048, 0.021, and 0.018 for 0.2, 0.8 and 2.0° character sizes. For controls, critical contrasts were 0.037, 0.017, and 0.017 for these three character sizes. Group mean critical contrasts are indicated with arrows (filled, dyslexic; open, control).

trast sensitivity deficits, our dyslexic participants do not show decreased contrast sensitivity for reading. Of further note, the adult participants were tested with the Pelli–Robson contrast sensitivity letter chart (see Table 2), and the control and dyslexic groups did not differ on this measure of contrast sensitivity for letter recognition ($P > 0.6$).

2. Fig. 4 shows pooled data for reading speed as a function of contrast for each print size. There is no indication of a reading speed improvement at low to intermediate contrasts. However, we did not perform the ANOVA for plateau reading speeds with these data because of the small number of participants with data at all character sizes. For this same reason we could not

evaluate the significance of the apparent improvement in reading speed with increasing character size for the dyslexic group.

3. Testing individuals' data for faster reading speed at 36% contrast revealed that three dyslexics showed significantly faster reading at this contrast (two for 0.8° characters in random words, and one for 0.3° characters in sentences). Two controls also read faster at this contrast (one with 0.8° characters in random words, and one with 0.2° characters in sentences and random words). In all cases, the improvement in reading speed was between 9 to 30%.

4. Testing individuals' data for faster reading speeds at any contrast range involved 108 or 324 comparisons for each participant (54 comparisons for each print size and context condition). Across all participants only 11 contrast ranges supported significantly faster reading. These ranges were distributed non-systematically across print size and contrast. Three controls and one dyslexic showed contrast ranges that supported significantly faster reading (listed in Table 2). There was little consistency in the contrast ranges or print sizes that supported faster reading among the controls. Moreover, the one dyslexic participant read significantly faster with 0.8° in the 14–19% contrast range, but this reading-speed improvement occurred only with random words and not with sentences. The magnitude of all these effects was an 11–19% increase in reading speed.

Thus, across a range of character sizes, some individuals showed particular contrast ranges that enabled faster reading. However, the effect was not specific to dyslexic readers, with more controls showing the effect, and the increase in reading speed was usually not very large (17% on average).

5. Study 3: oral and silent reading

It is possible that articulation limitations may have caused dyslexics to read slower, and thereby concealed any reading-speed improvement at low-contrasts. To address this possibility we compared performance for reading aloud and reading silently as a function of text contrast in dyslexic and control groups.

5.1. Method

5.1.1. Participants

Measurements were obtained from seven dyslexic and four control participants (see Table 3).

5.2. Procedure

At the viewing distance of 265 cm for oral sentence reading and 190 cm for silent passage reading, characters subtended 0.30 and 0.22°, respectively[6]. Silent and oral reading tasks were presented in random order, with contrast level randomized within blocks. Contrast levels were counterbalanced amongst passages. Different texts were used for each contrast level: for the oral reading task, all participants read the same text for a given contrast level, while in the silent reading task, the particular text presented at a given contrast level was counterbalanced across participants. Participants were timed while reading aloud and while reading silently. Participants responded 'done' or 'o.k.' when they had finished reading the silent passages. They were then asked to summarize the passage. Follow-up questions were given if they missed main points from the beginning, middle or end of the passage. After they were familiarized with the procedure on several practice trials, all participants were able to summarize the main points of the passages without having to be questioned.

5.3. Results

1. The ANOVA for critical contrast showed no group differences for either reading aloud or reading silently ($P > 0.4$), suggesting that there is no difference in contrast threshold for either mode of reading. Also, the groups did not differ on the contrast sensitivity measure for letter detection ($P > 0.4$) (see Pelli–Robson scores in Table 3).

2. The ANOVA for plateau reading speeds revealed a main effect of group, with slower reading speeds for dyslexic readers ($P = 0.01$)[7]. There were no significant interactions with group ($P > 0.2$). Both groups showed relatively constant performance across high to intermediate contrasts for silent as well as oral reading (see Fig. 5). Dyslexic readers showed no reading speed benefit at low or intermediate contrasts for silent as well as oral reading.

3. Testing individuals' data for faster reading speed at 36% contrast disclosed one dyslexic reader who read significantly faster aloud (6%). A second dyslexic (R10) who read aloud faster at this contrast in Study 2 did not show faster silent reading speed. In addition, two controls read aloud faster (by 6 and 10%) at this contrast.

4. Testing individuals' data for faster reading speeds at any contrast range showed three controls and three

[6] Although typical reading distances are around 40 cm, we used longer viewing distances that subtended character sizes similar to those of Williams et al. (1995). Due to the method of gray level printing that we used (see Appendix A), it was necessary to print fairly large letters to maintain a given sampling resolution. Also, a farther viewing distance assured that the printed pixels making up the letters were not resolvable.

