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Authors
Leung, Tommi
Boush, Fatima
Chen, Qiyang
et al.

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Eye Movements When Reading Spaced and Unspaced Texts in Arabic

Tommi Leung (leung@uaeu.ac.ae)
Department of Cognitive Sciences, United Arab Emirates University
P. O. Box 15551, Al-Ain, UAE

Fatima Boush (fatima.musa@uaeu.ac.ae)
Department of Cognitive Sciences, United Arab Emirates University
P. O. Box 15551, Al-Ain, UAE

Qiyang Chen (chenqy222@nenu.edu.cn)
School of Psychology, Northeast Normal University
5268 Renmin Street, Changchun, Jilin Province, China

Meera Al Kaabi (m_alkaabi@uaeu.ac.ae)
Department of Cognitive Sciences, United Arab Emirates University
P. O. Box 15551, Al-Ain, UAE

Abstract

This study investigated the extent to which varying interword spacing influences eye movement during reading in Arabic. Previous works conducted in Latin-script languages suggested that interword spaces facilitated word recognition. On the other hand, word recognition was inhibited when interword spaces were either removed or replaced by other characters (Rayner et al., 1998; Sheridan et al., 2013). We focused on the influence of interword spaces on reading Arabic which is characterized by the use of interword spaces and the position-informative allographic system. Based on an eye tracking experiment in which subjects read Arabic sentences presented in three levels of interword spacing and two levels of target word frequency, we found that eliminating interword spaces did not significantly inhibit reading, yet widening interword spaces exerted a facilitative effect. We argued that the effect of eliminating interword spaces was compensated by the ligating properties of Arabic letters during sentence reading, i.e. Arabic ligatures were position-informative which provided sufficient visual cues for word recognition regardless of the presence of interword spaces.

Keywords: eye movement; interword spacing; Arabic; linear mixed model

Introduction

This study investigated the extent to which varying interword spacing influences eye movement during reading in Arabic. Across languages, some make use of explicit visual cues to demarcate word boundaries and facilitate readers' visual word segmentation, whereas others don't. More specifically, many languages in the world use interword spaces as a visual cue to establish word boundaries. On the other hand, there exist *scriptio continua* languages in which interword boundaries are not visually expressed by a space. This resulted in a plethora of works on how interword spacing interacted with visual word recognition (e.g. Bai et al., 2008; Rayner, 1998; Rayner et al., 1998; Sainio et al., 2007; Winskel et al., 2009), which further shed light on various models of word recognition (McClelland & Rumelhart, 1981).

Readers of 'spaced' languages rely heavily upon the interword spaces for written text segmentation during reading. Rayner et al. (1998) found that increasing interword spaces resulted in shorter fixation durations, and condensing interword spaces resulted in longer fixation durations. However, the difference observed by Rayner et al. (1998) was not statistically significant. These effects may be explained by the visual crowding effect (Pelli et al., 2007), where early encoding of text is facilitated when spaces are expanded which reduces visual crowding, and is inhibited when spaces are condensed to increase visual crowding. Interword spaces can also facilitate the reading process by retrieving parafoveal information during reading. Morris et al. (1990) suggested that parafoveal information, such as letter identity, word length and interword space, assisted in planning attention shifts required to execute a saccade. During reading, the preferred viewing location always fell between the center and the beginning of the target word, and the exact position of the saccade landing site varied depending on the length of the previous word from which the current saccade was being launched (Vitu, 2011). In this case, spaces were used by the visual system as a guide to approximate the target word length and plan the next saccade. By contrast, the optimal viewing location falls at the center of the word when a normal (i.e. 'spaced') English sentence was presented (Rayner, 1979, Vitu et al., 1990).

On the other hand, some works showed that readers experienced difficulties in word identification and saccadic programming when reading English sentences in which interword spaces were erased (Perea & Acha, 2009; Pollatsek & Rayner, 1982; Rayner, 1998; Rayner et al., 1998; Veldre et al., 2017), or replaced by meaningless symbols and digits (Sheridan et al., 2013, 2016), though some works consistently argued for the contrary (Epelboim et al., 1994, 1996, 1997). Moreover, the word frequency effect was more salient in unspaced than spaced sentences (Rayner et al., 1998; Veldre et al., 2017). Eye movement research on skilled readers reading unspaced texts also led to reconsiderations of word identification and recognition models. For instance, recent work by Mirault et al. (2019) argued that removing interword spaces in French significantly reduced reading quality by affecting reading speed, increasing word fixation durations and number, making more regressions and refixations, exaggerating the effect of word frequency and decreasing word skipping rates.

