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BRIEF REPORT

Are the early stages of orthographic processing universal? Insights from masked priming with Semitic words

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Abstract

Two views contend to account for the processes at play during the early stages of visual word recognition. The first holds that these stages are not modulated by the idiosyncratic properties of different languages. The second maintains that the structural properties of the language determine the weighting of the different domains of linguistic knowledge (e.g., orthographic and morphological domains may be differentially weighted across languages). To explore this question, we focused on orthographic priming in Arabic. In this Semitic language, lexical representations are claimed to be based on morphological similarity, with little or no role for orthographic similarity. We conducted two masked priming experiments using the yes–no and go/no-go versions of the lexical decision task to determine if Arabic target words (e.g., مدير 'mudyr', *director*) are facilitated by nonword primes that are orthographically but not morphologically related (i.e., pairs share neither a root nor a word pattern; e.g.,مايز 'maAyr') relative to unrelated primes. Results showed faster responses for the orthographically related target words than for the unrelated target words in the two experiments. These findings favor the view that the early phases of visual word processing in Semitic and Indo-European languages are fundamentally the same.

Keywords Universal orthographic processing · Masked priming · Object processing · Semitic languages

Introduction

Research into orthographic processing has revealed a growing interest in establishing how the idiosyncratic properties of different languages affect visual word recognition (Carreiras et al., 2012; Fernandez et al., 2021; Kinoshita et al., 2018; Mousikou et al., 2020; Perea et al., 2010). In an influential paper, Frost (2012) claimed that the morphological and orthographic domains in Semitic languages and Indo-European languages are fundamentally different: Lexical space in Semitic languages is organized in terms of root and word pattern (hereafter, WP) morphemes, whereas this space is governed by orthographic constraints in Indo-European languages. The root typically consists of three letters and conveys general semantic information that will appear, to various degrees, in that root's family. The WP consists of vowels and a subset of consonants and conveys morphophonological and syntactic information (see Boudelaa & Marslen-Wilson, 2015). For instance, the Arabic word 'maxraj' *outlet* consists of the root 'xrj' with the general meaning of [going out] and the WP 'mafEal',[1] which conveys the meaning of [singular masculine place noun].[2] Within the Arabic lexical space, a word like مخرج 'maxraj' *outlet* would be equally distant from an orthographically

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[1] The letters 'f', 'E', 'l' are place holders for the first second and third letter of the root, respectively.

[2] Place noun is a term that denotes the place where the action conveyed by the root occurs. Hence, 'maxraj' means *outlet* because it is the place through which someone or something comes out. Similarly 'maTEam' means *restaurant* [a place where one can eat] because it combines the root 'TEm' [feeding/tasting] and the same place noun WP 'mafEal'.

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related word like مخرب ‘muxar~ib’ *vandal*, with which it shares 3 out of 4 letters, as it would be from a word like إصبع ‘<iSbiE’ *finger*, with which it has no letters in common at all. According to Frost (2012), what determines the perceptual distance between words for Semitic languages is the root and, to some extent, the WP. As reviewed below, this claim has been supported by a large number of studies in Hebrew and Arabic.

Semitic words sharing a root can prime each other even if the root letters are not in the same absolute position (e.g., Arabic: ‘maktwb’-‘kitAb’ *written-book*; Hebrew: ‘tzmwrt’-‘zmr’ *orchestra-sing*; Boudelaa & Marslen-Wilson, 2005; Frost et al., 1997). Priming is also obtained when the root conveys unrelated meanings across prime and target (e.g., كتاب - كتيبة ‘katybp’-‘kitAb’ *squadron-book*). These morphological effects occur not only in covert tasks like masked priming, as in Indo-European languages, but also in overt tasks like cross-modal and auditory priming (Boudelaa & Marslen-Wilson, 2004a, 2015; Frost et al., 1997, 2000; cf. Xu et al., 2023). Root priming is also observed in allomorphic cases when the root surfaces with different sets of letters. For instance, the Arabic root {wjh}[3] appears as ‘wjh’ in ‘wajyh’ *dignitary* and ‘tjh’ in ‘<it~ijAh’ *destination* because the ‘w’ is assimilated to the ‘t’ of the WP ‘<iftEAl’. Nevertheless, the variant ‘tjh’ of the underlying root ‘wjh’ serves as the basis for priming even in cases of semantic opacity, supporting the claim that it is a central processing unit in the Semitic lexicon (Boudelaa & Marslen-Wilson, 2004b).