[7] This ANOVA included only data for the six contrast levels for which data was collected in both the reading aloud and silent reading conditions. An ANOVA for oral reading speed across twelve contrast levels also showed no significant interactions with group ($P > 0.8$), just as in Study 1.

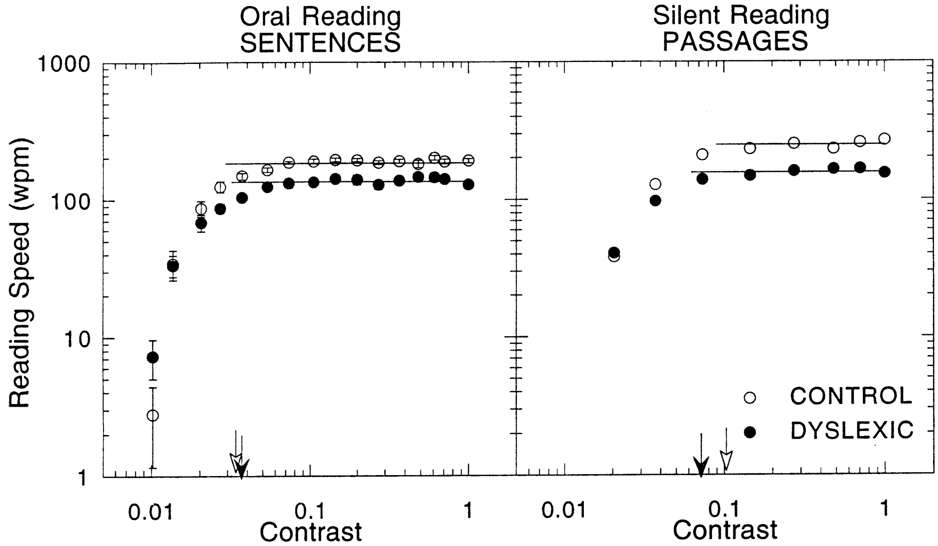

Fig. 5. Group mean data for oral and silent reading from Study 3. Both groups had critical contrasts of 3% (0.6 and 0.9% SE) for oral reading; for silent reading dyslexic readers had 6% (1.0% SE) and controls 9% (2.6% SE) critical contrasts, but the group by condition interaction was not significant ($P > 0.1$). Group mean critical contrasts are indicated with arrows (filled, dyslexic; open, control). For reading above critical contrast only the main group effect was significant ($F(1,9) = 10.4$, $P = 0.01$), with means of 145 words/min for dyslexics and 215 words/min for controls.

dyslexics with ranges of contrast that supported faster oral reading (listed in Table 3). One of these controls and one of these dyslexics also had contrast ranges that supported faster silent reading. In all cases the improvement in reading speed was between 9 and 15%.

Thus, for both oral and silent reading, although some of the participants read significantly faster at low contrasts, this effect did not discriminate the control and dyslexic groups, and the effect was never greater than a 15% increase in reading speed.

6. Discussion

From these three studies, we find that dyslexic readers show the same contrast dependence in reading as controls. This pattern holds for both children and adults, for reading with and without context across character sizes, and for reading aloud and silent reading. We find no evidence to suggest that (a) the reading curves of dyslexics are shifted to a higher contrast (Table 4), or (b) dyslexics show improved reading speed at low or intermediate contrasts.

There is evidence in the dyslexia literature for decreased sensitivity to contrast for sinewave gratings. An important question that has not been addressed is how such deficits contribute to visual processing under normal reading conditions. The fact that reading speed-by-contrast curves have a characteristic 'two-limb' shape allows us to discern whether decrements in reading performance are contrast or non-contrast-related. A contrast-related decrement would be indicated by a horizontal shift in the curve (e.g. see Fig. 1), whereas a vertical shift would indicate decrements that are not contrast-induced. This method of investigation has proven efficacious in other areas of vision research (e.g. Bradley & Freeman, 1985; Rubin & Legge, 1989). All of the reading performance deficits reported in the present study are indicated by vertical shifts, and there-

Table 4
Mean critical contrast values and standard errors (in parentheses) for Study 1–3, for each of the experimental conditions

	Group	Sentences	Random words	Silent passages
Study 1	Dyslexic	0.020 (0.001)	0.022 (0.001)	
	Control	0.020 (0.002)	0.021 (0.001)	
Study 2				
0.2° Char	Dyslexic	0.049 (0.004)	0.047 (0.008)	
	Control	0.036 (0.004)	0.038 (0.004)	
0.8° Char	Dyslexic	0.018 (0.003)	0.023 (0.005)	
	Control	0.016 (0.001)	0.020 (0.002)	
2.0° Char	Dyslexic	0.021 (0.010)	0.015 (0.001)	
	Control	0.017 (0.002)	0.016 (0.001)	
Study 3	Dyslexic	0.032 (0.006)		0.063 (0.010)
	Control	0.029 (0.006)		0.090 (0.026)

fore cannot be accounted for by reduced contrast sensitivity.

