Intact crowding and temporal masking in dyslexia

Adi Doron
The Edmond & Lily Safra Center for Brain Sciences (ELSC), Hebrew University, Jerusalem, Israel

Mauro Manassi
Laboratory of Psychophysics, Brain Mind Institute, Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland
Department of Psychology, University of California, Berkeley, CA, USA

Michael H. Herzog
Laboratory of Psychophysics, Brain Mind Institute, Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland

Merav Ahissar
The Edmond & Lily Safra Center for Brain Sciences (ELSC), Hebrew University, Jerusalem, Israel
Departments of Psychology and Cognitive Sciences, Hebrew University, Jerusalem, Israel

Phonological deficits in dyslexia are well documented. However, there is an ongoing discussion about whether visual deficits limit the reading skills of people with dyslexia. Here, we investigated visual crowding and backward masking. We presented a Vernier (i.e., two vertical bars slightly offset to the left or right) and asked observers to indicate the offset direction. Vernier stimuli are visually similar to letters and are strongly affected by crowding, even in the fovea. To increase task difficulty, Verniers are often followed by a mask (i.e., backward masking). We measured Vernier offset discrimination thresholds for the basic Vernier task, under crowding, and under backward masking, in students with dyslexia ($n = 19$) and age and intelligence matched students ($n = 27$). We found no group differences in any of these conditions. Controls with fast visual processing (good backward masking performance), were faster readers. By contrast, no such correlation was found among the students with dyslexia, suggesting that backward masking does not limit their reading efficiency. These findings indicate that neither elevated crowding nor elevated backward masking pose a bottleneck to reading skills of people with dyslexia.

Introduction

Dyslexia

Dyslexia is a specific reading disability, which affects approximately 7% of the population (Peterson & Pennington, 2012). Individuals with dyslexia fail to achieve adequate reading proficiency, despite having sufficient cognitive abilities and educational opportunities, and no obvious sensory or neurological damage (World Health Organization, 2008). Although reading skills of people with dyslexia usually improve throughout life, in most cases, their reading skills remain poor compared to those of their peers even in adulthood (Snowling, 2000).

Reading deficits of people with dyslexia have been mainly attributed to language related difficulties, particularly in the phonological domain (reviewed in Ramus & Ahissar, 2012). Different versions propose poor phonological representations (Shaywitz & Shaywitz, 2005; Snowling, 2000), inefficient access to them (Boets et al., 2013; Ramus & Szenkovits, 2008), or poor usage of sound regularities (e.g., Ahissar, 2007; Ahissar, Lubin, Putter-Katz, & Banai, 2006). However, the alphabetical system, which relies on efficient mapping of orthography to phonology, poses chal-

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lenges to visual mechanisms because one has to quickly identify small, dense, horizontally arranged symbols. Yet, the degree to which potentially impaired visual mechanisms pose an impediment to people with dyslexia is still disputed. While in the 1990s the "magnocellular deficit" was the prevailing hypothesis (e.g., Stein & Walsh, 1997), the lack of consistent supporting evidence for a deficit in simple low-level tasks (e.g., Amitay, Ben-Yehudah, Banai, & Ahissar, 2002; Ramus et al., 2003) led to revised conceptualizations. The revised version attributes visual deficits to spatio-temporal mechanisms of attention, in which underlying neural circuitry resides at higher stages of the "dorsal stream" pathway. For example, visual deficits of people with dyslexia were associated with spatio-temporal difficulties in allocating attention (Facoetti, Paganoni, Turatto, Marzola, & Mascetti, 2000; Hari & Renvall, 2001; Vidyasagar & Pammer, 2010). These studies proposed that, even though low-level (perhaps subcortical) mechanisms may be intact in people with dyslexia, visual deficits still limit their reading abilities.

Crowding in dyslexia

Written words are composed of letters (i.e., similar and small elements), each of which is hard to identify because of the neighboring letters. This phenomenon is known as visual crowding: the deleterious influence of nearby elements (in this case, letters) on visual perception (Levi, 2008). Crowding strongly depends on the eccentricity of the target letter and on the density of the surrounding letters (Bouma, 1970; Pelli & Tillman, 2008). The spacing between letters that is needed in order to avoid crowding increases with eccentricity (Bouma's law; Bouma, 1970). Legge et al. (2007) proposed that the "visual span," that is, the number of horizontally arranged characters that one can read without moving one's eyes, is affected by three factors: (a) crowding, (b) the decreasing resolution in peripheral vision, and (c) the errors of letter "mislocalization." However, Pelli et al. (2007) showed that the visual span is fully captured by the "uncrowded span" (i.e., the size of the restrictive window in which there is no crowding), which is in line with Bouma's findings. Together, these findings specify the impediment that elevated crowding may pose on adequate reading skills.

Several early studies have found evidence for abnormal crowding of letters in dyslexia. Bouma and Legein (1977) showed that children with dyslexia are more affected by crowding when they are asked to recognize a letter that is embedded within other letters, despite having adequate recognition of isolated letters. Atkinson (1991) later showed enhanced letter crowding in a subgroup of children with dyslexia, compared to both chronological-age– and reading-age–matched controls. Geiger and Lettvin (1987) found that people with dyslexia are more affected by crowding in the fovea, yet are better than controls in peripheral crowding conditions, due to a broader effective visual field for item identification, which they termed "form resolving field" (FRF), compared with normal readers (however, see Klein, Berry, Briand, D'Entremont, & Farmer, 1990).

Several recent studies found that people with dyslexia experience stronger crowding at all eccentricities when letter stimuli are used. A typical paradigm used in such studies is letter trigram presentation at different eccentricities, in which the participants are required to identify the central letter (e.g., Martelli, Di Filippo, Spinelli, & Zoccolotti, 2009) or all of the letters (e.g., Callens, Whitney, Tops, & Brysbaert, 2013). In addition, many studies use a paradigm in which participants are shown a string of letters or digits (usually five elements) for a brief exposure, and are required to report a single cued letter (partial report) or the whole letter string (whole report; e.g., Bosse, Tainturier, & Valdois, 2007). These studies found that individuals with dyslexia have longer exposure-thresholds (Hawelka, Huber, & Wimmer, 2006) and less accurate performance (Bosse et al., 2007), possibly indicating a difficulty stemming from excessive crowding. The elevated crowding may be compensated for by increasing stimulus duration, as reported by Martelli et al. (2009). They found that the difference in crowding between subjects with dyslexia and control subjects almost disappeared when the duration of the trigram presentation was increased (see also Moll & Jones 2013).

Importantly, all the studies described above used alphanumeric stimuli that were familiar to the participants. The findings in these studies are therefore difficult to interpret since participants' performance may be differentially affected by letter familiarity. In addition, the whole report studies, in which participants are asked to report the entire letter sequence (typically three to five letters), rely on verbal memory, known to be impaired in dyslexia. Moreover, these sequences can be read as pseudowords, thus "chunking" the sequence of letters that need be retained in memory. This process is based on phonological decoding, which is the basic deficiency that defines dyslexia. Thus, when familiar alphanumeric symbols are used it is very difficult to dissociate visual impairments from poor phonological decoding and verbal memory skills.

