SEE COMMENTARY

# Extra-large letter spacing improves reading in dyslexia

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**Although the causes of dyslexia are still debated, all researchers agree that the main challenge is to find ways that allow a child with dyslexia to read more words in less time, because reading more is undisputedly the most efficient intervention for dyslexia. Sophisticated training programs exist, but they typically target the component skills of reading, such as phonological awareness. After the component skills have improved, the main challenge remains (that is, reading deficits must be treated by reading more—a vicious circle for a dyslexic child). Here, we show that a simple manipulation of letter spacing substantially improved text reading performance on the fly (without any training) in a large, unselected sample of Italian and French dyslexic children. Extra-large letter spacing helps reading, because dyslexics are abnormally affected by crowding, a perceptual phenomenon with detrimental effects on letter recognition that is modulated by the spacing between letters. Extra-large letter spacing may help to break the vicious circle by rendering the reading material more easily accessible.**

visual-attentional deficits | word recognition | orthographic processing | print

Developmental dyslexia is a severely invalidating learning disability that affects literacy acquisition in about 5% of the school population despite normal intelligence and adequate instruction (1, 2). The causes of dyslexia are still hotly debated (3–8), but all researchers agree that the main challenge is remediation (that is, how to get dyslexic children to read more words in less time). Indeed, a dyslexic child reads in 1 year the same number of words as a good reader in 2 days (9). The most common approach has been to devise sophisticated remediation programs that train subskills of reading, especially phonological skills and auditory perception. Although rather successful, this approach is time-consuming and difficult to implement in realistic school settings, and the improvements in these subskills do not automatically improve reading (10, 11).

A second, complementary approach is to focus on the accessibility of the reading material by manipulating the physical properties of print (e.g., print size, font type, etc.).* However, very little research has investigated the potential effects of such manipulations (12, 13). Here, we pursue this approach, which is motivated by behavioral evidence showing that dyslexics are abnormally affected by crowding (14–17), a perceptual phenomenon with detrimental effects on letter recognition that is modulated by the spacing between letters (18, 19). Crowding refers to the interference of flanking letters on the recognition of target letters (review in refs. 20 and 21). Recognition is impaired when letters are closer than a critical spacing (19), which is proportional to eccentricity but independent of print size (22).

Crowding mostly affects peripheral vision in normal adult readers (22), but it also affects central vision in school-aged children (23). Moreover, there is mounting evidence that children with developmental dyslexia are more influenced by crowding than age-matched controls, even under optimal viewing condition (14–17, 24, 25). It is well-known that letter identification is a fundamental step in visual word recognition and reading aloud (26–28). Parsing of a letter string into its constituent graphemes is a key component of phonological decoding (28), which in turn, is fundamental for reading acquisition (29). Crowding might not only slow down reading speed (19, 22) but also induce reading errors, because crowding is accompanied by a jumbled percept that is thought to reflect pooling of features from the target and the flankers (21). These findings lead to the prediction that extra-wide interletter spacing in words should reduce crowding and ameliorate reading performance in dyslexics. Note that the standard letter spacing for text seems to be optimal in skilled adult readers. Both reduction and increase in spacing have a detrimental effect on reading performance (18, 19, 22). For instance, reading speed in skilled adult readers is slowed when letter spacing is doubled (19).

## Results

We tested the prediction that extra-wide interletter spacing should improve reading performance in dyslexia in an unselected sample of 74 children aged between 8 and 14 y (mean age = 10.4 y, SD = 1.5), all recruited in specialized hospitals where they had been diagnosed with developmental dyslexia. The dyslexic sample included 34 Italian and 40 French children. Note that Italian has a transparent writing system, whereas French has a relatively opaque writing system, which is similar to English. The inclusion of the two languages allowed us to generalize our findings across transparent and opaque writing systems (29, 30). Children had been diagnosed as dyslexics based on standard exclusion/inclusion criteria (31). Reading performance (accuracy and/or speed) of each individual was at least 2 SDs below age-appropriate norms (Table S1).

Children had to read a text consisting of 24 short meaningful sentences that were unrelated to each other to prevent the use of contextual cues. The text was printed in black on a white A4 paper sheet using Times-Roman font and print size of 14 point (pt; 1 pt = 0.353 mm in typesetting standards). The standard interletter spacing was increased by 2.5 pt in the spaced text condition. For example, the space between i and l in the Italian word il (the) was 2.7 pt in normal text vs. 5.2 pt in spaced text.

