Crowding, reading, and developmental dyslexia

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We tested the hypothesis that crowding effects are responsible for the reading slowness characteristic of developmental dyslexia. A total of twenty-nine Italian dyslexics and thirty-three age-matched controls participated in various parts of the study. In Experiment 1, we measured contrast thresholds for identifying letters and words as a function of stimulus duration. Thresholds were higher in dyslexics than controls for words (at a limited time exposure) but not for single letters. Adding noise to the stimuli produced comparable effects in dyslexics and controls. At the long time exposure thresholds were comparable in the two groups. In Experiment 2, we measured the spacing between a target letter and two flankers at a fixed level of performance as a function of eccentricity and size. With eccentricity, the critical spacing (CS) scaled in the control group with 0.62 proportionality (a value of *b* close to Bouma's law, 0.50) and with a greater proportionality (0.95) in the dyslexic group. CS was independent of size in both groups. In Experiment 3, we examined the critical print size (CPS), that is, the increase in reading rate up to a critical character size (S. T. Chung, J. S. Mansfield, & G. E. Legge, 1998). CPS of dyslexic children was greater than that of controls. Individual maximal reading speed was predicted by individual *b*s (from Experiment 2). The maximal reading rate achieved by dyslexics at CPS (and also for larger print sizes) was below the values observed in controls. We conclude that word analysis in dyslexics is slowed because of greater crowding effects, which limit letter identification in multi-letter arrays across the visual field. We propose that the peripheral reading of normal readers might constitute a model for dyslexic reading. The periphery model accounts for 60% of dyslexics' slowness. After compensating for crowding, the dyslexics' reading rate remains slower than that of proficient readers. This failure is discussed in terms of a developmental learning effect.

Introduction

In regular orthographies, such as German or Italian, the reading of developmental dyslexics is characteristically slow and fragmented; accuracy is also impaired, but much less than in opaque orthographies, such as English (Wimmer, 1993; Zoccolotti et al., 1999). However, it is still unclear, why these children are unable to read fluently.

The word length effect in Italian dyslexics

A robust observation in Italian dyslexics is the presence of a *length effect*. This can be shown using different techniques. If a word is displayed in the central visual field and naming is required, the vocal reaction times (RTs) to stimulus onset increase monotonically with word length in dyslexics, whereas they tend to be flat in skilled readers, at least up to words with five letters (Spinelli et al., 2005; Ziegler, Perry, Ma-Wyatt, Ladner, & Schulte-Körne, 2003). Moreover, when children are learning to read Italian they show a huge length effect. First graders vocal RTs as a function of the number of letters have a slope similar to what is observed in sixth-grade dyslexics. The length effect decreases rapidly with reading experience, on average up to third grade, after which only small improvements can be detected (Burani, Marcolini, & Stella, 2002; Spinelli et al., 2005; Zoccolotti, De Luca, Di Filippo, Judica, & Martelli, 2008; Zoccolotti, De Luca, Di Filippo, Judica, & Spinelli, 2005).

The length effect is also evident when eye movements are recorded during reading. In dyslexic children, the number of fixations depends upon the length of the word; they may produce from seven to ten fixations (or even more) to read a 10–12 letter word. By contrast, skilled readers flexibly adapt the size of their saccades and make a single fixation on most words, irrespective of their length (De Luca, Borrelli, Judica, Spinelli, & Zoccolotti, 2002; De Luca, Di Pace, Judica, Spinelli, & Zoccolotti, 1999; Hutzler & Wimmer, 2004). Using a lexical decision task (i.e., deciding whether a string of letters is a word or non-word) Di Filippo, De Luca, Judica, Spinelli, and Zoccolotti (2006) showed that the length effect survives also when dyslexics' data are normalized for a general factor responsible for slower processing of verbal material. Indeed, the length effect is specific and adds to this general factor.

Length effect and the hypothesis of crowding

The pervasiveness of the length effect in very young children and in dyslexic Italian readers and observation of dyslexics' eye movements suggest that, in order to read, dyslexic children fixate and process only a small portion of the word; then, their eyes move to the next letter or syllable. Duration of fixation is also longer than normal, indicating an impairment in extracting information within a single fixation (De Luca et al., 1999). In first graders, this parceled processing points to a slow reading procedure based on the grapheme-to-phoneme conversion of each letter or syllable. Evidently, unlike normal readers some children are unable to give up this type of processing and move to a more global procedure. Spinelli, De Luca, Judica, and Zoccolotti (2002) speculated that an abnormal level of crowding might be responsible for this developmental arrest.

Crowding refers to impaired recognition of a target due to the presence of neighboring objects in the peripheral visual field (Bouma, 1970). When the flanking letters are close to the target letter, observers "see" jumbled shapes that are hard to recognize. Object identification becomes easy when the flankers are moved far enough away from the target. The distance between letters (measured center-to-center) at which target recognition is restored is called critical spacing. Critical spacing scales with eccentricity; thus, letter identification is increasingly limited as letters are displayed at larger eccentricities (Bouma, 1970). Relative to the fovea, in the periphery more letters within words printed at fixed spacing will be unrecognizable because of crowding (Bouma, 1973). Thus, the longer a word, the stronger the effect of crowding in its not centrally fixated portions.

The idea that crowding plays a role in dyslexia is not new. In fact, Bouma and Legein (1977) presented letter triplets tachistoscopically to dyslexics at various eccentricities. These authors found that dyslexics' letter identification was more severely impaired by the presence of flankers, but only in the periphery. Atkinson (1991, 1993) measured visual acuity for letters presented singly or surrounded by other letters in the central vision of normal and dyslexic subjects and found abnormal crowding in dyslexics. The phenomenon was limited to a subgroup, and in some good readers crowding was as large as in dyslexics.

Spinelli et al. (2002) proposed that Italian-speaking dyslexics might be more prone to the influence of visual factors than English-speaking dyslexics. In fact, while phonology is considered by many authors as the most frequent cause of dyslexia in English-speaking children (e.g., Vellutino, Fletcher, Snowling, & Scanlon, 2004), there is little evidence of phonological problems (deficit in the phonological awareness: ability to segment or fuse phonemes) in Italian children. In particular, only those with a previous language delay show a mild phonological impairment; however, this is entirely absent in children with dyslexia but no previous language delay (Brizzolara et al., 2006). Thus, the effect of visual crowding could be prominent. Spinelli et al. (2002) reasoned that dyslexics might have difficulty in discriminating letters among letters (in a word) and words among words (in a sentence) and, more generally, any symbol among other symbols with features analogous to those of a written text (small, high-contrast, closely spaced objects). The authors tested this idea and obtained two main results. First, on average dyslexics displayed a stronger impairment in vocal RTs than controls when words were cluttered by other words; this was true also when symbol strings were used. Consistently with the influence of crowding, increasing inter-letter distance decreased word vocal RTs of dyslexics (by ca. 10%) but not of skilled readers. Second, both of these effects were more clearly present in a proportion of the children (ca. 30%). Based on these findings, the authors suggested that, in a proportion of dyslexic children, abnormal crowding impeded the development of a faster reading procedure. However, this proposal was not supported in a robust way: crowding was not directly measured; there was no evaluation of the critical spacing between letters; the relationship between crowding and reading rate was very indirect.

Additional results compatible with the crowding hypothesis in dyslexic children

Other studies of dyslexic children (in different countries) have reported results compatible with the idea of abnormal crowding. Nevertheless, in these studies the authors either did not refer explicitly to crowding or considered it within a set of possible alternative theoretical options. For example, Hawelka and Wimmer (2005) reported higher recognition thresholds in 4- and 6-digit arrays in dyslexic than in control children; this difference was not present in the case of 2-digit arrays. Furthermore, it was reported that dyslexics failed in a conjunction search task limited to a large number of closely spaced

distracters (Vidyasagar & Pammer, 1999). O'Brien, Mansfield, and Legge (2005) examined the relationship between reading speed and print size in developmental dyslexics and reading-matched controls. Dyslexics' critical print sizes were larger than those of controls; that is, they needed larger print to support maximum reading rates. O'Brien et al. (2005) posited that different theoretical proposals might account for these findings and that further work was needed to tease them apart.

Recent studies on crowding in good readers and in amblyopics

In the present study, we evaluated the hypothesis of abnormal crowding in developmental dyslexia in light of some recent findings on the characteristics of crowding and on its effect on reading speed in normal and amblyopic subjects.