Normalization may also pose a difficulty for adequate group comparisons. For example, Pernet, Valdois, Celsis, and Démonet (2006) used different categories of stimuli, that is, Latin and Korean letters (familiar and unfamiliar to the participants, respectively) and geometrical shapes, in a same–different identification and categorization task. The participants were required to indicate whether a target stimulus presented foveally was identical to a flanked stimulus (i.e., crowded identification task), or to an isolated stimulus presented in the periphery. In addition, they performed a categorization task in which participants needed to recognize whether the target stimulus was from the same category as the peripheral isolated or crowded stimulus. Subjects with dyslexia performed worse than the control subjects, both in the isolated and in the crowded conditions, and particularly in the categorization task, which perhaps taxed verbal memory to a larger extent. This suggests elevated crowding; however, when crowded performance was normalized by isolated performance, subjects with dyslexia did not differ from control subjects.

To control for these effects, Shovman and Ahissar (2006) conducted a crowding experiment with Georgian letters, which were not familiar to the participants. They found no differences between subjects with dyslexia and control subjects. Hawelka and Wimmer (2008) used a revised partial report paradigm, in which participants are asked to report one probed letter in a string. In order to minimize memory load, the probed letter and the string were presented simultaneously, and the response was nonverbal (the participants had to press a button if the probe appeared in the string). The performance of subjects with dyslexia was similar to that of controls, both when the string contained letters and when it contained symbols. In line with these results, Ziegler et al. (2010) compared performance of children aged 8–12 years, with and without dyslexia, in crowded presentations of alphanumeric and nonalphanumeric symbols. In contrast to a specific visual deficit, group differences were found only with alphanumeric symbols, which are mapped into phonological codes (see Collis, Kohnen, & Kinoshita, 2013, for a different interpretation). Moreover, a recent longitudinal study (Franceschini, Gori, Ruffino, Pedrolli, & Facoetti, 2012) investigated the visuospatial attentional skills of young children and their correlation with future reading acquisition. The children performed a spatial cue facilitation task, which included a peripheral crowding condition using geometric stimuli. The authors conclude that the children who showed reading acquisition deficits did not suffer from extensive crowding in comparison to normal readers. They did, however, show a deficit in attention shifting.

Still, several studies reported that adults with dyslexia have increased crowding in the periphery, even though they used stimuli that were unfamiliar to the participants. Thus, two studies (Cassim, Talcott, & Moores, 2014; Moores, Cassim, & Talcott, 2011) used a nonverbal memory-independent paradigm, in which the participants were asked to identify the orientation of a tilted Gabor stimulus presented in different crowded peripheral presentations (i.e., among other Gabors, which were vertically oriented) and found excessive crowding among adults with dyslexia. The performance on the visual task was correlated with reading and spelling measures. In addition, recent studies have found that increased letter spacing, which reduces crowding, is helpful for children with dyslexia (Perea, Panadero, Moret-Tatay, & Gómez, 2012; Spinelli, De Luca, Judica, & Zoccolotti, 2002; Zorzi et al., 2012). Given the variability of the reported results, the question of crowding in dyslexia remains open.

Backward masking in dyslexia

Visual backward masking, that is, the reduction of a target's visibility by a mask presented shortly after the target (Breitmeyer & Ogmen, 2000), is another phenomenon that has been proposed to be abnormal in dyslexia. The relevance of backward masking to reading is not intuitive. However, elevated backward masking was proposed as one manifestation of a general deficit in fast identification of serially presented elements. This hypothesis of "poor fast temporal processing" was first proposed for the auditory modality. Tallal (1980) showed that children with reading disabilities are poor in discriminating between the frequencies of rapidly presented brief tones and in judging their temporal order. She proposed that this difficulty reflects slow perceptual auditory processing. Inspired by this hypothesis, Wright et al. (1997) found that children with specific language impairment (often comorbid with dyslexia) have substantially elevated auditory backward masking. These findings were later replicated with adolescents with dyslexia (Rosen & Manganari, 2001) and with children with reading disabilities (Montgomery, Morris, Sevcik, & Clarkson, 2005).

Early studies of backward masking in the visual modality reported that people with dyslexia need longer temporal intervals in order to process brief, sequentially presented visual stimuli compared with adequate readers (Di Lollo, Hanson, & McIntyre, 1983; Stanley & Hall, 1973). More recent studies focused on attentional masking, namely on the need to explicitly identify (and name) stimuli rapidly. For example, Facoetti, Ruffino, Peru, Paganoni, and Chelazzi (2008) used a paradigm that requires sequential stimulus identification. They assessed the interference of identification of the second target on the identification of the first (assessing "engagement" difficulty, which they termed "attentional masking") and vice versa (i.e., the identification of the first target on the second, assessing "disengagement" difficulty, the more prevalently studied attentional blink). They found that target identification of people with dyslexia (using short, 200 ms stimulus onset asynchrony [SOA]), showed both types of interference. A similar attentional masking paradigm was subsequently administered to a larger group of children with dyslexia, using alphanumeric-like stimuli (Ruffino et al., 2010). This study found a deficit among subjects with dyslexia with a phonological deficit (assessed by nonword reading accuracy), but not among those without it. Finally, Ruffino, Gori, Boccardi, Molteni, and Facoetti (2014) found that attentional masking was greater (larger deficit) among individuals with dyslexia with more severe phonological deficits, assessed by pseudoword reading.

The slower serial identification process of individuals with dyslexia may reflect slower visual attention, but may also reflect slower access to explicit verbal identification, known to be impaired in dyslexia. In fact, one of the most consistent characteristics of people with dyslexia is slower rapid automatized naming (RAN; Denckla & Rudel, 1976).

The relevance of visual efficiency to reading rate

As described above, deciphering the efficiency of the visual system in the context of letter like stimuli is quite tricky, but important. Reduced visual efficiency, due either to slow allocation of spatio-temporal attention (reflected in elevated backward masking) or to a smaller effective visual span (elevated crowding) may directly reduce reading rate. Reading rate is limited by both the amount of information obtained within a single fixation (visual span), and by the number of fixations within each time unit (Rayner, 1998). Therefore, visual efficiency is expected to affect, and hence be correlated with, reading rate in the general population, especially when rate is measured for a paragraph rather than for isolated pseudowords (where phonological efficiency is bound to dominate), or even words. When reading a paragraph, both the rate of saccades and effective span are expected to be limiting factors.

Measuring visual efficiency: The current experiment

In order to assess differences in visual abilities between young adults with and without dyslexia, we examined both crowding and backward masking in foveal vision using nonalphanumeric stimuli. All the tasks consisted of a target Vernier: two vertically oriented bars were presented simultaneously and participants were asked to determine whether the lower bar was shifted to the left or to the right of the top bar.

