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Unsegmented text delays word identification: Evidence from a survival analysis of fixation durations

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The present study employed distributional analyses of fixation times to examine the impact of removing spaces between words during reading. Specifically, we presented high and low frequency target words in a normal text condition that contained spaces (e.g., "John decided to sell the table in the garage sale") and in an unsegmented text condition that contained random numbers instead of spaces (e.g., "John4decided8to5sell9the7table2in3the9garage6sale"). The unsegmented text condition produced larger word frequency effects relative to the normal text condition for the gaze duration and total time measures (for similar findings, see Rayner, Fischer, & Pollatsek, 1998), which indicates that removing spaces can impact the word identification stage of reading. To further examine the effect of spacing on word identification, we used distributional analyses of first-fixation durations to contrast the time course of word frequency effects in the normal versus the unsegmented text conditions. In replication of prior findings (Reingold, Reichle, Glaholt, & Sheridan, 2012; Staub, White, Drieghe, Hollway, & Rayner, 2010), ex-Gaussian fitting revealed that the word frequency variable impacted both the shift and the skew of the distributions, and this pattern of results occurred for both the normal and unsegmented text conditions. In addition, a survival analysis technique revealed a later time course of word frequency effects in the unsegmented relative to the normal condition, such that the earliest discernible influence of word frequency was 112 ms from the start of fixation in the normal text condition, and 152 ms in the unsegmented text condition. This delay in the temporal onset of word frequency effects in the unsegmented text condition strongly suggests that removing spaces delays the word identification stage of reading. Possible underlying mechanisms are discussed, including lateral masking and word segmentation.

Keywords: Distributional analysis; Eye movements; Lexical processing; Reading; Word frequency.

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What is the role of interword spaces during reading? Past studies have addressed this question by examining reading performance for text without spaces (i.e., unsegmented text). Removing spaces in English produces longer fixation durations and reduced reading rates (e.g., Malt & Seamon, 1978; Morris, Rayner, & Pollatsek, 1990; Perea & Acha, 2009; Pollatsek & Rayner, 1982; Rayner, Fischer, & Pollatsek, 1998; Spragins, Lefton, & Fisher, 1976; Yang & McConkie, 2001). For example, relative to normal text, there is a 30–50% decrement in reading rates when spaces are either removed entirely, or replaced with various types of filler characters, such as letters, digits, or bloblike gratings (Rayner et al., 1998). Moreover, investigations of languages that naturally do not contain spaces (e.g., Japanese, Chinese, Thai) have typically shown that adding interword spaces does not harm reading performance, and sometimes even improves performance (e.g., Bai, Yan, Liversedge, Zang, & Rayner, 2008; Sainio, Hyönä, Bingushi, & Bertram, 2007; Shen et al., 2012; Winskel, Perea, & Ratitamkul, 2012; Winskel, Radach, & Luksaneeyanawin, 2009). Taken together, these findings highlight the importance of spaces during reading. Although readers can still comprehend unsegmented text (Epelboim, Booth, & Steinman, 1994), they consistently show dramatic decreases in reading efficiency (Rayner et al., 1998).

To explain the disruption caused by unsegmented text, Rayner et al. (1998) proposed that unsegmented text separately interferes with both saccadic programming and word identification processes. Specifically, spaces facilitate saccadic programming by providing visual cues concerning word boundaries and word length. Thus, whereas normal text produces initial landing positions that are close to the centre of the word (i.e., the preferred viewing position, PVP; Rayner, 1979), unsegmented text disrupts saccadic programming such that initial landing locations are shifted closer to the beginning of the word (e.g., Paterson & Jordan, 2010; Perea & Acha, 2009; Rayner et al., 1998), and saccade amplitudes are shorter (Paterson & Jordan, 2010; Perea & Acha, 2009; Rayner et al., 1998; Yang & McConkie, 2001).

In addition to facilitating saccadic programming, spaces may also enhance word identification processes, either by facilitating word segmentation by demarcating which characters belong in a word (e.g., Li, Rayner, & Cave, 2009), or by reducing lateral masking (Bouma, 1973; Townsend, Taylor, & Brown, 1971). Consistent with this idea, several researchers have advanced the hypothesis that unsegmented text slows down reading because removing spaces disrupts word identification (Epelboim, Booth, & Steinman, 1994, 1996; Morris et al., 1990; Pollatsek & Rayner, 1982; Rayner et al., 1998). To test this hypothesis, Rayner et al. (1998) manipulated word frequency for target words that were imbedded in both normal and unsegmented sentences, in order to test for interactions between word frequency (high, low) and text condition (normal, unsegmented). It is well-established that fixation times during reading are longer for low frequency than for high frequency words (Inhoff & Rayner, 1986; Rayner & Duffy, 1986; see White, 2008, for a review), and such word frequency effects are considered to be a temporal marker of lexical processing (Rayner, 1998; Reingold, Reichle, Glaholt, & Sheridan, 2012). Rayner et al. observed that unsegmented text increases the magnitude of word frequency effects relative to normal text (for similar findings, see Paterson & Jordan, 2010; Perea & Acha, 2009), and they interpreted this interaction as evidence that unsegmented text disrupts word identification rather than interfering only with a more superficial level of visual processing (for a similar logic, see Booth, Epelboim, & Steinman, 1995; Sternberg, 1969).

Building on these findings, the goal of the present study was to provide fine-grained evidence concerning the extent to which removing spaces delays word identification. To accomplish this goal, we employed several distributional analysis techniques that have recently proven useful for examining the time course of the influence of different variables during reading (e.g., Reingold et al., 2012; Sheridan & Reingold, 2012a, 2012b; Staub, 2011; Staub, White, Drieghe, Hollway, & Rayner, 2010; White & Staub, 2012; White, Staub, Drieghe, & Liversedge, 2011; White, Warren, Staub, & Reichle, 2011). In particular, we used a survival analysis technique (Reingold et al., 2012), and ex-Gaussian fitting (Staub et al., 2010) to compare the time course of word frequency effects under normal versus unsegmented text conditions.