Critical spacing scales with eccentricity

Word recognition is mediated by letter identification (for a review, see McClelland & Rumelhart, 1981) and it cannot be better than what is predicted by the identification of the letters (Pelli, Burns, Farell, & Moore-Page, 2006; Pelli, Farell, & Moore, 2003). Letter identification is limited by crowding (Bouma, 1970). Critical spacing defines a region of the visual field around the object within which the features are integrated (Martelli, Majaj, & Pelli, 2005; Pelli, Levi, Chung, 2004). If a letter falls within a critical spacing it is recognizable; however, if more than one letter falls within a critical spacing the features are integrated, thus impairing identification. Beyond the critical spacing, recognition is unimpaired and additional spacing provides no additional benefit. As expected based on Bouma's (1973) findings, critical spacing scales with eccentricity and is independent of target and flanker size (Strasburger, Harvey, & Rentschler, 1991). The way critical spacing scales with eccentricity is constant according to Bouma (i.e., about half of the viewing eccentricity; often called "Bouma's law"); however, large individual variations were shown in a recent study (Pelli et al., 2007).

Reading rate is limited by crowding

Reading rate increases rapidly with letter size and reaches a maximum reading rate at a critical print size (CPS). Reading in the periphery moves the curve in log–log coordinates down and right (Chung, Mansfield, & Legge, 1998). The CPS, which is responsible for the rightward shift of the curve, depends on crowding, increases with eccentricity, and is proportional to the critical spacing for reading (Levi, Song, & Pelli, 2007). Legge, Mansfield, and Chung (2001) proposed that the

RSVP reading rate is limited by the visual span, that is, the number of characters in a line of text that can be read without moving one's eyes, which reduces with increasing eccentricity. Pelli et al. (2007) proposed that the visual span is the uncrowded span, that is, the number of letter positions that are uncrowded and show that the span is linearly related to maximum reading speed. Pelli and coworker generalized their results and suggested that under ordinary conditions (adequate light, correct vision) the only limit to reading rate is crowding. Overall, the link between crowding and reading speed was made clear only recently (Legge et al., 2007; Pelli et al., 2007).

Slow reading in amblyopics is due to crowding

The study of amblyopics' reading and its dependence on crowding is also relevant to our purpose. Amblyopia is a developmental disorder that generally affects one eye and reduces contrast sensitivity for small targets (for a review see Levi, 1991). Pelli, Palomares, and Majaj (2004) measured "equivalent noise" of amblyopic eyes in a task of near-acuity letter recognition and found little or no increase. Thus, poor recognition of small letters in amblyopia is mostly due to low "efficiency" (Pelli & Farell, 1999) at a higher level than spatial frequency tuning (Pelli, Palomares, et al., 2004). More recently, Levi et al. (2007) addressed the problem by studying reading rate instead of letter recognition in amblyopics. They showed that the very slow reading rate in the amblyopic fovea is due to crowding, not poor visual acuity. When the letters are adequately spaced by increasing print size, reading can be as fast as with the normal eye.

To sum up, for the purpose of the present study the most relevant conclusions of these studies are the following:

a. in normal subjects and in the special population of amblyopics, reading rate is limited only by crowding;
b. the properties of crowding have been described in terms of the effects of many variables, including spacing and eccentricity.

This description provides diagnostic tools for comprehensively testing this phenomenon in developmental dyslexics.

Goal of the present study

These recent studies offer a promising working hypothesis to explain developmental dyslexia in terms of abnormal visual crowding. In particular, evidence of increased crowding (but not masking) allows placing the reading deficit at a specific stage of perceptual processing (i.e., the integration not the detection level).

We investigated the relationship between the developmental reading impairment and crowding, taking into

account these new ideas. To discriminate the level (or levels) at which a deficit was present in dyslexics, we performed three experiments (whenever possible testing the same children).

Experiment 1: Contrast threshold for letter and word identification as a function of noise and stimulus duration

A preliminary step to reading is letter identification (McClelland & Rumelhart, 1981). This process is considered spared in dyslexic children because of their good performance in single letter reading, generally tested with simple, standard reading tests that assess accuracy and speed of letter recognition (for instance, in Italian, Sartori, Job, & Tressoldi, 1995). However, behavioral measures of letter identification can be influenced by ceiling effects. In the present study, we tested the assumption of spared letter processing directly, using a more sensitive test, that is, the contrast threshold for letters. If crowding is the limiting factor for dyslexic children, the threshold for single-letter identification should be spared, whereas the threshold for multiple-letter arrays should be impaired. In Experiment 1, contrast thresholds for identifying single letters and words were measured. We also applied a simplified version of Pelli and Farell's (1999) technique (i.e., adding external noise) to evaluate whether contrast sensitivity for letters and words was differentially affected in dyslexics and controls; this allowed testing for the presence of higher internal noise in the dyslexic group.

In the same experiment, we also investigated the effect of stimulus duration. Relatively long durations allow for exploratory eye movements; these may compensate for the limitations imposed by crowding, bringing successive portions of the word to the fovea. By varying signal duration, we examined whether in dyslexics contrast thresholds for words took advantage of long duration times. Investigating the phenomenon at the threshold rather than the supra-threshold level (as in the previous eye movement and vocal RT studies) might contribute to confirming the importance of the length effect in Italian dyslexics.

Methods

Characteristics of the general sample for the three experiments

Criteria for inclusion in the dyslexic sample were the following: marked reading delay (-2 SD in speed or accuracy) on a standard Italian reading test, MT reading test (Cornoldi & Colpo, 1981; Cornoldi, Colpo, & Gruppo, 1981); performance in the normal range on Raven's Colored Progressive Matrices (above the 10th percentile = score of 22; Pruneti, 1985; z scores: mean = -0.11; SD = 0.93); normal or corrected-to-normal visual acuity.

The dyslexics who participated in each study were recruited from a group of 29 sixth-grade children (19 M and 10 F). The actual number of participants varied in the different experiments and conditions. Overall, mean age was 11.7 years (SD = 0.5).

A group of 33 sixth-grade children (21 M and 12 F) with normal reading ability served as the control group. Overall, mean age was 11.2 years (SD = 0.5).

Functional reading assessment

Discrimination of dyslexics from proficient readers was based on a standard reading achievement test (MT reading test, Cornoldi & Colpo, 1981). Two meaningful passages were presented. In the first, the participant had to read aloud (with a 4-min time limit); speed (time in seconds per syllable read) and correctness (number of errors, adjusted for the amount of text read) were scored. To measure comprehension, the participant read a second passage without a time limit and responded to 10 multiple-choice questions. Stimulus materials (and related reference norms) vary depending on school level. Here, we used the texts appropriate for sixth graders for both controls and dyslexics. Performances were expressed in terms of z scores, indicating degree of deviation from the normative data (Cornoldi & Colpo, 1981).

The dyslexics' performance was impaired for accuracy (mean z score = -2.99, SD = 1.5) and speed (mean z score = -1.19, SD = 1.6). Ability to understand the text was only mildly affected (mean z score = -0.42, SD = 0.9). The controls' performance was within normal limits for all parameters (accuracy: mean z score = 0.39, SD = 0.33; speed: mean z score = 0.42, SD = 0.32; comprehension: mean z score = 0.40, SD = 0.54).

Reading performance was also examined using six lists from the Words and Non-words Reading Test (Zoccolotti, De Luca, Di Filippo, et al., 2005). These included short (four-to-five letter) and long (eight-to-nine letter) high-frequency and low-frequency words, and short and long non-words. Each list contained 30 items. A short practice sequence was presented separately for words and non-words. Lists were presented in the following order: non-word practice, short non-words, long non-words, word practice, short words, and long words (first low- and then high-frequency words). Speed (time in seconds per list) and accuracy (number of errors) were scored. Raw data were converted to z scores based on the normative sample (N = 93 sixth graders; Zoccolotti, De Luca, Di Pace, et al., 2005). Data for the dyslexics are presented in Table 1. Reading speed and accuracy were affected in all stimulus categories. Note that the impairment was always numerically higher in long than in short stimuli. Data for the controls (not shown) varied around zero, as expected. The median of the z-score distributions across conditions was

Stimulus	Accuracy		Speed	
	Mean	*SD*	Mean	*SD*
HF short words	−0.72	1.29	−0.73	1.48
HF long words	−1.67	2.16	−1.75	2.02
LF short words	−1.81	1.80	−1.61	2.04
LF long words	−3.11	2.62	−1.98	1.64
Short non-words	−2.29	2.04	−1.08	1.45
Long non-words	−2.54	1.64	−1.10	1.34

Table 1. Performance (in *z* scores) of the dyslexic sample in the *Words and Non-words Reading Test* (Zoccolotti, De Luca, Di Pace, et al., 2005).

0.48 for speed (ranging from 0.24 to 0.62) and 0.02 for accuracy (ranging from −0.35 to 0.21). In all cases, the dyslexics' values were lower than those of the controls for both speed and accuracy (at least $p < 0.02$).

Participants for Experiment 1

Five dyslexic observers and five controls recruited from the larger groups participated in the first experiment. The mean age of these subgroups did not differ from those of the total group ($t < 1$).

