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Improvements in reading accuracy as a result of increased interletter spacing are not specific to children with dyslexia

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ABSTRACT

Recently, increased interletter spacing (LS) has been studied as a way to enhance reading fluency. It is suggested that increased LS improves reading performance, especially in poor readers. Theoretically, these findings are well substantiated as a result of diminished crowding effects. Empirically, however, findings on LS are inconclusive. In two experiments, we examined whether effects of increased LS are specific to children with dyslexia and whether increased LS affects word or sentence processing. In the first experiment, 30 children with dyslexia and 30 controls (mean age = 9 years 11 months) read sentences in standard and increased LS conditions. In the second experiment, these sentences were read by an unselected sample of 189 readers (mean age = 9 years 3 months) in either a sentence or word-by-word reading condition. The first experiment showed that increased LS affected children with dyslexia and controls in similar ways. Participants made fewer errors in the increased LS condition than in the standard LS condition. Reading rates were not affected. There were no indications that the effect of LS was related to reading ability, not even for a subgroup of readers. Findings of the second experiment were similar. Increased LS resulted in fewer errors, not faster reading rates. This was found only when complete sentences were presented, not when sentences were read word by word. Three main

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conclusions can be drawn. First, increased LS appears to affect reading accuracy only. Second, the findings do not support claims that increased LS specifically affects poor readers. And third, the effect of LS seems to occur at the interword level. Theoretical and practical implications of these findings are discussed.

Introduction

Recently, increased interletter spacing (LS) has been studied as a way to enhance reading fluency. Zorzi et al. (2012), for example, showed that an increase in the space between two adjacent letters, and additional increases in the space between words and lines, fostered reading fluency, especially in readers with dyslexia. These improvements in reading performance in these poor readers are remarkable given that enhancing reading fluency for this group has proven to be difficult. The growth rate of reading speed in poor readers has been shown to be approximately half of that observed in typically developing peers (Tressoldi, Stella, & Faggella, 2001). As a result, the difference in reading speed between poor and average to good readers increases rapidly over time. Therefore, it is not surprising that the results of Zorzi et al. (2012) were picked up and praised by the research community (e.g., McCandliss, 2012). It was appreciated that an immediate increase in performance was achieved through relatively simple and ecologically valid methods. Furthermore, McCandliss (2012) mentioned that these results seem highly replicable. However, to date, few studies have managed to replicate that effects of increased LS are *specific* to individuals with dyslexia (e.g., Perea, Panadero, Moret-Tatay, & Gómez, 2012). A large number of studies found zero or negative effects of increased LS or found positive effects on speed or accuracy that were not specific to individuals with dyslexia; other groups of readers, such as skilled adult readers and young readers without dyslexia, sometimes also profit from an increase in LS (for an overview, see van den Boer & Hakvoort, 2015; see also Perea, Giner, Marcet, & Gomez, 2016; Sjoblom, Eaton, & Stagg, 2016). In the current article, we first describe the theoretical validation of the effects of increased LS and review the research findings on this topic. We then present two experiments that aimed to replicate and extend the results of Zorzi et al. (2012).

Theoretically, the potential effect of LS is substantiated with the literature on visual crowding. Although in most studies on LS crowding is not explicitly measured, LS can be considered one of several possible manipulations of crowding. LS is thought to reduce crowding, which is the negative effect in peripheral vision of surrounding visual elements on the recognition of an otherwise identifiable target (Bouma, 1970; Whitney & Levi, 2011). This crowding effect impedes the utility of peripheral vision for visual object recognition tasks (Millin, Arman, Chung, & Tjan, 2014; Whitney & Levi, 2011). Crowding appears to result from inappropriate feature integration in early visual processing but is also sensitive to top-down influences (Pelli & Tillman, 2008). Recognition is impaired when objects are closer together than the critical spacing, that is, the distance that is needed between target and flankers to allow for unimpaired recognition. This threshold eccentricity for accurate recognition appears to be a fundamental parameter of human vision and, thus, is the same for all objects (Pelli & Tillman, 2008). In terms of reading, visual crowding distorts the perception of peripherally presented letters that are surrounded by other letters and, consequently, has the potential to impede the reading process. The majority of visual word recognition processes occur while the word is fixated. The impact of visual crowding on these processes can be expected to be marginal because eccentricity is at a minimum (Slattery & Rayner, 2013). However, some reading processes, such as the processing of parafoveal preview information and the related saccade planning, are of a parafoveal nature (Marx, Hutzler, Schuster, & Hawelka, 2016; Schotter, Angele, & Rayner, 2012) and, thus, potentially subjected to visual crowding effects.

Notably, the effect of crowding, and more specifically the critical spacing, does appear to be sensitive to developmental processes and to differ across individuals. For example, crowding effects were found to be larger in children than in adults (Jeon, Hamid, Maurer, & Lewis, 2010). Whereas single letter acuity was found to be adult-like at 8 years of age, children, at least up to 11 years old, were more affected than adults by surrounding contours when naming letters. This protracted development of visual processing might contribute to, or even determine advances in, reading development. Nonetheless, the reversed direction of effects is also possible given that it has been shown that reading acquisition alters the organization of early visual (letter features) processing (Dehaene, Cohen, Morais, & Kolinsky, 2015) and that reading experience induces top-down influences on visual crowding (Williamson, Scolari, Jeong, Kim, & Awh, 2009).

There is general consensus on the importance of phonological processing skills for reading development (Vellutino, Fletcher, Snowling, & Scanlon, 2004) given that the large majority of both children (Saksida et al., 2016) and adults (e.g., Ramus et al., 2003) with dyslexia have been shown to suffer from phonological deficits. It has been suggested, however, that visual processing, such as increased crowding effects, also affects reading fluency instead of, or in addition to, phonological processing skills (e.g., Saksida et al., 2016; Vidyasagar & Pammer, 2010; but see the study by Ziegler, Pech-Georgel, Dufau, & Grainger (2010), which shows that these visual deficits might still result from phonological difficulties). Crowding effects have been found to be more marked in children with dyslexia than in controls (Martelli, Di Filippo, Spinelli, & Zoccolotti, 2009; Spinelli, De Luca, Judica, & Zoccolotti, 2002). In line with the assumption that effects of crowding are the same for all objects (Pelli & Tillman, 2008), this difference was similar in processing both words and symbols. It should be noted, however, that enlarged effects of crowding were found in only a minority of the participants with dyslexia. Furthermore, elevated crowding effects were not found for adults with dyslexia (Doron, Manassi, Herzog, & Ahissar, 2015; Hawelka & Wimmer, 2008). Importantly, these studies with adults did not use alphanumeric stimuli, or if alphanumeric stimuli were used, participants were not asked to verbally report on these items. In other words, it seems important to consider the items and tasks that are used when examining crowding effects in individuals with dyslexia because performance in participants with and without dyslexia might be differentially affected by letter familiarity or verbal coding, not merely by crowding (Doron et al., 2015).

Moreover, Moll and Jones (2013) suggested that increased crowding effects in parafoveal processing might be a result, rather than a cause, of the reading difficulties. In a recent study by Silva et al. (2016), it was indeed shown that apparent effects of crowding in parafovea might not stem from visuo-attentional factors; rather, they might reflect reduced parafoveal preview benefits, such that participants require more time to process the target item, which leaves less time for preprocessing of parafoveal items. Furthermore, differences between adults with and without dyslexia were found only in a letter-naming task, not in a letter-finding task, indicating that adults with dyslexia do not benefit from parafoveal preview because they need to focus all of their attention on activating phonology for the orthographic input in the fovea. This again indicates that it is important to critically consider which task is used to examine the effects of crowding. Taken together, the theoretical validation of the effect of increased LS in terms of decreased crowding effects seems plausible, albeit not unchallengeable. There are some indications that crowding is related to reading fluency. More specifically, crowding appears to be larger for children than for adults and larger for poor readers than for average readers.

