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Research Report

Optimizing text for an individual's visual system: The contribution of visual crowding to reading difficulties

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ABSTRACT

Reading is a complex process that involves low-level visual processing, phonological processing, and higher-level semantic processing. Given that skilled reading requires integrating information among these different systems, it is likely that reading difficulty—known as dyslexia—can emerge from impairments at any stage of the reading circuitry. To understand contributing factors to reading difficulties within individuals, it is necessary to diagnose the function of each component of the reading circuitry. Here, we investigated whether adults with dyslexia who have impairments in visual processing respond to a visual manipulation specifically targeting their impairment. We collected psychophysical measures of visual crowding and tested how each individual's reading performance was affected by increased text-spacing, a manipulation designed to alleviate severe crowding. Critically, we identified a sub-group of individuals with dyslexia showing elevated crowding and found that these individuals read faster when text was rendered with increased letter-, word- and line-spacing. Our findings point to a subtype of dyslexia involving elevated crowding and demonstrate that individuals benefit from interventions personalized to their specific impairments.

1. Introduction

Reading involves multiple stages of processing, including low-level sensory processing of the visual stimulus, phonological processing of the sounds associated with the printed letters, and higher-level semantic processing of the meaning of words and sentences. The complex and multi-faceted nature of reading suggests that impairments at any processing stage could cause difficulties with reading (Joo, Donnelly, & Yeatman, 2017; Paulesu et al., 2001; Pennington & Bishop,

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2009; Pennington, 2006; Peterson & Pennington, 2012; Siok, Perfetti, Jin, & Tan, 2004).

However, theories of dyslexia have been attempting to uncover a single underlying deficit. This effort has been frustrated by discrepant results obtained from similar experimental paradigms. For example, whether dyslexic readers have poor motion sensitivity or elevated visual crowding compared to typical readers has been a subject of heated debate (Amitay, Ben-Yehudah, Banai, & Ahissar, 2002; Bouma & Legein, 1977; Demb, Boynton, & Heeger, 1997; Doron, Manassi, Herzog, & Ahissar, 2015; Eden et al., 1996; Joo et al., 2017; Lovegrove, Bowling, Badcock, & Blackwood, 1980; Martelli, Di Filippo, Spinelli, & Zoccolotti, 2009; Olulade, Napoliello, & Eden, 2013; Skottun, 2000; Stein & Walsh, 1997). Furthermore, the phonological impairment theory of dyslexia cannot explain the collection of visual deficits reported in people with dyslexia unless these deficits are epiphenomenal and not causally related to reading skills (Franceschini, Gori, Ruffino, Pedrolli, & Facoetti, 2012; Ramus et al., 2003; Vellutino, Fletcher, Snowling, & Scanlon, 2004; Vidyasagar & Pammer, 2010). Given the complex nature of reading, the lack of replication across previous studies could be indicative of heterogeneity in dyslexia (Pennington, 2006)—individuals struggle with reading for a variety of reasons—instead of supporting or rejecting any specific theory.

Individual differences in dyslexia suggest that it is essential to characterize the function of multiple components of the reading circuitry in order to understand the factors contributing to an individual's reading difficulties (Wandell & Le, 2017). In the present study, we sought to diagnose limitations in an individual's visual system, at the initial stage of the reading circuitry, and establish the link between deficits in visual processing and reading difficulties. Beyond demonstrating a correlation between visual processing and reading skills, the critical test should show that individuals with a specific impairment respond to an intervention designed to ameliorate that impairment.

We first assessed limitations in the individual's visual system using a visual crowding paradigm in which the ability to identify an object is deteriorated by nearby items (Whitney & Levi, 2011), and then assessed the relation between individual differences in reading ability and visual crowding (Whitney & Levi, 2011). We next tested whether increased text-spacing, which may provide a less crowded visual environment, improves reading specifically for those who have elevated crowding. There is an appealing link between crowding and reading because successful decoding of single words in a crowded page of text is essential for skilled reading. In a typical page of text, letters outside the fovea crowd each other. Indeed, crowding is a determining factor for the number of letters that can be recognized in a single fixation for typical readers (Legge, Mansfield, & Chung, 2001; Pelli & Tillman, 2008; Yu, Cheung, Legge, & Chung, 2007) and is negatively correlated with reading skills in children with dyslexia (Bouma & Legein, 1977; Gori & Facoetti, 2015; Martelli et al., 2009; Spinelli, De Luca, Judica, & Zoccolotti, 2002). Furthermore, increased text-spacing, on average, helps dyslexic children perform a lexical decision task and read sentences out loud (Perea, Panadero, Moret-Tatay, & Gómez, 2012; Zorzi et al., 2012). However, it is not clear whether this text-spacing effect is related to general low reading skills, or specific to a subset of individuals with elevated crowding.

We identified individuals who have both elevated crowding and reading difficulties, and found that increased text-spacing results in better reading performance specifically for those individuals. As a control analysis, we used a cued visual search paradigm to rule out impaired spatial attention as the mechanism underlying our results. These findings point to a subtype of dyslexia potentially caused (or exacerbated) by elevated crowding and suggests that personalizing the reading environment by adjusting the properties of the visual input (e.g., increased text-spacing) at the front end of the reading process can improve reading performance.

2. Methods

All procedures, including recruitment, consent, and testing, followed the guidelines of the University of Washington Human Subjects Division and were reviewed and approved by the UW Institutional Review Board. To ensure reproducibility of our results, all experimental procedures, data, and analysis code are available in the study's github repository (https://github.com/YeatmanLab/Joo_2018).

