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Basic Processes in Reading: The Effect of Interletter Spacing

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Reading is acutely sensitive to the amount of space between letters within a string. In the present investigation, we explore the impairment caused by increasing interletter spacing when reading single words and nonwords aloud. Specifically, 2 hypotheses are tested: (a) whether increasing interletter spacing induces serial processing while reading aloud and (b) whether this serial processing results from an increased reliance on a serial sublexical mechanism similar to that implemented in dual route models of reading. Implications of the present results for understanding basic processes in reading are discussed with particular reference to different types of serial processing in reading aloud and the role of attention in reading.

Keywords: reading, attention, spacing

Understanding reading has often been advanced through investigating the influence of various alterations in the visual format of the letter string (e.g., stimulus contrast, Besner, O'Malley, & Robidoux, 2010; line alternation, Fiset, Arguin, Bub, Humphreys, & Riddoch, 2005; case alternation, Humphreys, Mayall, & Cooper, 2003; feature removal, Lanthier, Risko, Stolz, & Besner, 2009; masking, Perfetti, Bell, & Delany, 1988). Impairments wrought by such alterations provide important clues to the underlying mechanisms involved in transforming print to sound. In the present investigation, we extend this strategy to the assessment of the impairment caused by alterations in interletter spacing.

Reading is intimately sensitive to the spacing between letters in the string and, critically, this sensitivity is bidirectional; both too little and too much space between letters can impair performance. To date, research into the mechanisms responsible for the impairments to word and object recognition associated with spacing have generally involved *reductions* in spacing (i.e., crowding; Bouma, 1970; Chung, 2002; Pelli & Tillman, 2008; Risko, Stolz, & Besner, 2010; Yu, Cheung, Legge, & Chung, 2007; Wolford, 1975; Wolford & Chambers, 1983). The deleterious effects of *increased* interletter spacing in reading are only now beginning to receive attention (Cohen, Dehaene, Vinckier, Jobert, & Montavont, 2008; Van Overschelde & Healy, 2005; Paterson & Jordan, 2010). Here, we report novel empirical effects that strongly constrain viable theoretical explanations of the effect of increasing interletter spacing on reading aloud.

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The Effect of Increased Interletter Spacing

Increased interletter spacing impairs reading in experiments using single words (Cohen et al., 2008) as well as in connected text (Van Overschelde & Healy, 2005; Paterson & Jordan, 2010). Cohen et al. (2008) argued that increased interletter spacing disrupts parallel processing of letters in words. The idea that letters are initially identified in parallel is a popular view in extant theories of reading aloud at the single item level (e.g., Ans, Carbonnel, & Valdois, 1998; Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001; Perry, Ziegler, & Zorzi, 2007), although this view has not gone unchallenged (Blais et al., 2009; Davis, 2010; Whitney, 2001a, 2001b, 2008; Whitney & Cornelissen, 2008). Nevertheless, Cohen et al. (2008) argued that increased spacing leads to a serial attentional scan of the letter string. Consistent with this idea, Cohen et al. (2008) reported that increasing spacing led to a letter length effect when reading aloud single words. This is of particular interest because reading words aloud is not typically associated with a letter length effect, at least up to six letters (Weekes, 1997). Thus, increasing interletter spacing appears to disrupt one of the defining features of normal word processing and, in so doing, provides a window into the boundary conditions under which "typical" processing of a letter string can occur. In addition to the letter length effect, Cohen et al. (2008) reported increased activation of the posterior parietal cortex when spacing was increased, consistent with increased involvement of spatial attention (Corbetta, Shulman, Miezen, & Petersen, 1995).

Cohen and colleagues also suggested that the hypothesized serial processing induced by increasing spacing is the same as that which occurs during sublexical processing in several current models of reading aloud (e.g., the Connectionist Multi-Trace Model (CMT), Ans et al., 1998; the Dual Route Cascaded Model (DRC), Coltheart et al., 2001; the Connectionist Dual Process Model