The effects found in studies focused on LS vary (see van den Boer & Hakvoort, 2015, who reviewed 20 studies from 18 publications). Several studies have shown that in average readers—both children and adults—performance in sentence and text reading is not affected by increased LS (e.g., Paterson & Jordan, 2010; Perea et al., 2016; Reynolds & Walker, 2004). However, a recent study by Marinus et al. (2016) shows gains in reading speed for dyslexic readers as a function of increased LS. Furthermore, as already mentioned, Zorzi et al. (2012) found that children with dyslexia made fewer errors and read faster when sentences were presented with increased LS as compared with normal sentences. Similar findings were reported by Perea et al. (2012). In these last two studies, the findings have been ascribed to more efficient encoding of letters in words, and thus more efficient word identification, as a result of increased LS (Perea et al., 2012; Zorzi et al., 2012). Studies that specifically focused on the effect of increased LS on word reading, however, do not necessarily support this conclusion. Spinelli et al. (2002) found that a small increase in LS resulted in faster word reading in only about half of the children with dyslexia. It has also been found that young readers, as well as poor readers, do not benefit at all from increased LS when reading words (see the experimental study presented in van den Boer & Hakvoort, 2015). Furthermore, it has been shown that adjustments in LS can even harm word recognition both when LS is decreased (Montani, Facoetti, & Zorzi, 2015; van den Boer & Hakvoort, 2015) and when LS is too large (e.g., Risko, Lanthier, & Besner, 2011; Spinelli et al., 2002).

Taken together, findings on LS are inconclusive. Some studies have shown that readers benefit from increased LS, especially poor readers, because with increased LS the effects of crowding decrease. However, this finding has been reported in only a few studies, and several other studies challenged both the effect of LS and the importance of crowding for reading performance. The current study aimed to extend the body of research on LS. More specifically, two experiments examined whether effects of LS are specific to children with dyslexia and whether LS mainly affects word encoding or parafoveal processing.

Experiment 1

In this first experiment, we aimed to replicate the results of Zorzi et al. (2012). Following the paradigm used in that study, children with dyslexia and age-matched controls read sentences with both standard and increased LS. Furthermore, we aimed to address critiques that have been articulated about the study of Zorzi et al. Skottun and Skoyles (2012) noted that the average readers in the study of Zorzi et al. made very few errors and, therefore, did not have much room for improvement in terms of accuracy as a result of increased LS. Thus, the finding that the effect of increased LS on reading accuracy is specific to readers with dyslexia might be due to a ceiling effect in the performance of the average readers. In the current experiment, we addressed this issue by using more complex sentences of an age-appropriate difficulty level in order to avoid ceiling effects in typical readers. It was hypothesized that increased LS improves reading accuracy for all children, not specifically for children with dyslexia, when text is of an age-appropriate difficulty level, thereby allowing for improvement in reading accuracy.

Furthermore, Zorzi et al. (2012) found within-group differences between normal and increased LS only when the normally spaced text was read first and the text with increased LS was read second, not the other way around. This raises the question of whether the effect of increased LS in children with dyslexia could be due to the motivating nature of the unusual text layout in the increased LS condition. Compared with average readers, children with dyslexia need more attention and effort to decode printed words. An “attention boost” in terms of an unusual text layout, therefore, could temporarily foster their reading performance, whereas average readers, who read relatively effortlessly, are less affected. In the current experiment, we aimed to explore this issue by comparing the reading performance on the first and last blocks of sentences. It was hypothesized that, if indeed the effect of increased LS is due to heightened attention, we would find for all readers, but especially for children with dyslexia, an effect of increased LS for the first block of sentences but not, or to a much lesser extent, for the later block.

Method

Participants

A total of 30 children formally diagnosed with dyslexia (18 boys; mean age = 9 years 11 months, *SD* = 6.50 months) were recruited from the IWAL Institute (locations in Utrecht and Amsterdam, The Netherlands), a nationwide center specializing in learning disabilities. To be eligible for the experiment, children needed to score at least 1 standard deviation below the average of their age group on a standard word reading fluency test and to be referred to the center because of persistent reading problems (i.e., children had shown a poor response to weekly, specialized remedial teaching provided at school during a 5-month period). Exclusion criteria included comorbidity with another developmental disorder (e.g., attention deficit/hyperactivity disorder, autism spectrum disorders, specific language impairment) and below average IQ. Standardized tests of the diagnostic assessment (all in *T* scores with *M* = 50, *SD* = 10) indicate that the cognitive profile of our dyslexic sample is characterized by poor phoneme awareness ($M = 36.72$, $SD = 8.42$), letter–speech sound mapping (accuracy: $M = 36.83$, $SD = 12.26$; speed: $M = 40.27$, $SD = 9.33$), and rapid automatized naming (letters: $M = 39.20$, $SD = 10.04$; digits: $M = 38.17$, $SD = 8.21$) but with oral language skills ($M = 50.70$, $SD = 5.63$), morphological skills ($M = 49.50$, $SD = 6.10$), and intelligence ($M = 102.03$, $SD = 12.20$) within the normal range.

In addition, 30 typically developing age-matched controls (17 boys; mean age = 9 years 9 months, *SD* = 7.10 months) in third or fourth grade of elementary school participated in this experiment. Typically developing children were recruited at public elementary schools in Utrecht and Amsterdam. To be eligible, they needed to have a percentile score of 25 or higher on a standard word reading fluency test. All children had normal or corrected-to-normal visual acuity. Parents gave informed consent for the participation of their children.

Materials and procedure

Word reading fluency. The Dutch norm-referenced task One Minute Test (OMT; *Eén Minuut Test*; Brus & Voeten, 1995) was used to assess word reading fluency. The task consists of 116 mono- and polysyllabic words of increasing difficulty. Children are asked to read the words as fast and accurately as possible. The score is the total number of correctly read words in 1 min. These scores were also converted to standard scores ($M = 10$, $SD = 3$).

Sentence reading task. The sentence reading (SR) task consisted of 34 target sentences and 10 filler sentences, which were meaningful yet unrelated to one another. All sentences were of an age-appropriate difficulty level. Sentences were selected from the Dutch text reading test AVI (Visser, van Laarhoven, & ter Beek, 1994), the 2009 edition of AVI (Jongen & Krom, 2009), and the Flemish reading test VTBL (*Vlaamse Test Begrijpend Lezen*; van Vreckem, Desoete, de Paepe, & van Hove, 2010), totaling 17 target and 10 filler sentences. The other 17 target sentences were created by replacing the content words (verbs, nouns, and adjectives) in the original sentences by words from the CELEX database via the WebCelex site (Max Planck Institute for Psycholinguistics, 2001). The newly created sentences were meaningful as well. The replacement words were matched on word length, number of syllables, grammatical class, frequency, and (as closely as possible) orthographic complexity. For example, the sentence "Ze hadden de [picknickmand] al [ingepakt]" (They had already packed the picnic basket) was matched to "Ze hadden de [schoenenzaak] al [betreden]" (They had already entered the shoe store) (see also Fig. 1).