2.1. *Subjects*

To recruit a sample of adults with heterogeneous reading abilities we posted flyers soliciting research participants with and without dyslexia. Flyers were also disseminated through local organizations that provide support to people with dyslexia including the University of Washington Disability Resources for Students (DRS), Disabilities, Opportunities Internetworking and Technology (DO-IT), and Dyslexic Advantage (http://www.dyslexicadvantage.org/). Since there is no agreed upon definition of dyslexia, we used quantitative measures of reading abilities for all of our analyses rather than relying on specific diagnostic criteria for dyslexia. A total of 39 adults (aged 30 ± 11 y, 23 females, 15 males, and 1 unspecified) participated in the crowding and reading experiments (29 reported having dyslexia or reading difficulties). Thirty seven adults from this subject pool took part in the cueing experiment. Additionally, thirty eight children (aged 9.6 ± 1.8 y, 16 females and 22 males) participated in the crowding experiment to assess the generalizability of our results. All subjects had normal or corrected-to-normal vision and gave informed written consent in accordance with the University of Washington Institutional Review Board. A spreadsheet containing all behavioral measurements and subject demographics is available as a csv file within the study's github repository.

2.2. *Apparatus*

Stimuli were created using MATLAB (The Mathworks Corporation, Natick, MA, USA) in conjunction with the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997) on a Linux PC (Mint Mate, version 17). Stimuli were displayed on a LG liquid crystal display (1920 × 1080 resolution, 120 Hz refresh rate, subtending 50° horizontally at viewing distance of 58 cm). The subjects' response was collected using a joystick in the crowding experiment and a computer keyboard in the cueing experiment.

2.3. Stimuli and procedure

2.3.1. Crowding experiment

Fig. 1A depicts a schematic of our stimuli. Stimuli comprised four open circles (flankers; 1° diameter, .08° linewidth) and an open circle with a gap (target; an arc with reflex central angle of 330°). All Stimuli were black (0 cd/m^2) and displayed on a gray background (135 cd/m^2). The target eccentricity was defined by the center-to-center distance between the fixation mark at the center of display and the target. There were two target eccentricity conditions (near: 6°, far: 10°). We measured crowding effects at each target eccentricity separately. To quantify crowding effects, we defined critical spacing as the minimal center-to-center distance (threshold) between a target and flankers at which the observer can report the target identity at 82% correct. We used an adaptive staircase (QUEST; Watson & Pelli, 1983) to estimate each individual's critical spacing. In an experimental session, a target eccentricity was fixed and the initial starting target-flanker distance was set as 1.3 times greater than half the eccentricity (3.9° for 6° eccentricity; 6.5° for 10° eccentricity). The subsequent target-flanker distance was controlled by the QUEST procedure. There were two independent staircases (25 trials each) to prevent subjects from predicting the difficulty of the next trial. Each subject finished 4–6 session for each target eccentricity. The order of target eccentricity in each subject was alternated across sessions, and we counterbalanced the session order of which target eccentricity a subject encountered first across subjects. On a given trial, the fixation mark was displayed first and remained in the display for the entire trial. After 500 msec of fixation onset, the stimuli were displayed either the left or the right side of display for 150 msec. After the stimulus offset,