The Vernier stimuli were chosen for several reasons. First, the Vernier stimuli are similar to letter strings in size, shape and in the spacing between neighboring items. Second, adding flankers to a target Vernier induces crowding. Namely, it increases the participant's threshold, that is, the offset distance needed for accurate judgments of the offset direction. Similarly, it has been proposed that reading is based on identifying symbols in a crowded scene, and therefore large spacing, which reduces crowding, may facilitate reading. Importantly, Vernier stimuli show crowding effects both when presented foveally (Malania, Herzog, & Westheimer, 2007; Sayim, Westheimer, & Herzog, 2008) and when presented peripherally (Manassi, Sayim, & Herzog, 2012, 2013). Crowding at the fovea is important in analogy to reading, since in reading, letters are identified at the fovea, where visual acuity is best. Adequate readers tend to make the initial fixation on each word about halfway between the beginning and the middle of a word, where word recognition is maximized (Nazir, Heller, & Sussmann, 1992). Therefore, foveal visual abilities are most relevant for natural reading (Rayner & Bertera, 1979). Though para-foveal and peripheral visual processing also affect reading rate (e.g., Deutsch, Frost, Pollatsek, & Rayner, 2005), their impact is secondary (Rayner, 1975). Hence, while there might be a correlation between paragraph reading rate and elevated peripheral crowding among people with dyslexia (Cassim et al., 2014; Moores et al., 2011), excessive peripheral crowding cannot explain the main deficit in single word reading for people with dyslexia. Third, Vernier judgments are impaired by brief presentations, allowing parametric evaluation of backward masking. Fourth, Vernier judgments are spatial and, hence, do not rely on any temporal comparison. Sequential comparisons rely on working memory mechanisms, which were previously shown to be impaired in dyslexia even for visual stimuli (Ben-Yehudah & Ahissar, 2004; Ben-Yehudah, Sackett, Malchi-Ginzberg, & Ahissar, 2001). Finally, both crowding and backward masking with Vernier stimuli were previously used in psychiatric populations (Chkonia et al., 2010; Chkonia et al., 2012; Roinishvili et al., 2015), indicating that this task can be reliably assessed in very broad populations.

Methods

Cognitive and reading measures

Several standard cognitive tests and tests of reading proficiency were administered to all participants. Cognitive abilities were assessed by Block Design and Digit Span, two subtests from the Hebrew version of the Wechsler Adult Intelligence Scale (WAIS-III; Wechsler, 1997). The Block Design task measures visual spatial reasoning abilities, and is often used to match groups for nonverbal intelligence. The Digit Span task measures verbal working memory and is known to be substantially impaired in dyslexia (e.g., Ackerman, Dykman, & Gardner, 1990). The task is composed of two parts: Digit Forward, repetition of orally presented series of digits, and Digit Backward, repetition of orally presented series of digits in reversed order.

Reading proficiency was assessed by a series of reading assessments, composed of: single words, pseudowords, and nonwords reading. All words were presented with diacritics, in lists of 24 words for each assessment. Importantly, diacritics make Hebrew orthography transparent, but are usually used only during the initial stages of reading acquisition. The lists of real words and pseudowords were standard lists (Deutsch & Bentin, 1996). The nonwords were used in previous studies as a measure of phonological decoding skills (e.g., Ben-Yehudah & Ahissar, 2004). In addition, reading in context was assessed by oral reading of a four-paragraph academic-level text in Hebrew (standardized for students by our lab; Ben-Yehudah et al., 2001). In order to encourage text comprehension, participants were told in advance that they would be asked a simple content question once they finish reading. Both accuracy and rate were scored for each of the reading tests.

Rapid automatized naming of digits (RAN-D) and letters (RAN-L) were measured as well, in a counterbalanced order within each group. Rate of rapid naming has been found as a good predictor of dyslexia in children (Denckla & Rudel, 1976) and is correlated with reading rate also in adults (Shovman & Ahissar, 2006). The tasks consist of naming 50 (five rows with 10 symbols each) digits or letters as fast and as accurately as possible. Since both groups had practically no mistakes (near 100% accuracy), only rate (number of items named per minute) was scored.

Phonological awareness was assessed by a spoonerism task in which pairs of words (20 pairs in total) are presented orally and the participants are asked to swap the initial phonemes of the two words (Ben-Yehudah & Ahissar, 2004; Ben-Yehudah et al., 2001). Both accuracy and rate were scored.

Apparatus

We measured Vernier offset discrimination thresholds in three conditions: Vernier only, Vernier under crowding, and Vernier under backward masking. Target and flankers were composed of white bars presented on a black background. Stimuli were presented on a FlexScan F520 monitor driven by a standard accelerated graphics card. Screen resolution was set to 1024×768 pixels at a 100-Hz refresh rate. The luminance of the stimuli was 60 cd/m^2. Viewing distance was 250 cm.

Stimuli

The basic Vernier configuration was composed of two thin vertical bars, $600'' \times 30''$ (arcsec) each, presented for 150 ms. The lower bar was slightly shifted to the left or to the right relative to the upper bar. Observers were presented with four different stimulus configurations. In the basic condition (Vernier alone), only the Vernier was presented, as illustrated in Figure 1A. In the second configuration (crowding), the Vernier was flanked by arrays of 16 vertical equal-length lines on each side, illustrated in Figure 1B. The directly neighboring lines were placed at a horizontal distance of 150″ from the Vernier. Interflanker spacing was 200″, stimulus duration was 150 ms in both conditions, and the starting Vernier offset was 100″. In the third and fourth conditions (backward masking), the Vernier was followed by a grating of either five or 25 aligned lines, respectively, as illustrated in Figure 1C, D. The choice of these two conditions was based on our previous observation that the five-element mask exerts much stronger masking than the 25-element mask, even though the five-element mask is contained in the 25-element mask (i.e., shine-through effect; Herzog & Koch, 2001). Herzog and Fahle (2002) showed that this shine-through effect depends on complex spatial processing and cannot be explained by mask energy or by other simple explanations. Therefore, its main effects cannot be of retinal origin. This type of crowding induced by complex spatial processes should challenge people with dyslexia, whose potentially abnormal visual processing does not stem from impaired basic luminance or other simple feature processing. The Vernier was presented for 20 ms, Vernier offset size was 75″, and the duration of the masking grating was 300 ms. The adaptive measure was the SOA between the Vernier and the masking grating. The starting SOA was 200 ms (Vernier duration of 20 ms + an ISI of 180 ms).

Procedure

Observers were asked to indicate the direction of the Vernier offset by pressing either the left or right mouse button, respectively. Auditory feedback was provided after incorrect or omitted responses.