Accordingly, we presented both high and low frequency target words in a normal text condition that contained spaces (e.g., "John decided to sell the table in the garage sale") and in an unsegmented text condition that contained random numbers instead of spaces (e.g., "John4decided8to5 sell9the7table2in3the9garage6sale"). We selected random numbers as fillers because we expected them to be less predictable and thus more disruptive than uniform fillers, such as the letter "x" filler that was employed by Rayner et al. (1998). Using the survival analysis and ex-Gaussian techniques described later, we then tested for a delayed temporal onset of word frequency effects in the unsegmented relative to the normal text condition. On the premise that word frequency effects are a temporal marker of lexical processing (Rayner, 1998, 2009; Reingold et al., 2012), such a delay would support the hypothesis that unsegmented text slows down word identification.

Reingold et al. (2012) recently introduced a technique for examining survival curves of fixation durations during reading. Specifically, for a given time t, the percentage of first fixations with a duration greater than t are referred to as the percentage *survival* at time t. Thus, when t equals zero, survival is at 100%, but then declines as t increases and approaches 0% as t approaches the duration of the longest observed first fixation. Reingold et al. examined the time course of word frequency effects during reading by calculating separate survival curves for first-fixation durations on low frequency and high frequency target words. They then examined the earliest point in time at which the high and low frequency survival curves began to significantly diverge (henceforth referred to as the *divergence point*). Importantly, Reingold et al. argued that the divergence point provided an estimate of the earliest significant influence of the word frequency variable. Based on their survival curve analyses, they concluded that there is a significant influence of word frequency on fixation duration in normal reading as early as 145 ms from the start of fixation. Extending this finding, equally rapid divergence points have also been shown for several additional variables, including lexical ambiguity (Sheridan & Reingold, 2012a), and predictability (Sheridan & Reingold, 2012b). In the present study, we examined whether the normal versus unsegmented text manipulation impacts the location of the divergence point between the high and low frequency survival curves. If the unsegmented text condition produces a later divergence point relative to the normal text condition, then such a pattern of results would indicate that removing spaces delays word identification. However, if the normal and unsegmented text conditions produce equivalent divergence points, then such a pattern of results would indicate that removing spaces does not slow down lexical processing.

In addition to examining survival curves, we employed ex-Gaussian fitting (Staub et al., 2010) to model individual participants' distributions of fixation times during reading. A key advantage of ex-Gaussian fitting is that it clarifies whether a variable's impact on mean fixation times is due to a shift in the location of the distribution and/or a change in the degree of skew. As explained by Staub et al. (2010), a shift effect indicates that the variable is having an early acting influence on the majority of fixation durations, whereas a skew effect primarily stems from an influence on long fixation durations. Under normal reading conditions, the word frequency variable produces both a shift effect and a skew effect (Reingold et al., 2012; Staub et al., 2010). In the present study, we examined if this pattern of results could extend to the unsegmented text condition. In particular, given the hypothesis that word identification is slower for unsegmented text, we were interested in testing if the word frequency variable would still be fast acting enough to produce a shift effect for the unsegmented text condition.

Thus, our main goal was to employ distributional analyses to compare the time course of word frequency effects under both normal and unsegmented text conditions. However, as an additional question of interest, we also contrasted the pattern of results when text condition (normal, unsegmented) was manipulated within subjects (Experiment 1A) versus between subjects (Experiment 1B). These two types of manipulations were included to confirm that the pattern of distributional results could replicate across a variety of experimental contexts. To the extent that the disruption caused by unsegmented text is due to low-level visual factors (e.g., lateral masking) rather than higher level strategic influences, it is possible that the within- versus between-subjects manipulation will not influence the qualitative pattern of results. However, we speculated that overall levels of reading performance might differ across the within-subjects manipulation and between-subjects manipulation, because it has been previously shown that single word reading performance differs for items presented in "pure" blocks that contain a single type of trial, relative to "mixed" blocks that contain more than one type of trial (Lupker, Brown, & Colombo, 1997; Monsell, Patterson, Graham, Hughes, & Milroy, 1992; Rastle, Kinoshita, Lupker, & Coltheart, 2003). Given that previous studies have primarily used within-subjects manipulations to contrast normal and unsegmented text (e.g., Rayner et al., 1998), we wished to explore the ramifications of using a within- versus a between-subjects design.

METHOD

Participants

All 248 participants (104 in Experiment 1A and 144 in Experiment 1B) were undergraduate students at the University of Toronto. The participants were all native English speakers and were given either one course credit, or $10.00 (Canadian) per hour. All participants had normal or corrected to normal vision.

Materials and design

In both Experiments 1A and 1B, the target words consisted of 120 low frequency nouns and 120 high frequency nouns, which ranged in word length from 5 to 10 letters ($M = 6.5$). The mean word frequency was 2.5 occurrences per million for the low frequency targets, and 112.1 occurrences per million for the high frequency targets, according to the SUBTLex corpus of American English subtitles (Brysbaert & New, 2009). 120 pairs of high- and low-frequency words were then created (matched on word length), and two low-constraint sentence frames were composed for each word pair so that either word could plausibly fit into the sentences. For example, Sentences 1a and 1b were created for the pair of words, *table* and *banjo*:

1a. John decided to sell the **table/banjo** in the garage sale.
1b. I was told that the **table/banjo** was made out of expensive wood.

Target word predictability in these sentence frames was assessed by providing an additional group of 10 participants with the beginning of each sentence frame and asking them to write a word that could fit as the next word in the sentence. Average predictability was extremely low, amounting to 1.3% for the high-frequency target words and 0.1% for low-frequency target words.