All participants read the same 44 sentences twice in two separate test sessions (sessions were separated by a week): once with standard LS and once with increased LS. The order was counterbalanced between participants. Text was presented on paper in Times New Roman point size 14. The increased LS condition was similar to that in the study of Zorzi et al. (2012); LS was +2.5, the space between words was increased to 3 space characters, and the line spacing was doubled. Different from the study by Zorzi et al. (2012), however, each sentence was presented on a separate line. Examples of sentences in the standard and increased LS conditions are presented in Fig. 1. The text was divided into three (unmarked) parts: (a) the first block of 17 test sentences, (b) 10 filler sentences, and (c) the second block of 17 test sentences. Each block comprised a total of 119 words. The purpose of the filler sentences in the middle was to increase the distance between the two blocks of test sentences to allow for a possible habituation to the increased LS. The order of the sentences was randomized across tests

Ze hadden de schoenenzaak al betreden.
Ik oefen in die volle zaal daar.

Z e   h a d d e n   d e   p i c k n i c k m a n d   a l   i n g e p a k t .

I k   k l i m   i n   d i e   h o g e   b o o m   d a a r .

Fig. 1. Sentences with standard letter spacing (top) and increased letter spacing (bottom).

to minimize the effects of repetition. The test session was audio-recorded on a laptop with the computer program Praat (Boersma & Weenink, 2013) with an external microphone placed in front of the participants. Recordings were used to determine errors and reading rates. Scores consisted of the number of errors and reading speed. For reading speed, the reading time in seconds was converted to the number of words read per second.

Results

Descriptive statistics

To verify that the children with dyslexia read substantially poorer than the typically developing children, word reading fluency scores (OMT; see "Materials and procedure" section) were compared by means of an independent *t* test. Children with dyslexia ($M = 35.20$, $SD = 7.91$) scored significantly lower on the OMT than controls ($M = 68.57$, $SD = 7.84$), $t(58) = 16.41$, $p < .001$, Cohen's $d = 4.24$. Children with dyslexia (average standard score = 3) performed far below, and controls (average standard score = 11) performed slightly above, the reading level that is expected mid-Grade 4.

Prior to running analyses, data were checked for outliers. Scores that were more than 3 standard deviations above or below the group mean were removed from the dataset. For the accuracy data, the number of errors of 1 child with dyslexia was identified as an outlier on three of the four blocks. Data of this child, therefore, were left out of the analyses of reading accuracy. Furthermore, one outlier was identified on the standard LS condition (Block 1), and one outlier was identified on the increased LS condition (Block 2). No outliers were found for reading speed. Descriptive statistics for both accuracy and speed are presented in Table 1. Across blocks and conditions, children with dyslexia read on average 8.0% of the words incorrectly compared with 3.8% for the controls.

The improvement in reading accuracy and speed for children with and without dyslexia as a result of increased LS can be expressed in percentages to control for overall group differences in both the number of errors and reading speed (see Table 1). The effect of increased LS on reading accuracy is larger for controls than for children with dyslexia, especially in Block 1. The effect of increased LS on reading speed is very small across blocks and groups.

Effects of LS on reading accuracy

To assess the effect of LS on reading accuracy, a repeated-measures analysis of variance (ANOVA) was run with the between-participant factor group (dyslexia or controls) and the within-participant factors LS (standard or increased) and block (first or second). The main effect of group was significant, $F(1, 55) = 21.72$, $p < .001$, $\eta^2_p = .283$. Children with dyslexia made more errors than controls. In addition, a main effect of LS was found, $F(1, 55) = 16.97$, $p < .001$, $\eta^2_p = .236$, whereas the interaction between group and LS was not significant, $F(1, 55) = 0.04$, $p = .849$, $\eta^2_p = .001$. Both children with and without dyslexia made fewer errors in the increased LS condition than in the standard LS condition. The main effect of block was not significant, $F(1, 55) = 2.55$, $p = .116$, $\eta^2_p = .044$, but the interaction between block

Table 1
Means (and standard deviations) on the sentence reading task.

	Children with dyslexia		Controls	
	Errors	Speed	Errors	Speed
Standard LS				
Block 1	10.54 (6.30)	1.05 (0.32)	5.10 (2.99)	2.24 (0.36)
Block 2	9.86 (6.33)	1.06 (0.34)	5.67 (3.41)	2.21 (0.43)
Increased LS				
Block 1	10.00 (5.40)	1.06 (0.31)	3.60 (2.09)	2.24 (0.35)
Block 2	7.54 (4.62)	1.11 (0.31)	3.83 (2.61)	2.22 (0.35)
% Effect of LS				
Block 1	5.1	1.0	29.4	0.4
Block 2	23.5	4.7	32.5	0.4

Note. LS, letter spacing.

and group was significant, $F(1, 55) = 7.51$, $p = .008$, $\eta_p^2 = .120$. The interaction between LS and block, $F(1, 55) = 2.14$, $p = .149$, $\eta_p^2 = .037$, and the three-way interaction among LS, block, and group, $F(1, 55) = 0.814$, $p = .371$, $\eta_p^2 = .015$, were not significant. An analysis of the effects of LS and block in each group separately confirmed these findings. For both groups, there was a main effect of LS [children with dyslexia: $F(1, 26) = 4.615$, $p = .041$, $\eta_p^2 = .151$; controls: $F(1, 29) = 20.714$, $p < .001$, $\eta_p^2 = .417$]. The effect of block was significant only for children with dyslexia [children with dyslexia: $F(1, 26) = 6.51$, $p = .017$, $\eta_p^2 = .200$; controls: $F(1, 29) = 1.04$, $p = .317$, $\eta_p^2 = .035$], and the interaction between LS and block was not significant in either group [children with dyslexia: $F(1, 26) = 1.590$, $p = .219$, $\eta_p^2 = .058$; controls: $F(1, 29) = 0.42$, $p = .524$, $\eta_p^2 = .014$]. Taken together, these findings indicate that the difference in the number of errors between Block 1 and Block 2 was different for children with dyslexia and controls but not different for the two LS conditions. Children with dyslexia made more errors on the first block than on the second block, whereas for controls the number of errors did not differ across blocks.

Effects of LS on reading speed

To assess the effect of LS on reading speed, a repeated-measures ANOVA was run with the between-participant factor group (dyslexia or controls) and the within-participant factors LS (standard or increased) and block (first or second). As expected, a profound difference in reading speed between children with dyslexia and controls resulted in a significant main effect of group, $F(1, 58) = 191.10$, $p < .001$, $\eta_p^2 = .767$. On average, the controls read about twice as fast as the children with dyslexia. No other main or interaction effects were significant [main effect of LS: $F(1, 58) = 0.37$, $p = .547$, $\eta_p^2 = .006$; main effect of block: $F(1, 58) = 0.09$ $p = .766$, $\eta_p^2 = .002$; interaction between LS and group: $F(1, 58) = 0.07$, $p = .799$, $\eta_p^2 = .001$; interaction between LS and block: $F(1, 58) = 0.47$, $p = .497$, $\eta_p^2 = .008$; interaction between block and group: $F(1, 58) = 2.91$, $p = .093$, $\eta_p^2 = .048$; three-way interaction among LS, group, and block: $F(1, 58) = 0.53$, $p = .471$, $\eta_p^2 = .009$]. Analyses for the groups separately did not yield any effects of LS either [children with dyslexia: $F(1, 29) = 0.62$, $p = .437$, $\eta_p^2 = .021$; controls: $F(1, 29) = 0.04$, $p = .836$, $\eta_p^2 = .002$]. Thus, increased LS did not affect reading speed for either group.

