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Reading without spaces revisited: The role of word identification and sentence-level constraints☆

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ABSTRACT

The present study examined the relative contribution of bottom-up word identification and top-down sentence-level constraints in facilitating the reading of text printed without between-word spacing. We compared reading of grammatically correct sentences and shuffled versions of the same words presented both with normal spacing and without spaces. We found that reading was hampered by removing sentence structure as well as by removing spaces. A significantly greater impact of sentence structure when reading unspaced text was found in probe word identification accuracies and total viewing times per word, whereas the impact of sentence structure on the probability of making a regressive eye movement was greater when reading normally spaced text. Crucially, we also found that the length of the currently fixated word determined the amplitude of forward saccades leaving that word during the reading of unspaced text. We conclude that the relative ease with which skilled readers can read unspaced text is due to a combination of an increased use of bottom-up word identification in guiding the timing and targeting of eye movements, plus an increased interactivity between word identification and sentence-level processing.

1. Introduction

Anecdotally, it is quite striking to note the ease with which skilledreaderscanreadtext-presentedwithoutspacingbetweenwords. Nevertheless, it is important to note that (i) historically, Latin script was originally written without extra between-word spacing (*scriptura continua*; see Saenger, 1997), and (ii) many contemporary written languages such as Chinese, Japanese and Thai, do not use between-word spacing. Reading unspaced text is nevertheless harder than reading text with normal between-word spacing, a pattern revealed by a number of studies recording the eye movements of skilled readers while they read regularly spaced and unspaced text (Epelboim, Booth, Ashkenazy, Taleghani, & Steinman, 1997; Epelboim, Booth, & Steinman, 1994, 1996; Morris, Rayner, & Pollatsek, 1990; Perea & Acha, 2009; Pollatsek & Rayner, 1982; Rayner, 1998; Rayner, Fischer, & Pollatsek, 1998; Spragins, Lefton, & Fisher, 1976; Veldre, Drieghe, & Andrews, 2017).[1]

These studies have revealed that reading unspaced text is slower by about 40% to 70% than reading normally spaced text (Rayner et al., 1998; Rayner & Pollatsek, 1996). Readers make shorter saccades accompanied by longer fixations and more regressions when reading unspaced text, and the effect of word frequency on fixation durations is greater with unspaced text (Rayner et al., 1998; Veldre et al., 2017). Furthermore, given the overall shorter saccade lengths, initial landing positions are closer to the beginning of words in unspaced text (Paterson & Jordan, 2010; Perea & Acha, 2009). The conclusion that has emerged from this research is that removing the extra spacing between words disrupts two distinct processes: saccadic planning and word identification (Perea & Acha, 2009; Rayner et al., 1998). Firstly, given the key role for between-word spaces in guiding eye movements during the reading of normally spaced text (e.g., Inhoff, Eiter, Radach, & Juhasz, 2003), removing spaces will logically affect saccade programming. Indeed, as noted by Krügel and Engbert (2014), most models of eye-movement control and reading, including the prominent *E-Z* Reader (Reichle, Pollatsek, Fisher, & Rayner, 1998) and SWIFT (Engbert, Nuthmann, Richter, & Kliegl, 2005) models, agree that readers use word centers as functional target locations to guide eye movements. This works fine when words are clearly delimited by spaces but is problematical when the between-word spaces are removed. The general consensus that has emerged on the basis of prior findings is that readers of unspaced text revert to a more cautious saccade targeting

☆ Link to data on OSF: https://osf.io/zfuje/?view_only=86b20d7f02684bef9fd84981ed2d1345.

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[1] It is important to note that the above-cited studies and the present study investigated reading of text in which the between-word spaces have been removed, and not text in which the spaces have been replaced by filler stimuli (e.g., Malt & Seamon, 1978; Sheridan, Reichle, & Reingold, 2016).

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strategy involving shorter and more frequent saccades. In other words, these models predict that readers of unspaced text do not revert to more cognitively driven eye-guidance mechanisms, but simply adapt general-purpose oculomotor strategies. This fits with the second conclusion mentioned above, that word identification processes are hindered when reading unspaced text, and therefore that word identification is likely not a good candidate for guiding eye movements in these conditions. Word identification could be more difficult when reading unspaced text due to the absence of visual cues for word beginnings and endings, and also possibly due to crowding effects occurring not only for the word's inner-positioned letters, as is the case in normal (spaced) reading, but also for the word's outer-positioned letters.