In addition to the frequency manipulation, both Experiments 1A and 1B contrasted a normal text condition with an unsegmented text condition that contained random numbers between 2 and 9 instead of spaces (e.g., "John4decided8to5sell9the7table2in3the9garage6sale"). Thus, four experimental conditions resulted from crossing frequency (high vs. low) and text condition (normal vs. unsegmented). The word frequency variable was manipulated within subjects for both Experiments 1A and 1B, and text condition was manipulated within subjects for Experiment 1A (i.e., all 104 participants read a mixture of normal and unsegmented text trials), and as a between-subjects manipulation for Experiment 1B (i.e., 72 of the participants only read the normal text condition, and the remaining 72 participants only read the unsegmented text condition). In Experiment 1A, participants read 16 practice trials followed by 240 experimental trials and 40 filler trials. In Experiment 1B, the practice trials (five practice trials in the normal text condition, and 16 practice trials in the unsegmented text condition), were followed by 120 experimental trials and 160 filler trials. Thus, in both Experiments 1A and 1B, the participants read a total of 280 sentences plus practice trials. The experimental and filler sentences were presented in a random order, and each participant read any given target word or sentence frame only once. The assignment of target words to sentence frames and conditions was always counterbalanced across participants.

Apparatus and procedure

Eye movements were measured with an SR Research EyeLink 1000 system with high spatial resolution and a sampling rate of 1000 Hz. Viewing was binocular, but only the right eye was monitored. A chinrest and forehead rest were used to minimize head movements. Following calibration, gaze-position error was less than 0.5°. The sentences were displayed on a 21 in. ViewSonic monitor with a refresh rate of 150 Hz and a screen resolution of 1024×768 pixels. All letters were lowercase (except when capitals were appropriate). The text was presented in black (4.7 cd/m^2) on a white background (56 cd/m^2). Participants were seated 60 cm from the monitor, and 2.4 characters equalled approximately 1 degree of visual angle. All sentences were displayed on a single line, and the target words were located near the middle of the sentences. The average number of words in each sentence was 11.2 words (range = 6 to 16 words).

Prior to the experiment, all of the participants were told to focus on reading the sentences for comprehension. In addition, for Experiment 1A, and for Experiment 1B's unsegmented text condition, the participants were informed that they would encounter sentences that contained numbers instead of spaces. After reading each sentence, participants pressed a button to end the trial and proceed to the next sentence. To ensure that participants were reading for comprehension, about 15% of the sentences were followed by multiple-choice comprehension questions. The average accuracy rate was above 90% for both experiments (1A, 1B) and for both text conditions (normal, unsegmented).

RESULTS

Our main goal was to employ the ex-Gaussian and survival analysis techniques to examine the time course of word frequency effects in the unsegmented versus the normal text conditions. However, prior to reporting the distributional analyses, we first confirmed that we could replicate past findings by examining landing positions and a variety of standard global and target region measures. For the global analyses, trials were excluded due to data losses (less than 1% of trials), and the first and last fixations in a trial were always excluded. For the analysis of landing positions and the target region analyses, trials were excluded due to data losses (less than 1% of trials), and due to skipping of the target (3% to 11% of trials).[1]

Analysis of landing positions

We examined the impact of text condition (normal, unsegmented) on initial landing positions on the high and low frequency target words. Specifically, for each target word, we defined a target region from the middle of the space prior to this word to the middle of the space following this word. To obtain our measure of landing position, we then calculated the proportion of the target region that was to the left of the position of the first fixation on the target region (for a more detailed description of this measure, see Reingold et al., 2012). For each experiment, 2×2 analyses of variance (ANOVAs) were carried out on the landing position data via both participants (*F*1) and items (*F*2), with text condition (normal, unsegmented) and word frequency (high, low) as independent variables. Figure 1 displays the distribution of landing positions for each condition and for each experiment. To create this

[1] The location and target region analyses were also conducted using outlier rejection cutoff points. Specifically, in these analyses, we excluded all trials in which the first fixation on the target was below 80 ms or above 1000 ms. The percentage of outlier trials was extremely small (i.e., 1.7% for the normal condition and 1.4% for the unsegmented condition in Experiment 1A, and 1.2% for the normal condition and 0.9% for the unsegmented condition in Experiment 1B). Since the exclusion of these outlier trials did not affect the pattern of results, we reported the results without outlier rejection in the main text.

figure, we divided the target region into five equally spaced landing location bins (i.e., each bin contained 20% of the target region), and then calculated the proportion of fixations per bin. As can be seen from Figure 1, landing positions were closer to the beginning of the word for the unsegmented condition relative to the normal condition, all Fs > 18, all ps $< .001$, and the average size of this shift corresponded to a distance of 0.43 character spaces in Experiment 1A and 0.42 character spaces in Experiment 1B. This shift in the distribution of landing positions replicates past findings

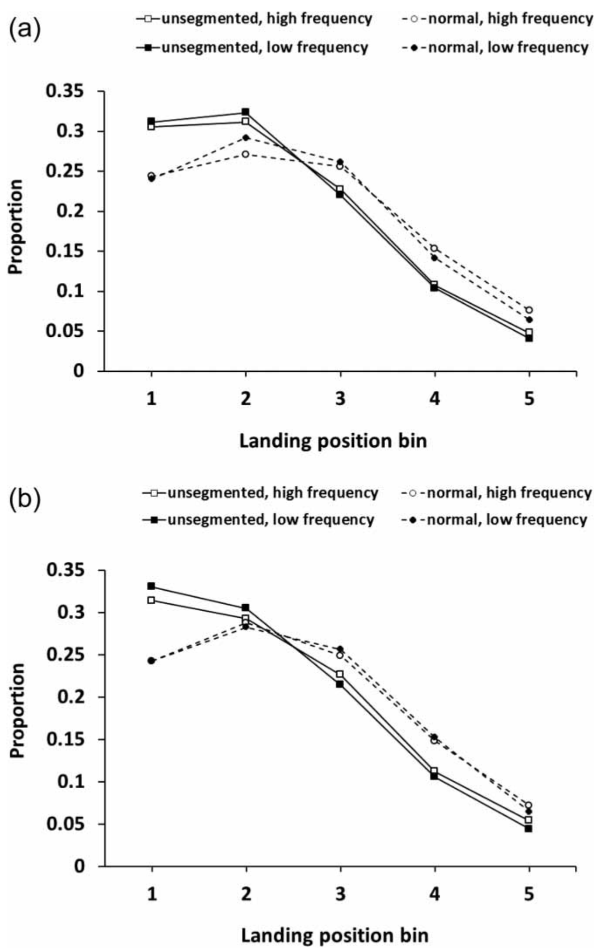

Figure 1. The distribution of initial landing positions by word frequency condition (high, low) and text condition (normal, unsegmented), in (a) Experiment 1A and (b) Experiment 1B. To create this figure, the target word region was divided into five equally spaced landing position bins, and we then calculated the proportion of fixations per bin (see text for details).