(CDP+ & CDP++), Perry et al., 2007, 2010). Although these models differ in many respects, a feature common to them all is that sublexical processing is serial. For example, in DRC, sublexical processing is achieved through the serial application of grapheme-to-phoneme conversion rules, and there is considerable evidence consistent with this claim (e.g., the position of irregularity effect, Roberts, Rastle, Coltheart, & Besner, 2003; the whammy effect, Rastle & Coltheart, 1998; the cross script length effect, Rastle, Havelka, Wydell, Coltheart, & Besner, 2009). For example, if processing via the sublexical route is serial, then nonwords (letter strings that do not have a lexical representation) should produce a letter length effect (i.e., response time [RT] should increase as the number of letters increases),[1] but words should not. This is in fact the case (i.e., the Length × Lexicality interaction; see Weekes, 1997, at least for words up to six letters in length). Relatedly, when individuals read aloud the same nonwords repeatedly, the letter length effect gets progressively smaller, consistent with individuals forming a lexical representation and thus subverting the need to apply serial sublexical procedures (Maloney, Risko, O'Malley, & Besner, 2009). According to Cohen et al. (2008), the serial processing induced by increasing spacing derives from the application of this serial sublexical mechanism. This would suggest that the balance in "route emphasis" (e.g., Reynolds & Besner, 2008) in normal reading is flexible and, in particular, can be altered by changes in the visual format of the letter string. This idea is consistent with the observation that both increased spacing and the operation of sublexical mechanisms in models of reading aloud lead to a letter length effect. This *argument by association* provides a reasonable motivation to associate the former effect (spacing leads to a letter length effect in RT for words) with the latter mechanism (increased use of a serial, sublexical mechanism).

The CMT, CDP+, and CDP++ models provide yet another theoretical reason to associate the increased spacing effect with the operation of a sublexical processing mechanism via their theoretical association with attention. That is, in these models, serial sublexical processing arises because of the serial application of spatial attention (Ans et al., 1998; Perry et al., 2007, 2010). Specifically, attention is applied serially, from left to right, in order to assemble a phonological representation.

On the Cohen et al. (2008) account then, the increased spacing effect fits neatly into existing computational models of reading aloud. The proposed explanation of the increased spacing effect in terms of an increasing reliance on a sublexical mechanism, however, has at least one potential issue. Specifically, in many of the models discussed above (DRC, CDP+, CDP++) letter identification occurs in parallel, and serial sublexical processing operates on the output of these resulting letter representations. Therefore, early letter level processing remains parallel even for letter strings that are read aloud with the serial sublexical routine. In other words, the serial processing is post letter identification. This opens the door to potential alternative accounts wherein increasing spacing has its effect at the letter level. Two potential accounts of this type are outlined next.

One alternative account of the increased spacing effect is that it results from the disruption of parallel letter identification and subsequent use of serial letter identification. That is, the impairment wrought by increasing spacing might be more similar to that postulated to occur in individuals with letter-by-letter dyslexia (Fiset et al., 2005). Fiset and colleagues (Fiset et al., 2005) suggested that when parallel letter processing breaks down, a compensatory mode of processing occurs, which consists of engaging serial (focused) attention at the level of letter encoding. Critically, this account does not fit into the existing models as neatly as does Cohen et al.'s (2008) because it requires adding a serial mechanism to existing accounts that currently rely entirely on parallel letter identification. The Cohen et al. (2008) account does not have this problem because it attempts to build on an existing serial mechanism.

Another alternative account can be derived from models of orthographic processing in which letter processing is, to some extent, always serial (e.g., Whitney, 2001a). For example in Whitney's SERIOL model, the putatively parallel processing when reading words is hypothesized to emerge because of counteracting inhibitory and facilitatory effects of letter length (Whitney, 2008; see Blais et al., 2009, for a different explanation). Whereas additional letters result in additional time needed to activate them because of serial processing, this effect can be counteracted by a positive effect of additional letters on settling time in the lexicon (Whitney, 2008). If increasing interletter spacing disrupts this balance between inhibitory and facilitatory effects of letter length, then an always present serial letter identification process could become evident.

Critically, both of the proposed alternative accounts place the increased spacing effect at the letter identification level (i.e., in one account serial letter identification is induced, and in the other, an always present serial letter identification is revealed) rather than appealing to an increased reliance on a serial sublexical procedure as in the Cohen et al. (2008) account. In the present investigation, we report two experiments that test the Cohen et al. (2008) account of the increased spacing effect. To foreshadow our results, the data are consistent with the hypothesis that the effect of increasing spacing reflects serial processing but are inconsistent with the idea that this serial processing reflects an increased reliance on the serial sublexical procedure in dual route models of reading.

Present Investigation

The Cohen et al. (2008) account of the increased spacing effect has two critical components: (a) increasing spacing disrupts normally occurring parallel processing and induces serial processing and (b) this serial processing reflects an increased reliance on a serial sublexical mechanism as implemented in current dual route models of reading (e.g., Ans et al., 1998; Coltheart et al., 2001; Perry et al., 2007, 2010). The present experiments provide tests of both of these ideas. Experiment 1 yields strong evidence for the use of serial processing occurring in some fashion when spacing is increased. Experiment 2 provides evidence inconsistent with the idea that this serial processing is caused by the serial sublexical mechanism postulated in dual route models of reading.