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*The British Dyslexia Association offers specific guidelines on how to create "dyslexia friendly" written material (http://www.bdadyslexia.org.uk/about-dyslexia/further-information/dyslexia-style-guide.html). Note that letter spacing is not mentioned in the guidelines.

PSYCHOLOGICAL AND COGNITIVE SCIENCES

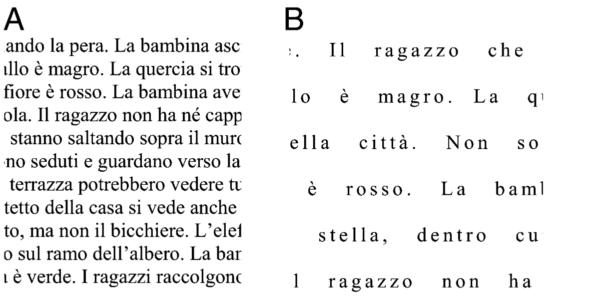


**Fig. 1.** Samples of the text read by the dyslexic and normally developing children matched for reading level. (*A*) Normal text. (*B*) Spaced text.

Space between words and interline spacing were also increased to maintain a proportionate appearance of the overall text (Fig. 1).

Each child was asked to read the same text in two different testing sessions, one for each condition (i.e., normal vs. spaced presentation). To minimize the effects of repetition, the sessions were separated by 2 weeks. Children in each country were randomly assigned to two groups. Group 1 was given normal text at the first time of testing (T1) and spaced text at the second time (T2). Group 2 had the opposite assignment (i.e., spaced text first and normal text second). The two groups (for both Italian and French samples) were matched for chronological age, IQ, word reading accuracy, and speed ($t$ tests: all $P$ values > 0.3).

Reading accuracy (number of errors) and speed (number of syllables per second) were analyzed using a mixed ANOVA with language (Italian vs. French) and group (group 1 vs. group 2) as between-subject factors and test time (T1 vs. T2) as the within-subject factor. For accuracy, the critical two-way interaction between test time and group was significant [$F(1,70) = 35.16$, $P < 0.0001$]. No other source of variance, including language, was significant (all $P$ values > 0.18). The cross-over interaction (Fig. 2*A*) shows that the spaced text condition ameliorated the reading performance of dyslexic children, regardless of the order with which the spaced condition was administered. That is, regardless of whether the spaced text came first or second, dyslexics always made fewer errors on the spaced than the normal text. The manipulation of letter spacing improved accuracy in text reading by a factor of two. To fully appreciate this finding, it is important to note that the relatively low number of errors at the group level hides substantial individual differences, because some dyslexic children made virtually no errors (i.e., they were only slow), whereas others made up to 20% errors.[†] Moreover, the sentences were short, made up of high-frequency words, and contained many monosyllabic (even one-letter) function words (determiners, conjunctions, etc.). Importantly, the benefit of letter spacing (i.e., accuracy gain) was negatively correlated with performance in a letter identification task that was administered to 20 of the French dyslexics ($r = -0.60$, $P = 0.005$). That is, the worse that children were at identifying letters, the more that they benefitted from the extra spacing.

The analysis of reading speed showed the same two-way interaction between test time and group [$F(1,70) = 27.96$, $P < 0.0001$]. The main effect of test time (repetition) was also significant [$F(1,70) = 29.37$, $P < 0.0001$]. Children who read normal text at T1 became faster with the spaced text at T2. In contrast, children who read spaced text at T1 did not show any change in reading speed with the normal text at T2 (Fig. 2*B*). For the second group, the spacing benefit at T1 was as large as the repetition benefit at T2, which resulted in a flat line between T1 and T2. To get an estimate of the pure spacing benefit uncontaminated by repetition, one can compare the spacing benefit at T1 across groups. This comparison shows that spacing generated a speed improvement of about 0.3 syllables/s, which corresponds to the average improvement across 1 school year for Italian dyslexic children (32).