(e.g., Paterson & Jordan, 2010; Perea & Acha, 2009; Rayner et al., 1998), and suggests that unsegmented text interferes with saccadic programming. In addition, landing positions were shifted closer to the beginning of the word for low frequency relative to high frequency words (by an average of 0.07 character spaces in both experiments), and this word frequency effect was significant in Experiment 1A, all *F*s > 8, all *p*s $< .01$, and in Experiment 1B for the by-items analysis, $F2(1, 119) = 4.28$, $p < .05$, but not for the by-participants analysis, $F1(1, 142) = 3.47$, $p = .065$. This word frequency effect might have stemmed from differences in orthographic familiarity across the high and low frequency words in our study. We did not control for orthographic familiarity, which has been previously shown to impact landing positions on target words (e.g., Plummer & Rayner, 2012; White & Liversedge, 2004). There were no significant interactions between word frequency and text condition, all *F*s < 4, all *p*s $> .05$.

Analysis of global and target region measures

For each of the global and target region measures reported later, two types of 2×2 ANOVAs were carried out on the data via both participants (*F*1) and items (*F*2). The first type of analysis examined the influence of text condition (unsegmented, normal) and word frequency (high, low) separately for each of the two experiments (1A, 1B). The second type of analysis was designed to contrast performance across the two experiments, by examining the influence of experiment (1A, 1B) and word frequency (high, low), separately for each of the two text conditions (normal, unsegmented).

For the global analyses, we calculated the average reading rate, fixation duration, number of fixations per sentence, forward saccade size, and the number of saccades per sentence. Table 1 summarizes the means and standard errors for these global measures. Within both experiments, there was less efficient reading performance (i.e., decrements in reading rates, longer fixation durations, shorter forward saccades, and an increase in the number of fixations and saccades per sentence) in the unsegmented condition relative to the normal condition, all *F*s > 20, all *p*s $< .001$, and in the low frequency condition relative to the high frequency condition, all *F*s > 14, all *p*s $< .001$.[2] There were typically no significant interactions between text condition and word frequency, all *F*s < 4, all *p*s $> .06$, with the exception that the forward saccade size measure showed a significant interaction in Experiment 1B (but not in Experiment 1A), such that there

[2] Although the word frequency effects for the global measures were small in magnitude (see Table 1), they were nonetheless significant. These effects were likely driven by differences in the processing of the target words rather than from global differences in the processing of the entire sentence.

TABLE 1
Global reading measures by text condition (normal vs. segmented), word frequency condition (high vs. low frequency), and experiment (1A, 1B)

	Normal text				*Unsegmented text*			
	High frequency		*Low frequency*		*High frequency*		*Low frequency*	
Measure	*M*	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*
Experiment 1A (within-subjects manipulation)								
Reading rate (words/min)	274	7.6	261	7.6	200	5.7	190	5.7
Fixation duration (ms)	200	2.4	203	2.4	224	2.3	227	2.4
Number of fixations per sentence	10.5	0.29	11.1	0.32	13.9	0.38	14.7	0.40
Forward saccade size (degrees of visual angle)	3.3	0.07	3.3	0.07	2.5	0.06	2.4	0.06
Number of saccades per sentence	11.3	0.29	11.9	0.32	14.7	0.38	15.5	0.40
Experiment 1B (between-subjects manipulation)								
Reading rate (words/min)	267	9.1	259	9.2	189	6.6	182	6.6
Fixation duration (ms)	208	3.2	210	3.1	228	2.8	230	2.8
Number of fixations per sentence	10.1	0.31	10.6	0.34	14.4	0.48	15.1	0.51
Forward saccade size (degrees of visual angle)	3.2	0.08	3.2	0.08	2.4	0.06	2.3	0.06
Number of saccades per sentence	11.0	0.31	11.4	0.33	15.3	0.48	16.0	0.51

The means and standard errors shown in the table are based on the by-participant analyses.

was a significantly larger word frequency effect on forward saccade size in the unsegmented condition relative to the normal condition, all *F*s > 4, all *p*s $< .05$. When performance was contrasted across the two experiments, both the normal and unsegmented conditions showed a numerical trend towards less efficient reading performance in Experiment 1B relative to 1A. For all of the global measures, this numerical trend was significant by items, all *F*s > 15, all *p*s $< .001$, but not by participants, all *F*s < 4, all *p*s $> .06$, and there was also an effect of word frequency, all *F*s > 10, all *p*s $< .01$, that did not interact with the experiment variable, all *F*s < 3, all *p*s $> .09$.

For the target region analyses, we calculated the following measures: (1) First-fixation duration (i.e., the duration of the first forward fixation on the target, regardless of the number of subsequent fixations on the target); (2) single-fixation duration (i.e., the first-fixation value for the subset of trials in which there was only one first-pass fixation on the target); (3) gaze duration (i.e., the sum of all the consecutive first-pass fixations on the target, prior to a saccade to another word); (4) total time (i.e., the sum of all fixations on the target); (5) the probability of skipping (i.e., trials in which there was no first-pass fixation on the target regardless of whether or not the target was fixated later in the trial); and (6) the probability of a single first-pass fixation. Table 2 summarizes the means and standard errors for these target region measures. Within both experiments, there were longer fixation

TABLE 2
Target region reading measures by text condition (normal vs. segmented), word frequency condition (high vs. low frequency), and experiment (1A, 1B)