The extent to which interword spaces influence word identification in unspaced languages is less conclusive. For instance, while Chinese is known for its lack of interword spaces, in most reading circumstances Chinese skilled readers do not find it difficult to process normal (unspaced) sentences. In fact, earlier works (e.g. Liu et al., 1974) argued that adding interword spaces to demarcate multisyllabic Chinese words did not improve the reader's performance. The seminal work by Bai et al. (2008) demonstrated that there existed no significant difference between normal (i.e. unspaced) and spaced Chinese sentences in terms of global and local eye movement measures. On the other hand, some later works suggested processing benefits by adding interword spaces in Chinese. For instance, Blythe et al. (2012) argued that adding spaces facilitated acquisition of novel Chinese words by children. Zang et al. (2013) showed that interword spaces in Chinese facilitated word identification by reducing the first-pass reading times and refixation probabilities. Cui et al. (2014) focused on the parafoveal preview benefit and argued that adding interword spaces in Chinese facilitated parafoveal word segmentation, and this effect was also true for skilled readers. Other unspaced languages such as Thai and Japanese demonstrated similar conclusions regarding the function of interword spaces (e.g. Kohsom & Gobet (1997) and Winskel et al. (2009) on Thai; Sainio et al. (2007) on Japanese)

In this study, we focus on the impact of interword spaces on Arabic reading. While Arabic is an alphabetical writing system, the fact that the writing system consists of allographs (See Figure 1) may lead researchers to reconsider the importance of interword spaces in word segmentation and recognition. That is, these peculiar visual aspects of Arabic orthography potentially facilitate word identification, which further obviates the significance of interword spacing. The purpose of the following experiment therefore describes whether there exists any significant differences between reading spaced and unspaced Arabic sentences. We also investigate whether the word frequency effect à la Rayner et al.'s (1998) is replicated in Arabic, and whether there is any interaction between word frequency and interword spacing (cf. Ma, 2017) in Arabic reading.

Arabic Orthography

The Arabic script consists of 28 consonant letters. Short vowels are expressed by the use of diacritics and are used merely in religious texts and beginning Arabic textbooks (Ryding, 2005). On the other hand, long vowels (e.g. /a:/, /i:/, /u:/) are expressed by the letters 'alif' /ʔ/ ا , 'yaa' /j/ ي , and 'waaw' /w/ و, respectively. In essence, the Arabic writing system is referred to as 'abjad', i.e. a consonantal writing system. One peculiar feature of the Arabic writing system is that words are written from right to left, and most letters are combined cursively (i.e. without interletter spaces) to form a word. Another feature of Arabic orthography is the system of allographs, i.e. a single letter can assume various written forms depending on their position (initial, medial, final) within a word. Notice that allographs are mutually exclusive in the sense that a letter assumes one-and-only-one allograph at a particular position, and one corollary is that allographs are position-informative. This orthographic feature potentially provides a visual cue to word recognition, e.g. the initial (and resp. final) allograph signals the beginning (and resp. ending) of a word boundary, which in turn alleviates the significance of interword spaces. Some examples of allographs are shown in Figure 1:

letter	Initial	Middle	Final
ء			
ا	ا	ـا	ـا
ب	بـ	ـبـ	ـب
ت	تـ	ـتـ	ـت
ث	ثـ	ـثـ	ـث
ج	جـ	ـجـ	ـج
ح	حـ	ـحـ	ـح
خ	خـ	ـخـ	ـخ
د	د	ـد	ـد

Figure 1: Some examples of Arabic allographs.

Experiment

This experiment was designed to measure eye movements of readers while they read spaced and unspaced Arabic sentences. In addition to measuring whether eliminating interword spaces would exert a main effect on eye movement measures, we also looked into the effect (if any) of widening interword spaces.

Method

Participants Thirty-four female undergraduate students from the United Arab Emirates University were recruited in the study (M_{Age} = 19.2, *S.D.* = 3.48). Six other students were initially recruited, but their datasets were excluded from further analysis due to problems with inaccurate calibration and/or early termination of the experiment caused by tracker loss. All participants declared Arabic as their first language and had normal or corrected-to-normal vision. The experiment obtained ethics approval from the Social Research Ethics Committee at the United Arab Emirates University, and all participants signed a written consent form prior to the experiment. Those who were enrolled in an eligible course were compensated with participation credits.