Apparatus and stimuli

The experiment was performed on Apple Power Macintosh computers using MATLAB software with the Psychophysics Toolbox extensions (http://psychtoolbox.org/; Brainard, 1997; Pelli, 1997). Observers viewed a gamma-corrected grayscale CRT monitor (Pelli & Zhang, 1991) with a background luminance of about 28 cd/m^2.

The fixation point was a 0.15-deg black square located in the center of the screen. Letters and words were drawn in white on a gray background and written in Courier uppercase font. Signal contrast was defined as the ratio of luminance increase to background luminance. In separate runs, noise was added to the signal. The noise was made up of square checks (2 pixels), each with a luminance increase or decrease independently sampled from a zero-mean Gaussian distribution truncated at ±2 standard deviations. The side of the check subtended 0.08 deg. The rms contrast of the noise was 0.14. Each letter subtended 1 deg. Words were 10 letters long.

Procedure: Contrast threshold

Contrast thresholds were measured in separate runs for letter and word identification in central vision. In each trial, the target was a random sample from the signal set comprised of letters or words. Each set included 10 signals.

The fixation point was presented for 200 ms. The signal appeared 400 ms after the fixation point at the same location and remained on the screen for 200 (or 2000) ms. Each target presentation was accompanied by a beep, followed by a response screen showing all possible signals

at 80% contrast. Observers were instructed to identify the signal corresponding to the target by clicking on one of the alternatives on the response screen. A correct response was rewarded with a beep. Letters were presented on the screen for 200 ms. In the case of words, contrast thresholds were measured at two signal durations (200 and 2000 ms) in separate runs. Prior to the experimental session the observers were asked to read aloud several times the letters and words presented consecutively on the response screen, until their performance was errorless.

The observers' threshold contrast was estimated in a 40-trial run, using the improved QUEST staircase procedure with a threshold criterion of 82% correct responses (Watson & Pelli, 1983). Log thresholds were averaged over three runs for each condition.

Data analysis

The effect of stimulus type (letters vs. words) was evaluated by carrying out a three-way ANOVA on log contrast thresholds, with group (controls, dyslexics) as unrepeated factor and stimulus type (letters, ten-letter words) and noise (blank, noise) as repeated factors. A separate analysis was performed to evaluate the effect of stimulus duration on word identification. In this analysis, group (controls, dyslexics) was the unrepeated factor and signal duration (200 ms, 2000 ms) and noise (present, absent) were the repeated factors.

Results
Effect of stimulus type: Letter vs. word

Figure 1 presents the effect of contrast thresholds on identifying a single letter and a ten-letter word.

An inspection of the figure indicates that:

1. dyslexics and controls need about the same amount of contrast to identify single letters, whereas they differ greatly in the case of long words;
2. controls need about the same amount of contrast at threshold to identify single letters and ten-letter words;
3. dyslexics show an increase in contrast threshold of about 0.3 log units to identify ten-letter words relative to single letters, both in white noise and on a blank field;
4. adding noise generally raises the threshold by about 0.7 log units for both dyslexics and controls, independent of stimulus length.

A three-way ANOVA on the log contrast thresholds was carried out with group (controls, dyslexics) as unrepeated factor and stimulus type (letters, ten-letter words) and noise (blank, noise) as repeated factors. The main effects of the group ($F_{(1, 8)} = 26.34$, $p < 0.0001$), stimulus type ($F_{(1, 8)} = 28.27$, $p < 0.0001$), and noise ($F_{(1, 8)} = 604.28$, $p < 0.0001$) factors were all significant. The group by stimulus type
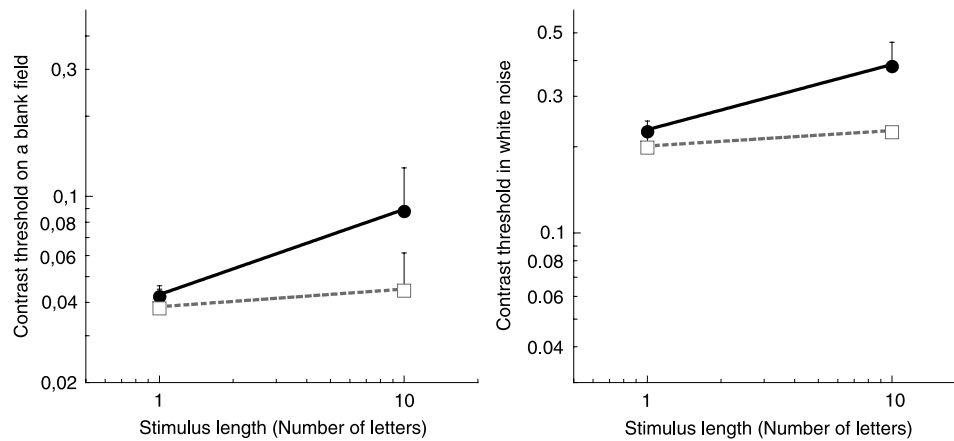
Figure 1. Contrast thresholds for identification of single letters and ten-letter words on a blank field (left) and in the presence of white noise (right) in central vision at a 200-ms presentation duration. The graphs show the geometric means and the standard deviations obtained by dyslexics (filled circles) and controls (open squares).

interaction was significant ($F_{(2, 8)} = 11.61$, $p < 0.005$). *A posteriori* Sheffe comparisons revealed significantly higher contrast thresholds for dyslexics than controls in the identification of words ($p < 0.005$) but no difference in the identification of single letters. Dyslexics, but not controls, showed an effect of stimulus type on contrast threshold ($p < 0.005$), that is, they needed more contrast to identify a ten-letter word than a letter. No other interactions were significant ($F < 1$).

Effect of stimulus duration

Results of the effect of signal duration on word identification are presented in Figure 2. An inspection of the figure indicates that:

1. increasing duration generally reduces thresholds in both noise and blank field conditions;

2. controls and dyslexics differ only in the case of short signal durations.

A three-way ANOVA on log contrast thresholds was carried out with group (controls, dyslexics) as unrepeated factor and signal duration (200 ms, 2000 ms) and noise (present, absent) as repeated factors. Effects of the group ($F_{(1, 8)} = 14$, $p < 0.01$), signal duration ($F_{(1, 8)} = 268.84$, $p < 0.0001$), and noise ($F_{(1, 8)} = 250.52$, $p < 0.0001$) factors were all significant. The group by signal duration interaction was significant ($F_{(2, 8)} = 22.05$, $p < 0.005$). *A posteriori* Sheffe revealed that dyslexics and controls differed at short ($p < 0.0001$) but not at long signal durations. The signal duration by noise interaction ($F_{(2, 8)} = 12.96$, $p < 0.01$) was significant, indicating a greater effect of noise on short than on long durations for both groups. No other interactions were significant ($F < 1$).
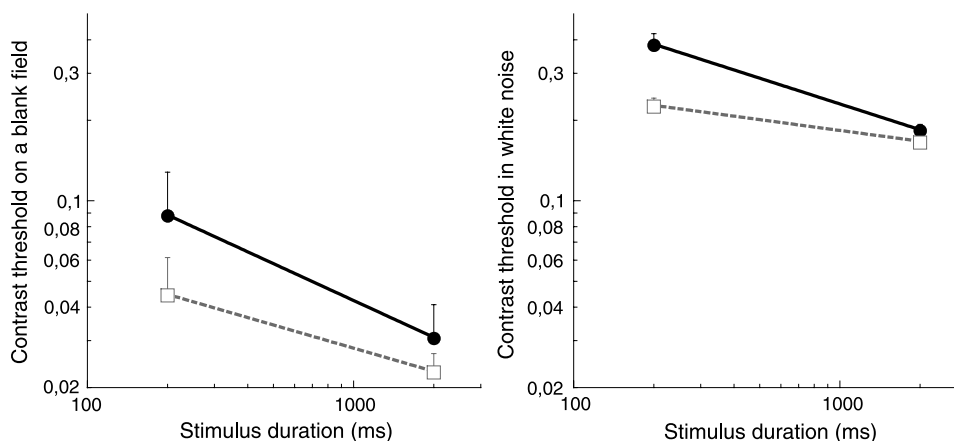

Figure 2. Contrast thresholds as a function of two stimulus durations (200 and 2000 ms) for identifying ten-letter words presented on a blank field (left) and in white noise (right) in central vision. The graphs show the geometric means and standard deviations of the contrast thresholds for dyslexics (filled circles) and controls (open squares).

Comments

Contrast thresholds for single-letter identification were similar in dyslexics and age-matched controls; however, dyslexics' thresholds were higher when they had to identify long words. By contrast, identifying long words only mildly affected the performance of controls. This indicates that controls easily identify meaningful long stimuli at 200-ms presentation duration.