Effect of LS for individual children

For both children with dyslexia and controls, reading accuracy was found to benefit from increased LS, whereas reading speed was not affected. It would be interesting to see, however, whether a subgroup of children, especially among the children with dyslexia, might benefit more than others. The effects of increased LS for individual children were examined by calculating the effect of LS for each child. Because there were no significant interactions between LS and block, we calculated the mean accuracy and speed of the two blocks. For reading accuracy, we subtracted the errors in the increased LS condition from the errors in the standard LS condition. For reading speed, we subtracted the words read per second in the standard LS condition from the words read per second in the increased LS condition. As a result, for both accuracy and speed, a positive effect score reflects a beneficial effect of increased LS.

The effects of LS for each individual child are plotted in Fig. 2. For the children with dyslexia, there was on average a positive effect of LS on reading accuracy, although the effects vary greatly ($M = 1.22$, $SD = 3.92$). Regarding reading speed, the average effect of LS was negligible ($M = .02$, $SD = .15$). For controls, there also was, on average, a positive effect of LS on reading accuracy ($M = 1.67$, $SD = 2.01$), and hardly any effect on reading speed ($M = .01$, $SD = .23$). Regarding accuracy, there was a negative effect or no effect (i.e., effect score ≥ 0) of increased LS for 41.4% of the children with dyslexia and for 23.3% of the controls. For 3 children with dyslexia (10%), the positive effect of increased LS on reading accuracy clearly surpassed the effect of increased LS for controls. However, note that there were also at least 2 children with dyslexia for whom particularly large negative effects of increased LS on reading accuracy were found. For reading speed, there was a negative effect or no effect of increased LS for 43.3% of the children with dyslexia and also for 43.3% of the controls. None of the children with dyslexia showed more positive or more negative effects of increased LS than the controls. Taken together, there are no clear indications that (subgroups of) children with dyslexia benefit or suffer more than controls from increased LS. Finally, the effects of LS did not correlate in any significant manner with word reading fluency, as measured by the OMT [all participants: $r(60) = -.02$, $p = .86$ for accuracy,

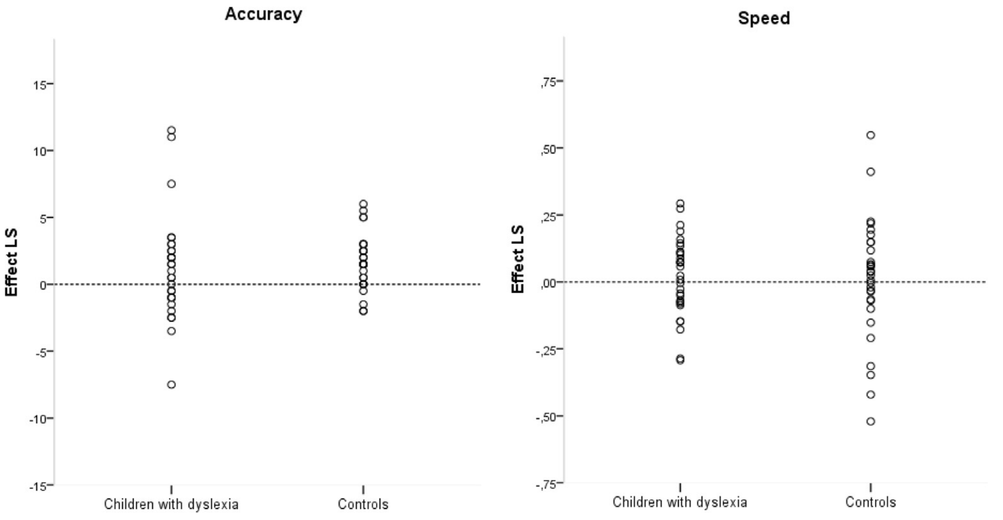

Fig. 2. Plots of the effects of increased letter spacing (LS) on reading accuracy (left) and reading speed (right) for individual children. For accuracy, the difference in number of errors is plotted. For speed, the graph reflects the difference in the number of words read per second.

$r(60) = -.06$, $p = .64$ for speed; dyslexic sample: $r(30) = -.03$, $p = .87$ for accuracy, $r(30) = -.12$, $p = .55$ for speed; controls: $r(30) = -.15$, $p = .42$ for accuracy, $r(30) = -.05$, $p = .80$ for speed].

Conclusion

Reading speed was not affected by increased LS, but reading accuracy improved significantly among children with and without dyslexia. These results are not in line with those of Zorzi et al. (2012), who reported increases in both reading speed and accuracy specifically for their participants with dyslexia. We used an age-appropriate text level to avoid ceiling effects in the accuracy of the control group. Our results suggest that when average readers have enough room for improvement in their accuracy rates, they do seem to benefit from increased LS. There were no indications that a subgroup of children with dyslexia might benefit more than controls from increased LS. If anything, the effects of increased LS were larger for controls than for children with dyslexia. Unlike Zorzi et al., we did not find any effects of increased LS on reading speed for either children with dyslexia or controls. It should be noted, however, that also in Zorzi et al.'s study the effects of increased LS on reading speed were not different for children with dyslexia and controls (i.e., the interaction between group and LS was not significant).

As an alternative explanation for the benefits in reading speed and accuracy found by Zorzi et al. (2012), we tested whether the effects of LS might be due to the unusual text layout, which might provide an attention boost to children with dyslexia. Therefore, we compared the performance on the first block of sentences with that on the last block of sentences. We found that if effects of LS occurred for children with dyslexia, they mainly occurred on the last block. Thus, these findings suggest that effects of increased LS for children with dyslexia should not be ascribed to heightened attention.

Experiment 2

In the second experiment, we aimed to replicate the finding of an effect of increased LS on reading accuracy in all readers, not specifically children with dyslexia (because no differential effects were present in dyslexic readers in Experiment 1). We presented the same sentences to a larger group of readers with a wide range of reading abilities. Slight adjustments were made to the presentation of the sentences to allow the investigation of our second research question: Does an effect of increased LS occur at the word level or at the sentence level? We presented readers with a self-paced reading task in which sentences were presented word by word, on the one hand, and a sentence reading task in which sentences were presented as a whole, on the other. If increased LS diminishes the negative effect of crowding on letter and word encoding, as suggested in previous studies (e.g., Perea et al., 2012; Zorzi et al., 2012), we would expect a positive effect of increased LS on reading speed and accuracy when sentences are presented word by word and also when they are presented as a whole. If, however, the effects of crowding are more pronounced in parafoveal and peripheral vision (e.g., Moll & Jones, 2013), it would be expected that increased LS has an effect on reading only when words are surrounded by other elements, as during sentence reading, but not when words are presented one by one. In addition, to be able to pinpoint whether potential reading benefits are due to LS specifically, only the LS was manipulated and not interline and interword spacing as in Experiment 1. If the results of Experiment 1 can indeed be ascribed to the increase in interletter spacing, we expected to find similar results in Experiment 2. If this is not the case, results from Experiment 1 can be attributed to the increased interword or interline spacing.