Stimuli In total 114 frame sentences were constructed and matched with an equal number of target word pairs (228 words in total). All sentences were between seven and 14 words long, and had the same basic grammatical structure without any word-order permutation or garden-path variety, which would impose additional processing load to the subjects. The target word pair consisted of one high-frequency and one low-frequency word both of which were felicitous in the sentence frame. All target words were between 5 and 9 letters long, without any specification of word class (e.g. nouns and verbs), and were extracted from the online Arabic corpus 'ArTenTen12' (Arts et al., 2014) which now contains more than 8 billion tokens and their frequency statistics. Target frequency (instances per million) was calculated using the following formula:

Word frequency = token frequency of the word / total number of tokens x 1,000,000

Target word frequencies were always selected to represent ideally very high (M = 140, $S.D.$ = 103.07) or very low (M = 1.36, $S.D.$ = 0.19) frequencies (i.e. entries in the upper and lower quartiles to represent high and low frequencies, respectively). This was confirmed by comparing the difference in mean frequency for high- and low-frequency words using a one-tailed independent samples t-test, which showed significant differences, $t(113) = 14.1$, $p < 0.001$. The first 62857 entries were extracted and arranged by frequency in descending order. The target word was always embedded in the center of each sentence. Target word pairs for the same sentence frame were matched in the number of letters. Each sentence appeared only once in either a high- or low-frequency target word condition for each participant. Moreover, each sentence appeared in one of three spacing conditions: 'hair', 'single' and 'double'. In the hair-spacing condition, each interword space character was replaced with a 'hair space' (U+200A; Unicode Standard 'Hair Space'), i.e. a space character which allows for minimizing interword spacing by removing any visible whitespace, while preventing the final letters of a word from automatically ligating with the first letter of the following word. The single-spacing condition referred to the default space character used between words (U+0020; Unicode Standard 'Space (SP)'), whereas the double-spacing condition was expressed by using two space characters between words. In addition, 20 comprehension questions with a yes/no response were displayed randomly following some of the sentences (17.5%). All sentences were displayed on a single line of text aligned to the center of the screen vertically. Sentences were right-aligned, and the first word always appeared at the same location horizontally. The text was displayed using the 'Multiline Text Resource' feature built into the Experiment Builder experiment creation tool, set to the default size 45 Times New Roman font, in which each character occupied roughly 0.36° of visual angle. The text was presented in black against a white background. Times New Roman was chosen as an example of commonly used proportionally spaced serif font, in which different letters occupy different horizontal spaces according to the letter design.

High frequency target word

Hair-spacing	رجعأحمدالى<u>البيت</u>بعديومطويل
Single-spacing	رجع أحمد الى <u>البيت</u> بعد يوم طويل
Double-spacing	رجع أحمد إلى <u>البيت</u> بعد يوم طويل

'Ahmed returned to the <u>house</u> after a long day.'

Low frequency target word

Hair-spacing	رجعأحمدالى<u>الكوخ</u>بعديومطويل
Single-spacing	رجع أحمد الى <u>الكوخ</u> بعد يوم طويل
Double-spacing	رجع أحمد إلى <u>الكوخ</u> بعد يوم طويل

'Ahmed returned to the <u>hut</u> after a long day.'

Figure 2 Six (2 x 3) Possible Combinations of Conditions

Apparatus The Eyelink 1000 Plus tracker (SR Research Ltd.) was used to administer the study while tracking eye movements via a high-speed 35 mm lens on a desktop mount. Recording eye movements was right-eye monocular at a sampling rate of 1000 Hz (i.e. 1000 images per second). Sentences were displayed on a high resolution (1920 x 1080 pixels) 24" BENQ ZOWIE XL 2430 monitor, set at 60 Hz refresh rate. A head-and-chin rest was used to reduce head movements.

Procedure Participants were seated 80 cm from the center of the screen such that 2.8 characters corresponded to 1° of visual angle. The experiment took place in a quiet isolated room. Instructions were presented in text on the screen, as well as verbally by the experimenter, prior to the experiment. The default nine-point grid calibration and validation was performed before the experiment. Participants completed eight practice trials, and were allowed to ask any questions before proceeding with the experiment. The experiment was divided into three blocks to allow participants to take breaks when necessary, with a central drift correction applied at the beginning of each block. For each trial, a right-aligned fixation asterisk was placed spatially at the onset site of the first letter for each sentence and disappeared immediately before the onset of the sentence on the screen. Sentences only appeared once participants were fixated continuously for a minimum of 800 ms at the fixation asterisk. In total, each experimental session lasted about 20 minutes. Participants pressed the 'spacebar' on a standard keyboard to indicate the end of each sentence reading and subsequently the end of a trial, and whenever appropriate, answered the comprehension questions by clicking 'yes' or 'no' on the screen using the 'left-click' mouse key.