Based on our own theoretical work incorporating word identification mechanisms in a model of eye-movement control and reading (OB1-Reader: Snell, van Leipsig, Grainger, & Meeter, 2018), in the present study we take a new look at the possible contributions of bottom-up word identification and top-down sentence-level constraints in facilitating the reading of unspaced text. We hypothesize that sentence reading generates a representation of the sentence in working memory, that in turn generates expectations about the identity and location of individual words (Grainger, 2018; Mirault, Snell, & Grainger, 2018; Snell et al., 2018; Snell & Grainger, 2017; Snell, Meeter, & Grainger, 2017). We follow the example of Schad, Nuthmann, and Engbert (2010) by introducing a “shuffled” text condition as a means to investigate the influence of higher-level sentence-level constraints. Schad et al. (2010) presented skilled readers with grammatically correct sentences and recorded their eye movements as they read the sentences for comprehension. The same participants also read shuffled ungrammatical sequences of the same words. Schad et al. (2010) found that in the shuffled text condition readers made more eye movements with shorter saccades and longer fixation durations, and that they skipped fewer words. This pattern of results can be explained by an increased difficulty in identifying words in the shuffled text condition. In other words, word identification during normal sentence reading would benefit from sentence-level constraints, and this benefit is lost when reading shuffled text. In *E*-Z Reader and SWIFT, ease of word identification affects the timing of saccades, and these models therefore have the potential to account for the effect of shuffled text on fixation durations, albeit in the absence of an implementation of true word identification processes. In OB1-Reader, ease of word identification not only affects the timing of eye movements but can also affect saccade targeting, in that identified words are no longer considered as potential targets. This therefore provides an explanation for the reduction in word skipping when reading shuffled text. More generally speaking, the effects of shuffled text are in line with interactive accounts of sentence comprehension, according to which sentence-level representations feed-back information to word-level representations, and this increases their likelihood of being identified when they are compatible with the sentence context (e.g., MacDonald, Pearlmutter, & Seidenberg, 1994; Snell et al., 2017). That is, syntactic and semantic sentence-level representations can modulate on-going lexical processing via feedback connections.

In the present study we recorded eye-movements as participants read either grammatically correct sentences or ungrammatical sequences of the same words and did so either under normal between-word spacing conditions or in a condition without extra spacing between words. We used a set of standard measures from the eye movements and reading literature (first fixation duration, gaze duration, total viewing time, number of within-word fixations, number of between-word fixations, word skipping rate, initial landing position, and saccade length - see the Results section for definitions of these measures), as well as a more general measure of reading speed (sentence reading time) and a measure specifically designed for the reading of shuffled text (probe word identification). Our measures largely overlap with those used in prior research on unspaced reading (e.g., Perea & Acha, 2009) and reading shuffled text (Schad et al., 2010).

As noted above, the main goal of the present study was to examine the relative contribution of sentence-level constraints and bottom-up word identification to the apparent ease with which skilled readers can read unspaced text. Our general approach is set within the scene of our recent theoretical work (Grainger, 2018; Snell et al., 2017, 2018) according to which between-word spaces enable parallel word identification during reading, and therefore removing such spaces should force readers to rely on sequential word identification driven by more fine-grained orthographic processing.[2] In this theoretical framework, between-word spaces provide crucial information for encoding word order, and in the absence of such information it is hypothesized that readers will resort to using information about the order in which words are identified as input for sentence-level processing. Sequential bottom-up word identification would enable the construction of a sentence-level representation, when this is available, and the on-going construction of a sentence-level representation would constrain word identification processes via top-down feedback (Snell et al., 2017; Snell et al., 2018).

Within this theoretical perspective, we make the clear hypothesis that sentence-level constraints should help word identification processes more when reading unspaced text than when reading normally spaced text. We note, nevertheless, that it remains to be seen whether sentence-level representations can indeed be generated fast enough when reading unspaced text. Given the general consensus that bottom-up word identification is harder in the absence of spaces, it is conceivable that the relative contribution of top-down feedback from the sentence-level to individual words is augmented when reading unspaced text. One possibility is that the increased contribution from sentence-level constraints during the reading of unspaced text will be observable in later measures of word recognition (e.g., total word viewing time), but not in earlier measures (e.g., the duration of the first fixation on the word).

Finally, between-word spaces are the principal guide for eye movements during reading, and we hypothesize that removing such information will force readers to resort to more cognitively driven saccade targeting, with the length of the currently fixated word being one important source of information here. That is, during the reading of unspaced text, the sequential identification of words could be used to guide eye-movements by providing information about the length of the currently fixated word and consequently where the next word begins.

In sum, examining the influence of sentence structure on reading spaced and unspaced text can be used to infer the relative efficiency with which such structures can be computed in the absence of extra between-word spacing, and the extent to which they influence word identification processes.

2. Method

2.1. Participants

Twenty participants (11 female) were recruited at Aix-Marseille University (Marseille, France). The participants were all native French speakers and received either course credit or monetary compensation (€10/h). All participants reported normal or corrected-to-normal vision and ranged in age from 18 to 24 years (M = 21 years, SD = 1.6). They were naïve to the purpose of the experiment and signed an informed consent form before starting the experiment.

[2] We note the interesting parallel here with the theory advanced by Paul Saenger (1997) that, historically, the introduction of spacing between words enabled the development of silent reading, given that unspaced text was traditionally read aloud in public (see also Rastle, 2019, for discussion of the implications of this transition for the relation between written and spoken language).

Table 1
Example French sentence as presented in each for the four conditions.

	Example word sequence
Spaced	
Normal	Il arrive que le soleil se couche (It happens that the sun sets)
Shuffled	Arrive couche il le que se soleil (Happens sets it the that sun)
Unspaced	
Normal	ilarrivequelesoleilsecouche (ithappensthatthesunsets)
Shuffled	arrivecoucheillequesesoleil (happenssetsitthethatsun)

Note. Between parentheses are English examples provided for convenience.