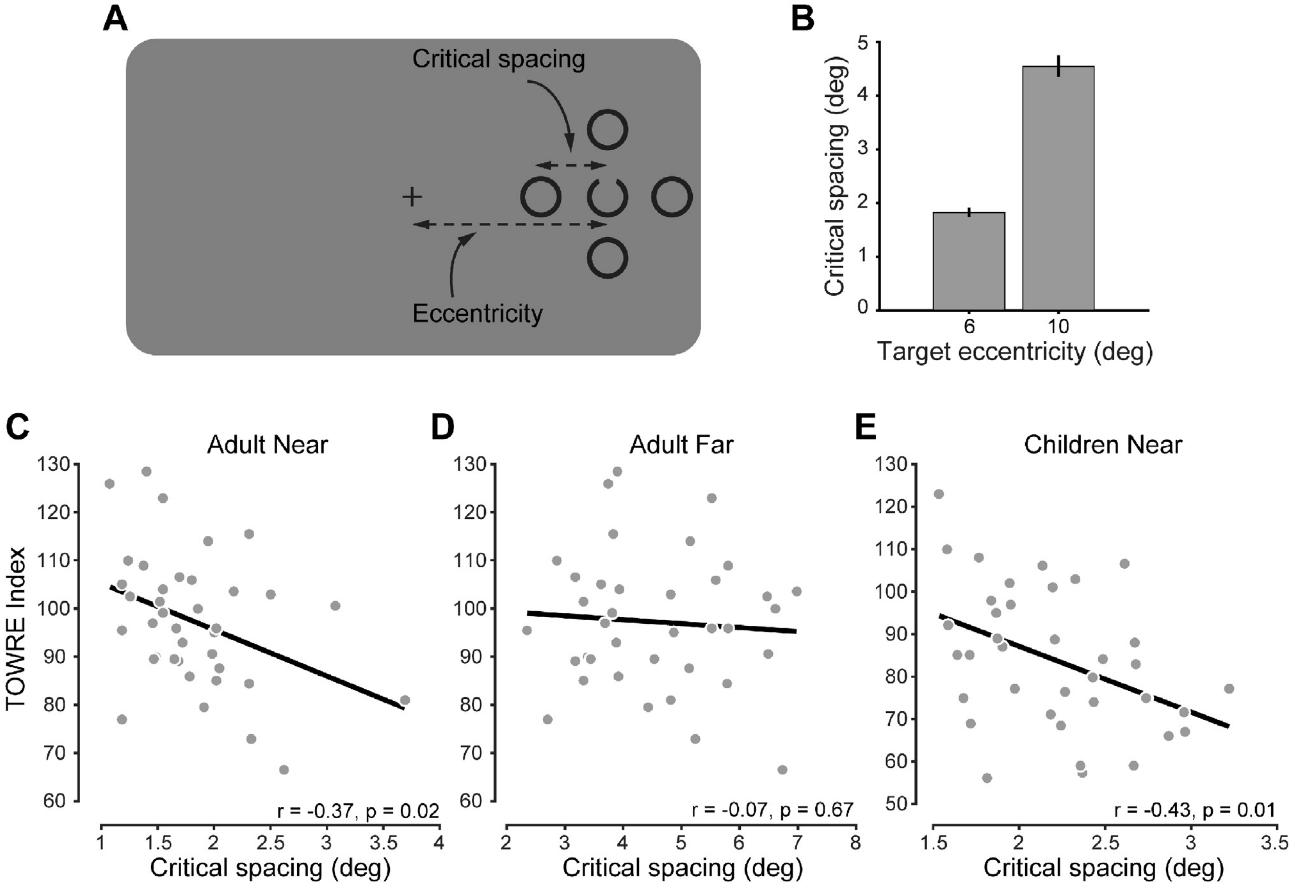

Fig. 1 – Crowding is correlated with reading skills. (A) Crowding stimuli. After 500 msec of fixation on the central mark, crowding stimuli appeared at either the left or the right side of the display. The stimuli disappeared after 150 msec and subjects reported the direction of the gap (up or down) using a joystick. We measured critical spacing at two target eccentricities (6° or 10°) in separate blocks of trials. (B) Critical spacing increases with target eccentricity (means: 1.82 at 6°; 4.55 at 10°). The error bars represent bootstrapped 68% confidence intervals (CIs). (C–D) The relationship between reading skills and critical spacing in adults. The y-axis indicates the TOWRE composite score, a standardized index of reading speed and accuracy that is normed by age (population mean = 100, SD = 15). The x-axis represents critical spacing at 6° (C) and 10° (D) eccentricity. Gray circles show individual data points, and the black line is the best-fitting linear regression line to the data. (E) The relationship between reading skills and critical spacing in children. The x-axis indicates critical spacing at 6° eccentricity.

only the fixation mark was displayed until subjects made a response: subjects reported the direction of the gap (either upward or downward) in the target by moving a joystick up (upward) or down (downward). Visual and auditory feedback was given for both correct (the fixation mark changed to '+' sign with a designated tone for correct responses) and incorrect (the fixation mark changed to '-' sign with a designated tone for incorrect responses). There was a 1 sec blank between feedback and the beginning of the next trial.

2.3.2. *Cueing experiment*

The search array consisted of eight Gabor patches: 50% contrast grayscale sinusoidal gratings with spatial frequency 2 cycles/°, windowed by a 2D Gaussian envelope with standard deviation .28°. The Gabor patches were equally spaced around an imaginary circle, centered on the fixation mark with 5° radius. The fixation mark was a black plus symbol .3° wide. On each trial, 7 of the Gabor patches were oriented vertically, and one (the target) was tilted. The position of the target was chosen randomly on each trial. The observer's task was to report the direction of the target's tilt (clockwise or counterclockwise from vertical) by pressing one of two keys. The magnitude of the tilt was controlled by a weighted up/down staircase that converged on a 75% correct threshold (García-Pérez, 1998).

Each trial began with a cue interval for 33 msec. In the uncued condition, this interval contained only the fixation mark. In the cued condition, it also contained a dark red dot .6° in diameter, at 3° eccentricity along the imaginary line that connected the fixation mark to the upcoming target. The cue interval was followed immediately by the search array for 83 msec, and then an open-ended response interval that ended when the observer pressed one of the two keys. A 75 msec tone provided immediate feedback (high *vs.* low pitch for correct *vs.* incorrect). In addition, the observer gained 3 points for each correct response and 0 points for each incorrect response. The number of points gained was displayed for 750 msec in green or red text immediately after the keypress. After an inter-trial interval of 580 msec, the next trial began. The cued and uncued conditions were separated into blocks of 52 trials. At the end of each block the total number of points gained was printed on the screen. Each observer completed two blocks of each condition.

2.3.3. *Reading experiment*

Real words were selected from the MRC Psycholinguistic Database (http://websites.psychology.uwa.edu.au/school/MRCDatabase/uwa_mrc.htm) by specifying the length in letters (between four and eight letters) and the Kucera-Francis frequency (>125). Words were selected by an author (DJS) with the goal of choosing words that were easily recognized, culturally neutral, and representative of a wide range of word forms. Longer lists of words were reviewed by 3 independent native English speakers (graduate students and postdocs who studied linguistics) and words indicated as being unfamiliar or more difficult were removed. Thirty two words of each length were selected for the final lists. Pseudowords were generated using MCWord Database (http://www.neuro.mcw.edu/mcword/) by specifying the length in letters (between four and eight letters) and generating constrained trigram-based strings. The lists of words were reviewed by the same 3 independent native English speakers and words indicated as being more difficult or having unclear pronunciations were removed. Thirty two words of each length were selected for the final lists.

We created four real word and pseudoword lists containing 40 words with normal and increased text-spacing (a total of 16 lists). We used Calibri font (11pt) for normal spacing and Fluent Calibri font (11pt; https://www.microsoft.com/en-us/download/details.aspx?id=50721) for increased spacing. Compared to 11 point Calibri, 11 point Fluent Calibri increases the letter space by 1.375 point, triples the size of the word space, and adds a complete 11 point empty line between each line of text.

Subjects completed this experiment across two sessions separated by at least a week. In each session, subjects were asked to read the 8 lists (4 real word and 4 pseudoword lists). In one session odd numbered lists were with normal text-spacing and even numbered lists were with increased text-spacing, and in the subsequent session the text-spacing condition was flipped. This order was counterbalanced across subjects. Subjects were instructed to read the words on the list as quickly and accurately as possible.

We measured the start time when the subject began saying the first word on the list and the stop time when they completed the last word. We used strict criteria for accuracy for real words (taking into account dialectal and articulatory differences). We marked correctness of each word during the session. On pseudowords, we used more liberal criteria. The goal was to make sure that individuals were decoding letters in the right order and applying rules of English phonology. Between each list we made sure to check in with the subject to ensure that they were ready to continue, providing them as much time as they needed before beginning the next list. PDFs of the word exact stimuli used in this experiment can be found in the study github repository.

2.4. *Standardized reading assessment*

We administered a battery of behavioral tests including subtests from the Wechsler Abbreviated Scales of Intelligence, Comprehensive Test of Phonological Processing, Test of Word Reading Efficiency and the Woodcock Johnson IV Tests of Achievement. Here we used the Test of Word Reading Efficiency (TOWRE) composite score because it includes measures of real word and pseudoword reading in a timed manner. Most of adult subjects were highly compensated university students and Woodcock Johnson scores were not suitable to distinguish reading ability among highly compensated individuals with dyslexia.