We determined two thresholds in the basic Vernier condition (Vernier1 and Vernier2), followed by two blocks of backward masking (five lines grating and 25 lines grating, counterbalanced across participants), and

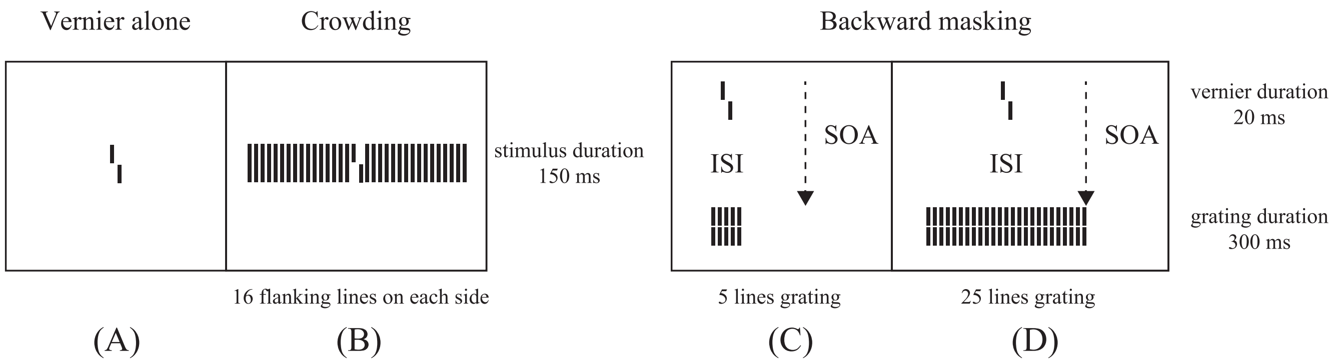

Figure 1. An illustration of the various stimulus configurations. (A) The basic Vernier paradigm. (B) Vernier under crowding conditions. The Vernier stimulus was flanked by 16 vertical lines on each side. We then determined the minimum offset that observers could discriminate with 75% accuracy. (C–D) Vernier assessed under backward masking. The basic stimulus configuration was followed by a black screen (for an adaptively determined duration) and then by a grating composed of five (C) or 25 (D) vertically aligned double lines. The offset size was fixed at 75″. We determined the minimum SOA (stimulus-to-mask interval) for which observers performed the Vernier task with 75% accuracy.

one block of the crowding condition. Each block consisted of 80 trials, with an equal number of left and right offsets. After each trial, the screen remained blank for a maximum period of 3 s, during which the observer was required to make a response. The screen was blank for 400 ms between the response and the next trial.

Before each condition, participants received short training, composed of 10 easy trials. Observers began the real assessment only after performing at least eight out of 10 trials correctly. In case of failure, this training procedure was repeated. This short training procedure was chosen following a pilot study, in which no such training was obtained. In spite of an oral explanation accompanied by a simple line drawing, many participants performed poorly. The short training protocol solved this problem, as detailed in the appendix.

In all of the Vernier assessments, an adaptive staircase procedure (Taylor & Creelman, 1967) was used to determine the threshold for which observers reached 75% correct responses. In the Vernier alone and in the crowding conditions, the adaptive parameter was the horizontal offset. In the backward masking conditions, the Vernier offset was fixed and the adaptive procedure determined the stimulus-onset asynchrony (SOA) between the Vernier and the grating onset for which responses were 75% correct. The Parameter Estimation by Sequential Testing (PEST) procedure was limited to twice the starting value for each condition (200″ in the Vernier alone and crowding conditions, 400 ms SOA for the backward masking conditions), in order to avoid extreme values. Thresholds were determined after fitting a cumulative Gaussian to the data using probit and likelihood analyses.

The fitting procedure did not converge for three controls and three participants with dyslexia (one block each). In order to avoid overweighting of outliers, we followed previous procedures (Herzog, Kopmann, & Brand, 2004) and assigned a value of 200″ in the crowding condition and 400 ms in the backward masking conditions (Herzog & Koch, 2001) when the PEST procedure was diverging (i.e., when observers were unable to do the task because of crowding or masking). This was the case in three out of the six data points. In three other cases, the PEST procedure did not converge because the starting value was at threshold. In these cases we assigned a performance level of approximately 75% correct performance.

Order of assessments

This study was conducted as part of a larger study, which included several testing sessions. The first session was dedicated to assessing cognitive and reading skills. The Vernier tasks and the RAN tasks were part of the fourth session, and were either performed first or last, counterbalanced within each group.

Participants: Recruitment and inclusion criteria

Participants were recruited through ads posted at the Hebrew University, and in two other colleges in Jerusalem. Participants were asked to complete a questionnaire about their learning and reading background (including previous diagnosis), musical background, and medical condition.

The preliminary screening and assignment to groups was based on participants' self-reports of reading abilities and past diagnosis. The initial *exclusion* criteria, for both groups, were:

- Musical background (i.e., more than 2 years of playing an instrument/vocal pedagogy),
- Hearing problems,

	Control group, $n = 27$ (15 female)	Dyslexia group, $n = 19$ (12 female)	t value
Age (years)	25.6 (2.8)	24.9 (2.8)	−0.8
Cognitive tests (scaled score)			
Block design	12.3 (2.9)	13.5 (2.7)	1.4
Digit span	11.0 (2.6)	7.7 (2.1)	−4.7***
Reading accuracy (% correct)			
Words	97.5 (3.9)	87.5 (6.5)	−6.0***
Pseudowords	90.4 (10.9)	57.7 (18.4)	−7.0***
Nonwords	87.8 (13.5)	50.0 (22.9)	−6.5***
Paragraph	98.6 (1.4)	95.8 (2.6)	−4.4***
Reading rate (words/min)			
Words	95.9 (29.2)	66.8 (26.8)	−3.5**
Pseudowords	58.8 (23.7)	32.4 (10.4)	−5.1***
Nonwords	41.8 (15.0)	26.4 (7.9)	−4.5***
Paragraph	141.0 (23.9)	102.4 (17.8)	−6.3***
RAN (words/min)			
Digits	155.7 (29.0)	136.5 (20.8)	−2.6*
Letters	142.3 (23.6)	129.3 (27.3)	−1.7 ($p = 0.1$)
Phonological awareness (spoonerism)			
% correct	92.0 (6.8)	76.3 (19.9)	−3.3**
pairs/min	10.1 (2.8)	6.2 (3.7)	−3.8***

Table 1. Means and *SD*s of the two groups' scores in cognitive, reading, and reading-related measures. *Notes*: *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

- Psychiatric medications other than attention deficit medication, and
- Below average cognitive scores (i.e., Block Design score < 7). Two participants with dyslexia and one control participant were excluded on this basis.

For the dyslexia group, adequate reading (within control range) was also a basis for exclusion. One participant with dyslexia was excluded on this basis (Scaled Digit Span score = 13, nonword accuracy = 100%).

All participants had normal or corrected-to-normal vision, and received all their schooling in Israel.

Results

Participants

Twenty-two participants with dyslexia and 29 control participants completed the assessments. Two control participants and three participants with dyslexia were excluded from the analysis due to highly inconsistent performance on the Vernier tasks. Thus, data shown are averages of 19 participants with dyslexia and 27 control participants.

Table 1 summarizes the performance of control participants and those with dyslexia in the cognitive and reading tasks. The groups did not differ in general reasoning skills (Block Design), and both groups' scores were above the average of the general population. As expected (e.g., Ackerman et al., 1990; Nergård-Nilssen & Hulme, 2014), the performance of participants with dyslexia performance on the Digit Span task (verbal working memory), and on all the reading proficiency and phonological awareness tasks, was significantly worse than that of control participants, both in accuracy and in rate.