2.2. Design & stimuli

We constructed 200 sentences in French, each containing 7 words without diacritics (see Table 1 for an example). Sentences were constructed so as to minimize semantic predictability within the sentence (i.e., neutral sentences) and to have a simple grammatical structure (i.e., no passive constructions, no relative clauses). The words had an average length of 5.64 letters, and an average frequency of 6.63 Zipf (van Heuven, Mandera, Keuleers, & Brysbaert, 2014). Word frequencies were obtained using the film subtitle frequencies of the Lexique2 database (New, Pallier, Brysbaert, & Ferrand, 2004).

Between-word spacing (spaced vs. unspaced) and the order of words in the sentences (normal vs. shuffled order) were manipulated in a 2 × 2 factorial design. A Latin-Square was used with participants divided into four groups such that all sentences were tested in all four conditions across the four groups, but were seen only once per participant, with 50 sentences assigned to each condition per participant. The sentences were presented in a different random order for each participant.

2.3. Apparatus

Stimuli were displayed using OpenSesame (Mathôt, Schreij, & Theeuwes, 2012) with each sentence occupying a single line. Eye movements were recorded with an EyeLink 1000 system (SR Research, Mississauga, ON, Canada) with high spatial resolution (0.01°) and a sampling rate of 1000 Hz. Viewing was binocular, but only the right eye was monitored. The sentences were displayed on a 20-inch ViewSonic CRT monitor with a refresh rate of 150 Hz and a screen resolution of 1024 × 768 pixels (30 × 40 cm). Stimuli were presented in lower case 18-point monospaced font (droid sans mono; the default monospaced font in OpenSesame) and the text was presented in black (0.15 Cd/m^2) on a grey background (21.70 Cd/m^2); crosses and dots were presented with the same colors. Participants were seated 86 cm from the monitor, such that every 3 characters equaled approximately 1° of visual angle. A chin-rest and forehead-rest were used to minimize head movements.

2.4. Procedure

At the beginning of the experiment, the participant's eye position was calibrated using a 9-point calibration grid. Each trial involved the presentation of one sentence. The trial started with a drift correction dot located 200 pixels (5°) to the right of the left edge of the display. Participants were instructed to focus on this dot, which would trigger the onset of the sentence stimulus, with the starting point of the sentence being located just to the right of the drift correction dot. Since our sentences had different lengths, the distance between the fixation point and the beginning of the sentence was randomly determined, within a range of 2 to 216 pixels. Participants were instructed to read each sentence from left to right, with the aim to achieve full comprehension. An invisible boundary was defined at the end of the sentence, such that the sentence disappeared when the eyes crossed that boundary. Next, participants were shown a question after each trial that allowed us to check whether they had paid attention to the word sequence. Specifically, participants were instructed to indicate whether they had seen a given word (e.g. "Did you see the word 'table'?") by means of a two-button response for respectively "yes" and "no" responses (probe word classification). Probe words were present on 50% of the trials, and the position of the probe word varied randomly across those trials. A feedback dot was presented during 2000 ms after the response (green if the response was correct or red if the response was incorrect).

2.5. Analyses

We used Linear Mixed Effects models (LMEs) to analyze our data, with items and participants as crossed random effects (including by-item and by-participant random intercepts (Baayen, Davidson, & Bates, 2008)). Items in these analyses were sentences or their shuffled version in the sentence-level analyses, and individual words (7 per sentence) for the local analyses. Generalized (logistic) LMEs were used to analyze error rates and fixation type probabilities (skips, regressions, refixations). The models were fitted with the lmer (for LMEs) and glmer (for GLMEs) functions from the lme4 package (Bates, Maechler, Bolker, & Walker, 2014) in the R statistical computing environment (R Core Team, 2014). We report regression coefficients (b), standard errors (SE) and t-values (for LMEs) or z-values (for GLMEs) for all factors. Fixed effects were deemed reliable if $|t|$ (or $|z|$) $>$ 1.96 (Baayen et al., 2008). We used the spaced and correctly ordered sentence condition as reference. All durations were inverse-transformed (-1000/duration) prior to analysis. Data and script (R) are available on the Open Science Framework (OSF): https://osf.io/zufuje/?view_only=86b20d7f02684bef9fd84981ed2d1345.

3. Results

All participants answered > 85% (M = 92.88%, SD = 0.25) of the probe trials correctly and depicted normal eye movement behavior. The raw data were pre-processed by EyeLink algorithms that detect saccades, fixations and eye-blinks. Analyses were carried out both at the sentence-level (sentence reading time, number of saccades, saccade amplitudes, probe word classification accuracy; Section 3.1.) as well as at the word level (fixation durations, fixation landing positions, skips, regressions and refixations; Section 3.2.). The first 10 trials were used as warm-up and were excluded prior to analysis, as were trials in which there was an eye-blink (8.18% of all trials).

3.1. Sentence-level analyses

We first analyzed probe word classification accuracy, sentence reading times, number of saccades and saccade amplitude across the experimental conditions. Saccade amplitudes were averaged per sentence. Hence, each sentence yielded one data point for each of these measures.

3.1.1. Probe word classification

Table 2 shows the average error rate for each condition. Significant main effects of both Spacing (b = 1.11; SE = 0.16; t = **6.84**) and Order (b = 0.32; SE = 0.10; t = **3.16**) were established, such that the error rate was significantly greater in the unspaced and shuffled sentences. The interaction was also significant (b = 0.40; SE = 0.12; t = **3.30**). As can be seen in Table 2, there was a larger effect of Order when reading unspaced text (b = 0.75; SE = 0.06; t = **10.81**) compared to spaced text (b = 0.17; SE = 0.11; t = 1.46).