[1] Although the letter length effect is typically interpreted as evidence of serial processing, it remains possible that a nonserial mechanism could produce a similar pattern (e.g., a parallel limited capacity mechanism).

Experiment 1

Experiment 1 provides a strong test of the hypothesis that increased interletter spacing induces a form of serial processing during reading aloud (for ease of exposition, we maintain the assumption of Cohen et al., 2008, that early processing is parallel but note that, as mentioned above and as we discuss again later, this is not necessarily the case; Whitney, 2001a, 2001b, 2008; Whitney & Cornelissen, 2008). This experiment crossed the increased spacing manipulation with another manipulation also held to induce serial processing, specifically, alternating the line on which the letters are presented (see Figure 1). This manipulation has been used previously to induce serial processing by Fiset et al. (2005) in patients suffering from letter-by-letter dyslexia.[2] If increasing spacing and presenting letters on alternating lines each independently induce serial processing, then the combined effects of these two manipulations should be *smaller* than the sum of the two independent effects. In other words, the joint effect of these two factors should be underadditive. In the present context, this would mean that the increased spacing effect would be larger when the letters appear on the same line than when the letters appear on alternating lines. This prediction is derived from the fact that inducing serial processing via one manipulation (line alternation) should effectively negate (or at least reduce) the impact of inducing serial processing via another manipulation (increasing spacing). In other words, if parallel processing of the letter string has already broken down (e.g., through presenting the stimuli on alternating lines), then the impact of introducing another manipulation that has qualitatively the same effect (e.g., increasing interletter spacing) would be reduced.

Method

Participants. Fifty-six undergraduates received either $5 or course credit for participating. All participants spoke fluent English.

Design. A 2 (spacing: increased spacing vs. normal spacing) × 2 (line alternation: line alternated vs. nonline alternated) within-subject design was used.

Apparatus. The stimuli were presented on a 17-in. (43.18 cm) monitor with a 1,024 × 768 pixel resolution. *E-prime* experimental software (Schneider, Eschman, & Zuccolotto, 2002) controlled timing and presentation of stimuli and logged response time (RT) and accuracy. Vocal RTs were recorded using a Plantronics microphone and a voice key.

Stimuli. The stimulus set consisted of 24 of the four-letter monosyllabic words from the high frequency list of Weekes (1997), except that the word *slog* was replaced with the word *slug* from the low frequency word list of Weekes (1997), given that the former is not an English word to most Canadian readers. The words were presented in an 18-point Courier font appearing in white on a black background.

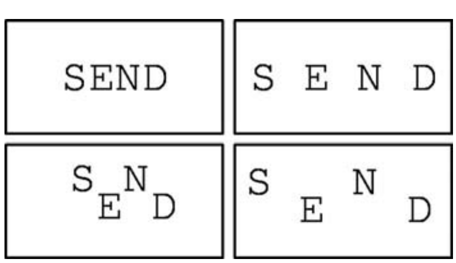

Figure 1. Examples of stimuli used in Experiment 1.

Following Cohen et al. (2008), spaced words had two spaces entered between letters. The words with extra spaces were approximately 55 mm horizontally, and the words with normal spaces were approximately 22 mm horizontally; both were 6 mm vertically.

The letters of line alternated words appeared on two lines, one above the other (see Figure 1). If the first letter of a line-alternated word appeared on the top line, the next letter appeared on the bottom line, and each subsequent letter would appear in the opposite location from the last. On half of the line alternated trials, the first letter appeared on the top line, and on the other half, the first letter appeared on the bottom line. Letters of nonline alternated words all appeared in one line. To control for letter location across conditions, on half of the nonline alternated trials, the letters appeared in the equivalent of the top line of a line alternated trial and on the other half of the trials, the letters appeared in the equivalent of the bottom line of a line alternated trial. Line alternated words were 14 mm vertically. The factorial combination of conditions yielded eight different stimulus configurations, and each word was presented in each of the different configurations an even number of times across participants.

Procedure. Participants were seated approximately 50 cm from the screen. Each trial began with the presentation of a fixation cross in the center of the screen for 750 ms. A word was then presented at fixation and remained there until the participant read it aloud, after which a blank screen was presented until the experimenter keyed in whether the response was accurate. Following this, the fixation cross for the upcoming trial appeared. Participants received four practice trials, followed by 24 experimental trials.