2.5. *Data analysis*

For the crowding experiment, we used QUEST (Watson & Pelli, 1983) staircases to generate the center-to-center distance for each trial. We re-fitted the psychometric function using QUEST procedure by setting the threshold and the slope as free parameters. We excluded staircases in which threshold estimate was greater than the maximum flanker-target distance (6° or 10°), which suggested that the staircase did not converge. We also excluded staircases with a threshold estimate being less than the minimum flanker-target distance (1°) where the flankers and the target overlap. Applying these criteria discarded a total number of 69 staircases out of 400 staircases, resulting in 4–6 staircases per eccentricity for each subject. We averaged the threshold estimates of those remaining staircases to define each subject's critical spacing. Including staircases with threshold estimates <1° did not change the results.

For the cueing experiment, we estimated 75% correct thresholds with maximum likelihood fits of Weibull psychometric functions to the raw data. To quantify the attention effect, we defined the attention index as follows: Attention index $= 1\text{-Thresh}_{\text{cued}}/\text{Thresh}_{\text{uncued}}$. The higher the attention index, the greater the attention effect.

For the reading experiment, we discarded pseudoword reading times greater than 3 SD above the mean. This procedure removed one subject as an outlier. All the analyses were based on the remaining 38 subjects.

We conducted a Bayesian analysis (Kruschke, 2013) to confirm each hypothesis test using a parametric t-test. For this analysis, we generated 20,000 Markov chain Monte Carlo (MCMC) samples of credible parameter values. We report the mean of the posterior distribution, 95% highest density interval (HDI), and the percentage of posterior distribution above zero (since we are testing the differences between means). We also report the Bayes Factor, which is the ratio of the likelihood of the alternative and null hypotheses.

3. Results

3.1. *Elevated crowding predicts reading difficulties*

We first sought to address the relationship between visual crowding and reading skills. Crowding has been suggested as a potential cause of dyslexia based on data showing that dyslexic subjects experience, on average, elevated crowding compared to typical readers (Bouma & Legein, 1977; Martelli et al., 2009). However, previous studies used letters to measure crowding, so differences in crowding might represent linguistic deficits in dyslexic subjects. To remove this potential confound, we measured crowding using non-linguistic stimuli (Fig. 1A; see Methods for details). The stimuli comprised circles (flankers) and a circle with a gap (target). On each trial, subjects reported which direction the gap in the target was facing (up or down). The magnitude of individual crowding effects was indexed by critical spacing, which is the minimal distance (threshold) between the target and flankers at which the observer can report the target identity.

Critical spacing increased as the eccentricity of the target increased (Fig. 1B), confirming conventional eccentricity-dependent crowding effects (Bouma, 1970; Levi, 2008; Whitney & Levi, 2011). With this simple perceptual judgment, critical spacing at near eccentricity (6°) was negatively correlated with reading skills (Fig. 1C; $r = -.37$, $p = .02$): subjects with high critical spacing (more crowding) have worse reading skills than subjects with low critical spacing (less crowding). Critical spacing at far eccentricity (10°) was not correlated with reading skills (Fig. 1D; $r = -.07$, $p = .67$). To ensure that these findings do not reflect specific characteristics of our adult sample, we ran a replication experiment in an independent sample of children ($N = 38$, 9.6 ± 1.8 y), and confirmed that critical spacing at near eccentricity is correlated with reading skills ($r = -.42$, $p = .01$). We focused on critical spacing at near eccentricity for subsequent analyses because crowding in the far periphery is less relevant for reading.

3.2. *Increased text-spacing improves reading performance for adults with elevated crowding*

The data presented above confirm previous reports that crowding and reading ability are correlated (Bouma & Legein, 1977; Martelli et al., 2009), and our data further rule out alternative explanations of this phenomenon by using non-linguistic stimuli. But is this relationship causal? To determine if crowding contributes to individual differences in reading abilities, we experimentally manipulated spacing between letters, words, and lines of text (Fig. 2A–D, see Method for details). Even though inter-letter spacing may not affect the number of letters that fit into an individual's uncrowded window (Denis G Pelli & Tillman, 2008), we hypothesized that increased letter, word and line spacing would alleviate the detrimental effects of a crowded visual environment for an impaired visual system (see Discussion for further details). Based on our hypothesis, we predicted that the extent to which an individual benefits from increased text-spacing would be dependent on their critical spacing.

Consistent with well-known word-frequency effects, there was a large difference in reading speed and accuracy for real versus pseudowords (pseudowords can be thought of as zero-frequency words). Accuracy was higher for high-frequency real words compared to pseudowords (Fig. 2E; 98.6 ± .3% versus 84.8 ± 2.7%; $F(1,37) = 31.74$, $p = 2 \times 10^{-6}$). Reading speed was faster for real words compared to pseudowords (Fig. 2F; 22.14 ± 1.17 msec versus 50.34 ± 3.98 msec; $F(1,37) = 83.96$, $p < 10^{-7}$). Accuracy did not depend on text-spacing for real words or for pseudowords (no main effect of text-spacing; $F(1,37) = .18$, $p = .67$)). Although a parametric paired t-test suggested that increased text-spacing decreased reading speed for pseudowords ($t(37) = 2.23$, $p = .03$) but not for real words ($t(37) = 1.58$, $p = .12$), it appears that this significant result of the parametric test is due to a subset of dyslexic subjects whose reading time for pseudowords is very slow, and whose text-spacing benefit is also very high (see Fig. 3B).