Table 2
Mean probe word classification errors (%) per condition.

		Order		
		Normal	Shuffled	Order effect
Spacing	Spaced	3.36 (0.45)	4.28 (0.51)	0.92
	Unspaced	7.75 (0.68)	13.83 (0.87)	6.08

Note. Values in between parentheses indicate 95% CIs (Cousineau, 2005).

Table 3
Sentence reading time (ms) per condition.

		Order		
		Normal	Shuffled	Order effect
Spacing	Spaced	1901 (27.38)	2136 (27.23)	235
	Unspaced	2583 (34.78)	2945 (42.00)	362

Note. Values in between parentheses indicate 95% CIs.

3.1.2. Sentence reading time

Sentence reading time was measured as the time from stimulus onset to the moment the participant's gaze crossed the invisible boundary at the end of the sentence. The average values (in ms) per condition are reported in Table 3.

We observed significant effects of Spacing ($b = 0.15$; SE = 0.01; $t = \mathbf{9.07}$) and Order ($b = 0.03$, SE = 0.01, $t = \mathbf{3.66}$), with longer reading times in the unspaced condition and in the shuffled condition. The interaction between Spacing and Order was marginally significant ($b = 0.03$; SE = 0.01; $t = 1.74$).

3.1.3. Saccades

The average number of saccades per condition and the average length of saccades per condition (expressed in degrees of visual angle) are reported in Table 4a (for number) and Table 4b (for length).

There was a significantly greater number of saccades when reading unspaced text compared with normally spaced text ($b = 1.59$; SE = 0.28; $t = \mathbf{5.57}$) and the average saccade length was shorter in the unspaced condition ($b = 0.53$; SE = 0.05; $t = \mathbf{10.08}$). Shuffling word order also caused a significant increase in the number of saccades ($b = 0.72$; SE = 0.19; $t = \mathbf{3.65}$) and a significant decrease in their length ($b = 0.13$; SE = 0.03; $t = \mathbf{4.29}$). The interactions were not significant (number of saccades: $b = 0.03$; SE = 0.27; $t = 0.14$; saccade length: $b = 0.03$; SE = 0.03; $t = 0.85$).

3.2. Local analyses

Here we analyzed eye movement behavior relative to each individual word in the sentences, examining fixation durations, the different types of eye movement, and initial landing positions.

3.2.1. Fixation durations

From the eye tracking data, we computed three variables: First Fixation Duration (FFD), which represents the duration of the fixation immediately following the first forward saccade into a word; Gaze Duration (GD), which is the sum of all first-pass fixations on a word;

Table 4a
Number of saccades per condition.

		Order		
		Normal	Shuffled	Order effect
Spacing	Spaced	7.09 (0.07)	7.83 (0.07)	0.74
	Unspaced	8.65 (0.09)	9.43 (0.10)	0.78

Table 4b
Length of saccades per condition in degrees of visual angle.

		Order		
		Normal	Shuffled	Order effect
Spacing	Spaced	2.35 (0.01)	2.22 (0.01)	−0.13
	Unspaced	1.83 (0.01)	1.73 (0.01)	−0.10

Note. Values in between parentheses indicate 95% CIs.

and Total Viewing Time (TVT), which is the sum of all fixation durations on a word (thus including regressions). For the analyses of FFD, GD and TVT, we excluded words that were fixated by means of a regressive saccade after initially being skipped (4.73%). From the remaining words we excluded approximately 2% with values beyond 2.5 SD from the grand mean (FFD: 2.01%, GD: 2.48%, TVT: 1.97%). The mean duration values (in ms) per experimental condition are presented in Fig. 1. Summary of the analysis of fixation durations (FFD, GD, and TVT) are reported in Table 5.

There were significant main effects of Spacing and Order in all the measures and also an interaction between these two factors in total viewing times, with the effect of Order being greater in the unspaced condition (49 ms) compared to the spaced condition (39 ms). This interaction prompted us to carry out an analysis of second-pass viewing times, i.e., the duration spent viewing a given word following a regressive saccade back to that word. The analysis revealed a significant interaction between Spacing and Order ($b = 124.54$; SE = 34.64; $t = \mathbf{3.59}$), with a greater effect of Order in the unspaced condition. When reading unspaced text, participants spent longer viewing words that they regressed back to in the shuffled condition (517 ms) compared with the ordered condition (435 ms: $b = 86.09$; SE = 23.25; $t = \mathbf{3.70}$), whereas a non-significant opposite pattern was found with normal spacing (shuffled = 342 ms; ordered = 398 ms: $b = 30.09$; SE = 26.57; $t = 1.16$).

3.2.2. Saccade probabilities

The average skipping, refixation, and regression probabilities (excluding skipped words when calculating refixations and regressions) per experimental condition are shown in Fig. 2.

As shown in Table 6, there were significant effects of Order for all the measures and significant effects of Spacing for the skipping and the refixation rates. There was a significant interaction between Spacing and Order in the regression rate, with a greater influence of Order in the spaced condition ($b = 0.52$; SE = 0.06; $t = \mathbf{7.85}$) compared to the unspaced condition ($b = 0.27$; SE = 0.06; $t = \mathbf{4.31}$). As can be seen in Fig. 1, although the interaction in skipping rates failed to reach statistical significance, Order only influenced skipping when reading spaced text (Spaced: $b = 0.09$; SE = 0.03; $t = \mathbf{2.35}$, Unspaced: $b = 0.01$; SE = 0.04; $t = 0.35$), with fewer skips in the shuffled text condition.