Results

Practice trials and spoiled trials (e.g., microphone errors) were removed prior to analysis. The RT and error data were analyzed with a linear mixed effects model with subjects and items as crossed random effects and spacing, line alternation, trial, and previous trial RT as fixed effects (Baayen, 2008; Baayen & Milin, 2010). We report regression coefficients from the final model and associated t values. In the RT analysis, we take a t value of greater than 2 to indicate significance at the $p < .05$ level (Baayen & Milin, 2010). All analyses were computed in the R programming environment, with the lme4 package (Bates, Maechler, & Bolker, 2011). Prior to the reported RT analysis, outliers were removed by first fitting the model and then removing RTs that were greater than 2.5 standard deviations from the predicted RT (Baayen & Milin, 2010). This outlier procedure led to the removal of 2.1% of the total observations. Means across conditions are presented in Table 1.

[2] Fiset et al. (2005) used this manipulation in a sample of patients with brain lesions. We have confirmed in a separate experiment that line alternation alone induces serial processing in a sample of intact university students, at least as indexed by an increased letter length effect when reading aloud words.

Table 1
Response Time and Percentage Error in Experiment 1

Line alternation	Spacing: RT Normal	RT Increased	% Error Normal	% Error Increased	Spacing effect RT	Spacing effect % Error
Nonalternated	554	594	0.6	1.0	40	0.4
Alternated	584	599	1.6	1.6	15	0.0

Note. Response times (RT) and percentage error (%) are shown as a function of spacing (normal versus increased) and line alternation (nonalternated versus alternated).

RTs. There were significant effects of trial ($\beta = 1.21$, $SE = 0.39$, $t = 3.08$) and previous trial RT ($\beta = 0.02$, $SE = 0.005$, $t = 4.83$). There was a significant effect of line alternation ($\beta = 32.65$, $SE = 7.57$, $t = 4.31$) and spacing ($\beta = 45.81$, $SE = 7.56$, $t = 6.05$). Critically, there was also a significant interaction between line alternation and spacing ($\beta = -27.07$, $SE = 10.69$, $t = 2.53$). The increased spacing effect was larger in the nonline alternated condition (40 ms) than in the line alternated condition (15 ms). The model's intercept was 518 ms, the standard deviation of the random effect of subjects was 75 ms, and the standard deviation of the random effect of items was 44 ms.

Errors. A generalized linear mixed effects model with a binomial distribution and a logit link function was used to analyze the accuracy data. This analysis yielded no significant effects. This was also true when the interaction term was removed from the model.

Discussion

The results of Experiment 1 are clear. There were effects of both increasing spacing and line alternation. Both manipulations significantly impaired reading aloud. Critically, there was also a significant interaction between increasing spacing and line alternation such that the combined effects of the two manipulations were underadditive. That is, when the letters were presented on alternating lines, the effect of increasing spacing was attenuated relative to when the letters all appeared on the same line.

The results of Experiment 1 are consistent with an interpretation of the increased spacing effect being caused by the induction of serial processing during reading aloud. When spacing is increased on line alternated trials (where serial processing is arguably already engaged), it has a reduced effect relative to nonline alternated trials in which serial processing is not already engaged. Thus, the increased spacing effect can be reduced if processing is independently induced to be serial.

If increasing spacing induces a form of serial processing, then the next theoretical question concerns the nature of the mechanism that produces this effect. In the introduction, we discussed Cohen et al.'s (2008) hypothesis that the serial processing induced by increasing spacing results from an increased reliance on a serial sublexical mechanism as implemented in current dual route models of reading aloud. On this account, reading a word with increased space between the letters would be equivalent to reading a nonword, in the sense that both would be subject to the same sublexical processing. The results of Experiment 1 are consistent with this account. However, as noted in the introduction, there are alternative accounts of the serial processing evident when spacing is increased, and these accounts are also consistent with the results of Experiment 1.

Experiment 2

Experiment 2 tests two direct predictions of the Cohen et al. (2008) account of the source of the serial processing caused by increasing spacing. The first prediction is that if increasing spacing induces participants to process words sublexically, this manipulation should have less of an effect on items that are already processed sublexically. According to dual route models (Ans et al., 1998; Coltheart et al., 2001; Perry et al., 2007), reading nonwords aloud *requires* the application of the serial sublexical mechanism. Lexical processing will not produce a correct response for nonwords because they do not have a lexical representation. Increasing spacing for nonwords (items already processed sublexically) should therefore have less impact (or possibly none) on reading aloud, compared with reading words aloud.

The second prediction follows a similar logic. Cohen et al. (2008) reported an interaction in which the magnitude of the increased spacing effect increased as letter length increased for words. This spacing by letter length interaction makes sense in the context of a serial mechanism (i.e., if there are more letters in the string, then it should take longer to process the string if the letters are processed one at a time). If increasing interletter spacing has its effect by increasing reliance on a serial sublexical mechanism, then this interaction between interletter spacing and letter length should not be present for nonwords because nonwords are already processed sublexically.