The effects of the WP have also been observed in Hebrew and Arabic. Arabic verbs like ‘Aakal’ *eat* and ‘xaraj’ *exit*, which share the WP ‘faEal’, prime each other in different tasks (Boudelaa et al., 2023; Boudelaa & Marslen-Wilson, 2004a, 2004b, 2015). So do Arabic nouns (e.g., ‘malEab’-‘maktab’ *stadium-office*; Boudelaa & Marslen-Wilson, 2005). However, for a priming effect to occur, the WP must be in the context of a productive root with a sizeable morphological family size (Boudelaa & Marslen-Wilson, 2011). The nominal WP ‘faElap’ does not prime in the pair ‘sajdap’-‘lakmap’ *prostration-punch* because the roots ‘sjd’ in ‘sajdap’ and ‘lkm’ in ‘lakmap’ are not productive, but it does in pairs like ‘Darbap’-‘Tardap’ *hit-dismissal,* where the respective roots ‘Drb’ and ‘Trd’ are productive. Besides, much like the root, the WP also has a distinct neurophysiological signature with an independent neural substrate (Boudelaa et al., 2010) that can be selectively impaired (Barkai, 1980) or spared (Prunet et al., 2000).

This pervasive evidence for roots and WPs contrasts sharply with the lack of evidence for orthographic effects in Semitic languages. Indeed, the standard transposed-letter effect commonly observed in Indo-European languages is elusive in Semitic languages, having been reported only when the root letters are not transposed (e.g., Perea et al., 2010), with nonnative Semitic words (Velan & Frost, 2007), and in nonlexical tasks like the same–different matching task (e.g., Boudelaa et al., 2019). Thus, in Semitic languages, a word target like يسهرون ‘yasharwn’ *stay up* is not facilitated by the transposed-letter prime يهسرون ‘yahsurwn’ relative to a substitution-letter prime like يمشرون ‘yam$urwn’ (Perea et al., 2010; Velan & Frost, 2011).

The strong morphological effects and the elusive orthographic effects have lent credence to Frost’s view that similarity in form per se cannot drive lexical processing in Semitic languages. However, one report directly contradicts this view and suggests that orthographic priming can be observed in Arabic (Perea et al., 2014). Specifically, Perea et al. (2014) reported three experiments in which a target word (e.g., كتابة *writing,* root ‘ktb’) was significantly facilitated by a nonword prime that differed by a single root letter (e.g., كخابة, nonexisting root ‘kxb’), suggesting that the integrity of the root may not be a *sine qua non* condition for orthographic priming during lexical access. This implies that contrary to Frost’s (2012) claim, there would be no qualitative difference in lexical space between Semitic and Indo-European languages. Instead, the same basic principles underlying lexical processes would apply to both families of languages.

Before embracing this far-reaching conclusion, however, it is important to note that by changing a single letter of the Arabic root within a word, Perea et al. (2014) preserved the integrity of the WP. Thus, one might argue that this morphological unit might have been the basis of the facilitation observed between pairs like كتابة-كخابة ‘kxAbp’-‘ktAbp’, which share the WP ‘fEAlp’. To address this possibility, in the present experiments, we seek to determine if priming can be observed not only among ‘kxAbp’-‘ktAbp’-like pairs (i.e., pairs similar to those used by Perea et al., 2014) but, more critically, also among pairs that differ by a single letter and share neither the root nor the WP (e.g., ماير-مدير ‘mAyr’-‘mdyr’). To do so, we used masked priming, an experimental technique ideally suited to studying the early orthographic stages of visual word recognition (Forster et al., 1987; Grainger, 2008).

[3] We use the Buckwalter transliteration scheme as used in the ARALEX database (Boudelaa & Marslen-Wilson, 2010).

Yes–No lexical decision experiment

Method

Participants

Eighty-four native speakers of Arabic, all students at the University of Alexandria, Egypt, voluntarily participated in the experiment. This allowed us to have 5,040 observations (84 subjects × 60 targets per condition) in each condition, which satisfies the recommendations made by Brysbaert and Stevens (2018). All participants reported using Modern Standard Arabic daily and had normal/corrected vision.