To further test the differences in average reading times within the full sample, we conducted a Bayesian analysis (Kruschke, 2013). For the real words, the difference of means (the mean of posterior distribution) between normal and increased text spacing was .266 sec and the 95% HDI [-.119, .649] included zero (Bayes factor = .5). For the pseudowords, the difference of means between normal and increased text spacing was .489 sec and 95% HDI [-.227, 1.29] also included zero (Bayes factor = 1.6). The non-parametric Bayesian analysis revealed that the difference of means for normal and increased spacing were not credibly different than zero in both the real words and pseudowords condition. Thus, when averaging across the full sample of subjects including both good and poor readers, text-spacing has, at most, a small effect on reading speed.

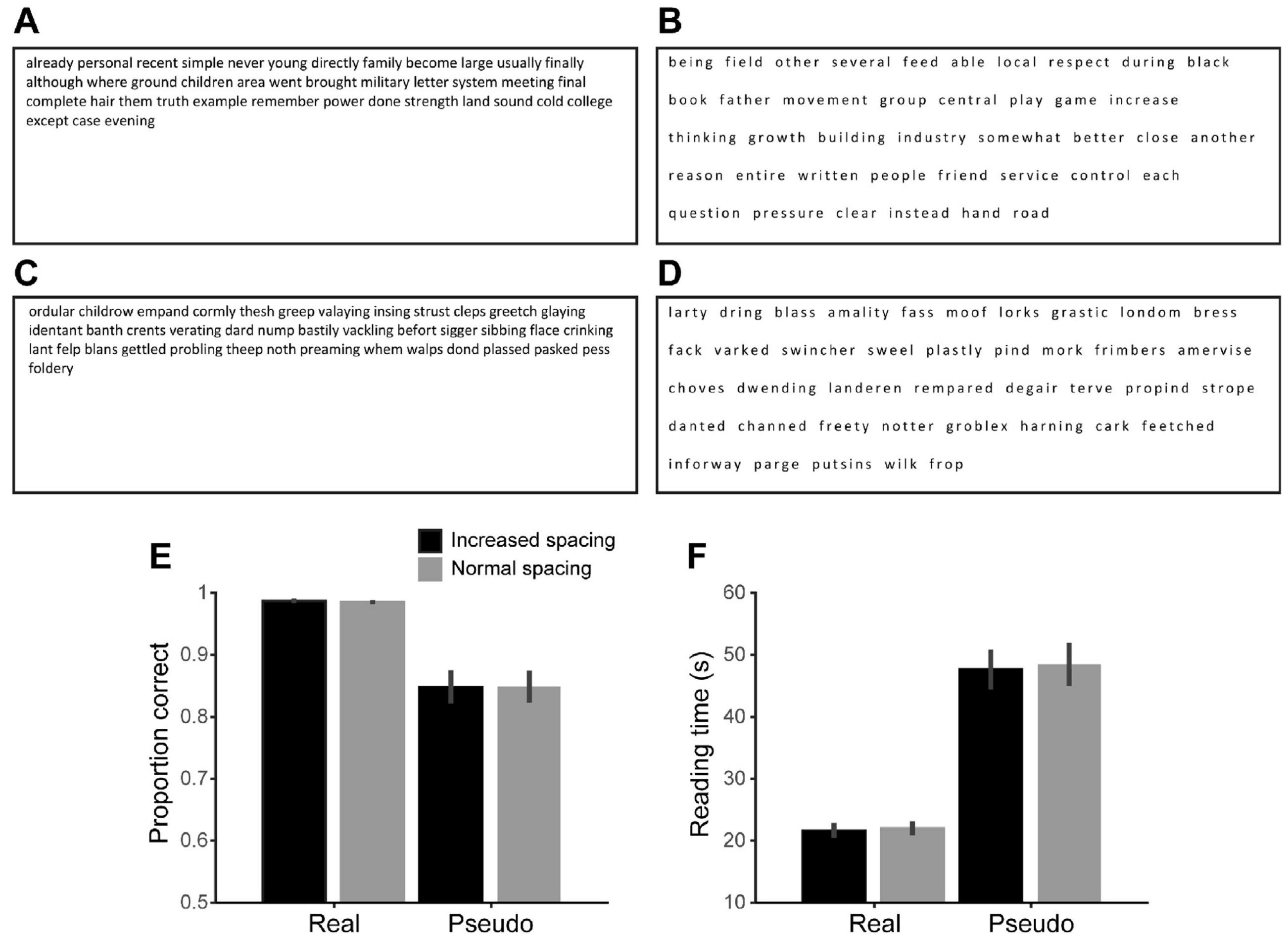

Fig. 2 – Increased text-spacing improves reading performance. (A–D) Examples of real word (A, B) and pseudoword (C, D) lists with normal (A, C) and increased (B, D) text-spacing. (E) Accuracy for each list. Black and gray bars represent proportion correct for increased and normal text-spacing, respectively. Accuracy was not affected by text-spacing. Error bars are bootstrapped 68% CIs, representing the between subject variance (equivalent to ±1 SEM). (F) Reading time for each list. Increased text-spacing had a small effect on reading speed for pseudowords at the group level. Error bars are bootstrapped 68% CIs.

Does text-spacing affect reading speed for individuals with dyslexia? Dividing our sample based on reading skills revealed that only the subjects with low reading skills (TOWRE score < 95) benefitted from increased text-spacing (Fig. 3A). The mean pseudoword text-spacing effect (difference in reading times for increased − normal spacing) for dyslexic readers was 1.91 sec versus .11 sec for typical readers (t (36) = 2.55, *p* = .02). Increased text-spacing did not affect reading speed for high-frequency real words in either group (Text-spacing effects for dyslexic versus typical readers: .54 sec versus .27 sec; t (36) = .53, *p* = .59).

Next, we assessed whether a subject's critical spacing is the main predictor of their text-spacing effect. Fig. 3B depicts individual reading times for pseudoword lists with increased and normal text-spacing. Critically, individuals with high critical spacing (orange) show text-spacing effects—data points are below the unity line—while individuals with low critical spacing (green) do not show improvement—data points are above or on the unity line. Consistent with this observation, critical spacing was correlated with text-spacing effects (Fig. 3C; r = .43, *p* = .007) suggesting that only subjects with elevated crowding benefit from increased text-spacing.