Computational Simulation

Cohen et al. (2008) framed their account in terms of dual route models of reading aloud (e.g., CMT, Ans et al., 1998; DRC, Coltheart et al., 2001; CDP+ & CDP++, Perry et al., 2007, 2010). To confirm our interpretations of what a dual route model would predict based on the Cohen et al. (2008) account, we simulated reading aloud three- and four-letter words and nonwords with CDP++ (Perry et al., 2010). Cohen et al. (2008) referred to CDP+ which, at the time, was the only version available but CDP+ and CDP++ are qualitatively similar for the purposes of the present discussion. We simulated the Cohen et al. (2008) account (i.e., increased reliance on the serial sublexical route) by increasing the frequency scaling factor (from 0.2 to 0.5). This parameter change makes lexical activation more difficult, thus increasing the relative contribution of the serial sublexical route. Perry et al. (2007) and Coltheart et al. (2001) used a similar strategy when simulating reading in the context of surface dyslexia (a disorder understood to reflect a functional nonlexical route and a damaged lexical route).

We compared the reading times of CDP++ for three- and four-letter words and nonwords with both the standard parameter set (i.e., "normal spacing") and a parameter set that increased the reliance on the serial sublexical procedure (i.e., "increased spacing"). After the removal of errors and outliers, there was a significant interaction between increasing reliance on the sublexical route (i.e., "spacing") and lexicality, $F(1, 86) = 235.00$, $MSE = 55.48$, $p < .05$, such that the effect of increasing reliance on the sublexical route was larger for words (34 cycles) than nonwords (0 cycles). Indeed, there is no effect of this manipulation on nonwords (i.e., no "spacing" effect in nonwords). This is because, as noted above, increasing reliance on a serial sublexical mechanism should have little to no impact on letter strings that are already processed sublexically. Furthermore, when words and nonwords were analyzed separately, there was a significant interaction between increasing reliance on the sublexical route (i.e., "spacing") and letter length for words, $F(1, 47) = 6.39$, $MSE = 101.51$, $p < .05$, but not for nonwords. This simulation successfully captures the patterns reported by Cohen et al. (2008) with words (i.e., a spacing effect; and a spacing by length interaction). Critically, the results of this simulation also demonstrate clearly that increasing reliance on a serial sublexical route will (a) have a larger effect for words than nonwords (and possibly no effect on nonwords) and (b) lead to an interaction with letter length for words but not for nonwords.

We next set out to test these predictions in skilled readers. It is important to note that the pattern predicted by the Cohen et al. (2008) account would be inconsistent with the alternative letter level accounts outlined above. This is because letter identification is common to both words and nonwords, and thus, there would be no reason for the manipulation to preferentially impact words. Thus, Experiment 2 provides a strong test of the locus of the increased spacing effect in reading aloud. In Experiment 2, participants read aloud three- and four-letter words and nonwords that were normally spaced or had extra space between letters.

Method

Participants. Sixty-four undergraduates received either $5 or course credit for participating. All participants spoke fluent English.

Design. A 2 (spacing: increased spacing vs. normal spacing) × 2 (lexicality: word vs. nonword) × 2 (letter length: three letters vs. four letters) within subject design was used.

Apparatus. The apparatus was the same as that used in Experiment 1.

Stimuli. The stimuli were the same as those used in Experiment 1, with the addition of the three letter words and nonwords from Weekes (1997). A three-letter string with normal spacing occupied 22 mm horizontally by 6 mm vertically, and a four-letter string with increased spacing was 55 mm horizontally by 6 mm vertically.

Procedure. The general procedure was the same as that used in Experiment 1, except that all letters always appeared on the same line, and participants now received four practice trials before beginning the experimental trials. There were 96 experiment trials.

Results

The RT and error data were again analyzed with a linear mixed effect model with subjects and items as crossed random effects and spacing, lexicality, length, trial, and previous trial RT as fixed effects (Baayen, 2008; Baayen & Milin, 2010). Outlier removal led to the removal of 2.2% of the total RT observations. Means across conditions are presented in Table 2.

Table 2
Response Time and Percentage Error in Experiment 2

Length–Lexicality	Spacing					
	RT		% Error		Spacing effect	
	Normal	Increased	Normal	Increased	RT	% Error
3-Letter word	509	532	0.3	0.5	23	0.2
3-Letter nonword	552	579	3.1	4.4	27	1.3
4-Letter word	519	558	0.4	0.5	39	0.1
4-Letter nonword	567	611	7.9	11.8	44	3.9

Note. Response times (RT) and percentage error (%) are shown as a function of spacing (normal versus increased), lexicality (word versus nonword), and length (3 versus 4 letters).