The group with dyslexia included 11 participants who had an attention deficit diagnosis, in line with previous literature about the comorbidity of dyslexia and attention deficits (Willcutt & Pennington, 2000). Six of them reported taking attention deficit medication (e.g., Ritalin) on a daily or occasional basis, and were asked to come to the experiment when they were not under the influence of the medication. We decided not to exclude them from the study because attention abilities of individuals with dyslexia were found to be uncorrelated with their performance on visual tasks (Ben-Yehudah & Ahissar, 2004).

Crowding

As shown in Figure 2 (left), the basic Vernier thresholds did not differ between the two groups ($t = 0.42$ $p = 0.68$), in line with a previous study (Everatt, Bradshaw, & Hibbard, 1999).

As expected (Malania et al., 2007; Sayim et al., 2008), both groups showed strong crowding. Namely, for both groups, thresholds in the crowding condition

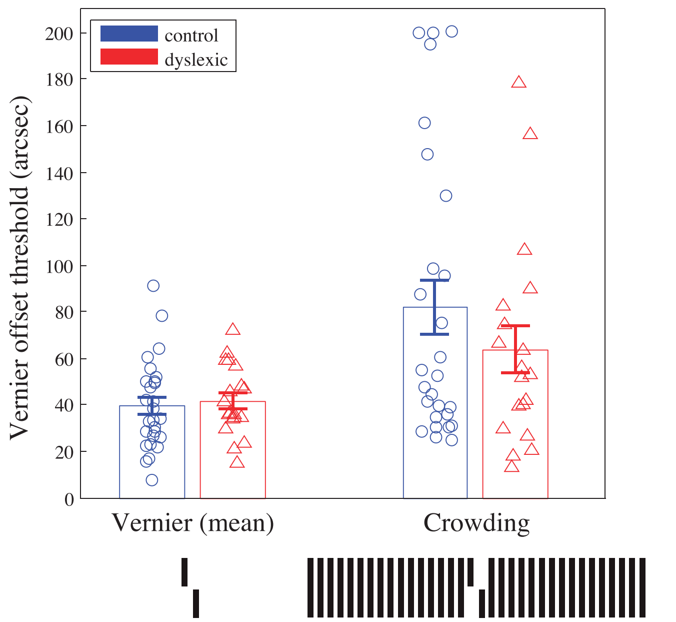

Figure 2. Mean thresholds of the control group (blue bars and symbols) and the dyslexia group (red bars and symbols) for the Vernier alone (left bars) and for the crowding conditions (right bars). Thresholds of the two groups are similar in both conditions. Each symbol denotes the threshold of a single participant (blue circles for controls and red triangles for participants with dyslexia). Error bars denote standard errors.

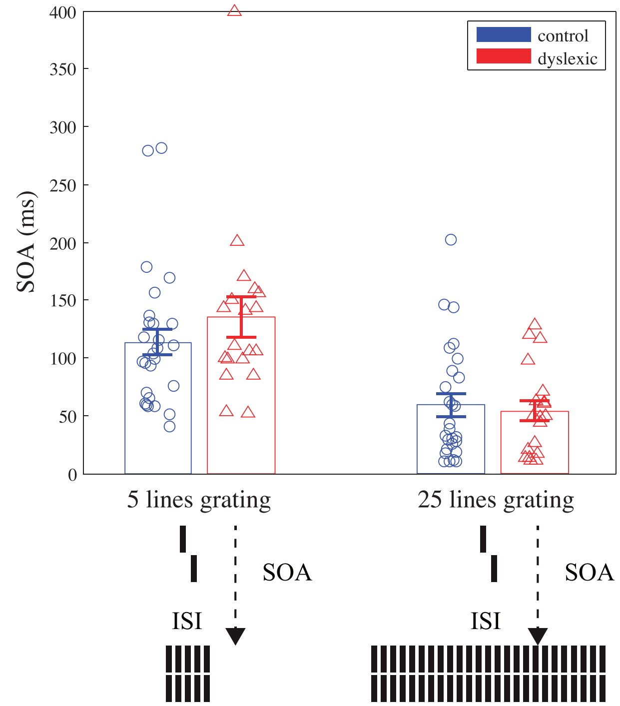

Figure 3. Mean thresholds of the two groups in the two backward masking conditions. For both groups, the five-line grating is a more effective masker. The thresholds of the two groups are similar in the two conditions. Individual performance for control participants is marked with blue circles, and marked with red triangles for participants with dyslexia. Error bars denote standard error.

were significantly poorer than in the Vernier alone assessments (rANOVA showed a main condition effect; $F = 17.38$, $p < 0.001$). This threshold elevation is evident when comparing the two left bars (showing thresholds in the basic Vernier condition for control participants and those with dyslexia) with the two right bars (showing thresholds in the crowding condition for control participants and those with dyslexia) of Figure 2. This comparison further shows that the crowding thresholds did not differ between the groups (group main effect: $F = 0.71$, $p = 0.4$), indicating a similar crowding effect (group X crowding interaction: $F = 1.75$, $p = 0.2$).

Backward masking

The degree of backward masking was measured by the SOA needed to obtain 75% correct performance, in the same Vernier configuration. As expected (Herzog & Koch, 2001), both groups needed a longer SOA with the five-line grating compared to the 25-line grating (rANOVA: $F = 59.84$, $p < 0.001$). However, here too, there was no significant group effect ($F = 0.32$, $p = 0.58$) or interaction ($F = 2.24$, $p = 0.14$). As shown in Figure 3, both thresholds were similar in the two groups.

Correlations between the Vernier conditions

Thresholds in the two assessments of the Vernier-only condition were strongly correlated within each of the two groups (control: $r = 0.66$, $rho = 0.67$, $p < 0.001$; dyslexia: $r = 0.6$, $p < 0.01$, $rho = 0.51$, $p < 0.05$).

Table 2 shows the correlations within the different Vernier conditions for the two groups. All the conditions were correlated in the control group, except the Vernier alone with the crowding condition, suggesting that crowding performance is dominated by additional bottlenecks. The pattern of correlation for participants with dyslexia showed a similar trend, though correlations were not consistently significant, perhaps due to reduced statistical power (i.e., a smaller group of participants). Indeed, nonparametric correlations, presented in parentheses in Table 2, show a similar pattern in both groups.