Does the correlation between critical spacing and text-spacing effects simply reflect a relationship between text-spacing effects and reading skills, given that critical spacing is also correlated with reading skills (Fig. 1C)? To rule out this possibility, we conducted a multivariate linear regression analysis using critical spacing and reading skills as independent predictor variables of the text-spacing effect. The results revealed that critical spacing is an independent predictor of text-spacing effects (*p* = .048) and reading skills are marginally significant (*p* = .061). In other words, critical spacing predicts the text-spacing benefit even after controlling for differences in reading skills. We confirmed this finding with a stepwise regression analysis using a bidirectional elimination procedure (Draper & Smith, 1998), which indicated that critical spacing is the main predictor of text-spacing effects. More importantly, text-spacing benefits were greater for subjects

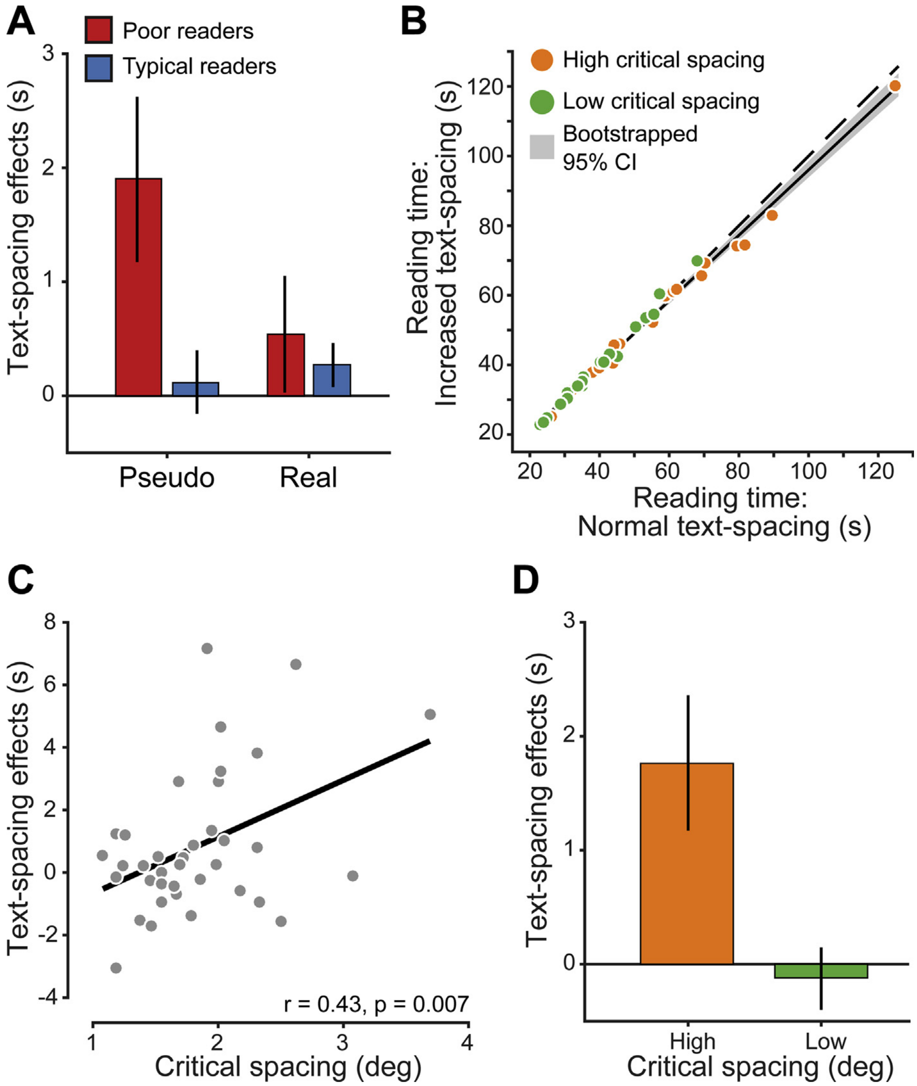

Fig. 3 – Increased text-spacing improves reading speed for poor readers with elevated crowding. (A) Subjects with low reading skills, but not typical readers, benefit from increased text-spacing. The y-axis is the difference between reading time for normal and increased text-spacing. Red and blue bars are for poor readers and typical readers, respectively. Poor readers: TOWRE index standard score <95; Typical readers: TOWRE >95. (B) Reading time for pseudowords with normal (x-axis) and increased (y-axis) text-spacing. Orange points represent individuals with high critical spacing and green points represent individuals with low critical spacing, based on a median split. The shaded region is a bootstrapped 95% confidence interval for the best-fitting line. The dashed line is the unity line. For slow readers there is a substantial benefit of increased text-spacing, demonstrated by the significant deviation of the linear fit from the identity line. (C) Critical spacing predicts the effect of text-spacing. The black line is the best-fitting regression. (D) Text-spacing benefits are pronounced for subjects with high critical spacing and not present in subjects with low critical spacing. Error bars are bootstrapped 68% CIs.

with high critical spacing compared to subjects with low critical spacing (Fig. 3D; 1.76 sec *vs.* −.12 sec for high *vs.* low critical spacing, t (36) = 2.78, *p* = .008, cohen's d = .9). The credible values from the Bayesian analysis are 1.67 (high critical spacing group) versus −.12 (low critical spacing group). The difference of means is 1.79 (the 95% HDI = [.316, 3.24]. 99.1% of the credible values of the difference of means are greater than zero. The Bayes factor was 5.7 showing substantial evidence for the hypothesis that the text-spacing manipulation is effective in subjects with high critical spacing, but not in subjects with normal critical spacing. Therefore, we conclude that the text-spacing effect is credibly different between individuals with high *vs.* low critical spacing, and the principal findings are supported by a parametric t-test and a Bayesian analysis. These findings demonstrate that elevated crowding, regardless of reading skills, is a significant predictor of text-spacing effects.