Materials

One hundred and eighty Arabic words were selected from the Aralex database (Boudelaa & Marslen-Wilson, 2010). They comprised a productive root (type frequency: 20.69 per million; range: 9–50), with an average surface frequency of 10.15 (range: 0.03–247.49). Each word was paired with three prime types to create three conditions. In the first condition, labeled One LD+WP[4] in Table 1, the prime was created by changing one root letter of the target word while preserving its WP. For instance, the root letter ‘f’ of the target word مفتاح ‘miftAH’ *key* was substituted by the letter ‘$’ to create the prime مشتاح ‘mi$tAH’. Although the target word مفتاح ‘miftAH’ and the nonword prime مشتاح ‘mi$tAH’ differ by one root letter, they share the same WP ‘mifEAl’. In the second condition, called One LD-WP, we disrupted the WP in the prime by using either the letter aliph ‘ا’ = ‘A’, waw ‘و’ = ‘w’, or yaa ‘ي’ = ‘y’, which function as consonants or long vowels, depending on context. Thus, the same root letter ‘f’ in ‘miftAH’ was replaced by the letter aliph ‘A’ to create the prime ماتاح ‘maAtAH’ with the non-existing root ‘mtH’ and the existing WP ‘fAEAl’. This means that both the One LD+WP and the One LD-WP are only ONE letter different from their associated target, except that one has the same WP as the target and one does not. In the final condition, an unrelated nonword prime is used (e.g., أوهوق ‘>uwhwq’). This baseline nonword prime shares neither the root nor the WP with the target مفتاح ‘miftAH’ and has little or no orthographic overlap with it, as shown in Table 1. As a consequence, it is different from both the One LD+WP and the One LD-WP condition, and it will be used as a baseline to gauge facilitation in these two conditions.

More specifically, the following constraints were placed on the orthographic properties of the nonword primes in the experiments:

1. All nonword primes were created by changing one to two root letters of an existing word.
2. The nonword items systematically consisted of a nonexisting root (i.e., one not attested in the ARALEX database; Boudelaa & Marslen-Wilson, 2010) and an existing WP. Accordingly, the One LD+WP nonword prime مشتاح ‘mi$tAH’ can be parsed into the nonexisting root ‘$tH’ and the existing WP ‘m--A-’. Similarly, the One LD-WP nonword prime ماتاح ‘maAtAH’ consists of the nonexisting root ‘mtH’ and the existing WP ‘fAEAl’ found in other words such as ساباط ‘saAbAT’.[5] The baseline nonword prime أوهوق ‘>uwhwq’ can also be parsed into the nonexisting root ‘whq’ and the existing pattern ‘>ufEwl’.[6]
3. All the nonword primes were orthotactically legal in the sense that they were in keeping with the sublexical orthographic patterns in the language, which feature only legal bigrams and trigrams.
4. All the nonword primes were also phonotactically legal, with the nonexisting roots fully complying with the Obligatory Contour Principle that governs root formation in Arabic (McCarthy, 1986). Thus, none of the nonexisting roots featured homorganic consonants in the first and second or first and third positions (e.g., ‘bbt’, ‘btf’).
5. All the WPs we used an be found in *The Dictionary of Word Patterns* (Yaqoub, 1993), an exhaustive list of all the existing WPs in Arabic.

Table 1 Mean orthographic characteristics of the stimuli with the standard deviations in parentheses

Lexicality	Items	N-L	OLD-20	N-L shared
Words	Target	4.86 (0.45)	1.78 (0.14)	n/a
	One LD+WP	4.86 (0.45)	1.93 (0.08)	3.86 (0.45)
	One LD-WP	4.86 (0.45)	1.91 (0.13)	3.86 (0.45)
	Baseline	4.86 (0.41)	2.08 (0.26)	0.20 (0.44)
Nonwords	Target	4.79 (0.48)	2.02 (0.20)	n/a
	One LD+WP	4.79 (0.48)	2.04 (0.19)	3.79 (0.48)
	One LD-WP	4.79 (0.48)	1.99 (0.18)	3.79 (0.48)
	Baseline	4.82 (0.46)	2.05 (0.25)	0.13 (0.33)

Note. N-L = number of letters; OLD-20 = orthographic Levenshtein distance. One LD+WP = One Letter Different, same Word Pattern; One LD-WP = One Letter Different, different Word Pattern; N-L shared = average number of letters shared between prime and target

[4] One LD+WP = One Letter Different plus shared Word Pattern

[5] According to Almaany dictionary, the word طاباس ‘sAbAT’ refers to ‘a shed between two walls with a passageway underneath it’ (cf. https://www.almaany.com/ar/dict/ar-ar/).

[6] The nonword ‘>uwhwq’ is very much like the existing word ‘>usbwE’, meaning *week*, which consists of the root ‘sbE’ and the WP ‘>ufEwl’.