RTs. There were significant effects of previous trial RT ($\beta = .02$, $SE = 0.003$, $t = 6.80$) but not trial ($\beta = -.03$, $SE = .03$, $t = 0.81$). There were significant effects of lexicality ($\beta = 45.98$, $SE = 8.29$, $t = 5.55$) and spacing ($\beta = 21.99$, $SE = 3.54$, $t = 6.22$) but not length ($\beta = 10.37$, $SE = 8.28$, $t = 1.25$). Critically, there was no significant interaction between lexicality and spacing ($\beta = 4.83$, $SE = 5.10$, $t = 0.95$); the magnitude of the increased spacing effect was similar for words (31 ms) and nonwords (36 ms). However, there was a significant interaction between length and spacing ($\beta = 18.33$, $SE = 5.05$, $t = 3.63$). The effect of increasing spacing was larger with four-letter words (42 ms) than three-letter words (25 ms). No other effects were significant. The model's intercept was 497 ms, the standard deviation of the random effect of subjects was 78 ms, and the standard deviation of the random effect of items was 26 ms. With the nonsignificant interactions removed from the model, the effect of length was significant ($\beta = 13.70$, $SE = 5.86$, $t = 2.34$).

The Cohen et al. (2008) account predicts that the Length × Spacing interaction observed above should be present for words and absent for nonwords. A separate analysis of words and nonwords reveals that this was not the case. Rather, there was a significant interaction between length and spacing in both words ($\beta = 18.25$, $SE = 4.50$, $t = 4.05$) and nonwords ($\beta = 19.22$, $SE = 5.65$, $t = 3.40$). The effect of spacing was also significant in nonwords alone ($\beta = 27.15$, $SE = 3.90$, $t = 6.95$).

Errors. An analysis of the accuracy data revealed only a main effect of lexicality ($\beta = -2.49$, $SE = 0.75$, $z = 3.30$); however, the removal of nonsignificant interactions and the fixed effects of trial and previous trial RT (all nonsignificant) revealed effects of lexicality ($\beta = -2.83$, $SE = 0.46$, $z = 6.14$), spacing ($\beta = -0.52$, $SE = 0.16$, $z = 3.23$), and length ($\beta = -1.22$, $SE = 0.39$, $z = 3.1$).

Discussion

There are a number of important results from Experiment 2. In RT, there were effects of spacing, lexicality, and letter length. Critically, Cohen et al.'s (2008) predicted interaction between increasing spacing and lexicality was not observed.

That is, nonwords failed to be *less* influenced by increasing spacing than were words. The magnitude of the spacing effect was statistically equivalent for words (31 ms) and nonwords (36 ms). Although this result relies on the acceptance of a null, there is good reason to be confident that the pattern is not the one predicted by Cohen et al.'s (2008) account (i.e., larger increased spacing effect for words than nonwords). That is, the numerical (5 ms) trend toward an interaction was actually in the wrong direction (i.e., smaller interletter spacing effect for words; this trend was also present in errors). In addition, we have replicated Experiment 2 with another 32 participants (using only four letter items) and found identical results. The increased spacing effect was again statistically equivalent for words (33 ms) and nonwords (34 ms; $\beta = 2.90$, $SE = 8.42$, $t = 0.34$). Thus, it appears that the increased spacing effect is not larger for words than for nonwords.

It should be noted that we were able to replicate Cohen et al.'s (2008) report of an interaction between increasing spacing and letter length for words. Increasing interletter spacing had a greater effect on four letter words and nonwords than it did on three letter words and nonwords. Critically, this interaction was present when nonwords were analyzed separately, which is, again, inconsistent with the Cohen et al. (2008) account. Unlike the Spacing $\times$ Lexicality interaction, falsification of this prediction does not rely on a null (i.e., an effect is present that should not be according to an account based on increasing reliance on the serial sublexical mechanisms of dual route models). Taken together, the results of Experiment 2 disconfirm the idea that increasing spacing increases the reliance on a serial sublexical mechanism (at least the ones implemented in the models considered here). These results, however, are consistent with the two alternative accounts outlined above that posit that the locus of the increased spacing effect is at the letter level, namely, that increasing spacing either (a) induces serial letter identification or (b) reveals an always present seriality in letter identification by disrupting the balance of inhibitory and facilitatory effects of letter length (e.g., Whitney, 2001a, 2001b, 2008; Whitney & Cornelissen, 2008).