3.2.3. Initial landing position

We also examined initial landing positions (ILPs), which correspond to the location of the first fixation on a word immediately following a forward incoming saccade. The ILP was measured using a normalized scale from 0 (word beginning) to 1 (word ending). Overall, the ILP was slightly to the left of the word's center (i.e., values < 0.5; see Table 7). Unspaced sentences further caused a leftward shift in the ILP compared to intact sentences ($b = 0.03$; SE = 0.00; $t = \mathbf{4.48}$). Order did not affect the ILP ($b = 0.00$; SE = 0.00; $t = 0.15$), and the interaction between Spacing and Order was not significant ($b = 0.00$; SE = 0.01; $t = 0.94$).

3.3. Effects of word frequency and word length

In these analyses we examined the effects of word frequency (Zipf values: van Heuven et al., 2014) and word length (in letters) on fixation

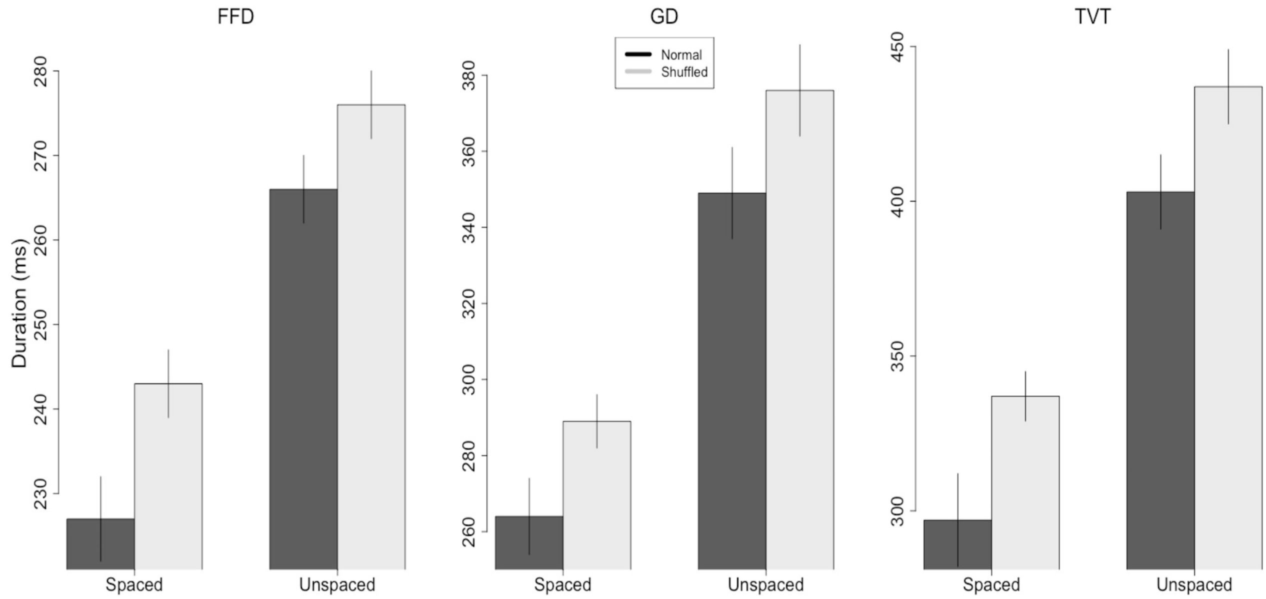

Fig. 1. Means of the different duration measures (in milliseconds) for each condition.
Error bars are the within-participants 95% CIs (Cousineau, 2005). Y-axis scales were individually adapted to each measure.

Table 5
Summary of the analyses of FFD, GD and TVT.

	FFD			GD			TVT		
	b	*SE*	*t*	*b*	*SE*	*t*	*b*	*SE*	*t*
Spacing (S)	0.67	0.09	**6.29**	0.92	0.07	**11.61**	0.93	0.07	**12.53**
Order (O)	0.29	0.06	**4.62**	0.36	0.05	**6.13**	0.48	0.04	**10.36**
S × O	0.09	0.12	0.75	0.11	0.09	1.18	0.17	0.06	**2.72**

Note. Significant t values are shown in bold.

Table 6
Summary of the analyses of skipping, regression, and refixation probabilities.

	Skipping			Refixation			Regression		
	b	*SE*	*z*	*b*	*SE*	*z*	*b*	*SE*	*z*
Spacing (S)	0.21	0.04	**4.42**	0.62	0.09	**6.73**	0.10	0.11	0.90
Order (O)	0.09	0.36	**2.54**	0.37	0.08	**4.27**	0.51	0.06	**7.71**
S × O	0.08	0.51	1.70	0.10	0.09	1.13	0.23	0.09	**2.57**

Note. Significant z values are shown in bold.

durations in the different experimental conditions, as well as the influence of the length of the currently fixated word on the amplitude of saccades leaving that word.