Separate analyses of the two dyslexic samples (Italian vs. French) confirmed the overall pattern. For accuracy, the critical two-way interaction between test time and group was the only significant effect for both samples [Italian: $F(1,32) = 30.05$, $P < 0.0001$; French: $F(1,38) = 11.4$, $P < 0.005$]. For reading speed, the data of both samples showed a significant two-way interaction [Italian: $F(1,32) = 23.5$, $P < 0.0001$; French: $F(1,38) = 9.5$, $P < 0.005$] as well as a main effect of test time [Italian: $F(1,32) = 17.31$, $P < 0.0001$; French: $F(1,38) = 14.4$, $P < 0.005$].

It is important to show that letter spacing is particularly beneficial to dyslexic children, because they are thought to suffer more from letter crowding than normally developing children. For this purpose, we compared 30 of the Italian dyslexics (mean age = 10.9 y) with a group of younger normal readers (mean age = 7.8 y) that were matched for reading level and IQ (Table S2). Note that the comparison with reading-level controls is a much more conservative and stringent test than the more typically used comparison with chronological age controls. If deficits persist with regard to reading-level controls, they are thought to reflect fundamental deficits that are not simply a consequence of the lack of reading (33). Previous studies on crowding in dyslexia have not used reading-level controls. A mixed two-way ANOVA on errors, with group as the between-subject factor and text type (normal vs. spaced) as the within-subject factor, showed a significant interaction [$F(1,58) = 5.95$, $P = 0.018$]. The effect of spacing (normal vs. spaced text) was significant for dyslexics ($P < 0.001$) but not for controls ($P = 0.1$) (Fig. 2*C*). The same analysis on reading speed showed a main effect of text type [$F(1,58) = 10.7$, $P < 0.005$], whereas the interaction between text type and group was only marginally significant [$F(1,58) = 2.81$, $P = 0.09$]. Nevertheless, planned contrasts showed that the effect of spacing (normal vs. spaced) was significant for dyslexics (1.75 vs. 1.94 syllables/s, $P = 0.001$) but not for controls (1.87 vs. 1.93 syllables/s, $P > 0.3$). This finding suggests that increased crowding is most likely a fundamental deficit in dyslexia that can be specifically improved by increasing interletter spacing.

To confirm the efficacy of the spacing manipulation, the sample of Italian dyslexic children was retested 2 months later (T3) using the same text condition that they were given at T1. Nine children were unavailable for the third testing session. Thus, there were 14 children in group 1 (normal–spaced–normal), and 11 children in group 2 (spaced–normal–spaced). A mixed two-way ANOVA on errors, with group as the between-subject factor and test time (T1, T2, and T3) as the within-subject factor, showed a significant interaction between group and test time [$F(2,46) = 12.78$, $P < 0.0001$; $P > 0.22$ for all other sources of variance]. Notably, performance of both groups at T3 was virtually identical to the respective performance at T1. Children in group 1 who showed improved performance from T1 to T2 (i.e., from normal to spaced text) returned to a higher error rate when reading normal text at T3. Conversely, group 2 decreased from T1 to T2 (i.e., from spaced to normal text) but returned to the T1 level when reading spaced text at T3 (Fig. 2*D*). The analysis on reading speed showed the same critical interaction between group and test time [$F(2,46) = 5.4$, $P < 0.01$] as well as the effect of repetition [i.e., main effect of test time; $F(2,46) = 7.3$, $P < 0.005$].

To test whether spacing benefits would be observed "on the fly" (i.e., within the same test session) and assess the effect on reading speed in a more stringent way (i.e., uncontaminated by repetition), we performed a second experiment on a new group of 20 Italian dyslexic children recruited using the same diagnostic criteria used in the first experiment (Table S1, experiment 2

[†]Errors were mostly lexical (i.e., misreading that produced a different word) and phonological (misreading that produced a nonword), accounting for about 95% of all errors (lexical errors were predominant—about 80% of the total). The remaining errors were mostly word omissions; line skipping and word misordering were virtually absent. The distribution of errors was similar in the normal and spaced versions of the text.