3.3. *Impaired visual attention does not predict text-spacing effects*

We have demonstrated that poor readers with elevated crowding show better reading performance with increased text-spacing, suggesting that increased text-spacing alleviates crowding for these individuals. However, an alternative mechanism that could explain our results involves spatial attention (Grainger, Dufau, & Ziegler, 2016; Vidyasagar & Pammer, 2010). Several studies have shown that dyslexic readers have impairments in visuospatial attention (Bosse, Tainturier, & Valdois, 2007; Franceschini et al., 2012; Roach & Hogben, 2004). It is possible that visuospatial attention is necessary to select one word from neighboring text during reading. Those with an attentional deficit would therefore benefit from increased text-spacing. Under this hypothesis, if increased crowding is due to an attentional deficit, some theories would interpret it as an indication of a general "dorsal stream dysfunction" (Vidyasagar & Pammer, 2010).

To test this possibility, we used a cued visual search paradigm (Roach & Hogben, 2004) in which subjects judge the orientation of a tilted Gabor patch in an array of seven vertical distractors (Fig. 4A). All subjects had lower orientation thresholds in the cued than the uncued condition, indicating that the cue was effective to direct attention to the target location (Fig. 4B). However, there was no relationship between the attention index and either text-spacing effects (Fig. 4C; $r = -.10$, $p = .54$) or critical spacing (Fig. 4D; $r = -.09$, $p = .60$). Thus, we conclude that the text-spacing manipulation does not target attentional deficiencies in dyslexia.

4. Discussion

Our results show that crowding correlates with reading skills in adults and children, and that adult dyslexic readers with elevated crowding benefit from an experimental manipulation that alleviates crowding in printed text. The reading improvement conferred by text-spacing is not explained by an impairment in selective attention measured using a cueing paradigm. More generally, crowding and selective attention do not reflect a common mechanism. Thus, our results indicate that visual crowding is one mechanism that contributes to reading difficulties in a subset of people with dyslexia. It is

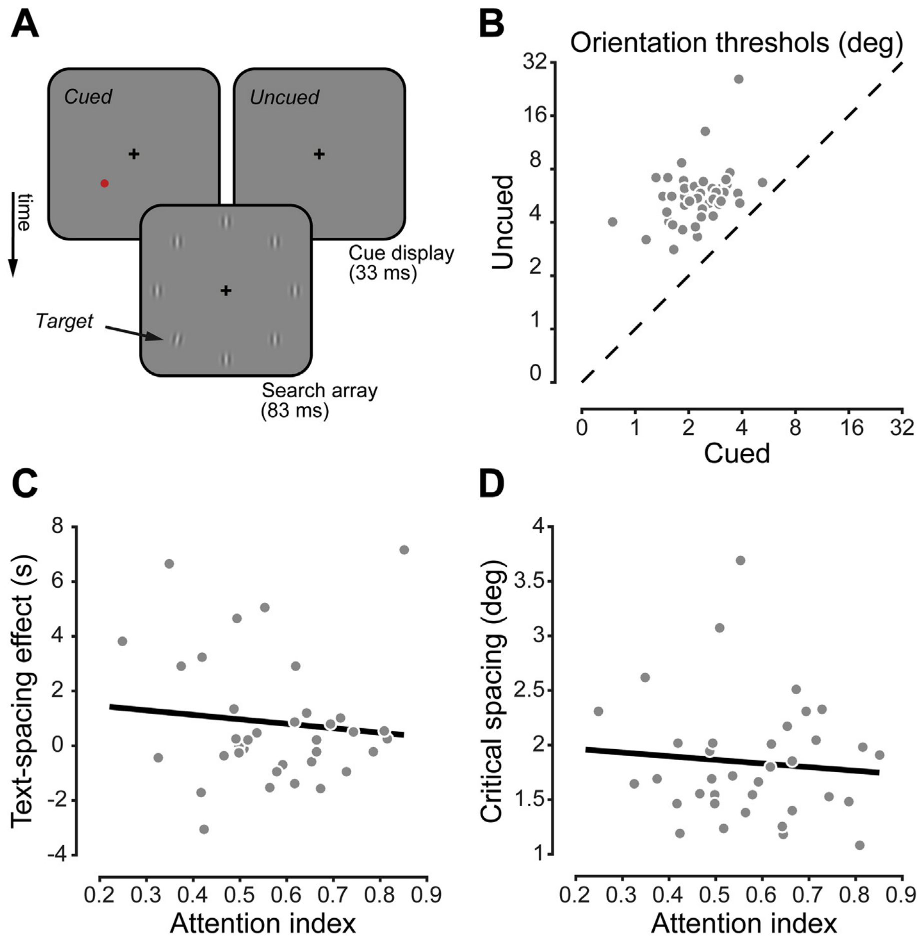

Fig. 4 – Text-spacing effects are not due to impaired spatial attention. (A) The stimuli and procedure for the cueing experiment. The search array (83 msec) comprised 7 vertically oriented distractor Gabors and a tilted target Gabor. Observers reported the direction of the target's tilt. In the cued condition, a 100% valid peripheral pre-cue (red dot) appeared in the 33 msec preceding the search array. In the uncued condition there was no pre-cue. Orientation thresholds were measured with a staircase procedure (See Methods). (B) Orientation thresholds in the cued and uncued conditions. The dashed line represents the unity line. All subjects' thresholds were lower in the cued condition, suggesting that our subjects effectively used the cue to focus spatial attention and exclude distractors. (C) The attention index (cueing effect) does not predict text-spacing effects. (D) The attention index does not predict critical spacing.

important to note that the reverse inference—dyslexic readers have elevated crowding—does not logically follow from our conclusion. In fact, many children and adults with poor reading skills have low critical spacing (less crowding) (Fig. 1C). This is consistent with previous data showing that only a subset of people with dyslexia have elevated crowding, while a majority of people with dyslexia show crowding effects within the typical range (Bouma & Legein, 1977; Doron et al., 2015; Martelli et al., 2009). While previous studies have argued that the overlapping distribution of critical spacing values between dyslexic and control subjects indicates that crowding does not contribute to dyslexia, our data offer a different interpretation. Rather than interpreting an individual's critical spacing as evidence for or against a deficit that characterizes dyslexics as a group, we demonstrate that critical spacing is indicative of limits on information processing within that individual's visual system. Our results suggest that there are some individuals with reading difficulty due to the characteristics of their visual system, and that a simple manipulation of the visual input (i.e., text-spacing) improves their reading behavior.