The pattern of results with a blank field presentation remained the same when noise was added to the display. Manipulations that lead to changes in contrast threshold for white noise versus blank field presentations point to the role of different levels of internal noise in determining the group differences (Pelli & Farell, 1999). The lack of difference between groups for single letters without noise (and with noise) suggests that dyslexics do not have higher neural noise than controls; also, dyslexics' impairment on words is roughly the same in white noise and in a blank field. Thus, it appears that this latter group uses the information present in the stimuli less efficiently than good readers.

The impairment observed for words is selective for the short signal duration condition. Increasing the stimulus duration by a factor of ten facilitates the task for both controls and dyslexics, and at long durations the threshold difference between groups washes out. This indicates that dyslexics are penalized at short durations allowing a single fixation but are able to extract the useful features to perform the task at a level of contrast comparable to that of controls when enough time is provided.

The dyslexics' impairment at short presentation durations might also indicate differences at a linguistic level. These could reflect damage in accessibility to the lexicon and/or could be the consequence of an impoverished structure of the mental lexicon, possibly due to the dyslexics' lack of experience. Future research is needed to assess this issue. Note that in the present study we minimized the role of differences in lexical competences using a matching paradigm with a limited set of words.

Overall, the results indicate that dyslexics are selectively impaired when they have to identify more than one letter in a glimpse. This result is compatible with the hypothesis of abnormal crowding in dyslexia.

Experiment 2: Dependency of critical spacing on eccentricity and size

The proportional scaling of critical spacing as a function of eccentricity is a feature of crowding. In Experiment 2, we used a flanked letter identification task to examine the dependency of critical spacing on eccentricity. In dyslexics, abnormal crowding may affect identification in two non-alternative ways: critical spacing may be larger at all eccentricities, it may scale with eccentricity (with a greater proportionality than in controls), or both phenomena may be present. Thus, exploring this issue was the first goal of the experiment.

To measure critical spacing, Pelli, Levi, et al. (2004) measured the contrast threshold for target identification as a function of the space between the target and the flankers. Contrast threshold drops with increased spacing and then flattens out. The authors defined critical spacing as the knee of this function. Due to the relatively short time available with the children, we adopted a faster procedure and measured the center-to-center distance between the target and the flankers needed to make 95% correct identifications (from now on critical spacing or CS).

Crowding and masking are both sensitive to eccentricity. Pelli, Levi, et al. (2004) investigated the kind of process impaired by crowding and distinguished it from masking. In crowding, the object remains visible but is unrecognizable; in masking, the object disappears. Masking describes the early feature detection stage and crowding acts at the level of feature integration (Parkes, Lund, Angelucci, Solomon, & Morgan, 2001; Pelli, Levi, et al., 2004). One critical feature that distinguishes between crowding and masking is the dependence of critical spacing on size and eccentricity: masking depends on size and crowding is independent of it. Overall, the proportional dependence of critical spacing on eccentricity, independent of signal size, is diagnostic of crowding (Pelli, Levi, et al., 2004). Based on these findings, we hypothesized that if the limitation in the dyslexic group was due to crowding, not visual masking, critical spacing in the periphery would be independent of letter size. Clarifying this point was the second goal of Experiment 2.

Methods

Participants in Experiment 2

The entire group of 29 dyslexics participated in the experiment; 32 normal readers, selected from the 33 controls, also took part in the study.

Apparatus and stimuli

The same apparatus described for Experiment 1 was used in this experiment.

The fixation point was a 0.15-deg black square. The signals were presented in the right visual field on the horizontal meridian and the fixation point was positioned at half of the letter x-height above the baseline of the text. The signal was always displayed in the center of the screen; the viewing eccentricity of the signal was determined by the location of the fixation point.

The signals were high contrast (90%) letters written in Courier uppercase font, drawn in gray on a white

background. In each trial, letter triplets were randomly chosen from a set of 10 alternatives (AEMNCRSUVZ) so that they were not the same as the central target letter. In separate conditions, each letter subtended 1 and 3 deg.

Procedure: Critical spacing

The center-to-center distance between the target letter and the two flanker letters was systematically varied to obtain an estimate of the critical spacing (CS), at which 95% of the correct responses were made, i.e., discrimination of the target letter among the flankers. The same procedure adopted for the contrast threshold measurements in Experiment 1 was used. In this case, QUEST controlled the distance between letters.

The fixation point remained on the screen for the entire duration of the trial. The stimulus appeared 200 ms after the fixation point and remained on the screen for 200 ms. Similar to Experiment 1 after a 200-ms delay a response screen was presented. The observers were instructed to choose among the alternatives, indicating to the experimenter the identity of the central letter in the triplet. The experimenter recorded the response by pressing the corresponding key. Stability of eye fixation was monitored visually by a second experimenter; the trials in which the eyes moved were rejected by pressing a key on the keyboard; a new trial was given to the observer.

The CS was measured at four different stimuli positions along the horizontal meridian in the right visual field: 4, 8, 10, and 12 degrees from the fovea. To evaluate the effect of size, the CS was measured for the same triplets at two stimulus sizes, that is, 1 and 3 degrees. This measurement was taken at 8 degrees of eccentricity.

Data analysis

For each subject, the slope of the function relating CS and eccentricity was evaluated based on a linear fit of the raw data on target letter identification. All observers (29 dyslexics and 32 controls) were tested at eccentricities of 4 and 8 deg. Thirteen dyslexics were also tested at eccentricity 10 and twelve at eccentricity 12; five controls were tested at eccentricity 10 and twenty-one at eccentricity 12. The results of the individual fits (slope, intercept) of controls and dyslexics were compared by means of Student's t.

To examine individual differences, we used the procedure proposed by Crawford and Garthwaite (2004). A point estimate of the abnormality of the slope of each individual dyslexic with respect to the control group as well as of the percentage of the population that would obtain a lower slope was computed. This statistic requires that the error variances within the reference group be treated as equivalent; it was verified using Bartlett's test. When the error variance of the individual dyslexics was significantly different from that of controls, the Satterthwaite test was

applied; otherwise, the data were analyzed with Crawford and Howell's test (for details on the procedure, see Crawford & Garthwaite, 2004).

We calculated b_e values (CS/eccentricity) for each individual; this allows for a statistical analysis of the variance, while the physiologically large change of CS with eccentricity would mask all other effects. To evaluate group differences, comparisons on b_e values were carried out for the two eccentricities for which all data points were available (4 and 8 deg); the ANOVA had group (controls, dyslexics) as unrepeated factor and eccentricity (4, 8 deg) as repeated measure.

To evaluate the presence of group differences on the effect of size on CS, an ANOVA with group (18 controls, 20 dyslexics) as unrepeated factor and letter size (1, 3 deg) as repeated measure was carried out.

Results

Effect of eccentricity

Figure 3 shows the critical spacing for flanked letter identification as a function of eccentricity. Individual CSs are presented for controls (left) and dyslexics (right). The mean linear fits are also shown in the figure. Bouma's law prediction ($b = 0.5$: CS/eccentricity) is shown as a solid gray line.

An inspection of the figure indicates that:

1. CSs in controls increase with eccentricity, with a proportionality close to Bouma's law prediction.
2. CSs in dyslexics are larger and more variable at all eccentricities than those of controls, on average increasing with a greater proportionality than Bouma's constant b.

CSs were larger for dyslexics than controls at all eccentricities tested (eccentricity 4 deg: $t = 2.29$, $p < 0.05$; eccentricity 8 deg: $t = 3.57$, $p < 0.005$; eccentricity 10 deg: $t = 2.14$, $p < 0.05$; eccentricity 12 deg: $t = 2.8$, $p < 0.01$).

The mean intercept was -1.12 deg ($SD = 3.6$) for dyslexics and -0.59 ($SD = 1.98$) for controls (the two means were not different: $t = -0.71$, n.s.). The mean slope of the linear fit (b) was 0.95 ($SD = 0.59$) for dyslexics and 0.62 ($SD = 0.3$) for controls ($t = 2.78$, $p < 0.01$). Overall, CS at all eccentricities tested and mean b of the two groups were different, with dyslexics having higher values.

Using Crawford and Garthwaite's (2004) procedure, 35% of the dyslexics obtained a significantly higher slope than controls ($t > 1.6$, $p < 0.05$); 60% of the dyslexics left 85% of the normal reader population below their slope.