3.3.1. Effects on fixation durations

We found a significant effect of Word Frequency (WF) for all the duration measures (FFD: $b = 0.07$; SE = 0.02; $t = \mathbf{2.77}$, GD: $b = 0.06$; SE = 0.02; $t = \mathbf{2.54}$, TVT: $b = 0.27$; SE = 0.02; $t = \mathbf{11.00}$). Most

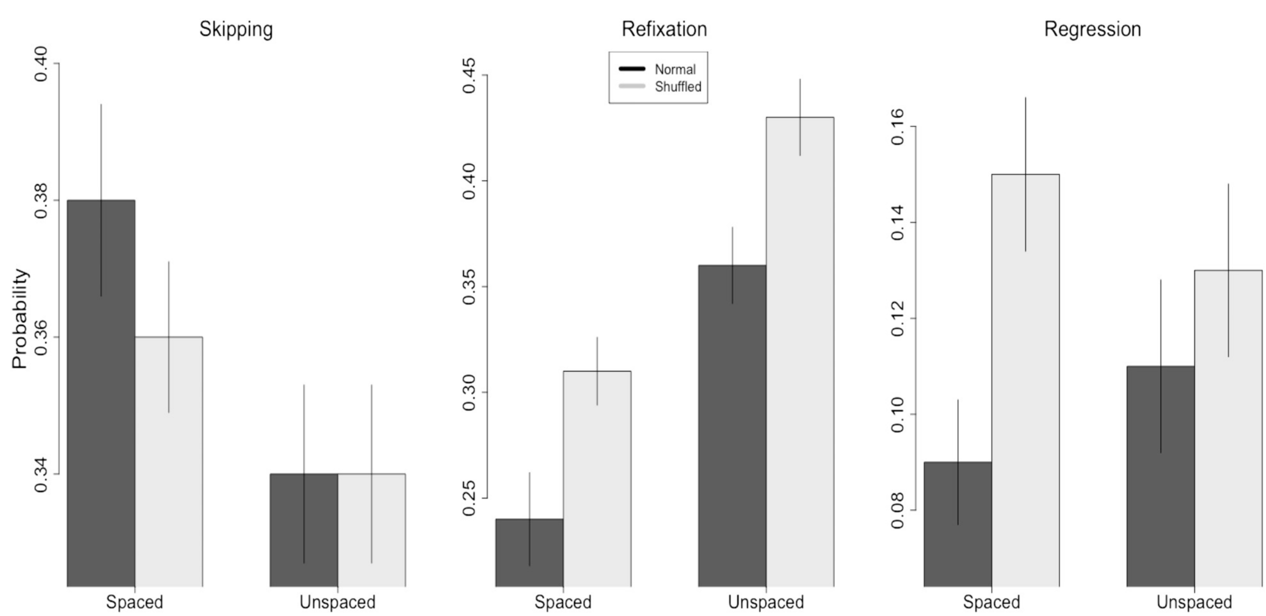

Fig. 2. Average skipping, refixation, and regression probabilities per experimental condition. Error bars are the within-participants 95% CIs (Cousineau, 2005). Y-axis scales were individually adapted to each measure.

Table 7
Initial landing position means per condition.

		Order		
		Normal	Shuffled	Order effect
Spacing	Spaced	0.440 (0.008)	0.434 (0.008)	−0.001
	Unspaced	0.403 (0.008)	0.394 (0.008)	−0.009

Note. Values are normalized to a 0–1 scale, with 0 corresponding to the left edge of the word, and 1 corresponding to the right edge of the word. Values in between parentheses indicate 95% CIs.

important is that there was a significant interaction between Spacing and Word Frequency in total viewing times ($b = 0.08$; SE = 0.03; $t =$ **2.33**), with frequency effects being greater when reading unspaced text. Word Frequency was also found to interact with Order in gaze durations ($b = 0.26$; SE = 0.03; $t =$ **7.25**) and total viewing times ($b = 0.24$; SE = 0.03; $t =$ **6.91**), with frequency effects being greater when reading shuffled text. The three-way interactions involving Spacing, Order, and Word Frequency were not significant (FFD: $b = 0.08$; SE = 0.05; $t = 1.61$, GD: $b = 0.02$; SE = 0.05; $t = 0.51$, TVT: $b = 0.05$; SE = 0.04; $t = 1.16$).

We found a significant effect of Word Length for all the duration measures (FFD: $b = 0.04$; SE = 0.01; $t =$ **2.78**, GD: $b = 0.17$; SE = 0.01; $t =$ **12.03**, TVT: $b = 0.18$; SE = 0.01; $t =$ **13.35**), with an increase in length leading to longer fixation durations. We also found significant interactions between Spacing and Word Length for FFD ($b = 0.04$; SE = 0.02; $t =$ **2.01**), GD ($b = 0.04$; SE = 0.01; $t =$ **2.06**) and TVT ($b = 0.04$; SE = 0.01; $t =$ **2.21**). Word length exerted a greater influence when reading normally spaced text. Once again, the three-way interactions were not significant (FFD: $b = 0.00$; SE = 0.03; $t = 0.17$, GD: $b = 0.00$; SE = 0.02; $t = 0.10$, TVT: $b = 0.00$; SE = 0.02; $t = 0.10$).