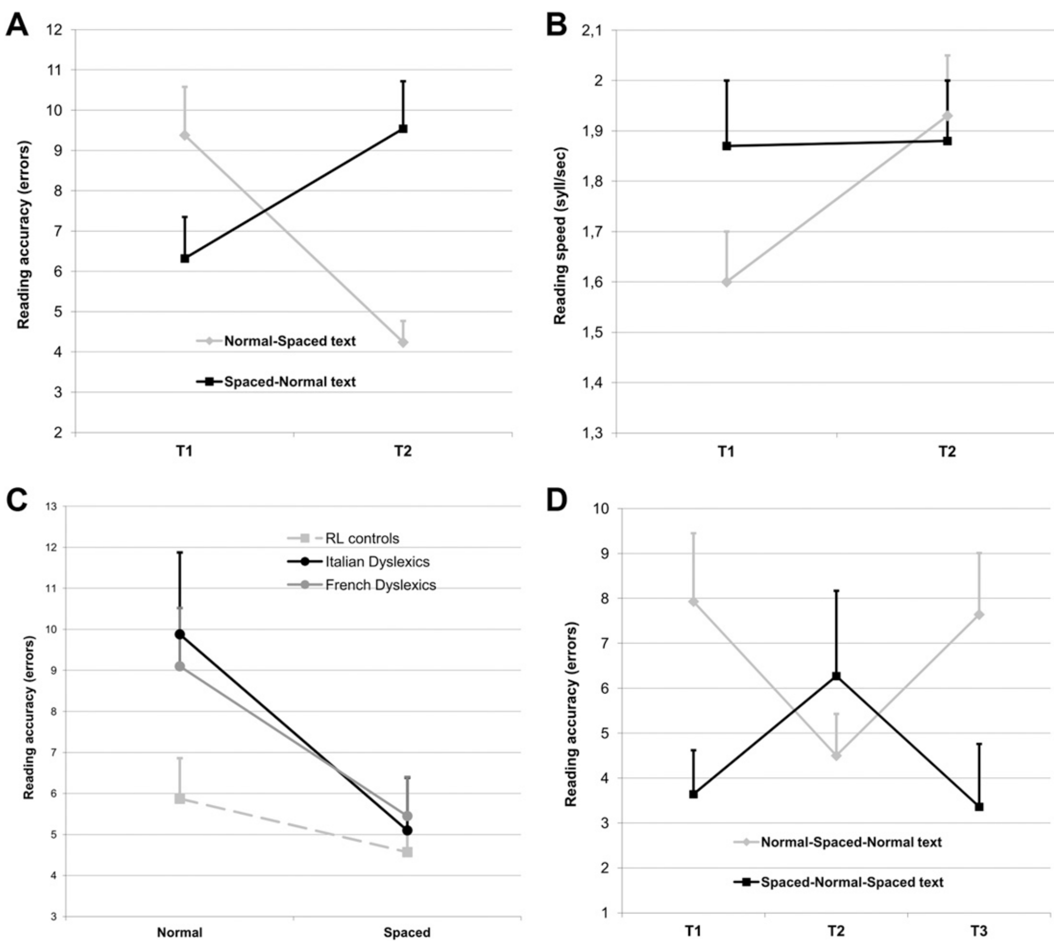


**Fig. 2.** (*A*) Reading accuracy measured in terms of number of errors (incorrect words) as a function of group and testing time. Group 1 read normal text at the first time of testing (T1) and spaced text at the second time (T2), whereas group 2 had the opposite assignment. (*B*) Reading speed, in syllables per second, as a function of group and testing time. (*C*) Reading accuracy (number of errors) in the normal and spaced text conditions for Italian dyslexics, French dyslexics, and a younger group of Italian control children matched for reading level (RL) to the Italian dyslexic sample. (*D*). Reading accuracy (number of errors) for a subsample of dyslexic children that was tested a third time. Group 1 read normal text at T1, spaced text at T2, and normal text at T3, whereas group 2 had the opposite assignment. Error bars show SEM.

shows sample details). We used two texts that were perfectly matched on number of words, number of syllables, word frequency, and grammatical class. This matching was achieved by replacing the content words of the text used in the previous experiment with words of the same grammatical class, word frequency, and length. Moreover, the spacing between lines in the normal text was doubled to match the line spacing of the spaced text. This spacing allowed us to assess the effect of extra-wide letter spacing disentangled from any potential contribution of the wider line spacing. Both the order of the two spacing conditions (normal vs. spaced) and the order of the two texts were fully counterbalanced across participants. Children were also tested in a second session (2 weeks apart), in which the assignment of each text to the spacing condition was reversed with respect to the first session. In the second session, the normal text had normal line spacing, which replicated the manipulation of the first experiment. Finally, to firmly exclude any potential experimenter bias, reading performance was scored offline in a double blind fashion.