Method

Participants

Participants were recruited from primary schools in The Netherlands. A total of 92 children from Grade 3 (47 girls) and 97 children from Grade 4 (49 girls) took part in the study. Their mean age was 9 years 3 months (SD = 7.98 months). A total of 54 children indicated that they spoke a second language besides Dutch, but for all except 7 children Dutch was their preferred language. Standardized scores on the OMT (Brus & Voeten, 1995) indicated that the sample included a representative range of reading abilities (M = 10.11, SD = 3.02).

Children were divided into four groups pseudorandomly, keeping an equal division of age and sex. Each group was then assigned to one condition (Sentence Reading, standard LS first; Sentence Reading, increased LS first; Self-Paced Reading, standard LS fist; Self-Paced Reading, increased LS first; see also "Materials and procedure" section). Age, gender, and average reading ability for each of these groups are presented in Table 2. The groups did not differ significantly in age, $F(3, 185) = 0.160$, $p = .923$, gender, $\chi^2(3, N = 189) = 4.591$, $p = .204$, or reading ability, $F(3, 185) = 0.099$, $p = .961$.

Materials and procedure

The reading task consisted of 34 target sentences. Children were presented with two blocks of 17 sentences each: one block with standard LS and one block with increased LS. Each block was preceded by 5 filler sentences that served as practice items. The sentences were the same as for Experiment 1. Different from Experiment 1, in Experiment 2 sentences were presented via a laptop using E-Prime 2.0 (Schneider, Eschman, & Zuccolotto, 2002). Different from Zorzi et al. (2012) and different from Experiment 1, the sentences in the spaced condition had an increase in LS of +1.2. This spacing was chosen

Table 2
Age, gender, and reading ability of children in four experimental conditions.

	Sentence reading		Self-paced reading	
	S/I LS [*M* (*SD*)]	I/S LS [*M* (*SD*)]	S/I LS [*M* (*SD*)]	I/S LS [*M* (*SD*)]
N	47	49	47	46
Age[a]	9;2 (8.38)	9;3 (7.80)	9;3 (8.28)	9;2 (7.64)
Gender[b]	26	27	17	23
Word reading[c]	59.26 (13.96)	59.39 (11.78)	60.57 (13.42)	59.30 (15.18)

Note. S/I LS, standard LS, then increased LS; I/S LS, increased LS, then standard LS.
[a] Expressed in years; months (standard deviations are in months).
[b] Expressed in number of boys.
[c] Expressed in number of words read correctly per minute.

to ensure that the sentences were presented on one line and fitted the screen. In addition, to test whether the potential effects of increased LS should indeed be ascribed to LS and not to increased interword spacing, the spaces between words were proportional rather than increased. Because sentences were presented one by one, interline spacing was not a factor in this study.

Half of the children were in the Sentence Reading (SR) condition, and half were in the Self-Paced Reading (SPR) condition. Within each condition, half of the children read the standard LS sentences first, whereas the other half started with the increased LS sentences. In the SR condition, sentences were presented as a whole. Sentences were presented in the middle of the screen and were preceded by a fixation cross (+). Children were asked to read each sentence out loud and to press the spacebar when they had read the sentence. Reaction times (RTs) per sentence were recorded. The experimenter recorded the number of errors per sentence. In the SPR condition, sentences were presented word by word. Prior to each sentence, a target cross (+) appeared. Words were presented in the middle of the screen. Children were asked to read each word out loud and to press the spacebar after each word was read, which made the next word of that sentence appear. RTs were recorded per word, and the experimenter recorded the number of errors. In both conditions, sentences were interspersed with comprehension questions to ensure that sentences were read carefully.

Results

Descriptive statistics

Prior to analyses, RTs on words and sentences were screened for outliers. Values below 200 ms and more than 3 standard deviations of a participant's mean RT were coded as missing in both the SPR and SR conditions. In the SPR condition, RTs to incorrectly read words were coded as missing as well. This was not possible in the SR condition because only sentence reading times were recorded. Next, the mean RT per sentence was calculated. For the SPR condition, RTs per sentence were calculated by adding RTs of individual words. For both conditions, mean RT was converted to the number of words read per second. Following that, for all variables, mean scores that were more than 3 standard deviations above or below the group mean were removed from the dataset. For SR, we removed two outliers in the increased LS condition, two outliers in the standard LS condition for accuracy, and one outlier each for speed. For SPR, one outlier was removed in the standard LS condition for accuracy. For speed, one outlier was removed in the increased LS condition and one in the standard LS condition. Descriptive statistics for both accuracy and speed are presented in Table 3. Lastly, effects of order (the presentation of increased LS vs. standard LS first) on the effect of LS were addressed for both speed and accuracy. No significant results were found; therefore, order of presentation was left out of further analyses.

Correlations of SR and SPR with word reading fluency

First, to validate the scores on the SR and SPR tests as indicators of reading performance, correlations of these reading tasks (the standard LS condition only) with the scores on the OMT (Brus & Voeten, 1995) were examined. The correlations are presented in Table 4. Moderate correlations were found between word reading fluency and accuracy in both SR and SPR. For reading speed, high correlations were found with reading fluency in the SR condition. The correlations with reading speed in the

Table 3
Accuracy and reading speed as a function of letter spacing.

	Sentence reading ($N = 96$)		Self-paced reading ($N = 93$)	
	Errors [*M* (*SD*)]	Speed [*M* (*SD*)]	Errors [*M* (*SD*)]	Speed [*M* (*SD*)]
Standard LS	3.87 (2.53)	1.63 (0.41)	1.99 (2.14)	1.14 (0.39)
Increased LS	2.76 (2.35)	1.63 (0.43)	1.71 (1.90)	1.14 (0.39)
% Effect LS	28.7	0.3	14.0	0.0

Note. LS, letter spacing.

Table 4
Correlations of word reading fluency with the sentence reading task and the self-paced reading task.

	Sentence reading × OMT	Self-paced reading × OMT
Accuracy, standard LS	−.61***	−.60***
Reading speed, standard LS	.86***	.60***

Note. OMT, One Minutes Test; LS, letter spacing.
*** $p < .001$.

SPR condition were lower, which is not surprising given the nature of the task, which required both reading and button presses.

Effects of LS on reading accuracy

First, effects of LS on accuracy were assessed. To this end, a repeated-measures ANOVA was run on the total number of errors with the within-participant factor spacing (standard or increased) and the between-participant factor condition (SR or SPR). Main effects were found for spacing, $F(1, 183) = 25.41$, $p < .001$, $\eta_p^2 = .122$, and condition, $F(1, 183) = 24.00$, $p < .001$, $\eta_p^2 = .116$, and there was an interaction effect between spacing and condition, $F(1, 183) = 7.46$, $p = .007$, $\eta_p^2 = .039$. These results indicate that the two conditions yielded significantly different amounts of errors. More errors were made in the SR condition compared with the SPR condition. The amount of errors is also dependent on LS. However, the significant interaction effect suggests that this is not the case for both conditions. Post hoc *t* tests were carried out to examine the effect of LS per condition. Results show that the effect of LS was significant in the SR condition, $t(92) = 5.07$, $p < .001$, but was not significant in the SPR condition, $t(91) = 1.80$, $p = .075$. Thus, increased LS mainly has an effect on accuracy when sentences are presented as a whole and less so when sentences are presented word by word.