Correlations between Vernier thresholds and reading and cognitive scores

The performance of the dyslexia group on the Vernier tasks was not correlated with either their rate

	Crowding	Backward masking: Five-line grating	Backward masking: 25-line grating
Within the control group			
Vernier	0.38 (0.38)	0.5** (0.78***)	0.62*** (0.67***)
Crowding		0.53** (0.44*)	0.53** (0.61***)
Backward masking (five-line grating)			0.63*** (0.77***)
Within the dyslexia group			
Vernier	0.36 (0.38)	0.51* (0.72**)	0.36 (0.51*)
Crowding		0.58** (0.43)	0.2 (0.44)
Backward masking (five-line grating)			0.36 (0.65**)

Table 2. Correlations within the Vernier conditions. Nonparametric rank correlation coefficients (i.e., Spearman's rho) are shown in parentheses. *Notes*: *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

or their accuracy in any of the reading related measures. However, among controls, paragraph reading rate was significantly correlated with their backward masking scores, both with the 25-line masks ($r = -0.45$, $p < 0.05$), and with the five-lines masks ($r = -0.44$; $p < 0.05$), as shown in the two plots of Figure 4. Similar correlations were found using nonparametric tests ($rho = -0.47$, $p < 0.01$ and $rho = -0.42$, $p < 0.05$; for 25- and 5-line masks, respectively).

Given the correlation between reading rate and backward masking that we found in the control group, we asked whether backward masking has a unique contribution in accounting for paragraph reading rate beyond that explained by phonological and single word decoding, and RAN rates. We conducted a regression analysis with these three parameters as predictors of paragraph reading rate in the control group. The value of each predicting variable was set as the average of two relevant tasks (i.e., backward masking: five- and 25-line grating thresholds; reading proficiency: pseudoword and nonword reading rate; RAN: RAN-D and RAN-L rates).

As shown in Table 3, performance on backward masking contributed significantly to the variance of paragraph reading rate, beyond the contribution of reading proficiency. By contrast, the RAN rates did not have an additional explanatory value. The regression model was significant for the control group ($F = 8.4$, $p < 0.001$, $R^2 = 0.52$), but not for the dyslexia group ($F = 1.5$, $p = 0.2$, $R^2 = 0.25$). None of the Vernier measures were correlated with age or general reasoning (Block Design) scores in either group.

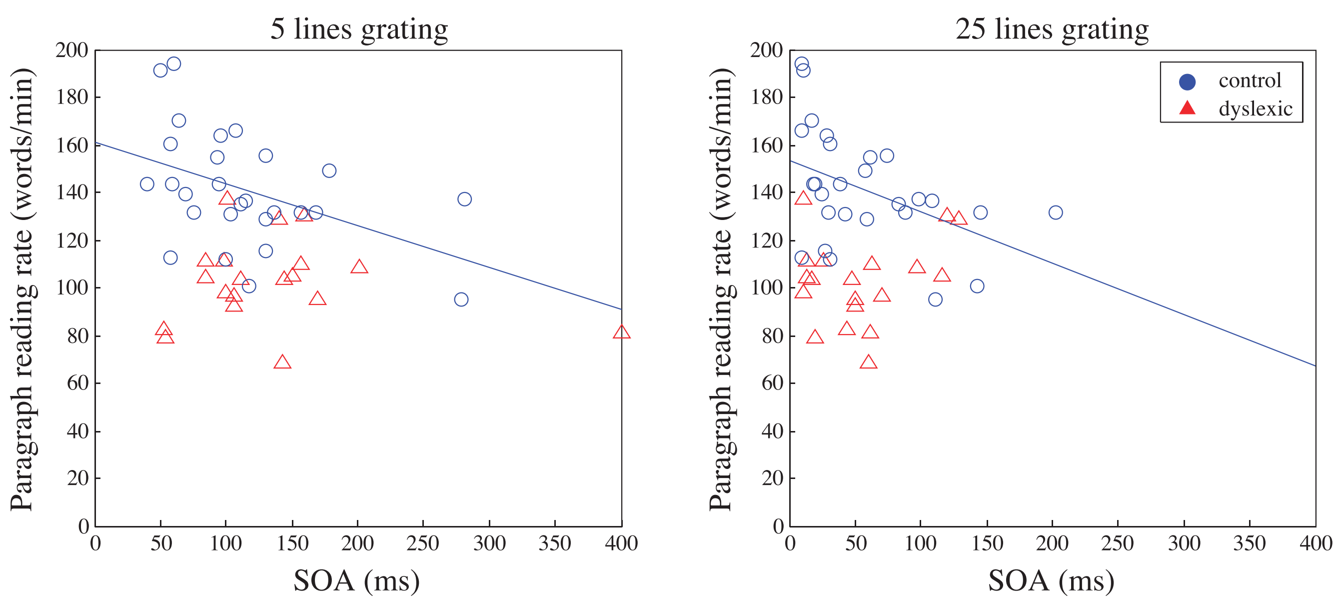

Figure 4. Scatterplots illustrating the correlations between thresholds in the two backward masking conditions and paragraph reading rate in the two groups. Among controls, individuals with lower backward masking were faster readers. No such correlation was found in the dyslexia group. Individual performance for control participants is denoted by blue circles, and by red triangles for participants with dyslexia.

Predicting variable	Standardized coefficients	t value
Reading proficiency	0.5	2.8**
Backward masking	−0.49	−3.3***
RAN	0.05	0.2

Table 3. Results of regression conducted for predicting paragraph reading rate in the control group. *Notes*: $*p < 0.05$, $**p < 0.01$, $***p < 0.001$.

Dyslexic participants with attention deficits

Eleven participants with dyslexia were individuals diagnosed with ADHD or ADD. Their performance on the Vernier tasks did not differ from that of their peers with dyslexia (both t test and Mann Whitney not significant, $p > 0.05$). Six of these participants reported taking attention deficit medication. Their performance was similar to that of their peers, even though they were not on medications when tested in the lab.

Discussion

Performance of participants with dyslexia did not differ from that of age- and intelligence-matched controls in any of the four conditions. There were no group differences in Vernier acuity with and without crowding, and in two different backward masking configurations. Task difficulty increased in the crowding condition, as expected, but it had a similar effect on the two groups.

These results do not indicate that the visual skills that our tests measure are not relevant for reading. For example, we found a significant correlation between backward masking thresholds and paragraph reading rate in the control group. Moreover, performance of control subjects on the backward masking tasks had a unique contribution in accounting for the variance of paragraph reading rate beyond that explained by their phonological skills. These observations suggest that visual efficiency contributes to the efficiency of multi-word reading. However, we did not find such a correlation in the population with dyslexia, suggesting that the bottleneck to their reading rates lies elsewhere. Hence, our results imply that the visual mechanisms that we measured do not pose a reading bottleneck for individuals with dyslexia.

Comparison with previous studies

As described in the Introduction, several previous studies found that performance of individuals with dyslexia in related visual tasks was impaired. What could account for the difference between these observations and the results of the current study?