The results replicated and extended our previous findings (Fig. 3). Dyslexic children made significantly fewer errors in the spaced than the normal version [6 versus 11.8; two-tailed paired $t$ test: $t(19) = 4.22$, $P < 0.001$], and they read significantly faster in the spaced than the normal version [1.87 versus 1.64 syllables/s; $t(19) = 2.16$, $P < 0.05$]. This result shows that the spacing benefit is driven by the extra-wide letter spacing rather than the wider spacing between lines. The results were virtually identical at the second testing session, with the spaced text yielding less than one-half of the errors than the normal text [4.95 vs. 13.5; $t(19) = 5.97$, $P < 0.001$] as well as faster reading speed [2.07 vs. 1.72 syllables/s; $t(19) = 3.25$, $P < 0.005$]. Comparison of the two different texts with normal spacing across sessions showed no significant differences in both speed and accuracy ($P$ values > 0.2), confirming that the two texts were well-matched.

## Discussion

Overall, our results show that extra-large letter spacing provides an efficient way to improve text reading performance on the fly. We found identical effects in Italian, a shallow writing system with one-to-one correspondences between letters and sounds, and French, an opaque writing system similar to English. This finding is consistent with our hypothesis that the manipulation of spacing influences the letter identification stage, which is assumed to be identical across different alphabetic languages (28, 29). Developing a specialized neural system for visual word recognition (34) demands optimized processing to handle parallel independent identification of letters in the extreme crowding condition of printed words (35). If such optimization fails in dyslexic children, their optimal letter spacing will be increased compared with normal

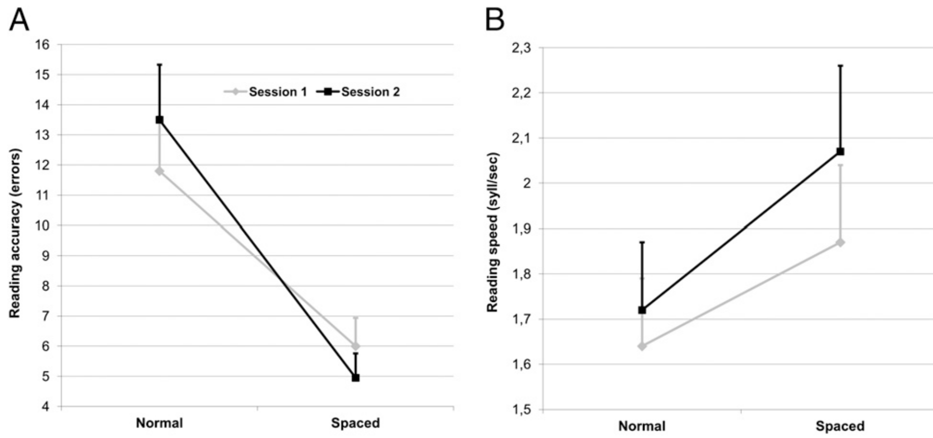


**Fig. 3.** Experiment 2. (*A*) Reading accuracy measured in terms of number of errors (incorrect words) and (*B*) reading speed, measured in syllables per second, as a function of spacing condition and testing session. Two matched texts were administered in each testing session. The two texts in session 1 had the same (wide) line spacing, whereas in session 2, the normal text had normal line spacing (as in experiment 1). The assignment of each text to the spacing condition in session 2 was reversed with respect to session 1. Error bars show SEM.

readers. The beneficial effect of extra-large letter spacing might also be linked to sluggish visuospatial attention in dyslexic children (7, 36). Indeed, spatial attention diminishes crowding by improving accuracy of target identification or reducing the critical spacing (21, 37). Sluggish spatial attention has recently been observed even in at-risk prereaders who later became dyslexic (38, 39).

To conclude, our findings offer a practical way to ameliorate dyslexics' reading achievement without any training. This finding does not detract from individual remediation based on training deficient component skills. However, practitioners only know too well that getting dyslexic children to read more is a key component in achieving long-lasting improvements in reading skills. Extra-large letter spacing, which could even be optimized adaptively on an individual basis, can certainly contribute to achieving this goal.