3.3.2. Word length and saccade amplitude

Here we investigated the relationship between the amplitude of the outgoing forward saccade (in degrees of visual angle), and the length of the fixated word (in letters). Fig. 3 shows the average saccade amplitude per word length for lengths between 2 and 10. There was a significant effect of Spacing ($b = 0.51$; SE = 0.04; $t =$ **10.95**), with longer saccades when reading normally spaced text. There was a significant main effect of Word Length ($b = 0.06$; SE = 0.00; $t =$ **7.67**), and crucially, this variable influenced saccade amplitudes equally in the spaced and unspaced condition, as reflected by the absence of an interaction between Word Length and Spacing ($b = 0.00$; SE = 0.00; $t = 1.14$). As can be seen in Fig. 3, the amplitude of outgoing forward saccades increased as word length increased in both the spaced ($b = 0.05$; SE = 0.00; $t =$ **7.15**) and unspaced conditions ($b = 0.07$; SE = 0.01; $t =$ **5.58**).

4. Discussion

The present study was designed to investigate the relative contribution of bottom-up word identification and top-down sentence-level constraints on the ability of skilled readers to read unspaced text. We did so by comparing reading performance for spaced versus unspaced word sequences that were either grammatically correct (normal sentences) or grammatically incorrect (the same sentences with a shuffled word order). In line with previous research on the reading of unspaced text (e.g. Perea & Acha, 2009; Rayner et al., 1998), we found that removing between-word spaces had a deleterious impact on reading speed, as reflected both by the total amount of time needed to read sentences, as well as by the time spent fixating individual words. Removing spaces also led to a decreased word skipping rate and an increase in the number of between-word regressions and within-word refixations, suggesting, in line with the above-mentioned studies, that unspaced text drives readers to make more fixations, that are longer and that are connected by shorter saccades. This explains why the initial landing position was closer to the beginning of words in the unspaced condition. The removal of spaces also significantly impaired participants' ability to decide whether or not a given probe word was part of the sequence they had just read, and the effects of word frequency on individual word reading times were significantly greater in the unspaced text condition (see also Rayner et al., 1998; Veldre et al., 2017).

Like removing between-word spaces, and in line with Schad et al. (2010), shuffling the order of words also led to an increase in the duration measures, a decreased skipping rate, and an increase in the number of within-word refixations and between-word regressions, as well as lower accuracy in probe word classification. The effects of word frequency on word viewing times were also greater when reading shuffled text. Concerning regressions, we found a large increase in the probability of making a regression when reading shuffled text compared with normal sentences, and this effect of word order was larger under normal spacing conditions. Finally, initial landing positions were not affected by word order, which is in line with the general consensus

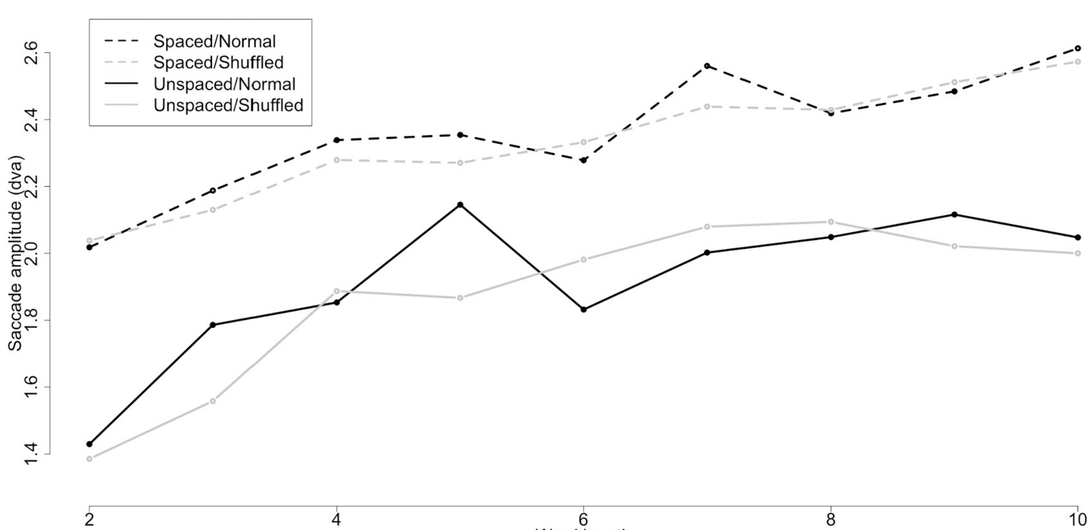

Fig. 3. Relation between the amplitude of outgoing forward saccades in degrees of visual angle (dva) and the length of the fixated word in number of letters. Dashed lines represent the spaced condition and solid lines the unspaced condition. Normal ordered sequences are displayed in black and the shuffled sequences in grey.

that these are generally impervious to higher-level cognitive influences.

As concerns interactions between the Spacing and Order factors, our theoretical framework (Grainger, 2018; Snell et al., 2017, 2018) led us to predict a scenario whereby the relative contribution of sentence-level constraints to word identification processes would be greater when reading unspaced text. In line with this scenario we found significant interactions between these factors in our measures of probe word classification accuracy and the total viewing times for individual words, with the effects of word order being greater when reading unspaced text. The effect seen on total viewing times was due to the larger effect of word order on second-pass viewing times (i.e., following a regressive saccade back to the critical word) when reading unspaced text. We also observed a reduced impact of shuffling word order on the probability of making regressions in the unspaced condition. The interaction was not significant for the other duration measures, or for the number and length of saccades, within-word refixation probabilities, and initial landing positions. This is most likely due to the importance of between-word spaces in guiding accurate skipping and regressive eye movements and is in line with current models of eye-movements in reading including *E*-Z Reader (Reichle et al., 1998), SWIFT (Engbert et al., 2005), and OB1-Reader (Snell et al., 2018).