Beyond this, the substituted letter was evenly distributed across the three positions of the root but never corresponded to the word's absolute first or last letter. We chose not to replace the word's first and last absolute letters because exterior letters (in particular, the initial letter) are commonly thought to play a greater role than internal letters during word recognition (Grainger et al., 2016). We acknowledge, however, that the evidence for a special role for external letter positions in masked priming is not conclusive (see Adelman et al., 2014, in English; Perea et al., 2010, in Arabic).

We also constructed 180 nonwords to use as foils in the lexical decision task by changing one to two letters of existing Arabic words. For example, the second letter خ 'x' and the third letter ل 'l' of the existing word مخلوق 'maxlwq' *creature* were respectively changed into ح 'H' and ج 'j' to build the nonword محجوق 'maHjwq'. The priming conditions for the nonword targets were parallel to those in the word targets to create three priming conditions: One LD+WP 'maTjwq', One LD-WP 'maAjwq', and an unrelated baseline 'taAkyr'.

Table 1 provides the mean length in letters, the mean overlap in letters between prime and target, and an index of orthographic neighborhood density, OLD-20 (short for orthographic Levenshtein distance 20), which provides the mean Levenshtein distance from a word to its 20 closest orthographic neighbors. Note that the OLD-20 measure is not limited to letter substitution, as it includes neighbors of different lengths (e.g., addition-letter and substitution-letter neighbors; see Yarkoni et al., 2008).

Three counterbalanced lists of materials were constructed so that each target appeared only once per list, each time in a different priming condition. Each participant received only one list. To ascertain that participants would decode the nonwords of interest as intended, the One LD+WP and One LD-WP items were mixed with another 360 actual words and presented to 40 participants who did not take part in the main experiments. Each nonword was paired with a real word that had the same WP, and the participant's task was to read loudly the real word followed by the associated nonword. The participants systematically generalized the WP of the real word to the nonword. The decoding of the WP was further verified by asking each participant in the main experiments to name the stimuli aloud during a practice session composed of stimuli similar to the experimental items. Again, participants decoded the nonwords using the intended WPs.

Procedure

Presentation of the stimuli and recording of response times (RTs) were controlled by SuperLab™ 6.0 (Cedrus Corp, San Pedro, CA). On each trial, a forward mask (######) was presented for 500 ms in the center of the screen. Next, the prime was presented in 28-pt Arabic font (Traditional Arabic Regular) for 50 ms. The target stimulus in 58-pt Arabic font then replaced the prime. The target remained on the screen until the participants responded or until 2 s had elapsed. RTs were measured from the target onset to the participant response. Participants were instructed to press the 'yes' button if the letter string was a real word and the 'no' button if it was not. Each participant received 20 practice trials before the 360 experimental trials (180 words and 180 nonwords) in a different order. Participants were given auditory feedback on each response they made. The whole session lasted around 25 minutes. Postexperimental debriefing established that participants were completely unaware of the prime.

Data analyses

For the inferential statistics, correct RTs and error rates were analyzed using linear mixed-effects (LME) modeling, with subjects and stimuli as crossed random factors (Baayen, 2008), using the packages lme4 (Version 1.1-17; Bates et al., 2015) and lmerTest (Version 3.0-1; Kuznetsova et al., 2017) implemented in R (Version 4.1.3, 2022– 03-10; R Core Team, 2022). There was only one fixed factor (i.e., prime–target relatedness) with three levels. We used the unrelated baseline condition as the reference level to compare it (1) with the condition that preserved the WP (i.e., as in Perea et al.'s, 2014, experiments) and (2) with the novel condition that did not preserve the root and WP. For the RT analysis, the data were log-transformed to meet the assumptions of LMEs. Data points slower than 2,000 ms or faster than 100 ms were excluded as outliers (2.26% of the data). We also excluded 2.06% of the data as incorrect responses. We tested the LMEs with maximal random terms for slopes and intercepts and simplified the structure of the model until it converged.

Table 2 Mean response times (in ms), standard errors (*SE*) in parentheses, percent error rates, and magnitude of priming (in ms) in Experiment 1

Lexicality	Condition	RT (*SE*)	%Error	Priming
Word	One LD+WP	698 (2.64)	2.18	9*
	One LD-WP	689 (2.67)	2.08	18*
	Baseline	707 (2.66)	1.91	
Nonword	One LD+WP	800 (3.36)	3.18	−11
	One LD-WP	810 (3.74)	4.03	−21*
	Baseline	789 (3.04)	2.76	

Note. One LD+WP = One Letter Different, same Word Pattern; One LD-WP = One Letter Different, different Word pattern; * =

The raw data and analysis file of the experiment are on the Open Science Framework (https://osf.io/zhg5m/).