	Normal text				*Unsegmented text*			
	High frequency		*Low frequency*		*High frequency*		*Low frequency*	
Measure	*M*	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*
Experiment 1A (within-subjects manipulation)								
First fixation (ms)	203	2.6	223	2.7	235	2.6	255	3.4
Single fixation (ms)	205	2.9	228	3.2	239	2.8	270	7.4
Gaze duration (ms)	231	4.1	281	6.7	323	6.4	426	11.9
Total time (ms)	299	6.5	391	11.9	412	10.4	607	21.0
Probability of skipping	.11	.01	.08	.01	.04	.01	.03	.01
Probability of single fixation	.75	.01	.69	.01	.59	.02	.49	.02
Experiment 1B (between-subjects manipulation)								
First fixation (ms)	213	3.4	232	4.2	238	3.3	258	3.7
Single fixation (ms)	215	3.6	237	4.5	245	4.6	267	4.2
Gaze duration (ms)	245	5.2	299	9.6	334	7.8	425	13.3
Total time (ms)	310	9.1	399	17.0	434	11.9	622	22.4
Probability of skipping	.11	.01	.07	.01	.04	.01	.03	.01
Probability of single fixation	.73	.01	.66	.01	.58	.02	.49	.02

The means and standard errors shown in the table are based on the by-participant analyses.

times, lower skipping rates, and lower probabilities of a single fixation for the unsegmented relative to the normal condition (all Fs > 20 all ps $< .001$), and for the low frequency relative to the high frequency condition (all Fs > 40 all ps $< .001$). For the first-fixation and single fixation measures, word frequency effects were equal in magnitude across the normal and unsegmented conditions as indicated by a lack of interactions (all Fs < 2 all ps $> .1$). However, in replication of Rayner et al. (1998), the remaining measures (i.e., gaze duration, total time, probability of skipping, probability of single fixation) produced larger word frequency effects in the unsegmented condition than in the normal condition, and this interaction was significant in both experiments for gaze duration, total time, and probability of skipping (all Fs > 13, all ps $< .001$). For the probability of a single fixation measure, the interactions were significant for Experiment 1A (all Fs > 13, all ps $< .001$), but not for Experiment 1B (all Fs < 3, all ps $> .1$). As previously argued by Rayner et al. (1998), these interactions between word frequency and text condition indicate that unsegmented text interferes with the word identification stage of reading.

When the target region measures were compared across the two experiments, fixation times were longer in Experiment 1B than in Experiment 1A. For the by-participant analyses, this effect was significant for the early fixation time measures (i.e., first fixation, single fixation) in the normal condition, all Fs > 3, all ps $< .05$, but not in the unsegmented condition (all Fs < 1), and none of the gaze duration and total time by-participant analyses were significant, all Fs < 4, all ps $> .06$. However, the by-item analyses were significant for all of the fixation time analyses and conditions, all Fs > 7, all ps $< .01$, except for the gaze duration measure in the unsegmented text condition, $F2(1, 119) = 1.63$, $p = .204$. There were no differences between the skipping rates across experiments, all Fs < 2, all ps $> .2$, but there was a numerical trend towards lower probabilities of a single fixation in Experiment 1A than in 1B that was significant for the by-items analysis in the normal condition, $F2(1, 119) = 14.15$, $p < .001$, but not in the unsegmented condition ($F2 < 1$) and not for the by-participant analyses, all Fs < 3, all ps $> .09$. Finally, there was a significant word frequency effect, all Fs > 20, all ps $< .001$, which did not show any significant interactions with experiment, all Fs < 4, all ps $> .05$.

In sum, the global and the target region mean analyses replicated past findings that removing spaces reduces reading efficiency (e.g., Malt & Seamon, 1978; Morris et al., 1990; Perea & Acha, 2009; Pollatsek & Rayner, 1982; Rayner et al., 1998; Spragins et al., 1976; Yang & McConkie, 2001). In addition, both the normal and unsegmented conditions produced robust word frequency effects (Inhoff & Rayner, 1986; Rayner & Duffy, 1986; White, 2008), and there was some evidence that reading efficiency was reduced for Experiment 1B relative to Experiment 1A.

Analyses of distributions

Next, we report on the findings obtained from the analyses of the distribution of first-fixation duration by fitting fixation time data using the ex-Gaussian distribution, as well as by employing a survival analysis technique.

Fitting first-fixation duration with the ex-Gaussian distribution. Figures 2 and 3 (see Panels a and b) display the distributions of first-fixation durations by text condition (normal, unsegmented). To create these figures, we separately computed the proportion of first-fixation durations that fell within each successive 25 ms bin over the range from 0 to 600 ms for each participant and each condition, and we then averaged these values across participants. As can be seen from Figures 2 and 3, the distributions of first-fixation durations tended to be approximately normal in shape with some degree of rightward skew. Such distributions can be modelled using the ex-Gaussian distribution (e.g., Staub et al., 2010), which is the convolution of the Gaussian normal distribution and an exponential distribution. The shape of the ex-Gaussian distribution can be specified with three parameters:

μ (the mean of the Gaussian normal distribution), σ (the standard deviation of the Gaussian normal distribution), and τ (the mean and standard deviation of the exponential function). Following Staub et al. (2010), we fitted the ex-Gaussian distribution to our first-fixation duration data using an algorithm known as quantile maximum likelihood estimation (QMPE; Cousineau, Brown, & Heathcote, 2004; Heathcote, Brown, & Mewhort, 2002). First-fixation duration data for each participant in each condition were fitted separately. The mean number of usable observations per cell ranged from 53 to 58 (see Table 3), and all fits successfully converged. Table 3 displays the mean number of usable observations per cell, the parameter estimates, and the magnitude and significance of the word frequency effects, and Figures 2 and 3 (see Panels c and d) display the density functions generated from the best-fitting ex-Gaussian parameters averaged across participants.