Results

First, fixations shorter than 70 ms were merged with adjacent longer fixations which fell within 0.4° of visual angle of each other. Subsequently, trials with individual fixation durations of less than 80 ms (n = 20) or more than 800 ms (n = 16), and those with a loss in tracking and no fixations were detected (12.3%) were removed from the analysis. Dependent variables were defined and split into two measure groups: (1) Global measures are variables that describe sentence-level observations, which include *average fixation duration* (AFD), *average saccade amplitude* (ASA), *total reading time* (RT), and sentence reading rate in terms of *Words Per Minute* (WPM); (2) Local measures are the variables which correspond to observations at the target word Region of Interest (ROI), which include the *first fixation duration* (FFD) and *gaze duration* (GD).

All dependent measures, except for ASA, were log transformed. The data were analyzed using R (R Development Core Team, 2014) and the *lme4* package (Bates et al., 2014). Linear mixed-effects model (LMM) modeling and analysis were carried out for each of the variables described above. Space, target word frequency and the interaction thereof were used as predictors, and the method of model comparison was adopted to evaluate whether the data fitted the model for the two explanatory variables and their interaction. First of all, the maximum random effects structure was adopted, that was, all fixed factors and their interactions were added to the model as random effects. The original model could not be fitted and was gradually trimmed by removing correlations (r > 0.9) and their interactions, which resulted in a final model that was not significantly different from the simplest random effects model. Therefore, the best-fitting model included space, target word frequency and their interaction as the fixed effects, and subjects and items as the random effects. The single-spacing condition was used as the baseline and was compared against the two space manipulations (i.e. hair- and double-spacing). Fixed effects are generally reported as significant if the absolute t value is greater than 1.96. In general, $|t|$ greater than two is considered a reasonable approximation for estimating the degrees of freedom of fixed effects in a mixed effects model, and this criterion would be adopted in the current study. Only statistically significant results will be reported henceforth. Table 1 shows a descriptive summary of the data (means & standard deviations) of all eye movement measures.

Word-Level Local Measures

First Fixation Duration (FFD) FFD refers to the duration of the first fixation at the ROI (i.e. the target word). As shown in Table 1, there was a significant main effect of target word frequency on FFD, p < 0.001. FFD was longer for low-frequency (M = 258 *ms*, $S.D.$ = 108) than high-frequency (M = 245 *ms*, $S.D.$ = 100) target words (b = 0.02, $S.E.$ = 0.01, t = 3.78). The main effect of spacing on FFD was not significant, and there was no significant interaction between target word frequency and spacing.

Gaze Duration (GD) GD, or sometimes called the first-pass reading time, refers to the total sum of fixation durations at the ROI until the fixation leaves to the right/left of the ROI. As shown in Table 1, there was a significant main effect of target word frequency on GD, p < 0.001, with GD significantly longer for low-frequency (M = 411 *ms*, $S.D.$ = 283) than high-frequency (M = 345 *ms*, $S.D.$= 200) target words, b = 0.08, $S.E.$ = 0.01, t = 6.25. The main effect of spacing on FFD failed to reach statistical significance (p = 0.055), and there was no significant interaction between frequency and spacing.

Sentence-level global measures

Average Fixation Duration (AFD) AFD refers to the average length of fixations during reading. As shown in Table 1, there was a significant main effect of spacing on AFD, p < 0.001. AFD was significant longer in the single-spacing (M = 225 *ms*, $S.D.$ = 36.2) than the double-spacing (M = 221 *ms*, $S.D.$ = 34) condition, b = 0.01, $S.E.$ = 0.003, t = 2.73. The main effect of frequency on AFD was not significant, and there was no significant interaction between target word frequency and interword spacing.

Average Saccade Amplitude (ASA) ASA refers to the average angular distance of a saccade during reading (measured in degrees of visual angle). As shown in Table 1, there was a significant main effect of spacing on ASA, p < 0.001. ASA was significantly larger in the double-spacing (M = 2.77°, $S.D.$ = 0.87) than the single-spacing (M = 2.52°, $S.D.$ = 0.80) condition, b = 0.24, $S.E.$ = 0.03, t = 9.91, and was also significantly larger for the single-spacing than the hair-spacing condition (M = 2.3°, $S.D.$ = 0.73), b = 0.21, $S.E.$ = 0.03, t = 8.35. The main effect of frequency on ASA was not significant, and there was no significant interaction between target word frequency and interword spacing.

Total Reading Time (RT) RT refers to the total time it takes to complete each sentence reading in milliseconds. As shown in Table 1, there was a significant main effect of target frequency on RT, p < 0.001. RT was significantly longer for low-frequency (M = 5222 *ms*, $S.D.$ = 3047) than high-frequency (M = 5043 *ms*, $S.D.$= 2976) target words, b = 0.02, $S.E.$ = 0.01, t = 3.92. The main effect of spacing on RT was not significant, and there was no significant interaction between target word frequency and interword spacing.