There is an extensive literature documenting perceptual deficits (e.g., crowding) in people with dyslexia (Bouma & Legein, 1977; Demb et al., 1997; Eden et al., 1996; Martelli et al., 2009) and, more recently, a number of studies have tested the efficacy of font manipulations that are intended to target specific perceptual deficits (e.g., increased text spacing) (Perea et al., 2012; Zorzi et al., 2012). However, the direct link between any specific deficit and the efficacy of a particular font manipulation has not been tested. Our study is the first to provide this link by demonstrating that the severity of an individual's crowding predicts the efficacy of the text spacing manipulation for that individual. This finding has important theoretical implications for the debate over causal mechanisms of dyslexia and lends support to the multiple deficit model whereby the severity of an individual's reading difficulties reflects the interaction between multiple underlying deficits (Joo et al., 2017; Pennington, 2006). On a practical level, our study is the first to demonstrate how a simple perceptual test could be used to personalize properties of a visual display to improve reading performance in people with dyslexia. Based on these findings, there are a number of important follow-up studies to (1) test how these results generalize to more natural reading conditions and (2) investigate the efficacy of font manipulations designed to target the myriad of other perceptual deficits reported in people with dyslexia.

One of the influential theories of crowding suggests that increased spacing between letters will not help alleviate crowding because increasing spacing puts letters further into the periphery where crowding is greater, effectively canceling out the letter-spacing benefit (Herzog, Sayim, Manassi, & Chicherov, 2016; Pelli & Tillman, 2008). Consistent with this theoretical standpoint, typical readers in our study did not show any improvements in reading with increased text-spacing, and poor readers did not show any improvements when they read high-frequency real words (Fig. 3A). So what made poor readers benefit from increased text-spacing for pseudowords? First, in an impaired visual system there may not be the characteristic linear relationship between critical spacing and eccentricity (Pelli & Tillman, 2008; Whitney & Levi, 2011). Subtle nonlinearities would affect the optimal text-spacing. Second, and consistent with Pelli and colleagues (Pelli & Tillman, 2008), it is not likely that more letters are being processed in a single fixation with increased text-spacing. Even so, increased spacing may facilitate the chunking of letters during phonological decoding: the process of converting letters and letter groups into individual sounds. Phonological decoding is especially difficult for dyslexic readers with unfamiliar words, so this hypothesis could explain why our text-spacing effect was specific to poor readers. In an impaired visual system, with elevated crowding, nearby letters and words are more likely to interfere with the process of selectively processing chunks of letters. These interpretations remain open questions, and future research will shed light on how the subtle differences in the visual systems of people with dyslexia play a role in processing letters, chunks of letters, and the whole word in text with increased spacing.

How are our results related to natural reading? Normal text comprises words with frequency ranging from low to high, and pseudowords can be viewed as the extreme case of low frequency words, or words that a novice reader does not yet know. Our results suggest that people with elevated crowding would benefit from increased text-spacing while learning to read or when reading sentences that contain low frequency words (Perea & Gomez, 2012b). Furthermore, increasing text-spacing not only facilitates natural reading speed but also decreases reaction time in lexical decision experiments (Perea & Gomez, 2012a). Finally, a crowded page of text in the periphery might make it more difficult to plan optimal eye movements between sequential words in a line of text. Thus, the relationship between crowding and text-spacing might reflect the benefit conferred to individuals with elevated crowding by reducing the amount of clutter in peripheral vision.

While our results show that individuals with elevated crowding benefit from increased text spacing, the underlying mechanisms of increased text spacing are still unknown. Specifically, our manipulation included inter-letter, inter-word, and inter-line spacing. On the basis of the present experiments, we cannot determine which of those manipulations was responsible for the effect. Previous studies manipulating text spacing have reported mixed results. In typical adult readers, increased line spacing improves reading speed (Chung, 2004) whereas increased letter spacing does not (Chung, 2002) when subjects read one word at a time in a rapid serial visual presentation (RSVP). In children with dyslexia, increased letter spacing seems to improve the speed of reading passages (Hakvoort, van den Boer, Leenaars, Bos, & Tijms, 2017; Marinus et al., 2016; Perea et al., 2012; Zorzi et al., 2012). Future research that independently manipulates spacing between letters, words, and lines, during single word and passage reading, would shed light on the underlying mechanisms of the benefits conferred by text-spacing, and provide an important theoretical constraint in developing methods to help people with dyslexia.

Eye-tracking experiments using skilled readers have shown some mixed effects of text-spacing. While gaze fixation duration is shorter, the number of fixations is higher, effectively canceling out the increased inter-letter spacing effect on reading speed (Perea, Giner, Marcet, & Gomez, 2016). It appears that inter-letter spacing interacts with inter-word spacing during sentence reading in skilled readers (Slattery, Yates, & Angele, 2016). In conjunction with manipulating spacing between letters, words, and lines, studying how increased text spacing affects eye movements in poor readers with elevated crowding during natural reading may be essential to understand the relationship between impaired crowding and reading.

In summary, our results show that elevated crowding is one mechanism that contributes to reading difficulties and is the main predictor of whether a subject will benefit from increased text-spacing. Our results further imply that it is important to develop effective methods to characterize the collection of impairments that contribute to an individual's reading difficulties. By doing so, we can design personalized interventions that specifically target these mechanisms akin to personalized medicine, rather than searching for a single, one-size-fits-all approach to dyslexia treatment.

Author contributions

All authors developed the study concept and contributed to the study design. Data collection was performed by DJS, and SJJ and ALW performed the data analysis and interpretation under the supervision of JDY. SJJ, ALW, and JDY wrote the manuscript. All authors approved the final version of the manuscript for submission.

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