The orthographical account

One possible account is the unique requirements posed by different orthographies. Thus, reading performance in less transparent orthographies, such as English and French, is more strongly correlated with phonological awareness than in more transparent languages (Ziegler, Pech-Georgel, Dufau, & Grainger, 2010). In addition, individuals with dyslexia have more pronounced reading deficits in opaque orthographies, reflected in both inaccurate and very slow reading (Landerl, Wimmer, & Frith, 1997; Paulesu et al., 2001). By contrast, shallow orthographies might be more sensitive to different perceptual and attentional skills, such as visual abilities, since they might demand less phonological processing. Therefore, one might assume that the cognitive mechanisms that are taxed in different languages are somewhat different, leading to different subtypes of dyslexia, in accordance with these different characteristics. Thus, Hebrew orthography may induce a smaller amount of visual crowding since the average number of letters per word is smaller than in European languages. This smaller number of letters per word stems from two different aspects. First, in the Hebrew orthography, vowels are not letters. They appear in the form of punctuation, which is absent from most adult literature. Second, syllables are mostly simple, and typically do not contain more than one or two consonants. Taken together, Hebrew may not load complex spatial visual mechanisms as, perhaps, English.

Yet, cross-linguistic studies imply that this is not the case. First, there is no evidence that different alphabetical orthographies differ in the visual mechanisms they tax. For example, earlier studies aimed to assess a magnocellular deficit in dyslexia measured temporal contrast sensitivity and got mixed results. Thus, one study, administered to Italian speakers with dyslexia (transparent orthography; Spinelli et al., 1997) found no deficit, whereas another study, administered to English-speakers with dyslexia (opaque orthography; Borsting et al., 1996) did find a deficit. These seemingly contrasting results were explained as reflecting the impact of the different demands imposed by these different orthographies. However, both sets of results were replicated within the same population of Israelis with dyslexia when the two visual paradigms used in the two studies were replicated exactly (Ben-Yehudah et al., 2001).

Indeed, in the context of crowding, the studies that either found or did not find elevated crowding in dyslexia do not segregate according to the language assessed. Thus, elevated crowding was reported for

French (Pernet et al., 2006), which is relatively opaque, and for Italian (Martelli et al., 2009) and Dutch (Callens et al., 2013), which are transparent. Related findings, reporting that extrawide spacing was helpful for individuals with dyslexia, were obtained for French (Zorzi et al., 2012), as well as for Italian and Spanish (Perea et al., 2012; Spinelli et al., 2002; Zorzi et al., 2012), which are more transparent.

Therefore, the difference in orthography does not seem to account for the cross study variability.

The developmental account

Another possible explanation for the lack of elevated crowding and masking in our sample of people with dyslexia might be the fact that we tested adults, in contrast to other studies that assessed children and found related deficits (e.g., Martelli et al., 2009; Ruffino et al., 2014; Spinelli et al., 2002). Indeed, children are more susceptible to crowding than adults (Jeon, Hamid, Maurer, & Lewis, 2010; Semenov, Chernova, & Bondarko, 2000). Similarly, the visual span (i.e., the number of horizontally arranged characters that one can read without moving one's eyes) increases with age, and is correlated with reading rate (Kwon, Legge, & Dubbels, 2007; Pelli & Tillman, 2008). Additionally, the pattern of eye movements changes throughout life, particularly in reading (reviewed in Rayner, 1998).

Still, this does not seem to be the case for crowding, for two reasons. First, it was recently shown that the crowding effect assessed in kindergarten is similar among normal and poor future readers (Franceschini et al., 2012), indicating that crowding might not be a limiting factor in reading acquisition and proficiency. Second, the adults with dyslexia in our study were still substantially poorer readers than controls, indicating that even though their reading skills are not compensated, elevated crowding or backward masking do not contribute to their current reading deficits.

However, while there are several crowding experiments that found elevated crowding among adults with dyslexia (e.g., Callens et al., 2013; Moores, Cassim, & Talcott, 2011), this is not the case in backward masking. To our knowledge, all previous experiments that tested backward masking in dyslexia assessed children with dyslexia and not adults. Thus, it is possible that the masking deficit appears in children, and improves by adulthood.

In general, however, similar perceptual deficits were reported in studies assessing both children and adults with dyslexia. This is the case for various visual tasks, such as motion sensitivity. Impaired motion discrimination was reported for both adults (e.g., Talcott, Hansen, Assoku, & Stein, 2000) and children (e.g., Slaghuis & Ryan, 1999). Similarly, in the auditory modality, the same types of discrimination deficits were reported for both children and adults (e.g., poor two-tone frequency discrimination, in children [Mengler, Hogben, Michie, & Bishop, 2005] and in adults [Ahissar, Protopapas, Reid, & Merzenich, 2000; Amitay et al., 2002]). This observation may reflect the proposal of Wright and Zecker (2004) that if delayed development of certain skills does not reach a critical level by approximately 10 years, it ceases to improve, and remains impaired in adulthood. It follows that if we do not find such deficits in adults, perhaps they were not there even in childhood.

Dyslexics' crowding deficit is, at most, minor

The straightforward explanation for our findings is that there is no robust crowding or masking deficit in dyslexia. This account suggests that the studies that found such deficits either measured very mild deficits or confounded nonvisual aspects.

As described above, most studies that report such deficits used familiar alphabetical symbols and had memory requirements, which, in normal readers, could have been reduced via actual reading (e.g., Facoetti et al., 2008; Martelli et al., 2009). Naturally, such studies put people with dyslexia at a disadvantage that does not stem from visual deficits. Indeed, when these limitations were eliminated, by reducing the memory load, crowding for those with dyslexia was not elevated (Franceschini et al., 2012; Hawelka & Wimmer, 2008; Shovman & Ahissar, 2006).

Another line of studies shows that extrawide spaced texts improve reading abilities for people with dyslexia, suggesting that their reading is impaired due to elevated crowding. However, this effect is not very robust, as originally noted by Spinelli et al. (2002) in one of the early studies advocating crowding in dyslexia. A more recent study (Zorzi et al., 2012), that assessed reading rate in wide-spaced text compared with a regular-spaced text, found a benefit in one group of people with dyslexia, but this benefit was not replicated when the extrawide spaced text was read first rather than second. A more recent study (van den Boer & Hakvoorta, 2015) found no benefit for extrawide spacing in single words. The authors emphasize that it is important to examine both accuracy and rate, since improvement in one might be traded with the other, as was the case in their study.

The visual span of individuals with dyslexia

Pelli et al. (2007) proposed that the visual span is the uncrowded span, which is correlated with reading performance. The visual span of people with dyslexia was evaluated as smaller than that of age matched controls (Martelli et al., 2009), implying elevated crowding. However, we found no elevation in crowding, suggesting that visual span for those with dyslexia should not differ from that of control participants. The difference may reside in the technique used to evaluate the visual span, which measures the effective reading span. Visual spans are typically assessed by oral naming of letter trigrams, which include both consonants and vowels (Legge, Mansfield, & Chung, 2001).

Martelli et al. (2009) report that naming of single letters is not impaired among people with dyslexia. However, when presented with letter-based trigrams and asked to identify the central letter, those with dyslexia performed poorer than control participants. This deficit may reflect their poor reading, since the trigrams were composed of three letters randomly chosen from a 10-letter set, consisting of both vowels consonants. Therefore, the trigrams were typically not composed of CCC letters (three consecutive consonant letters), which are difficult to pronounce. They could typically be read as pseudowords, facilitating letter identification. Other studies excluded vowels from the presented letter string, thus reducing the tendency to read the string of letters (e.g., Lobier, Zoubrinetzky, & Valdois, 2012). However, paradigms that require post presentation report of several elements, which are typically remembered verbally, rely on memory processes that are assumed to be impaired in dyslexia, and hence, do not directly point to impaired basic visual processes.