General Discussion

In the present investigation, we sought to discriminate between accounts of the impairment observed when the spaces between letters in a letter string are increased during reading aloud. The two experiments reported here provide novel constraints on any such theory. Experiment 1 provided compelling evidence that increasing spacing induces (or reveals) some form of serial processing. This is consistent with the account suggested by Cohen et al. (2008). The results of Experiment 2 demonstrate that this serial processing cannot be attributed to an increased reliance on a serial sublexical mechanism, contrary to the explanation advanced by Cohen et al. (2008). The evidence against this view consists of the lack of an interaction between spacing and lexicality and the presence of a Spacing $\times$ Length interaction in nonwords. An alternative hypothesis is that the increased spacing effect occurs at an earlier stage of processing common to both words and nonwords.[3] For example, increasing interletter spacing could induce (e.g., Fiset et al., 2005) or reveal (Whitney, 2001a) serial letter identification. We discuss both of these accounts below in order to clear the theoretical landscape for future investigations of the influence of spacing.

It is important to note that the increase in interletter spacing used here (and elsewhere; Cohen et al., 1998) consisted of only an additional two letter spaces being added, nevertheless reading appears to shift from a parallel to a serial mode. This boundary condition on parallel processing suggests that "normal" letter string processing (in the context of reading aloud at least) is rather fragile. On this account, what remains to be explained is why parallel letter processing breaks down under such conditions. Fiset et al. (2005) suggested that the signal-to-noise ratio in individuals with letter-by-letter dyslexia (another place where serial processing is evident) is too low when attention is distributed across the entire string. This leads to a focusing of attention on individual letters (i.e., serial letter processing) so as to increase the signal-to-noise ratio. A similar account could be proposed to explain the breakdown in parallel letter identification for intact subjects in the present experiments. Specifically, increasing spacing increases the horizontal extent of the letter string resulting in an increase in the area over which attention is distributed and, as a result, lowering its resolving power (Eriksen & St. James, 1986). Thus, as the size of the letter string increases, the resulting decrease in the signal-to-noise ratio would increase the likelihood of a transition to the serial application of attention to individual letters. That said, this account runs into difficulty when we consider the fact that in a paragraph-reading task, Van Overschelde and Healy (2005) demonstrated that controlling for string width did not eliminate the effect of spacing. In addition, although increasing interletter spacing would effectively decrease the signal-to-noise ratio by spreading spatial attention, it should also *increase* the signal-to-noise ratio by decreasing the likelihood of feature crosstalk between letters (e.g., reduce crowding; Pelli & Tillman, 2008; Risko et al., 2010; Wolford, 1975). Thus, although increasing the size of the attentional window might reduce the resolving power of attention, the increased space between letters would also reduce the need for that resolving power.

A different account of the breakdown in parallel letter identification when spacing is increased is that the added space disrupts an early grouping process (Humphreys, Mayall, & Cooper, 2003; Pelli et al., 2009). Several researchers have suggested that the visual scene is parsed according to particular grouping rules (e.g., Kanwisher & Driver, 1992), including grouping by proximity (i.e., objects that are close together get grouped together). These groupings can then determine how attention is distributed. On this account, increased interletter spacing could lead to the perception of multiple objects (e.g., four in the case of a four letter spaced word) rather than a single object. The parsing of the scene into multiple objects could engender an attentional routine consisting of the serial application of attention to each object. If the letters are grouped together, then attention can be applied to the entire letter string. Thus, in this account, serial or parallel letter identification is determined by the initial parsing of the scene, which is determined by well-established grouping principles. The role of grouping principles in the visual recognition of a word has been largely ignored in models of normal reading despite evidence that manipulations that would influence this process clearly impact reading (Humphreys et al., 2003; Reynolds, Kwan, & Smilek, 2010). Critically, the importance of grouping for early processes in reading is only revealed through the use of manipulations that disrupt this process (e.g., increasing interletter spacing).

[3] This is not to suggest that there are no other potential accounts that could in principle account for the observed effects of increasing interletter spacing (e.g., a lexical level account).

The idea that increasing spacing induces serial letter identification presupposes that letter identification is not already achieved in a serial fashion. However, in the SERIOL model of letter position encoding (Whitney, 2001a, 2001b, 2008, Whitney & Cornelissen, 2008), letter identification is always serial. Whitney (2008) suggested that processing only appears parallel because there are counteracting facilitatory and inhibitory influences of letter length. From this perspective, the effect of increasing spacing could be viewed as revealing an ever-present seriality in letter processing by disrupting the balance in the counteracting facilitatory and inhibitory influences of letter length. The issue then becomes discerning the mechanism responsible for this disruption. One mechanism, suggested by Whitney (2010), is that increasing spacing disrupts the bottom up activation gradient that underlies reading under typical conditions. This disruption could lead to the need for the top-down application of attention and, potentially an increase in the time required for the activation of each letter to reach some critical level. In addition, this disruption of the bottom-up formation of the activation gradient could ameliorate the lexical advantage for longer words (i.e., the facilitatory effect of increased letter length). Whatever the mechanism, it is clear that further work is required to test between these various letter level accounts of the spacing effect.