Effects of LS on reading speed

Next, the effects of LS on reading speed were assessed. To investigate whether reading times decreased as a function of LS, and whether the manner of presentation of the sentences affected reading times, a repeated-measures ANOVA with the within-participant factor spacing (standard or increased) and the between-participant factor condition (SR or SPR) was conducted. The main effect of spacing was not significant, $F(1, 184) = 0.61$, $p = .435$, $\eta_p^2 = .003$, nor was the interaction between spacing and condition, $F(1, 184) = 0.13$, $p = .721$, $\eta_p^2 = .001$, indicating that increased LS did not affect the number of words read per second. A main effect was found for condition, $F(1, 184) = 74.80$, $p < .001$, $\eta_p^2 = .289$, showing that, overall, performance was slower in the SPR condition compared with the SR condition. This is unsurprising given that the SPR condition required multiple button presses that take up time.

Relation between effect of LS and reading ability

To examine whether the effect of LS might be more pronounced for either poorer or better readers, we calculated the effect of LS for each child as described for Experiment 1. We then examined the correlation of the effect of LS with reading ability. For sentence reading, there was no correlation between reading fluency and the effect of LS on accuracy ($r = -.07$, $p = .509$) or speed ($r = .08$, $p = .443$). For self-paced reading, the correlations between reading fluency and the effect of LS on accuracy ($r = -.17$, $p = .105$) and speed ($r = -.035$, $p = .744$) were not significant either. Importantly, there was also no correlation between the effect of LS on accuracy and speed in either SR ($r = -.024$, $p = .817$) or SPR ($r = -.107$, $p = .315$).

Conclusion

In Experiment 2, effects of LS on sentence reading were addressed in a large sample of children from Grades 3 and 4. No effects of LS were found on accuracy when sentences were read word by word, in line with van den Boer and Hakvoort (2015), who reported the same results for single word reading. However, in line with Experiment 1, increased LS had an effect on accuracy in the SR condition; fewer mistakes were made when LS was increased. Given the single manipulation of LS in Experiment 2, the results suggest that benefits in accuracy are due to increased interletter spacing and not interword spacing. Our research design did not allow a direct comparison between interletter and interword spacing. However, the results are the same as in Experiment 1, suggesting that it is not the additional interword spacing in Experiment 1 that caused the results. Thus, the results are not directly in line with findings by Marinus et al. (2016), who showed that poor readers benefit most from relatively larger spacing between words than within words. Future studies that specifically manipulate interletter, interword, and interline spacing should be undertaken. For reading speed, no effects were found in either condition. Furthermore, no correlations were found between the effects of LS and reading ability. Taken together, the results of this experiment suggest that word identification per se does not improve when LS is increased, as indicated by the absence of effects in the SPR condition, but that LS improves the identification of items in a broader visual field, as reflected in the SR condition (in line with Moll & Jones, 2013). These effects were not related to reading ability.

General discussion

In this study, we tested the effects of increased interletter spacing on sentence reading in typically developing children and in children with dyslexia. We carried out two experiments that yielded three main conclusions. First, our results show that reading accuracy, but not reading rate, is affected by increased LS. These effects were found both when interword spacing was also increased by inserting multiple space characters and when interword spacing was proportional to the spacing of the font. Second, normal readers and readers with dyslexia were found to profit equally from an increase in LS. Both average and poor readers read sentences with increased LS more accurately compared with sentences with standard LS. No relation was found between reading ability and the effect of LS, nor were subgroups from whom increased LS was especially beneficial identified. Third, the effect of LS seems to occur at the sentence level. Accuracy was found to improve only if sentences were presented as a whole, not when they were presented word by word.

Importantly, these conclusions differ from previous claims suggesting that dyslexic readers in particular benefit from an increase in LS (Zorzi et al., 2012). Zorzi et al. (2012) presented increased LS as a way to enhance reading performance in readers with dyslexia. This suggestion is attractive because, on the one hand, it has proven to be especially difficult to enhance reading fluency in children with dyslexia (e.g., Tijms, 2011) and because, on the other, current electronic devices offer ample possibilities to adjust parameters of text presentation to the reader's specific needs and preferences (Rello & Barbosa, 2013). However, the findings of the current experiments showed that it is not reading fluency that is supported, given that effects were found for accuracy only, and that the effects are not specific to children with dyslexia but rather are the same for all young readers.

In terms of reading accuracy, the different findings in our study as compared with the study of Zorzi et al. (2012) could be due to the difficulty level of the stimuli. In the study of Zorzi et al., the average readers made very few errors and, thus, could not improve much in their reading accuracy (Skottun & Skoyles, 2012). In the current study, in contrast, we used sentences of an age-appropriate difficulty level. The results show that when average readers have enough room for improvement in their accuracy rates, they do seem to benefit from increased LS. The difference in the effect of LS between average readers and those with dyslexia was not significant. The trend, however, was for average readers to benefit more, not less, than readers with dyslexia. More difficult to understand, however, is the fact that Zorzi and colleagues found significant effects of increased LS on reading speed, whereas we did not. There is no ready explanation for this difference. It might originate from the difference in presentation; sentences in their study were presented in text, whereas sentences in our study were each presented on a separate line. Important, however, is the fact that findings seem to be similar for readers with and without dyslexia. Also in the study of Zorzi et al., the interaction effect denoting the difference in the effect of LS on reading speed between poor and average readers did not reach significance (Skottun & Skoyles, 2012). The finding that the effect of LS reached significance for the readers with dyslexia but not for the average readers by itself does not allow for the conclusion of a group difference.

The beneficial effects of increased LS have been suggested to result from diminished crowding. Crowding is suggested to hamper letter identification, leading to reading difficulties in readers with dyslexia (Martelli et al., 2009; Spinelli et al., 2002). Increased LS might aid letter identification and, as such, resolve possible negative effects of crowding on reading speed and accuracy. However, the finding that normal readers also appear to benefit from enlarged LS in sentence reading, suggests that crowding might not contribute to poor reading in that it delimits decoding ability. This is supported by our previous study in which we failed to find positive effects of increased LS on single word reading for both poor and average readers (van den Boer & Hakvoort, 2015).

Overall, our results might indicate that increased LS seems to have an effect on the quality of parafoveal preprocessing in reading, although this would need to be validated using eye-tracking measures. This finding fits nicely with the literature on visual crowding in which this effect is considered to impede the utility of peripheral vision for visual object recognition (Millin et al., 2014). Thus, the more peripheral the visual orthographic stimuli are perceived, the more likely a crowding effect is to occur. Consequently, crowding effects are more likely to interfere with peripheral reading processes captured by the perceptual span such as information about between-word spaces, word length, and other cues to plan a saccade (Risse, 2014; Schotter et al., 2012). As a result, crowding can be expected to affect reading at the interword level in sentence reading. Similarly, it has been suggested that differences in crowding should mainly be sought in the width of the visual span in which effects are found (Moll & Jones, 2013). Interestingly, several studies investigating the effects of LS in sentence reading in adult normal readers show no effects of increased LS on reading rate and accuracy (e.g., Perea & Gomez, 2012; Yu, Cheung, Legge, & Chung, 2007). It is possible that beneficial effects of LS found in children may find their origin in the still maturating visual system. In addition, print processing is an acquired skill that needs ample time to develop. Neural areas responsible for processing other visual information need to become attuned to print during reading development (Dehaene et al., 2010). The effects of LS might cease to exist during adulthood as a function of a fully developed neural system for print processing.