Several studies emphasize the role of visual attention in reading (e.g., Franceschini et al., 2012; Ruffino et al., 2014), and view the visual span as an attention mediated factor (Bosse et al., 2007). Our tasks require visual attention. However, they may lack reading related aspects of attention, such as disengagement, which is required for fast serial letter scanning. Since our tasks required identification of one Vernier, they had no disengagement component. A recent study trained children with dyslexia using an action video game and reported substantial improvement in their reading (Franceschini et al., 2013). This study did not directly assess these children's crowding or backward masking. We hypothesize that their pure visual crowding was not impaired. Yet, it could be that some aspects of visual attention that were not tapped in our study, such as fast disengagement (Vidyasagar & Pammer, 2010), are impaired in dyslexia and improved by such games.

Visual efficiency: Serial identification versus backward masking

The visual factors that underlie the rate of switching visual attention are also difficult to decipher. Thus, when participants are asked to identify two sequentially presented targets, explicit identification also requires efficient mechanisms of working memory. When two targets were presented quickly and serially with an interleaving masking stimulus, identification for participants with dyslexia was poorer than that of controls (Facoetti et al., 2008; Ruffino et al., 2010; Ruffino et al., 2014). This deficit may be related to inefficient mechanisms of access to working memory, rather than to purely visual impairments, as suggested by longer attentional blink for individuals with dyslexia (i.e., minimal interval between two sequentially presented targets, at which the identification of the first target does not impair the identification of the second target, approximately 400 ms; Hari, Valta, & Uutela, 1999). Here too, however, observations are mixed. A more recent study found that slower responses by individuals with dyslexia can be fully accounted for by general performance factors (McLean, Castles, Coltheart, & Stuart, 2010).

This slowness in identification is consistent with the observations of impaired rapid serial identification of brief sounds by people with dyslexia (Tallal, 1980). Both may be due to inefficient access to memory representations rather than inefficient auditory processing (Ramus, 2014). This interpretation is also in line with findings that performance by those with dyslexia is impaired in visual tasks that require comparisons between sequentially presented visual stimuli (Ben-Yehudah & Ahissar, 2004; Ben-Yehudah et al., 2001), but not when the same visual task is conducted by spatial comparisons. Indeed, performance by control participants in the two versions of a spatial frequency discrimination task is not correlated (Weiss, Biron, Lieder, Granot, & Ahissar, 2014). Performance in their serial visual discriminations is correlated with verbal memory, whereas performance in spatial discriminations (two-alternative spatial forced choice) is not.

Interestingly, our measures of backward masking were related to reading rate even though they did not require serial identification, suggesting that visual factors that do not require attentional shifts do play a role in paragraph reading. Perhaps our backward masking task reflects the efficiency with which visual information is retrieved within a given amount of time. This efficiency dictates the maximal rate of effective fixations, which is particularly important in paragraph reading (Rayner, 1998). Paragraph reading is more similar to daily reading experiences than single word reading. Adequate readers may benefit from intact complete word representations and sight word reading, which enhance their visual span via earlier phonological processes that enable reading automaticity (Ehri, 2005).

Conclusions

In this study we found no evidence for elevated crowding or backward masking for individuals with dyslexia. Yet, we did find support for the hypothesis that elevated backward masking reduced reading efficiency, as revealed by correlated performances in the control population. A potentially slower mechanism of sequential attention shifting was not explored.

Keywords: dyslexia, reading disability, crowding, backward masking, visual efficiency, Vernier

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Corresponding author: Merav Ahissar.
Email: msmerava@gmail.com.
Address: The Edmond & Lily Safra Center for Brain Sciences (ELSC), Hebrew University, Jerusalem, Israel.

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Appendix

The impact of the short practice on Vernier thresholds

Prior to the actual experiment, we conducted two pilot studies in which we assessed the thresholds for the basic Vernier condition. In the first pilot, we explained the task verbally and showed a schematic "pencil on paper" example. Nevertheless, results from the first pilot (shown in Figure A1) indicated that many participants did not fully grasp the task, and did not show improvement throughout the 80-trial block. Therefore, we conducted a second pilot, in which a short demo of 10 easy trials was administered before each condition. This demo had the same stimuli as described in the Methods. In the basic Vernier and crowding conditions, the Vernier offset was fixed at 200″. In the backward masking conditions, the initial SOA was set at 400 ms, and the PEST procedure was used (yielding two different SOAs). Participants had to answer at least 8 out of 10 trials correctly before continuing to the test block.

The aim of this short training procedure was to enable perceptual understanding, by an actual exposure to very easy conditions of the stimulus (a "eureka" effect; Ahissar & Hochstein, 1997). As shown in Figure A1, this procedure was successful, and practically eliminated the extreme outliers. Figure A1 also shows the thresholds attained by the control group on the Vernier-only assessments, following the same short training procedure. Thresholds on both assessments were similar to that obtained in the second pilot. This suggests that these thresholds are consistent across groups of participants and do not further improve with additional short practice (second assessment).

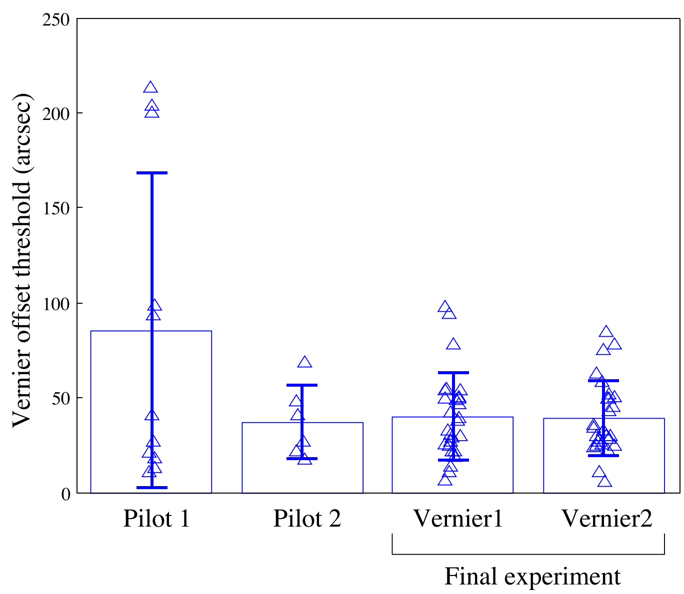

Figure A1. Vernier thresholds attained by adequate readers that participated in two pilot studies, and of the experiment's control group, who performed two assessments (their average is plotted in the left blue bar of Figure 2). Note that in Pilot 1, few participants had extremely high thresholds. However, when a short practice session was introduced, in Pilot 2, such outliers disappeared. The thresholds obtained in Pilot 2 were similar to those obtained by the control group in each of 2 assessments. Error bars denote STD.