The low contrast improvements in visual search reported by Williams et al. (1995) did not generalize here to reading performance for our group of dyslexics. There were some individuals who read faster at lower contrasts, but these individuals were more likely to be controls than dyslexics (11 vs. 7). We would predict that a low-contrast benefit should be specific to dyslexic readers, or at least the benefit should be greater than that found for the controls. Yet the magnitude of increased reading rates was the same for controls and dyslexics, most ranging from 10 to 15% increases. Only one dyslexic read 30% faster at low contrast. Further, we would expect that if these individual improvements at low-contrast are reliable, they should generalize across experimental conditions for that individual. For some controls, this was true, but for all but one of the dyslexics the effect was inconsistent, occurring in only one experimental condition. For the five dyslexics showing increases in sentence reading speed, at least the effect should generalize to either random word or silent reading conditions, assuming that contextual constraint and articulation requirements mask small abnormalities. Yet only one of these five showed low-contrast benefits across conditions, but at different contrasts. Thus, the low-contrast increases were idiosyncratic, occurring only in selected experimental conditions and within both reading ability groups.

Our failure to find contrast effects on reading cannot be attributed to the size and composition of our sample of dyslexic readers, which was similar to that of previous studies reporting contrast differences (e.g. Williams et al., 1995; Borsting et al., 1996). Each dyslexic participant had a history of reading difficulties, and in terms of ability levels, the discrepancy formula that we used to identify these individuals yielded the same, if not more severe, forms of reading disability. All but one of our dyslexic readers scored more than 1.5 levels below grade on standardized measures of reading rate and accuracy or comprehension.

One possible explanation for the lack of contrast effects on reading is that none of our dyslexic participants had contrast sensitivity deficits. To completely eliminate this possibility would require testing contrast sensitivity across a wide range of spatial and temporal frequencies. However, it is likely that at least some of our dyslexic participants had contrast deficits: Up to 70% of dyslexics are estimated to have a contrast sensitivity deficit (Lovegrove et al., 1986), and our sample included individuals who were classified as the dysphoneidetic subtype that has been specifically associated with contrast sensitivity deficits (Borsting et al., 1996)[8]. (Also note that the individuals who showed spurious low-contrast benefits were of different subtype classifications.)

Finally, we used stimuli typical of normal reading conditions: dark text printed on white cards with an illumination of 100 cd/m^2. This differed from the conditions of Williams et al. (1995), who used light letters presented on a dark (1.2 cd/m^2) background. Our interest was in investigating contrast processing for reading under typical reading conditions. Under these conditions (with the exception of viewing distance[6]), reading-rate-by-contrast curves of dyslexics have a normal shape and are not shifted along the log-contrast axis. This indicates that dyslexics have contrast processing and contrast thresholds for reading that are similar to controls.

Contrast sensitivity differences in individuals with dyslexia have been taken as support for the theory that the magnocellular visual pathway is deficient (i.e. slow or weak) in dyslexic individuals. Evidence of motion sensitivity deficits is consistent with this claim. Our study suggests that the proposed M-pathway deficit is not manifest at the early sensory level for reading, at least not in terms of contrast coding. It is possible, however, that such a visual deficit could be manifest at a higher level of visual processing for reading. For example, Cornelissen, Hansen, Gilchrist, Cormack, Essex and Frankish (1998) propose that spatial localization properties of the M pathway may relate directly to letter position information. In this case, a deficient M pathway will disrupt reading due to the mislocalization of letters within words.

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[8] Although we found no group difference in Pelli–Robson letter contrast sensitivity for our adult participants, and Atkinson (1993) similarly reported no group difference in children's Pelli–Robson score, this does not imply that there are no other contrast deficits. The Pelli–Robson score is a good predictor of contrast sensitivity for static, low spatial-frequency gratings (Leat & Woo, 1997), yet it may not be indicative of the contrast sensitivity for temporally modulated (e.g. 20 Hz) high-frequency gratings for which dyslexics are reported to have the greatest deficits.