As shown in Table 3 and Figures 2 and 3, the overall pattern of ex-Gaussian results was the same for both Experiments 1A and 1B. Specifically, both the normal and the unsegmented text conditions produced a significant

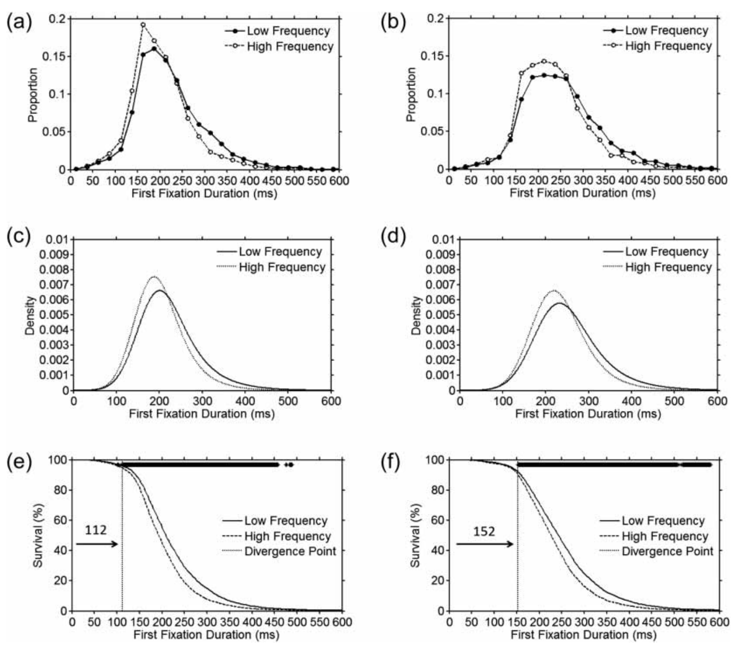

Figure 2. Experiment 1A distributions of first-fixation duration on high-frequency and low-frequency targets in (a) the normal text condition, (b) the unsegmented text condition, (c–d) ex-Gaussian density functions, and (e–f) survival curves that were generated from these distributions (the row asterisks at the top of Panels e–f indicate time bins with a significant differences between the low frequency and high frequency curves). See text for details.

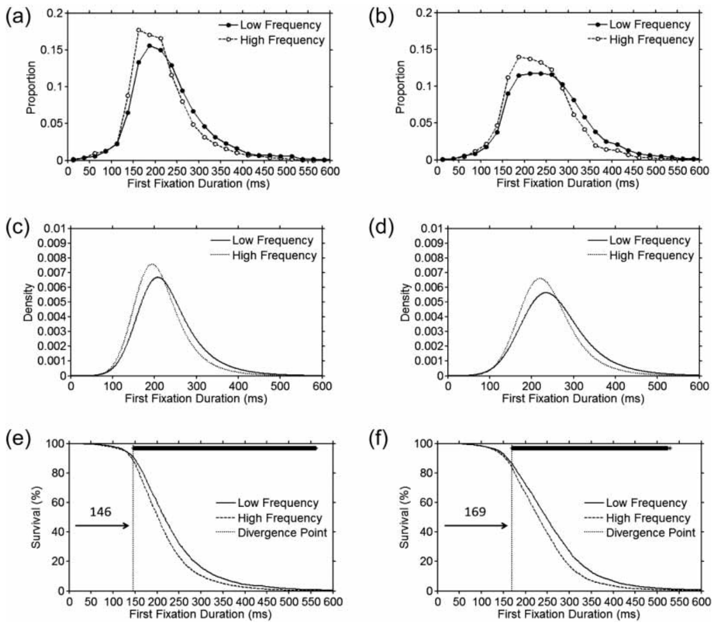

Figure 3. Experiment 1B distributions of first-fixation duration on high-frequency and low-frequency targets in (a) the normal text condition and (b) the unsegmented text condition, (c–d) ex-Gaussian density functions, and (e–f) survival curves that were generated from these distributions (the row asterisks at the top of Panels e–f indicate time bins with a significant differences between the low frequency and high frequency curves). See text for details.

μ effect, such that the low frequency distribution was shifted to the right of the high frequency distribution, as well as a significant τ effect, such that the low frequency distribution also exhibited greater rightward skew as compared to the high frequency distribution. In addition, for the unsegmented condition (but not for the normal condition) there was a significant increase in σ for the low frequency relative to the high frequency condition. This σ effect might indicate that the amount of interference produced by unsegmented text is more variable for low frequency than for high frequency words (for a related discussion, see White & Staub, 2012). Overall, the pattern of ex-Gaussian results replicates past findings that the word frequency manipulation produces both μ and τ effects under normal reading conditions (Reingold et al., 2012; Staub et al., 2010), and we extend this finding to the case of unsegmented text.

To further contrast the pattern of ex-Gaussian results across the unsegmented versus the normal conditions we also performed 2×2 ANOVAs for each experiment and each parameter, with text condition (normal, unsegmented), and word frequency (high, low) as independent

TABLE 3
Number of observations per cell and ex-Gaussian parameters by text condition (normal vs. segmented), word frequency condition (high vs. low frequency), and experiment (1A, 1B), with standard errors in parentheses

	n	*Mu* (μ)	*Sigma* (σ)	*Tau* (τ)
Experiment 1A (within-subjects manipulation)				
Normal text				
Low frequency	55 (0.4)	165 (2.6)	43 (1.7)	58 (2.3)
High frequency	53 (0.5)	158 (1.8)	40 (1.3)	45 (2.3)
Frequency effect	2***	7**	3	13***
Unsegmented text				
Low frequency	58 (0.9)	192 (3.1)	50 (2.1)	63 (2.9)
High frequency	57 (1.0)	185 (2.9)	46 (1.7)	50 (2.5)
Frequency effect	1***	7*	4*	13***
Experiment 1B (between-subjects manipulation)				
Normal text				
Low frequency	56 (0.6)	172 (3.5)	41 (2.2)	59 (3.9)
High frequency	53 (0.7)	163 (2.8)	37 (1.8)	50 (2.9)
Frequency effect	3***	9**	4	9**
Unsegmented text				
Low frequency	58 (0.3)	193 (3.8)	51 (2.2)	65 (3.3)
High frequency	57 (0.4)	186 (3.1)	45 (2.0)	53 (3.1)
Frequency effect	1***	7*	6**	12***

For the *t*-test results shown here, Experiment 1A $df = 103$; Experiment 1B $df = 71$. *$p < .05$, **$p < .01$, ***$p < .001$.

variables. In both Experiments 1A and 1B, μ and σ were significantly higher in the unsegmented condition relative to the normal condition in both experiments, all Fs > 12, all ps $< .01$, and the τ parameter showed a similar effect that was significant in Experiment 1A, $F(1, 103) = 5.54$, $p < .05$, but not Experiment 1B, $F(1, 142) = 1.12$, $p = .293$. In addition, all three parameters (μ, σ, τ) were significantly higher for low frequency relative to high frequency words, all Fs > 6, all ps $< .05$. There were no significant interactions (all Fs < 1), which indicates that the word frequency effects on the ex-Gaussian parameters were similar in magnitude for the normal and the unsegmented text conditions.