Pelli et al. (2007) showed that in normal readers there are large individual differences in the way b varies with eccentricity (see their Figure 9): one observer conformed to Bouma's prediction, that is, with b of equal value at all
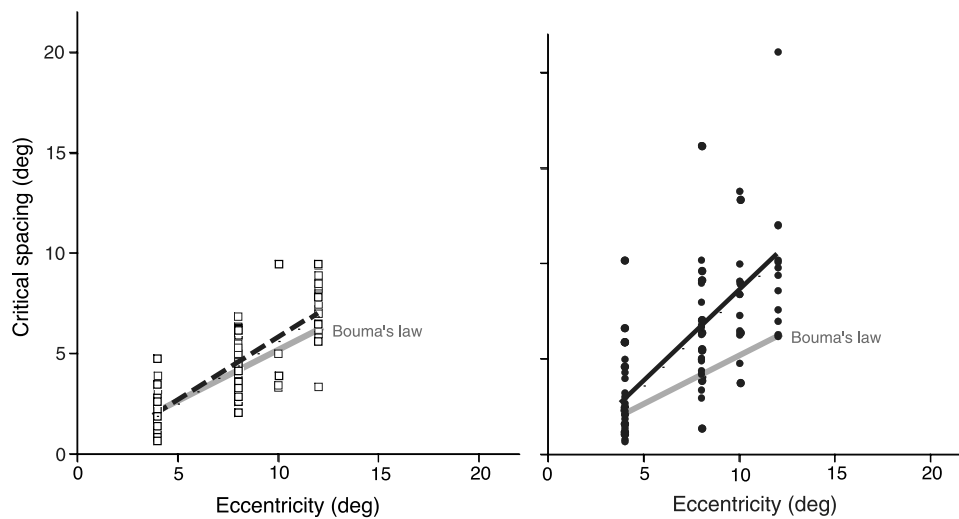
Figure 3. Flanked letter identification task. Individual CSs as a function of eccentricity for controls (left) and dyslexics (right). The black lines represent the mean of the individual linear fits (median R^2 of 0.97 and 0.98 for controls and dyslexics, respectively). The prediction, based on Bouma's constant b = 0.5, is shown in solid gray.

eccentricities, another observer showed a steep increase of b with eccentricity, whereas the remaining observers showed a modest increase. The authors concluded that in order to obtain a model for critical spacing it must be considered that b has a linear dependency on eccentricity, which is subject to individual differences.

Values of b_e (CS/eccentricity) for each observer are plotted in Figure 4 as a function of eccentricity. Inspection of the figure indicates that many observers (7 dyslexics and 11 controls) conform to Bouma's prediction of constant proportionality, as shown by their nearly flat function; few have a b_e value that increases rapidly with eccentricity (4 dyslexics and 1 control), and most of the observers have a modest non-zero slope, as shown by Pelli et al. (2007). Unlike Pelli et al.'s (2007) findings, in this

study four dyslexic subjects showed a marked reduction of b_e with eccentricity, that is, their critical spacing was disproportionately large at 4 deg relative to their impairment at larger eccentricities. It seems that parafoveal information is particularly damaged relative to information at larger eccentricities; the latter plays a less relevant role in reading single words. Consistently, three of the four children were the slowest readers of the entire group when evaluated with the words/non-words screening test. Nonetheless, caution must be taken not to over interpret the individual differences found in these data. Compared with Pelli et al.'s (2007) results, these b_e values, which are based on fewer measurements, are considerably variable. It is also possible that the 95% threshold criterion might have produced unwarranted noisiness in the measure.
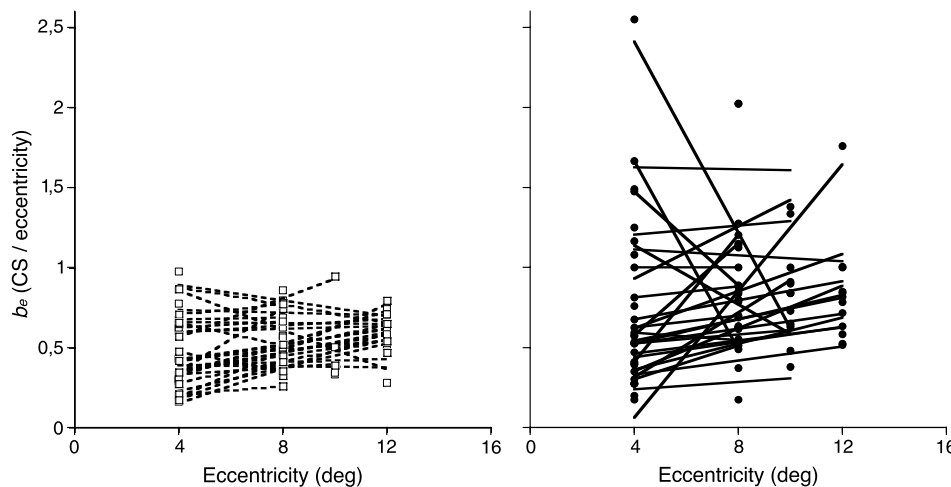

Figure 4. Individual b_e (CS/eccentricity) as a function of eccentricity for controls (left) and dyslexics (right). Non-zero slope data violate Bouma's prediction that b is a proportionality constant. Note that when b_e values are greater than 1 the leftmost flanker at the spacing threshold is located in the contralateral hemifield relative to the target.

Overall, the two groups did not significantly differ in the slope of the function relating b_e with eccentricity ($t = 0.10$; n.s.).

The two-way ANOVA on the b_e values revealed a main effect of group ($F_{(1, 59)} = 12.65$, $p < 0.001$): for controls' mean $b_e = 0.51$; for dyslexics' mean $b_e = 0.78$. No effect of the eccentricity factor ($F_{(1, 59)} = 1.44$, n.s.) or of the group by eccentricity interaction were found ($F_{(1, 59)} < 1$). Note that the dependency of b_e on eccentricity bends the curve relating CS to eccentricity. Thus, the estimates of b and b_e are not equivalent; both b and b_e are larger in dyslexics than controls.

Effect of size

The main results of the influence of letter size on CS are presented in Figure 5. The accuracy of letter identification within flankers was measured at 8 deg of eccentricity. An inspection of the figure indicates that CS (which is greater for dyslexics than controls) is independent of letter size for both groups.

The two-way ANOVA on the CS values indicated a main effect of group ($F_{(1, 36)} = 13.24$, $p < 0.001$). The letter size factor ($F < 1$) and the group by letter size interaction ($F < 1$) were not significant.

Comments

In order to identify a letter in the peripheral visual field at the same criterion level as controls, dyslexics needed larger spacing (a factor of about 1.5) between the target letter and the flankers. Indeed, the critical spacing was larger in dyslexics at all eccentricities tested. Also, it
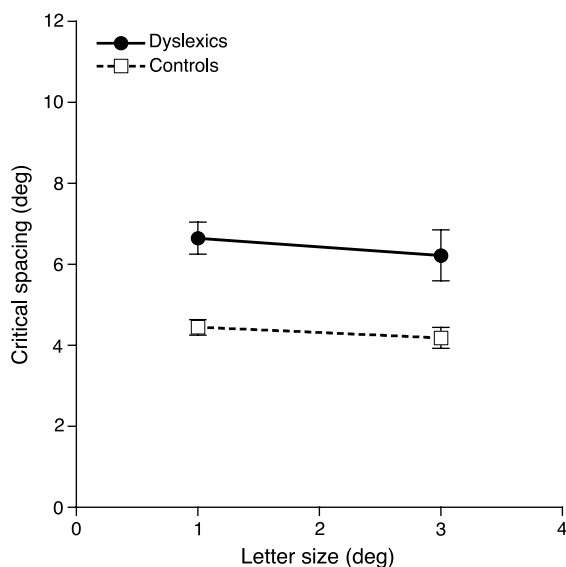

Figure 5. Flanked letter identification task. Mean (and *SD*s) of CS at 8 deg eccentricity as a function of letter size for dyslexics (filled circles) and controls (open squares).

scaled with eccentricity, with a larger proportionality (b) in dyslexics (0.95) than controls (0.62). These findings are consistent with the view that dyslexia is associated with abnormal crowding in the periphery. Notably, individual differences in b were quite large in both controls and dyslexics.

Consistent with previous observations (Pelli, Levi, et al., 2004), CS was independent of letter size in both groups of subjects. In particular, increasing letter size did not reduce the CS deficit in dyslexics. This finding reinforces the view that crowding, not masking, limits the identification capability of dyslexics, as already shown in good readers (Pelli et al., 2007).

Experiment 3: Reading rate as a function of print size

In Experiment 3, we measured reading rate for long words as a function of print size. Reading rate improves with print size up to a critical point and then flattens out (Chung et al., 1998; Legge et al., 2001). Increasing print size modifies both letter size and letter spacing (center to center); however, based on previous findings (Pelli et al., 2007; Strasburger et al., 1991) we know that only the latter affects crowding. If the reading rate limitation of dyslexics is due to crowding, they should reach their maximum reading rate at a larger print size (i.e., at larger spacing) than the control group.

The second part of this experiment was to evaluate how close the reading rate of dyslexics is to that of controls when crowding is compensated for. In the case of amblyopics, compensation is sufficient for them to reach the same reading rate as controls. However, the developmental nature of the reading disturbance of dyslexics may be critical here. Although amblyopics show a fast reading rate limited to the normal eye, dyslexics' reading is typically slow. Previous data on vocal RTs (Spinelli et al., 2002) and on maximum reading speed (O'Brien et al., 2005) indicated the presence of only partial compensation in children with dyslexia. However, in light of recent findings by Pelli et al. (2007) and Levi et al. (2007) it is crucial to compare critical spacing (Experiment 2) with reading rate data (Experiment 3) to account for the reading deficit in developmental dyslexia.