The Role of Spatial Attention in Reading

Recent research on the contribution of spatial attention to reading has focused on the comparison of word processing when the word is attended or unattended via the use of a spatial cuing manipulation (e.g., Besner, Risko, & Sklair, 2005; McCann, Folk, & Johnston, 1992; Stolz & McCann, 2000; Risko et al., 2010, 2011; Waechter, Besner, & Stolz, 2011). This research has demonstrated that spatial attention contributes to prelexical processes. Specifically, Risko et al. (2010) suggested that attention limited the amount of feature crosstalk between letters. The "on/off" spatial cuing manipulations (i.e., to achieve attended or unattended states) employed in these experiments, however, provide limited insight into how attention might contribute to processing within a word (Auclair & Siéroff, 2002; Risko et al., 2010).

The serial identification of letters represents yet another way that attention could contribute to reading. For example, in both of the accounts suggested above, attention is argued to contribute to string processing under degraded reading conditions. For example, Cohen et al. (2008) and Fiset et al. (2005) suggested that when parallel processing breaks down, serial processing is realized through the serial application of spatial attention. Thus, attention is used to "repair" early processes in reading under degraded conditions. According to this idea, increasing spacing may provide a means of investigating a role for attention within words while reading. Interestingly, in order to induce "letter-by-letter reading" in nondyslexic readers, Fiset, Gosselin, Blais, and Arguin (2006) degraded the letters very heavily, resulting in reading aloud times that were sometimes longer than 5 s. These slow responses are characteristic of letter-by-letter dyslexia, which was the phenomenon they were attempting to model. Critically, the present results make clear that this level of degradation is not required to induce the serial processing that could be subserved by spatial attention. Rather, increasing spacing appears to have a similar effect (i.e., induces a word length effect). Thus, the spacing manipulation could be used in neurocognitive investigations into the function of spatial attention during reading, providing further insights into reading impairments (e.g., Fiset et al., 2005, 2006; Vidyasagar & Pammer, 2010). It is important to note that the mechanism by which serial processing is induced in Fiset et al. (2006) and the present work may be different (what exactly induces the serial processing under increased interletter spacing is unknown). Nonetheless, as suggested above, the serial application of attention to letters may represent a means through which to deal with early difficulties in stimulus processing (what causes the difficulties may vary from one context to the next).

Another important issue to address is the extent to which the hypothesized serial letter identification reflects covert and/or overt shifts of attention. Recently, Paterson and Jordan (2010) provided clear evidence that when reading connected text, increasing spacing can have an effect on overt attention. Although increasing spacing might influence eye movements in ways that are unique to reading connected text, it seems reasonable to assume that even in a single item design (as used here), increasing spacing could increase the number of fixations on the letter string. Future work with a single word design combined with eye tracking measures is needed to discriminate between the relative contributions of covert and overt shifts of attention while reading spaced letter strings.

Increasing Spacing and the Critical Proximity

Recent research into the effects of increasing spacing promises to complement the extensive work on the converse manipulation in reading and object recognition in general (i.e., Bouma, 1970; Chung, 2002; Pelli & Tillman, 2008; Risko et al., 2010; Yu et al., 2007; Wolford, 1975; Wolford & Chambers, 1983). This latter research has focused on the concept of critical spacing, which represents the distance between object and flankers required for successful recognition (Pelli & Tillman, 2008). Target–flanker distances smaller than this critical spacing impair object recognition, whereas target-flanker distances larger than the critical spacing do not lead to any additional benefits in terms of object recognition. The present work suggests that at least in the context of reading, we need an analogous concept to capture the distance between letters beyond which reading is impaired (i.e., the critical proximity). The distance between the critical spacing and this "critical proximity" would reflect the ideal interletter distances for visual word recognition. The identification and elucidation of this critical proximity will provide important information regarding normal word recognition. Furthermore, the present work also demonstrates the potential utility of the spacing manipulation for understanding the distribution between parallel and serial processes occurring during early stages in reading.

Conclusion

The present investigation has provided a new understanding of the impact of increasing spacing on reading aloud. This manipulation promises to provide new insight into early stages of visual word identification through its influence on (at least) the appearance of parallel letter processing, letter grouping, and the contribution of attention to these early processes. Further work that discriminates between the different accounts developed here is needed for a more complete understanding of early processes in reading.

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