## Materials and Methods

**Italian Dyslexic Children.** All Italian dyslexic children were recruited at the Institute for Maternal and Child Health "Burlo Garofolo" (Trieste, Italy). Before the study, all dyslexics received a complete medical, psychological, neuropsychological, and cognitive assessment. This assessment was done by an interdisciplinary team of psychologists, neurologists, and speech therapists. Dyslexics were included in the study if their reading performance (accuracy and/or speed) was 2 SDs below the norm on at least one of the age-standardized Italian tests included in the reading battery (40) and their global IQ was above 85 on the Wechsler Intelligence Scale for Children—Revised (WISC-R). Exclusion criteria were oral language skills in pathological range or presence of Attention Deficit Hyperactivity Disorder. All children had normal or corrected-to-normal visual acuity. Accuracy and speed in word and nonword reading were measured with specific subtests of the standardized battery (40). Means and SD of all tests are presented in Table S1.

**French Dyslexic Children.** Dyslexic children in France were recruited at the University Hospital La Timone Marseille, France. Before the study, all dyslexics received a complete medical, psychological, neuropsychological, and cognitive assessment by an interdisciplinary team of psychologists, neurologists, and speech therapists. Dyslexics were included if their reading performance was at least 2 SDs below the normal level on a standardized reading test (41) and their performance IQ was above 80 on the WISC—III (WISC-III). They were excluded from the study if their oral language skills were in pathological range or they were diagnosed with Attention Deficit Hyperactivity Disorder. All children had normal or corrected-to-normal visual acuity. Accuracy and speed in word and nonword reading were measured with a standardized computerized battery (42). Means and SD of all tests are presented in Table S1.

**Italian Reading-Level Control Children.** Thirty Italian children from a public primary school in Trieste, recommended as normal readers by their teachers, were tested individually by an experimenter in a quiet classroom. Reading abilities were assessed by means of the dyslexia battery (Table S2 shows the means and SDs of all common tests across groups). The control children matched the dyslexics for reading ability, which was measured by an efficiency index calculated as the ratio between word reading speed (in seconds) and accuracy rate. The two groups were also matched for general intelligence, which was measured by WISC-R's Similarities and Block Design subtests (for verbal and nonverbal IQ, respectively).

**Materials and Procedure.** Children were asked to read aloud sentences presented as black print on an A4 paper sheet. The text had 24 short, meaningful sentences taken from the Test for Reception of Grammar (43). Sentences were unrelated to each other to prevent the use of contextual cues (e.g., "The girl had a red backpack. The bottle is bigger than the fork. The star is above the circle."). The total number of words was 180. The text was presented on an A4 sheet that was left-justified and printed in Times-Roman font with print size of 14 pt. The standard letter spacing was increased by 2.5 pt in the spaced text condition. For example, the space between i and l in the Italian function word il was 2.7 pt in normal text vs. 5.2 pt. in spaced text. Words in the spaced text were separated by three space characters, and the interline space was doubled to maintain a proportionate appearance of the overall text. Note that Times-Roman is the most widely used font across publishers. Moreover, print size meets the recommendations (i.e., 12–14 p) of the British Dyslexia Association guidelines* on creating "dyslexia friendly" written material.

**Letter Identification Task.** Twenty French dyslexic children were administered a computerized letter identification task. Children were individually tested in a quiet room and seated at a distance of 40 cm from the computer screen. At each trial, a string of five consonant letters, randomly chosen among the set (G, S, T, P, H, L) but excluding repetitions, was presented at fixation for 1,000 ms. Letters were printed in Geneva 18 bold font [height = 1.14 degrees of visual angle (deg), width = 0.86 deg], and the space between letters was 1.07 deg. Children had to identify the letter indicated by a cue—a red dot (diameter = 0.42 deg) placed below the target letter (distance = 0.54 deg) that lasted for 200 ms. Cueing positions were positions 2–4 (outer letters are easier to perceive). Children responded at the end of each trial by manually pointing to the target letter on a response screen that displayed the entire set of consonants, and the experimenter typed the response on the computer keyboard. In one-half of the trials, the cue was presented 150 ms before the onset of the letter string, and in the remaining one-half of the trials, the cue was presented at the offset of the letter string. The total number of trials was 60. For the purpose of correlating letter identification performance with spacing benefits, a letter identification score was obtained for each subject by averaging the letter identification accuracy across the six conditions (three positions by two cuing conditions) and then correlating this score with the spacing benefit, which was calculated by subtracting error rates in the normal version of the text from error rates in the spaced version of the text.

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