Methods

Participants for Experiment 3

Thirteen dyslexics and 16 controls recruited from the larger samples participated in the experiment. The mean ages of the subgroups did not differ from those of the total group ($t < 1$).

Apparatus and stimuli

The same apparatus used in the other experiments was adopted in this one.

The fixation point was defined by two small black squares that appeared above and below the center of the word. The fixation point was always present on the screen.

Words stimuli were gray high contrast (90%) signals drawn on a white background. Words were written in Courier uppercase font. Letter size was varied (from 0.1 to 2 deg) to measure the CPS. All subjects were tested with 4 print sizes. In order to have at least two data points in the sloping part of the function, sizes varied slightly across observers. Four morphologically simple lists of noun, balanced for frequency of the words read/written by the children (6 to 9 letters long), were created from a database of 626 words (Barca, Burani, & Arduino, 2002) containing 400 words of the appropriate length. Each list was comprised of 160 words; thus, in order to obtain 4 sets of stimuli, 37% of the words in each list were repeated. The association between the letter size tested and the word list was randomized for each participant. Four different sets of words were generated randomizing the words within each list. Each observer saw one of the four possible randomizations.

Procedure: Reading rate

Reading rate was measured using the Rapid Serial Visual Presentation (RSVP) procedure, which minimizes the need for eye movements (Potter, 1984). In each trial 10 words were presented centrally, one word at a time. When observers were ready, they started each trial by clicking the mouse. Participants were instructed to read the words aloud as quickly and correctly as possible. There was no time limit for completing the response. Reading rate (the rate at which the words were presented) was measured in a 16-trial run, using a criterion level of 75% correct. The observer's reading performance was recorded. At the end of each trial, the experimenter counted the words read incorrectly by comparing the participant's production with the stimuli list printed in the random order presented. Accuracy was computed regardless of word order. QUEST increased or decreased the presentation rate according to the observer's level of responding. Omissions, mispronunciations, and substitutions were considered errors. Reading rate was measured as a function of letter size, ranging from 0.1 to 2 deg, in separate runs.

Data analysis

All observers were tested at four print sizes, which ranged from 0.1 to 2 deg. For each observer, we plotted reading rate (wpm) as a function of character size. The Levenberg–Marquardt algorithm, based on Chi Square values, was used to fit a two-limb function (two straight lines in log–log coordinates) to each set of data, with the slope of the second line set to zero. In each individual plot the intersection of the two lines provides an estimate of critical print size, whereas the flat portion represents maximum reading speed above the critical print size. To test the model, four data points for the two-line fit are at the lower limit. In any case, the two-limb function provided a good fit for both controls (R^2 ranging from 0.73 to 0.99) and dyslexics (R^2 ranging from 0.78 to 0.99). To evaluate group differences, the critical print sizes were compared by means of Student's ts.

The relationship between the maximum reading rate (ceiling of the two-line fit) and critical print size (knee of the fit) was examined by simple linear regression.

To explore the relationship between reading performance and crowding range, the maximum reading rate (Experiment 3) and the b_e values (Experiment 2) were submitted to a linear regression analysis.

Results

Reading rate and the effect of print size

The main results of the effect of increasing letter size on reading rate are presented in Figure 6. The average two-line fit is shown as a black line. An inspection of the figure shows that:

1. reading rate improved with letter size for each individual up to a maximum;
2. critical print size (the knee of the function) defined the size requirement to obtain the maximum reading rate; it was larger for dyslexics than controls;
3. regardless of critical print size, the maximum reading rate of dyslexics remained lower than that of controls.

A two-line model was fit to the reading rates of each observer (not shown in the figure) to obtain an estimate of CPS and the maximum reading rate for each individual. The geometric mean of the critical print size was significantly larger in the dyslexic (0.34 deg) than the control group (0.21 deg; $t = 3.13$; $p < 0.005$).

Figure 7 (left panel) reports the line fit of dyslexics from Figure 6 (right panel). We also added the estimated value of the controls' periphery reading curve. Chung et al. (1998) found that moving from the fovea to the periphery the shape of the RSVP function remains unaltered, but the CPS and the maximum reading rate change with a proportionality constant. E_2 is the rate of change of the variable of interest as a function of eccentricity. The authors found an E_2 value of 1.4 deg for critical print size (changing rapidly with eccentricity) and one of 4.14 for maximum reading rate (changing slowly with eccentricity). We used the E_2 values found by Chung et al. (1998)
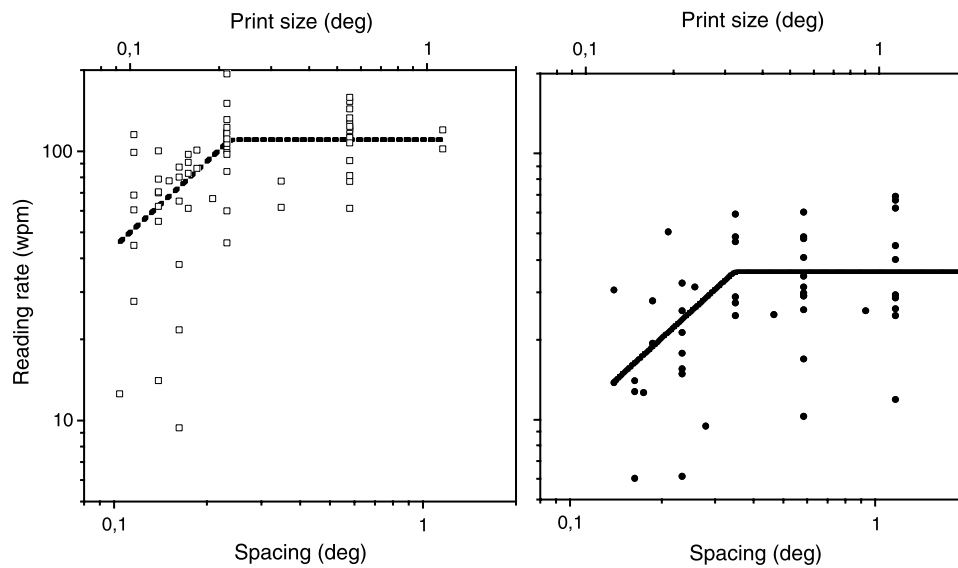
Figure 6. Reading rate in central vision as a function of spacing (bottom axis) and print size (top axis) for the control group (left panel) and the dyslexic group (right panel). The average fit through the data is shown. The individual fits are not shown but provided the parameters that entered the data analysis.

and moved the curve obtained by the control group (Figure 6, left panel) close to the one obtained by dyslexics using the formula

$$T = T_0 * \left(1 + \frac{Ecc}{E_2} \right), \qquad (1)$$

where T is either the CPS or the word exposure duration, T_0 is the CPS or the duration for maximum reading rate obtained in the fovea (from Figure 6), Ecc is the eccentric viewing position (which was set to 2 deg), and E_2 is the Chung et al. constant. The solid gray area represents the

spread of control data moved to the periphery, that is, the results of this calculation performed on the foveal data ± 1 *SD* The figure shows that for print sizes smaller than critical ones, dyslexics' reading rate in the fovea is similar to that of normal readers at 2 deg of eccentricity, that is, the solid curve lies within the gray area. When print size is larger than critical, dyslexics' reading in the fovea is slower than that of controls at 2 deg of eccentricity.