Survival analysis. We computed survival curves for first-fixation durations in the high and low frequency conditions, using the same procedure as Reingold et al. (2012). Specifically, for each 1 ms time bin t (t was varied from 0 to 600 ms), the percentage of first fixations with a duration greater than t constituted the percentage survival at time t. The survival curve was computed separately for each condition and for each participant, and then averaged across participants. As shown in Figures 2 and 3 (see Panels e and f), the high and low frequency survival curves appear to diverge. Importantly, this divergence point corresponds by definition to the shortest first-fixation duration value at which the word frequency manipulation had a significant impact. To estimate the divergence point, we employed a bootstrap resampling procedure (Efron & Tibshirani, 1994). The procedure that we used is outlined in detail by Reingold et al. (2012). On each iteration of this procedure, the set of observations (first-fixation durations) for each participant in each condition was randomly resampled with replacement. For each iteration of the bootstrap procedure, individual participant's survival curves were then computed and averaged. Next, the value for each 1 ms bin in the high frequency survival curve was subtracted from the corresponding value in the low frequency survival curve. This procedure was repeated 10,000 times, and the obtained differences for each bin were then sorted in order of magnitude. The range between the fifth and the 9995th value was then defined as the confidence interval of the difference for each bin (given the multiple comparisons we performed, we used this conservative confidence interval in order to protect against making a Type I error). To compute the divergence point between the high and low frequency survival curves, we identified the time bins for which the low frequency survival rate was significantly greater than the high frequency survival rate (i.e., for which the lower bound of the confidence interval of the difference between the high and low frequency curves was greater than zero). The divergence point was then defined as the earliest significant difference point that was part of a run of five consecutive significant difference points (significant differences between the high and low frequency curves are shown in Figures 2 and 3 as a row of asterisks above the survival curves).

As seen from Figures 2 and 3, both of the experiments produced earlier divergence points in the normal condition relative to the unsegmented condition. Specifically, in Experiment 1A, the high and low frequency survival curves significantly diverged at a duration of 112 ms in the normal condition and 152 ms in the unsegmented condition, whereas in Experiment 1B the corresponding divergence points were 146 ms in the normal condition, and 169 ms in the unsegmented condition.[3] Furthermore, the divergence point defines the percentage of first fixations with durations that were too short to exhibit an influence of word frequency. In Experiment 1A,

[3] We also used the survival analysis technique to examine the single-fixation and gaze duration measures, and our results were qualitatively similar to the first-fixation measure. Specifically, in Experiment 1A, the single-fixation divergence points were 100 ms in the normal condition and 166 ms in the unsegmented condition, and the gaze duration divergence points were 100 ms in the normal condition and 151 ms in the unsegmented condition. In Experiment 1B, the single-fixation divergence points were 142 ms in the normal condition and 178 ms in the unsegmented condition, and the gaze duration divergence points were 135 ms in the normal condition and 169 ms in the unsegmented condition. In the main text, we focus on the first-fixation measure that has been used in previous investigations (e.g., Reingold et al., 2012).

the percentage of first-fixation durations that were shorter than the divergence point was 5% in the normal condition and 9% in the unsegmented condition, whereas in Experiment 1B the corresponding percentages were 10% in the normal condition and 15% in the unsegmented condition. These percentages indicated that the vast majority of fixations were impacted by the word frequency manipulation, which is consistent with the ex-Gaussian findings that the word frequency manipulation produces a shift in the distribution (see Staub et al., 2010, for a related discussion). Finally, the survival analysis values for the normal condition in Experiment 1B closely replicate the results from a similar condition employed by Reingold et al. (2012).

To sum up, these survival analyses indicate that the temporal onset of word frequency effects is delayed for the unsegmented relative to the normal condition, which strongly supports the hypothesis that the unsegmented condition delayed word identification (Rayner et al., 1998). In addition, there were later divergence points in Experiment 1B relative to Experiment 1A. Taken together with the global and target region analyses reported earlier, this difference across experiments suggests that lexical processing was more efficient for Experiment 1A, relative to Experiment 1B. This difference may have occurred because the within-subject manipulation in Experiment 1A exposed participants to a mixture of trial types, whereas the between-subject manipulation in Experiment 1B employed only a single trial type (for related findings, see Lupker et al., 1997; Monsell et al., 1992; Rastle et al., 2003). However, we cannot rule out the alternative possibility that there were intergroup differences, such that the participants in Experiment 1A were more skilled readers than the participants in Experiment 1B. Most importantly, even though the overall level of reading performance differed across the experiments, the impact of the normal versus unsegmented text manipulation was still qualitatively similar for both of the experiments.