Words Per Minute (WPM) The sentence reading rate, which can be thought of as the ‘speed’ of reading, was calculated in terms of Words Per Minute, or the average number of words read in 1 minute. There was a significant main effect of target frequency on Reading rate, p < 0.001. Reading rate was lower for low-frequency (M = 156 *WPM*, $S.D.$ = 74.4) than high-frequency (M = 160 *WPM*, $S.D.$ = 72.8) target words, b = 0.02, $S.E.$ = 0.01, t = 3.92. The main effect of spacing on WPM was not significant, and there was no significant interaction between target word frequency and interword spacing.

Table 1. Means and standard deviations of eye movement measures

		FFD	GD	AFD
		M (SD)	*M (SD)*	*M (SD)*
Hair	low	261(110.38)	422(324.84)	226(36.89)
	high	245(94.36)	341(198.92)	228(36.75)
Sgl	low	265(109.96)	418(263.70)	227(35.92)
	high	246(104.69)	351(216.58)	223(36.44)
Dbl	low	248(101.99)	392(255.62)	221(33.73)
	high	244(99.99)	342(184.33)	221(35.26)

		ASA	RT	WPM
		M (SD)	*M (SD)*	*M (SD)*
Hair	low	2.29(0.75)	5342(3184.97)	154(72.60)
	high	2.33(0.72)	5183(3119.24)	160(76.81)
Sgl	low	2.50(0.79)	5205(2939.66)	156(77.23)
	high	2.55(0.81)	5073(3162.38)	159(68.45)
Dbl	low	2.77(0.91)	5114(3005.86)	158(73.30)
	high	2.76(0.82)	4889 (2632.58)	162(73.22)

Table 2: The interaction between Space (S) and Target (T) in Linear Mixed Model

	FFD		GD		AFD	
	F	*p*	*F*	*p*	*F*	*p*
S	2.11	.12	2.9	.06	11.43	.001***
T	14.27	.001***	92.4	.001***	3.29	.07
S×T	1.41	.244	1.44	.24	2.67	.07

	ASA		RT		WPM	
	F	*p*	*F*	*p*	*F*	*p*
S	167.13	.001***	2.36	.09	1.89	.15
T	3.19	.07	15.37	.001***	15.37	.001***
S×T	.18	.84	.12	.89	.27	.77

Discussion

As expected, we found evidence for the target word frequency effect on reading which has been consistently reported in the literature (Brysbaert et al., 2018; Rayner & Raney, 1996). That is, high-frequency target words were read more efficiently than low-frequency ones, as shown by their shorter AFD and GD. Moreover, sentences that embedded a high-frequency word were read faster, i.e. shorter RT and higher WPM, compared to those with a low-frequency target word. The differences in ASA across spacing conditions can be naturally described by different visual length of the space between words. The eye movement measures at the target word level suggested that the spacing effect did not exist for Arabic words. That is, reducing or increasing interword spaces neither facilitated nor inhibited the readability of the target word. The eye movement measures at the sentence level were slightly different, as doubling interword spaces had an overall facilitatory effect, shown by the AFD. Interestingly, eliminating the interword spaces did not inhibit sentence reading, though it did not improve RT and WPM either. This result stands in stark contrast with similar experiments conducted in Latin-script languages (Morris et al., 1990; Perea & Acha, 2009; Pollatsek & Rayner, 1982; Rayner, 1998; Rayner et al., 1998; Sheridan et al., 2013; Veldre et al., 2017). The overall lack of main effect of minimizing spacing and interaction effect between spacing and target word frequency suggests that interword spaces in written Arabic text merely serve a non-linguistic function: to visually demarcate word boundaries (cf. Ma, 2017). There was no evidence that interword spaces were processed at the linguistic (i.e. lexical) level. Visualizing an interword space (regardless of its size) involves nothing more than a visual recognition process which happens prior to any lexical processing initiated. As one reviewer pointed out, the typographical properties of visual words may also affect readability and interact with the interword spaces. Alluhaybi and Witzel (2020) recently studied the relation between letter connectedness and visual word recognition. They demonstrated that Arabic words written in one chunks (i.e. fully connected, e.g. عَسَل 'honey') had the longest processing times, whereas those written in two (e.g. نُور 'light') and three chunks (e.g. دَرْس 'lesson') are processed faster. While our current study focuses mainly on the effect of interword spaces and treat the connectedness property of Arabic words as random, it is plausible that interface spaces interact with the letter connectedness in affecting readability, an issue which should be studied in subsequent experiments.

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