In Figure 7 (left panel) the dyslexic group is modeled as having crowding characteristics similar to those at a normal periphery of 2 deg, assuming there is homogeneity within the dyslexic group. However, although 2 deg is a good
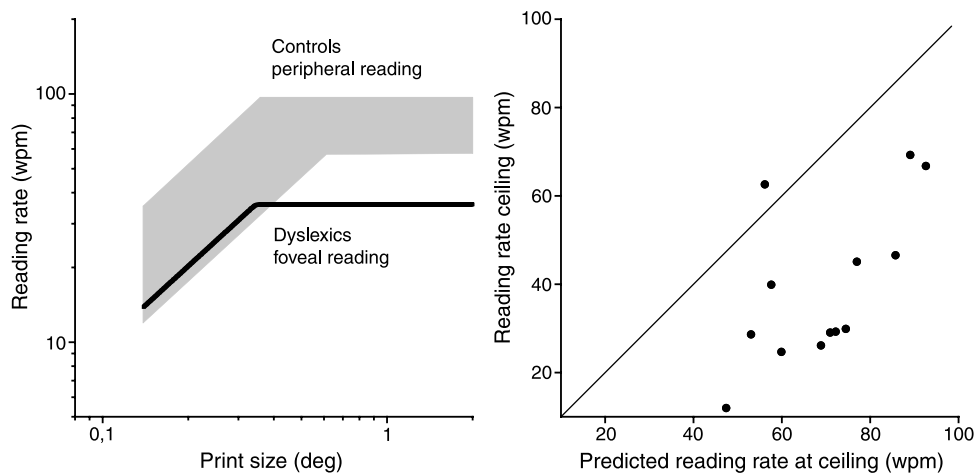

Figure 7. *Left panel*: The mean fit for dyslexics (solid line) from Figure 6 (right panel). The solid gray area results from the convolution of the fit line for control subjects (left panel of Figure 6) ± 1 *SD* and proportionality indexes E_2 for CPS and maximum reading rate derived from Chung et al. (1998). The proportionality indexes were selected to simulate peripheral reading at 2 deg of eccentricity. *Right panel*: The maximum reading rate measured in individual dyslexics as a function of the reading rate predicted by the peripheral model. Predictions derive from controls' reading rate modeled at the specific eccentricity to match individual dyslexics' CPS.

choice for the average CPS data, individual differences in CPS are quite large in the dyslexic group. Figure 7 (right panel) reports these individual differences. The figure was obtained using the controls' foveal data, shifted in the periphery according to Chung et al.'s (1998) constants and using an eccentricity chosen to match the CPS of each individual dyslexic. As a consequence, the reading performance of each dyslexic is predicted based on variable eccentricities. The figure shows the maximum reading rate measured in each dyslexic as a function of the reading rate predicted by this transformation. With the exception of one observer, all data points fall below the equality line, indicating that the peripheral reading model overestimates the maximum reading rate by about 30 wpm; therefore, it accounts for about 60% of the dyslexic deficit.

Comments

For all observers, the reading rate increased with print size up to a maximum. In dyslexics, the fastest rate was obtained at a significantly larger character size than in controls.

Manipulating character size changes letter spacing, which, in turn, affects crowding. If dyslexics suffer from abnormal crowding, it would follow that they need a larger print size to obtain their maximum reading rate. Indeed, larger print size (spacing that exceeds critical spacing) improves dyslexics' reading rate. Nevertheless, even with larger print sizes dyslexics still showed slower reading rates (ca. 40 wpm) than controls (ca. 110 wpm).

In light of Chung et al.'s (1998) results, the present data suggest that the peripheral reading of normal readers may be a model for dyslexic reading, at least up to the critical print size, where crowding is the limiting factor. However, the maximum reading rate remains below the predicted values. This outcome is substantially different from what was observed for amblyopic reading (Levi et al., 2007). An interpretation based on a developmental learning effect will be discussed below.

General discussion

Assessing the level of the deficit in dyslexia

Reading is a complex task involving visual, phonological, and linguistic aspects. Reading deficits, such as developmental dyslexia, may be due to impairments at all of these levels. In the present study, we focused on the part of the deficit that can be defined as perceptual and we found that abnormal crowding accounts for 60% of dyslexics' slow reading. This percentage, obtained in a group of native speakers in a transparent orthography, may not apply directly to opaque orthographies, where phonological deficits may be prominent (for a review, see Vellutino et al., 2004).

Our goal was to evaluate the deficit at one or more specific stages of perceptual processing. Experiments 1 and 2 allowed excluding differences in early visual processing between dyslexics and controls. In Experiment 1, there was no difference between groups in the contrast threshold for single letters centrally viewed; moreover, adding noise to the target (letters or words) elevated thresholds to a similar extent in both groups. In Experiment 2, the critical spacing (CS) for high-contrast flanked letter identification was independent of size in both groups.

Large differences between groups were present when the task involved letter strings. More contrast was necessary to allow word identification in central vision (Experiment 1); more space between the flankers and the target was necessary to allow target identification at all eccentricities, that is, the CSs were systematically larger in dyslexics (Experiment 2).

These results (a) allow excluding differences between dyslexics and controls at the level of the letter identification threshold and (b) indicate that the larger CSs measured in dyslexics cannot be explained at the level of masking; moreover, they (c) exclude the presence of higher internal noise in dyslexics. By contrast, the data point toward a deficit in processing strings of letters, evident at both threshold and supra-threshold levels. Thus, dyslexics do not have an early visual deficit in processing information but in *integrating information* across the visual field. In particular, dyslexics appear to integrate information over a larger region of the visual field than control readers. In fact, such excessive feature integration impairs recognition of the target object (Pelli et al., 2007).

The use of a standard psychophysical approach (Experiment 2) allowed testing the predictions on crowding based on Bouma's law for the first time in dyslexics. CS was larger in dyslexics than controls at all eccentricities, and the much steeper slope of the CSs vs. eccentricity function in dyslexics indicated the presence of abnormally higher crowding in this group. This confirms and extends the findings of previous studies showing the detrimental effect of closely spaced flankers on the orthographic recognition of dyslexics in terms of accuracy (Atkinson, 1991; Bouma & Legein, 1977) or vocal RTs (Spinelli et al., 2002). We observed large individual variations of b_e in both controls and dyslexics, in keeping with the notion of individual differences in Bouma's constant recently reported by Pelli et al. (2007).

Crowding, exposure time, and the effect of word length

The presence of abnormally high crowding may be crucial for interpreting the poor contrast threshold for word identification of dyslexics and the modulation of this performance by exposure time. Performances on briefly presented words revealed large differences between groups. Indeed, dyslexics were impaired when they had

to process several letters in a limited amount of time. Nevertheless, differences washed out when longer exposure was allowed (Experiment 1). When they measured reading rate for random printed words at different contrasts in unconstrained time conditions, O'Brien, Mansfield, and Legge (2000) found that although dyslexics were slower readers (about 50 wpm, i.e., 1 second per word) they obtained the same critical contrast as controls. This is in keeping with the idea that allowing more than one fixation on the word eliminates contrast threshold differences between groups.

Crowding impairs letter-string identification more and more the greater the distance from the fovea. Increased crowding hampers reading performance, particularly in the case of long words extending further into the visual periphery. In order to reduce the effect of crowding in any given fixation, dyslexic observers can limit their analysis to relatively short word segments. Then, they integrate the information obtained from a (large) number of eye fixations over time. Eye movement studies document the large increase in the number of saccadic eye movements of these children (De Luca et al., 1999, 2002; Hutzler & Wimmer, 2004). Overall, crowding limits the number of recognizable letters in a word; abnormally high crowding in dyslexics reduces the number of available letters and requires a corresponding increase in the number of eye fixations. Thus, the number of eye fixations may be considered inversely proportional to the visual span, or the uncrowded span (Pelli et al., 2007). The robust length effect generally observed in Italian dyslexics can be explained by this mechanism.

Besides spatially sensitive mechanisms, the reading slowness of dyslexics might also depend on deficiencies in temporal processing (for a review, see Farmer & Klein, 1995). Indeed, some of the evidence in our study is broadly consistent with this view; namely dyslexics were impaired in short but not long presentations (Experiment 1). Nevertheless, the small sampling of exposure durations is insufficient for evaluating the characteristics of slower information processing in dyslexics; indeed, further work is needed on this topic.

Is the reading rate in dyslexics predicted by crowding?

According to Pelli et al. (2007), Legge's visual span (Legge et al., 2001) corresponds to the number of uncrowded letters; both critical print size and maximum reading rate as a function of eccentricity can be predicted by crowding.

Experiment 3, which measured RSVP reading rate as a function of print size, allowed bridging crowding with functional reading in dyslexics. The critical print size for obtaining the maximum reading rate was larger for dyslexics than controls, indicating abnormal crowding.

However, despite the use of very large print sizes, which were effective in compensating crowding, dyslexics' reading rate remained below that of control subjects by about 70 wpm. Note that similar results for dyslexics have been reported by other authors (O'Brien et al., 2005). At face value, this latter result seems to contrast with the general rule proposed by Pelli et al. (2007) for good readers, that is, crowding, and only crowding, limits reading in peripheral and central vision.

To evaluate whether the individual maximum reading rate is predicted by crowding (Pelli et al., 2007), in Figure 8 we plotted the individual reading rate measured in central vision (Experiment 3) as a function of individual b_es (Experiment 2).

Inspection of the figure shows that there is a linear relation between log maximum reading rate and log b_e. When all subjects are considered, the correlation analysis is significant ($r(29) = -0.60$, $p = 0.0004$); the correlation holds for dyslexics ($r(13) = -0.61$, $p = 0.027$), but not for controls ($r(16) = 0.25$, n.s.). The lack of correlation in controls might be due to the smaller spread of performances, possibly reflecting achievement of a near-optimal reading strategy.