DISCUSSION

Consistent with past work (e.g., Malt & Seamon, 1978; Morris et al., 1990; Perea & Acha, 2009; Pollatsek & Rayner, 1982; Rayner et al., 1998; Spragins et al., 1976; Yang & McConkie, 2001), removing interword spaces disrupted reading as indicated by longer fixation times, reduced reading rates, shorter saccades, and initial landing positions that were shifted towards the beginning of the word. Moreover, in replication of Rayner et al. (1998), the unsegmented text condition produced larger word frequency effects than normal text for the gaze duration and total time fixation time measures. As discussed by Rayner et al., such interactions suggest that unsegmented text interferes with word identification. Extending these findings, we employed a survival analysis technique (Reingold et al., 2012) to provide strong evidence that removing spaces delays the word identification stage of reading. Specifically, we derived estimates of the earliest influence of the word frequency variable, which is considered to be a good empirical marker of lexical processing (Rayner, 1998, 2009; Reingold et al., 2012). Word frequency effects emerged as early as 112 ms from the start of fixation in the normal text condition, and as early as 152 ms in the unsegmented text condition. Thus, the unsegmented text condition produced a delay in the onset of word frequency effects, which indicates that removing spaces delays lexical processing. In addition, we used ex-Gaussian fitting to demonstrate that the word frequency variable produces both a shift and a skew effect under normal and unsegmented text conditions. Finally, both the survival analyses and the ex-Gaussian analyses revealed a qualitatively similar pattern of results regardless of whether the unsegmented versus normal text variable was manipulated within subjects (Experiment 1A), or between subjects (Experiment 1B).

Most importantly, the survival analysis findings are consistent with the hypothesis that unsegmented text delays word identification (Epelboim et al., 1994, 1996; Morris et al., 1990; Pollatsek & Rayner, 1982; Rayner et al., 1998). As discussed by Rayner et al. (1998), there are several potential reasons for this delay, including the possibility that word segmentation is more difficult without spaces to demarcate which characters belong in a word (e.g., Li et al., 2009), as well as interference due to lateral masking (Bouma, 1973; Townsend et al., 1971). For the present study's unsegmented text manipulation, word segmentation information was at least partially preserved because we replaced the spaces with nonletter fillers (i.e., random numbers between 2 and 9), and we avoided using numbers that might resemble letters (i.e., 1 and 0). However, our number fillers might have provided less predictable word segmentation cues than uniform fillers, such as the letter "x" (see e.g., Rayner et al., 1998), and they might have produced additional processing difficulty if readers spent some of their time processing the numbers rather than the text. To further investigate the role of word segmentation processes, future research could test whether the delay in word frequency effects shown by the survival analysis would be more dramatic for unsegmented text manipulations that reduce word segmentation cues even further (e.g., by using random letters as fillers or by removing spaces entirely instead of using fillers).

Alternatively, the word identification delays might have been driven by lateral masking (Bouma, 1973; Townsend et al., 1971), such that the numbers interfered with the visibility of adjacent letters. Lateral masking has been previously discussed as a mechanism for explaining improvements in reading speed due to increases in interword spacing (e.g., Drieghe, Brysbaert, & Desmet, 2005; Rayner et al., 1998), increases in interletter spacing (Paterson

& Jordan, 2010; Perea, Moret-Tatay, & Gómez, 2011), and increases in the amount of spacing between lines of text (Bentley, 1921; Chung, 2004). In the present study, the lateral masking explanation is consistent with the fact that there were no qualitative differences as a function of strategic factors (i.e., the qualitatively similar pattern of results across Experiments 1A and 1B). In addition, it is possible that reduced parafoveal processing of target words in the unsegmented text condition partially contributed to the delays in word identification. In line with this explanation, the unsegmented text condition produced lower skipping rates than the normal condition, and prior work has shown that preventing parafoveal preview produces dramatic delays in the onset of word frequency effects during reading (Reingold et al., 2012).

Furthermore, the word identification delays could have occurred because unsegmented text constitutes an unfamiliar visual format for English readers. As discussed by Bai et al. (2008), a less familiar visual format would be expected to produce longer reading times relative to a familiar format. However, although familiarity may have played a role in the present study, prior results indicate that familiarity was not the sole cause of the delays produced by unsegmented text condition. Specifically, English readers were still impaired by unsegmented text even after they received extensive practice to familiarize them with the format (Malt & Seamon, 1978), and Thai (Winskel et al., 2009, 2012), Japanese (Sainio et al., 2007), and Chinese readers (Bai et al., 2008; Shen et al., 2012) have occasionally shown improvements after spaces were added to the text, even though unsegmented text is the more familiar format for these languages. Clearly, further work is required to ascertain the exact mechanisms that led to a delay in the onset of word frequency effects in the unsegmented text condition.

In addition to the survival analyses, ex-Gaussian fitting was used to compare the time course of word frequency effects in the normal and unsegmented text conditions. As mentioned previously, the word frequency variable produced both a shift and a skew effect under both normal and unsegmented text conditions, which replicates the pattern of results that was shown previously for normal text (Reingold et al., 2012; Staub et al., 2010). The presence of a shift effect indicates that the word frequency variable was fast-acting enough to influence the vast majority of fixations, in both the normal and unsegmented text conditions (Staub et al., 2010).

More generally, there is now ample evidence that reading performance is impacted by a variety of manipulations of the visual appearance of the text, including typography (e.g., Barnhart & Goldinger, 2010; Kolers, 1968; Paterson & Tinker, 1947; Rayner, Reichle, Stroud, Williams, & Pollatsek, 2006; Reingold & Rayner, 2006; Sheridan & Reingold, 2012c; Slattery & Rayner, 2010; Tinker & Paterson, 1955), stimulus quality (e.g., Reingold & Rayner, 2006; White & Staub, 2012), and interword spacing (e.g., Rayner et al., 1998). Empirical findings concerning the visual characteristics of the text can provide insights into the complex processes that support skilled reading, and can inform models of eye movements control during reading (for reviews, see Rayner, 1998, 2009). For example, the E-Z Reader model (Reichle, Pollatsek, Fisher, & Rayner, 1998; Reichle, Warren, & McConnell, 2009) was extended to Chinese text, which does not contain spaces (Rayner, Li, & Pollatsek, 2007), and was used to generate novel predictions concerning the impact of typography and stimulus quality manipulations (Reingold & Rayner, 2006). In the present study, we provide convergent evidence for the hypothesis that removing spaces during reading interferes with both word identification and saccadic programming (Rayner et al., 1998), and our findings highlight the usefulness of distributional analyses in providing fine-grained time course information that is not available from mean analyses alone.

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