But what about readers with dyslexia? On the one hand, the effects of increased LS do not seem specific to them. On the other hand, it has been suggested that for them crowding extends to a larger visual field (Moll & Jones, 2013). It is not yet clear, however, whether these differences in the effect of crowding on individuals with dyslexia are truly the cause of their reading difficulties. Several studies have shown that the effects of crowding are the same for adults with and without dyslexia when non-alphanumeric stimuli are used (Doron et al., 2015; Hawelka & Wimmer, 2008). Furthermore, it has been shown that differences in the effects of crowding should be interpreted as a reduced parafoveal preview effect in poor readers (Silva et al., 2016). Likewise, it has been shown that both children and adults with dyslexia are slower in identifying single letters or words but are especially affected when lists of stimuli are presented (Jones, Branigan, & Kelly, 2009; Zoccolotti et al., 2013). Surrounding stimuli seem to evoke the activation of multiple orthographic and phonological representations, which compete with the representation of the target word and, as such, hamper processing of the target word. Taken together, these findings suggest that increased effects of crowding found for poor readers might be a consequence, rather than a cause, of their reading difficulties and highlight the importance of selecting unbiased stimuli when comparing groups that differ in reading ability and, thus, in their experience with alphanumeric stimuli.

There are a number of limitations to the current study that should be mentioned. First, the setup of Experiment 1 was different from that of Experiment 2. Of specific importance here are the choices for different increases in LS and +3 character spaces versus proportional interword spacing. Although these manipulations allowed the testing of specific hypotheses, we did not consistently test the effects of interletter versus interword spacing across a range of spacing settings. Recent studies (Marinus et al., 2016; Slattery, Yates, & Angele, 2016) suggest that interword spacing should depend on the chosen interletter spacing, such that the interword spacing is larger than the interletter spacing. Future studies are needed to pinpoint certain effects of increased spacing specifically to interletter, interword, and/or interline spacing.

Second, our findings in Experiments 1 and 2, as well as in the two conditions of Experiment 2, might not be directly comparable. Whereas the sentences were the same across conditions, they were presented on paper in Experiment 1 and on a computer in Experiment 2. To date, findings on the equivalence of computer- and paper-based tasks are mixed, although a review of the literature suggests that the equivalence has greatly improved over the past 20 years due to technological advances (Noyes & Garland, 2008). Furthermore, whereas sentences were presented as a whole in both Experiment 1 and the SR condition of Experiment 2, sentences were presented word by word in the SPR condition of Experiment 2. Reading sentences word by word might affect the ecological validity of sentence reading, for example, because a button needs to be pressed for the next word to appear. However, data were cleaned following the procedure suggested by Jegerski (2014) for SPR measures to optimize the reliability of the data. Moreover, the effect of LS was first and foremost studied within the SPR condition, between standard and increased LS conditions, and there are no indications that possible objections to the SPR methodology might affect reading with standard LS more than with increased LS or vice versa.

Moreover, in our study it was possible to examine only total reading times of sentences. It would be interesting to study the effects of LS with online measures such as eye tracking. Interestingly, Perea et al. (2016), using an eye tracker, showed that average fixation durations were shorter with increased LS but that total reading times were not affected by increased LS because the effect of shorter average fixation times was cancelled out by a larger number of fixations in the increased LS condition. Based on the current findings—that is, an effect of increased LS on reading accuracy but not on speed—we would predict exactly this pattern of eye movements.

Finally, future studies that include both a standard crowding paradigm and a manipulation of LS are needed to establish whether effects of increased LS indeed relate to crowding given that LS is generally suggested to be a manipulation of crowding but this relation is rarely directly established.

In sum, the current experiments do not support previous claims that increases in LS specifically benefit readers with dyslexia and, thus, do not indicate that changes in LS should be used as a means to foster reading ability in this group. Rather, we found a positive effect of increased LS on reading accuracy for the entire group of young readers, indicating that more research into the text characteristics that are most supportive of reading for children is needed. In general, there is very little empirical support for the guidelines for printed text used by publishing companies, and data on readability for children are especially scarce (Woods, Davis, & Scharff, 2005). Recent studies have shown that poor readers benefited especially from shorter lines (Schneps et al., 2013), and from increased spacing, when the spacing between words was larger than that within words (Marinus et al., 2016). Future studies could examine these effects for all readers because the current findings suggest that young average readers might benefit as well.

References

Boersma, P., & Weenink, D. (2013). *Praat [computer software]*. Amsterdam: University of Amsterdam.

Bouma, H. (1970). Interaction effects in parafoveal letter recognition. *Nature, 226*, 177–178.

Brus, B., & Voeten, B. (1995). *Eén Minuut Test vorm A en B: Verantwoording en handleiding [one minute test manual]*. Lisse, The Netherlands: Swets & Zeitlinger.

Dehaene, S., Cohen, L., Morais, J., & Kolinsky, R. (2015). Illiterate to literate: Behavioural and cerebral changes induced by reading acquisition. *Nature Neuroscience Review, 16*, 234–244.

Dehaene, S., Pegado, F., Braga, L. W., Ventura, P., Nunes Filho, G., Jobert, A., ... Cohen, L. (2010). How learning to read changes the cortical networks for vision and language. *Science, 330*, 1359–1364.

Doron, A., Manassi, M., Herzog, M. H., & Ahissar, M. (2015). Intact crowding and temporal masking in dyslexia. *Journal of Vision, 15*. http://dx.doi.org/10.1167/15.14.13.

Hawelka, S., & Wimmer, H. (2008). Visual target detection is not impaired in dyslexic readers. *Vision Research, 48*, 850–852.

Jegerski, J. (2014). Self-paced reading. In J. Jegerski & B. VanPatten (Eds.), *Research methods in second language psycholinguistics* (pp. 20–49). New York: Routledge.

Jeon, S. T., Hamid, J., Maurer, D., & Lewis, T. L. (2010). Developmental changes during childhood in single-letter acuity and its crowding by surrounding contours. *Journal of Experimental Child Psychology, 107*, 423–437.

Jones, M. W., Branigan, H. P., & Kelly, M. L. (2009). Dyslexic and nondyslexic reading fluency: Rapid automatized naming and the importance of continuous lists. *Psychonomic Bulletin & Review, 16*, 567–572.

Jongen, I., & Krom, R. (2009). *DMT en AVI*. Arnhem, The Netherlands: Cito.

Marinus, E., Mostard, M., Segers, E., Schubert, T. M., Madelaine, A., & Wheldall, K. (2016). A special font for people with dyslexia: Does it work and if so, why? *Dyslexia, 22*, 233–244.

Martelli, M., Di Filippo, G., Spinelli, D., & Zoccolotti, P. (2009). Crowding, reading, and developmental dyslexia. *Journal of Vision, 9*. http://dx.doi.org/10.1167/9.4.14.

Marx, C., Hutzler, F., Schuster, S., & Hawelka, S. (2016). On the development of parafoveal processing: Evidence from the incremental boundary paradigm. *Frontiers in Psychology, 7*. http://dx.doi.org/10.3389/fpsyg.2016.00514.