Overall, in agreement with the general rule (Pelli et al., 2007), individual b_e predicts the maximum reading rate achievable by each dyslexic subject. On the other hand, it is also evident (Figures 6 and 7) that at print sizes larger than critical sizes the reading rate remains lower than normal and that abnormal crowding is not the only factor accounting for the reading deficit in developmental dyslexia. For a better understanding of these results, it may be useful to compare the dyslexics' data with those of the amblyopics.
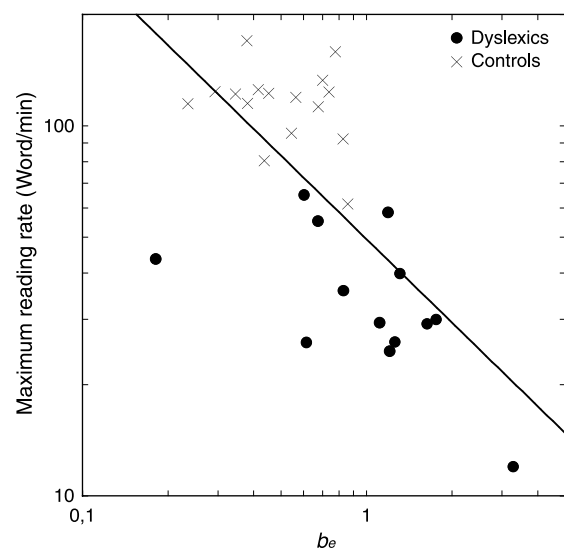

Figure 8. Individual maximum foveal reading rate as a function of b_e (CS/eccentricity) for dyslexics (filled circles) and controls (x symbols) measured in the present study.

Comparison between dyslexics and amblyopics

The data presented in Figure 6 were replotted in Figure 9 to compare dyslexics and controls with the data of amblyopics taken from Table 2 of Levi et al.'s (2007) work.

The maximum reading rate of amblyopic eyes is comparable to that of non-amblyopic eyes, once crowding is compensated, by increasing the print size beyond CPS. The reading rate values collected in non-amblyopic eyes and amblyopic eyes compensated for crowding are also close to the reading rate measured in controls in the present study. By contrast, as noted above, for dyslexics print-size compensation is not sufficient to reach controls' reading rate. Performance is lower by a factor of two with the largest (and saturated) print size used. O'Brien et al. (2005) reported that the maximum reading rate of dyslexics was ca. 30% slower than that of controls (controls were younger than dyslexic children, that is, they were not age-matched, as in the present study, but were matched for reading single words).

The failure to reach a normal reading rate, despite compensation for crowding, seems to be a specific feature of dyslexic children. Enlarging the text size cures amblyopic but not dyslexic reading. This may be due to three, non-alternative and perhaps additive, causes. First, the critical spacing for the amblyopic eye in the periphery is normal, and the abnormal crowding only affects letters located close to the fovea. By contrast, abnormal crowding affects both the fovea and the periphery of dyslexics. Second, fast reading is an overlearned process. Developmental changes in the visual span for reading, mostly
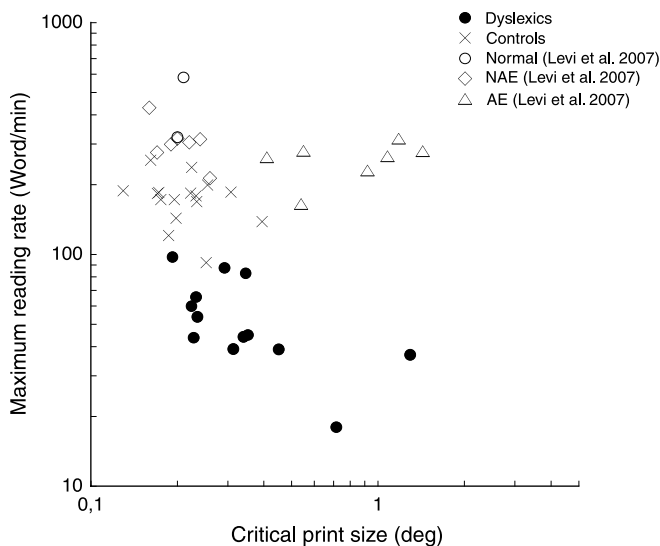

Figure 9. Individual maximum reading rate (as a function of critical print size) achieved by dyslexics (filled circles) and controls (x symbols) in the present study and by amblyopic eyes, non-amblyopic eyes, and normal adults in Levi et al. (2007).

explained by sensory factors, have been documented from third to seventh grade and into adulthood (Kwon, Legge, & Dubbels, 2007). Subjects with one amblyopic eye have long experience reading through the other, good eye. Once normalized for stimulus characteristics that compensate for crowding, the input from the amblyopic eye is efficiently processed by a trained reading mechanism, which is beyond the level of binocular convergence. By contrast, dyslexics do not have a well-trained mechanism for reading. In fact, the expectation that compensating for abnormal crowding will immediately compensate for the reading deficit in dyslexia is implausible in a developmental perspective: when the cast that constrained the leg is removed, one can hardly walk let alone run. Third, part of the dyslexics' reading slowness could be due to linguistic not perceptual factors, a possibility not formally evaluated in the present study. Future research should evaluate whether reading is still slower in children with dyslexia when lexical factors are controlled for.

Overall, amblyopic reading is not a good model for dyslexic reading.

Peripheral reading in good readers: Analogy with dyslexia

Proficient readers' peripheral reading might be a good model for dyslexia (see Figure 7). Moving from the fovea to the periphery, the reading rate drops and CPS increases, as it does when comparing normal and dyslexic reading in central vision. Using the normal periphery to model dyslexic reading, we were able to account for about 60% of the dyslexics' deficit. In this study it is not possible to exclude that linguistic factors, such as lexical competence, may contribute to explaining the remaining difference. However, note that O'Brien et al. (2005) compared dyslexics and reading age-matched controls (i.e., who were matched for single word reading performance) and found similar results. Moreover, similarly to what we observed here in dyslexics, Pelli et al. (2007) showed that even taking into account the linear dependency of b_e on eccentricity, subject to individual variations, crowding falls too short in predicting the reading rate drop with eccentricity. Thus, in both cases we observed a failure to achieve optimal reading fluency, even after compensating for crowding.

In the attempt to interpret dyslexic and peripheral reading, we would like to stress the *long-term tuning* of the mechanisms underlying reading. Kwon et al. (2007) described the development of visual span from 3rd to 7th grade and to adulthood, which is mostly attributable to sensory aspects mediated by practice. Pelli et al. (2006) showed that a few thousand trials are sufficient to reach optimal efficiency for letter identification with novel alphabets; however, the memory span for several characters develops more slowly. Reading is so difficult and

painstaking for dyslexics (and crowding may play an important role here) that they normally avoid it as much as possible. Therefore, lack of training may contribute to their reading slowness. In proficient readers, only a small portion of the periphery close to the fovea is regularly trained in reading, and failure to reach foveal reading speed in the periphery, after controlling for crowding, might be due to lack of practice with this type of stimuli. In this vein, the dyslexics' failure to reach the controls' reading speed (once crowding was removed) and the good readers' failure to read fluently in the periphery (even when crowding was compensated for) should both be due to lack of specific training.

There is some evidence for the existence of spatially selective learning mechanisms. For example, the length effect is nearly absent in adult readers but reappears if words are presented in unusual formats, such as vertically or confined to the left visual field (Lavidor & Ellis, 2002). Furthermore, Chung (2002) reported failure in transferring foveally learned new characters to the periphery (Chung, 2002). Consistent with the idea that lack of training can be crucial in explaining reading performance once crowding has been removed, experiments studying the effect of practice show that reading speed improves in the periphery. Short training (ca. 6 days) with trigrams and letters displayed in the periphery produces an increase in reading speed, which varies from 40% to 7% (Chung, 2007; Chung, Legge, & Cheung, 2004). In dyslexics, small but reliable improvements were observed after training undertaken to enlarge their visual span (e.g., Judica, De Luca, Spinelli, & Zoccolotti, 2002). Nevertheless, the time constants to reach the normal values are expected to be very long, in the order of 12 years (Carver, 1990), and clearly out of the range of most experimental studies.

Summary

Reading involves visual, phonological, and linguistic processing, and there is a long debate over the contribution of purely visual factors to reading. The present study focuses on this latter aspect and shows that dyslexics are limited by crowding. The properties of the phenomenon place the perceptual deficit at the level of letters integration for word recognition. Using the normal periphery as a model for dyslexia, we accounted for 60% of the reading slowness. Compensating for crowding improves the reading rate of dyslexics but not to the level of skilled readers. It is hypothesized that for dyslexics to reach a fast reading rate perceptual learning must take place over a long period of training.

While in these children perceptual limitations due to crowding may be present across different visual stimuli, the dependency of reading upon the identification of parts and the high density of the visual array in reading place the deficit in the identification of orthographic material in the foreground.

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