Here, we will argue that the pattern of effects found in the present study is due to the support from sentence-level structures operating primarily via feedback to lexical representations, and that such feedback depends on the time it takes to generate a sentence-level representation. Firstly, the greater impact of the order factor on probe word classification accuracy when reading unspaced text points directly to a greater role for sentence structures in improving explicit word identification in that condition. This is in line with the finding reported by Snell and Grainger (2017) that sentence structure facilitates post-cued word identification following the brief presentation of a sequence of words. Further, the observed interaction on total viewing times, but absence of an interaction in shorter duration measures such as first fixation durations and gaze durations, indicate that sentence-level constraints in unspaced reading manifest themselves at a relatively late point in time - possibly because the generation of the sentence-level representation, during unspaced reading, is driven by sequential bottom-up word identification, and thus proceeds more slowly.

Skipping rates were higher in spaced texts and with regular word ordering, but the effects of order on skipping rates only emerged in the spaced condition. This suggests that the identification of upcoming words supported by sentence-level constraints drives skipping behavior in normally spaced text, which is in line with the way that identified words influence saccade targeting in OB1-Reader (Snell et al., 2018). On the other hand, skipping behavior during the reading of unspaced text would be the result of specific strategies that are impervious to sentence-level constraints. One such strategy, to be discussed below, would be to identify the currently fixated word and use information about its length to estimate where the next word might lie. Overall, the pattern of skipping behavior is in line with our hypothesis that reading unspaced text involves a serial word-by-word identification process that contrasts with the more parallel word identification processes that occur during the reading of normally spaced text.

One key finding of the present study was that the length of forward saccades leaving a word was determined by the length of the currently fixated word when reading unspaced text (see Fig. 3). This is clear evidence that the fixated word was identified, thus enabling retrieval of information about its length, and this length information was used to program a saccade beyond the word boundary. This is evidence that the serial word-by-word identification strategy that is implemented in order to read unspaced text not only governs the timing of eye movement behavior, as seen in word frequency effects for example, but also controls the decision about where to move the eyes in order to optimize identification of the next word in the sentence. The OB1-Reader model (Snell et al., 2018) incorporates word identification mechanisms that allow the model to access word length information and to implement such an eye-guidance strategy. Although such word identification processes are absent in other models such as *E*-Z Reader and SWIFT, their addition to these models would in principle enable them to implement the same saccade-targeting strategy. Until such modifications are made, we would simply reiterate that the implementation of bottom-up word identification processes in OB1-Reader provides a straight forward account of skilled readers' ability to read unspaced text.

The overall pattern of results seen in the present study points to an important distinction between how sentence-level constraints support identification of the fixated word, and how they support identification of upcoming words in the parafovea. For fixated words, the evidence suggests that the support increases in the unspaced condition, due to the importance of identifying fixated words for reading unspaced text. On the other hand, the fact that sentence structure only affected skipping rates when reading normally spaced text (see Fig. 2) suggests that sentence-level support for upcoming words is greatest when reading normally spaced text. In our theoretical framework, this arises because top-down support from sentence-level structure operates via a spatiotopic representation of words along a line of text that can only be generated in the presence of between-word spaces.

Finally, the present results provide a further demonstration that efficient word identification is one of the key factors facilitating the reading of unspaced text. In spite of the absence of extra between-word spacing, skilled readers are able to segment the continuous orthographic stimulus by identifying embedded words. This therefore raises the question as to how such word identification processes might operate when reading unspaced text. In other words, how can word identification operate in the absence of visual cues for word boundaries? Practically all orthographic coding schemes require information about the beginning and the end of words in order to specify letter-in-word position. Only one particular class of coding scheme does not require this information; these are schemes that encode letter order using letter combinations (e.g., Dehaene, Cohen, Sigman, & Vinckier, 2005; Grainger & van Heuven, 2004; Whitney, 2001). Although information about word edges can be used in such coding schemes, this is not a necessary component (e.g., Hannagan & Grainger, 2012). In order to minimize interference from inappropriate combinations computed when reading unspaced text, letter combinations could be limited to adjacent letters. This would amount to adjusting an inter-letter distance parameter in open-bigram coding, as proposed by Hannagan and Grainger (2012). In line with this proposal is the finding reported by Veldre et al. (2017) that better spellers were less affected by the removal of between-word spaces compared to good spellers. This suggests that reading unspaced text requires a more precise encoding of the order of letters in words. Further evidence in favor of this was reported by Mirault, Snell, and Grainger (2019), who found that the disruption caused by transposing letters in words (e.g., Rayner, White, & Liversedge, 2006) was disproportionately greater when reading unspaced text.

In sum, the results of the present study provide further support for the key role played by serial word identification processes when reading unspaced text and suggest that sentence-level structures facilitate such processes particularly when first-pass processing fails and when explicit identification of a given word is required. Future research could use the contrast between reading normally spaced text and unspaced text in order to further explore the serial versus parallel nature of word identification processes during reading.

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