Max Planck Institute for Psycholinguistics (2001). *WebCelex* [database] Retrieved from http://celex.mpi.nl/.
McCandliss, B. D. (2012). Helping dyslexic children attend to letters within visual word forms. *Proceedings of the National Academy of Sciences of the United States of America, 109*, 11064–11065.
Millin, R., Arman, A. C., Chung, S. T. I., & Tjan, B. S. (2014). Visual crowding in V1. *Cerebral Cortex, 24*, 3107–3115.
Moll, K., & Jones, M. (2013). Naming fluency in dyslexic and nondyslexic readers: Differential effects of visual crowding in foveal, parafoveal, and peripheral vision. *Quarterly Journal of Experimental Psychology, 66*, 2085–2091.
Montani, V., Facoetti, A., & Zorzi, M. (2015). The effect of decreased interletter spacing on orthographic processing. *Psychonomic Bulletin & Review, 22*, 824–832.
Noyes, J. M., & Garland, K. J. (2008). Computer- vs. paper-based tasks: Are they equivalent? *Ergonomics, 51*, 1352–1375.
Paterson, K. B., & Jordan, T. R. (2010). Effects of increased letter spacing on word identification and eye guidance during reading. *Memory & Cognition, 38*, 502–512.
Pelli, D. G., & Tillman, K. A. (2008). The uncrowded window of object recognition. *Nature Neuroscience, 11*, 1129–1135.
Perea, M., Giner, L., Marcet, A., & Gomez, P. (2016). Does extra interletter spacing help text reading in skilled adult readers? *Spanish Journal of Psychology, 19*, E26.
Perea, M., & Gomez, P. (2012). Subtle increases in interletter spacing facilitate the encoding of words during normal reading. *PLoS ONE, 7*(10), e47568.
Perea, M., Panadero, V., Moret-Tatay, C., & Gómez, P. (2012). The effects of inter-letter spacing in visual-word recognition: Evidence with young normal readers and developmental dyslexics. *Learning and Instruction, 22*, 420–430.
Ramus, F., Rosen, S., Dakin, S. C., Day, B. L., Castellote, J. M., White, S., & Frith, U. (2003). Theories of developmental dyslexia: Insights from a multiple case study of dyslexic adults. *Brain, 126*, 841–865.
Rello, L., & Barbosa, S. D. (2013). Do people with dyslexia need special reading software? In *Paper presented at INTERACT 2013 Workshop on Rethinking Universal Accessibility: A broader approach considering the digital gap, Cape Town, South Africa*. .
Reynolds, L., & Walker, S. (2004). "You can't see what the words say": Word spacing and letter spacing in children's reading books. *Journal of Research in Reading, 27*, 87–98.
Risko, E. F., Lanthier, S. N., & Besner, D. (2011). Basic processes in reading: The effect of interletter spacing. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 37*, 1449–1457.
Risse, S. (2014). Effects of visual span on reading speed and parafoveal processing in eye movements during sentence reading. *Journal of Vision, 14*. http://dx.doi.org/10.1167/14.8.11.
Saksida, A., Iannuzzi, S., Bogliotti, C., Chaix, Y., Démonet, J. F., Bricout, L., ... Ramus, F. (2016). Phonological skills, visual attention span, and visual stress in developmental dyslexia. *Developmental Psychology, 52*, 1503–1516.
Schneider, W., Eschman, A., & Zuccolotto, A. (2002). *E-Prime: User's guide*. Pittsburgh, PA: Psychology Software.
Schneps, M. H., Thomson, J. M., Sonnert, G., Pomplun, M., Chen, C., & Heffner-Wong, A. (2013). Shorter lines facilitate reading in those who struggle. *PLoS ONE, 8*(8), e71161.
Schotter, E. R., Angele, B., & Rayner, K. (2012). Parafoveal processing in reading. *Attention, Perception, & Psychophysics, 74*, 5–35.
Silva, S., Faísca, L., Araújo, S., Casaca, L., Carvalho, L., Petersson, K. M., & Reis, A. (2016). Too little or too much? Parafoveal preview benefits and parafoveal load costs in dyslexic adults. *Annals of Dyslexia, 66*, 187–201.
Sjoblom, A. M., Eaton, E., & Stagg, S. D. (2016). The effects of letter spacing and coloured overlays on reading speed and accuracy in adult dyslexia. *British Journal of Educational Psychology, 86*, 630–639.
Skottun, B. C., & Skoyles, J. R. (2012). Interletter spacing and dyslexia. *Proceedings of the National Academy of Sciences of the United States of America, 109*, E2958.
Slattery, T. J., & Rayner, K. (2013). Effects of intraword and interword spacing on eye movements during reading: Exploring the optimal use of space in a line of text. *Attention, Perception, & Psychophysics, 75*, 1275–1292.
Slattery, T. J., Yates, M., & Angele, B. (2016). Interword and interletter spacing effects during reading revisited: Interactions with word and font characteristics. *Journal of Experimental Psychology: Applied, 22*, 406–422.
Spinelli, D., De Luca, M., Judica, A., & Zoccolotti, P. (2002). Crowding effects on word identification in developmental dyslexia. *Cortex, 38*, 179–200.
Tijms, J. (2011). Effectiveness of computer-based treatment for dyslexia in a clinical care setting: Outcomes and moderators. *Educational Psychology, 31*, 873–896.
Tressoldi, P. E., Stella, G., & Faggella, M. (2001). The development of reading speed in Italians with dyslexia: A longitudinal study. *Journal of Learning Disabilities, 34*, 414–417.
van den Boer, M., & Hakvoort, B. E. (2015). Default spacing is the optimal spacing for word reading. *Quarterly Journal of Experimental Psychology, 68*, 697–709.
van Vreckem, C., Desoete, A., de Paepe, L., & van Hove, H. (2010). *VTBL: Vlaamse Test Begrijpend Lezen*. Ghent, Belgium: Academia Press.
Vellutino, F. R., Fletcher, J. M., Snowling, M. J., & Scanlon, D. M. (2004). Specific reading disability (dyslexia): What have we learned in the past four decades? *Journal of Child Psychology and Psychiatry, 45*, 2–40.
Vidyasagar, T. R., & Pammer, K. (2010). Dyslexia: A deficit in visuo-spatial attention, not in phonological processing. *Trends in Cognitive Sciences, 14*, 57–63.
Visser, J., van Laarhoven, A., & ter Beek, A. (1994). *AVI: Toetspakket*. Hertogenbosch, The Netherlands: Katholiek Pedagogisch Centrum.
Whitney, D., & Levi, D. M. (2011). Visual crowding: A fundamental limit on conscious perception and object recognition. *Trends in Cognitive Neuroscience, 15*, 160–168.
Williamson, K., Scolari, M., Jeong, S., Kim, M., & Awh, E. (2009). Experience-dependent changes in the topography of visual crowding. *Journal of Vision, 9*. http://dx.doi.org/10.1167/9.11.15.
Woods, R. J., Davis, K., & Scharff, L. F. V. (2005). Effects of typeface and font size on legibility for children. *American Journal of Psychological Research, 1*, 86–102.
Yu, D., Cheung, S. H., Legge, G. E., & Chung, S. T. L. (2007). Effect of letter spacing on visual span and reading speed. *Journal of Vision, 7*. http://dx.doi.org/10.1167/7.2.2.
Ziegler, J. C., Pech-Georgel, C., Dufau, S., & Grainger, J. (2010). Rapid processing of letters, digits, and symbols: What purely visual–attentional deficit in developmental dyslexia? *Developmental Science, 13*, F8–F14.

Zoccolotti, P., De Luca, M., Lami, L., Pizzoli, C., Pontillo, M., & Spinelli, D. (2013). Multiple stimulus presentation yields larger deficits in children with developmental dyslexia: A study with reading and RAN-type tasks. *Child Neuropsychology, 19*, 639–647.

Zorzi, M., Barbiero, C., Facoetti, A., Lonciari, L., Carrozzi, M., Montico, M., ... Ziegler, J. C. (2012). Extra-large letter spacing improves reading in dyslexia. *Proceedings of the National Academy of Sciences of the United States of America, 109*, 11455–11459.