Appendix A

Percent of words according to rank for sentences and passages used for reading aloud and silent reading (based on word frequency norms of Zeno et al., 1995)

Rank	Percent of words	
	Sentences	Passages
1–599	75	72
600–1199	8	7
1200–2399	5	6
2400–4799	5	6
4800–20 000	6	8
>20 000	1	1

Appendix B. Control of contrast on text cards

B.1. Halftone screen

Reading cards were printed using a HP *LaserJet 4+* printer with resolution of 600 dots per inch (dpi). Contrast was adjusted by varying the text gray level using a halftone screen. Gray level is determined by the proportion of pixels in each halftone cell that are turned 'on'. The resolution with which gray level can be adjusted is determined by the total number of pixels in each halftone cell. Our need to allow fine control of text contrast right down to threshold levels required relatively large halftone cells. We used a halftone screen with 30 lines/in. which allowed us to set the text to any of 401 different gray levels ranging from 0 to 400 dots/cell.

B.2. Print size

Each cell in our halftone screen was 0.86 mm square. Our use of a large cell size required large print to ensure that each letter was adequately sampled by the halftone screen. For the reading cards we used print with a 14 mm x-height, so that each letter was sampled on a 16×16 grid. Print for the passages used in Study 3 had a 7.5 mm x-height, sampled on an 8×8 grid. This sampling resolution is substantially better than the minimum 4×4 samples that support rapid reading (Legge et al., 1985).

B.3. Spot function

In level 1 PostScript, the characteristics of the halftone screen are set by three parameters: (1) the screen frequency, the number of halftone cells per inch; (2) the screen angle; and (3) the spot function, a procedure that defines the sequence in which the pixels within each halftone cell are turned on. A common spot function is the 'dot screen' in which the black pixels cluster in a circle whose area is proportional to the gray level. This simple screen proved to be inappropriate for use with our large halftone cell, however, because for some gray levels, the spots in each cell were individually resolvable at the 1 m viewing distance. Instead we used a 'four-dot' spot function in which the black pixels clustered to make four smaller circles (positioned in each quadrant of the halftone cell). The total area across all four dots was proportional to the gray level. By using this 'four-dot' spot function the half-tone cells were not resolvable from the 1 m viewing distance.

Appendix C. Non-parametric bootstrap method for contrast range comparisons

The resampling analysis was performed separately for each individual within each experimental condition (e.g. sentences versus random words, silent versus oral reading, or for each character size condition). Only data from the contrast levels above the individual's critical contrast were used in the analysis.

For a given comparison, mean reading speed S_i within a contrast range ($a \le c_i \ge b$) is compared with the mean reading speed S_j across contrasts outside that range ($c_j < a$ and $c_j > b$, and $c_j >$ critical contrast), where N_i is the number of data points inside the range and N_j the number outside the range. The difference of these mean reading speeds was used for the comparison ($S_i - S_j$).

The first step in the analysis was to randomly sample with replacement N_i reading speeds from inside the contrast range (c_i) and calculate the mean R_i of the resampled reading speeds. This same random sampling with replacement was then performed for N_j reading speeds from outside the contrast range (c_j), and the mean R_j calculated. We then took the difference of these resampled means ($R_i - R_j$).

This resampling procedure was repeated 5000–10 000 times, yielding a distribution of $R_i - R_j$. The actual difference in reading speed inside-versus-outside the given contrast range ($S_i - S_j$) was compared to this distribution of resampled differences to determine the probability of obtaining that actual difference. For example, with 10 000 iterations, if $S_i - S_j > 9500$ of the $R_i - R_j$ distribution, then the actual reading speed for $a \le c_i \ge b$ is considered significantly faster at the 0.05 alpha level.

For Analysis 3 in each study, reading speeds at $c_i = 36\%$ were compared to S_j. For this comparison, the data were resampled over 10 000 iterations, and any difference with a P-value less than 0.05 was considered a significantly faster reading speed at that contrast. For Analysis 4 in each study, the $S_i - S_j$ comparison was performed across an exhaustive set of contrast ranges, where $c_i >$ critical contrast and $c_i < 100\%$ contrast. For these comparisons, the data were resampled over 5000 iterations. Any difference with a P-value less than 0.0009 in Studies 1 and 2, and 0.0056 in Study 3 was considered as a significantly faster reading speed inside that contrast range. This criterion P-value is based on a 0.05 alpha level with a Bonferroni correction for the number of unique comparisons made (54 in Studies 1 and 2, and 9 in Study 3).

If multiple ranges were significant for a given individual in a given experimental condition, the range with the largest effect is reported. Where the effects were equal, smaller contrast ranges that were contained within larger significant ranges are reported.

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