Results and discussion

The mean correct RT and error rates for word and nonword data are shown in Table 2. For the word data, we found faster RTs in the form-related condition that preserved the WP than the unrelated baseline, $t(19699) = -3.65$, $p < .001$; $b = -0.05$, 95% CI [−0.08, −0.02]). Similarly, the responses in the orthographically related condition that did not preserve the integrity of the WP were faster than the unrelated baseline, $t(19699) = -6.87$, $p < .001$; $b = -0.10$, 95% CI [−0.13, −0.07]). The error rates for words were analyzed with a logit model with a structure similar to the RT model (Jaeger, 2008). The results revealed no significant effects.

The nonword data were subjected to the same statistical analyses as the words. The results showed that the RTs to the orthographically related condition that did not preserve the integrity of the WP were slower than the baseline condition, $t(19406) = 2.89$, $p = .004$; $b = 0.02$, 95% CI [6.10e-03, 0.03]). No other contrast was significant. In the error analysis, and despite the overall low error rate, the orthographically related condition that did not preserve the integrity of the WP was more error-prone than the baseline condition (4.03% vs. 2.76%, respectively; $z = 2.833$, $b = 0.52$, 95% CI [0.16, 0.88], $p = 0.004$).

The present experiment replicates and extends the original results by Perea et al. (2014). We observed significant facilitation over the unrelated condition (i.e., form priming) not only in the form-related condition that altered the root and kept the WP (i.e., as in the Perea et al., 2014, experiments; e.g., مشتاح- مفتاح 'mi$tAH'-'miftAH') but, more importantly, also in the purely form-related condition that kept neither the root nor WP (e.g., ماتاح-مفتاح 'maAtAH'-'miftAH'). Thus, this is the first demonstration that neither the integrity of the root nor that of the WP is necessary for lexical access processes in Arabic, suggesting that there is a dimension in Arabic lexical organization that is sensitive to purely orthographic similarities. An interesting—albeit unexpected—outcome is the small advantage in priming effects for the form-related condition that did not keep the root and WP over the form-related condition that kept the WP. Although this difference could have been due to competition among roots combined with the same WP, we prefer not to dwell on it until we examine whether this pattern also arises in Experiment 2. The focal point here is that lexical organization in a Semitic language like Arabic can be based on orthographic information, thus aligning Semitic languages with the rest of the world languages.

Finally, regarding the priming effects in the nonword data, we found slower responses in the one-letter-different condition that did not preserve the WP than in the unrelated condition. Inhibitory form-priming effects for nonword targets, like those observed in the current experiment, are quite uncommon (see Forster & Veres, 1998, for another exception)—note that, in general, masked priming effects for nonwords in lexical decision experiments are small and unreliable (Forster, 1998; Perea et al., 2010). Therefore, we will not dwell on this outcome. Instead, we emphasize that our primary goal was to examine whether orthographic factors influence the initial stages of word recognition in Arabic (i.e., focusing on 'yes' responses to words) rather than on how participants make 'no' responses to nonwords, which can involve other distinct processes (Dufau et al., 2012).

In sum, the mainstay of this experiment is that orthographic similarity can lead to masked form priming effects when the pseudoword prime does not preserve the integrity of the root or the WP. In Experiment 2, we seek to generalize this original outcome to a go/no-go lexical decision paradigm. This task obviates the need for a 'no' response and allows us to focus more closely on the orthographic effects of interest.

Go/no-go lexical decision task

In the go/no-go lexical decision task (LDT), participants respond to words and ignore the nonwords. Previous research has shown that the go/no-go LDT can be highly sensitive to lexical factors (e.g., word frequency, associative priming, orthographic priming; Gomez et al., 2007; Perea et al., 2002; Vergara-Martínez et al., 2020; see also Perea et al., 2014, for evidence in Arabic). Thus, orthographic priming with the go/no-go LDT is expected to be sizeable.

Method

Participants

A sample of 84 participants from the same population as in Experiment 1 took part voluntarily.

Materials

Materials were the same as in Experiment 1.

Procedure

The procedure was the same as in Experiment 1, except that participants were instructed to press the 'yes' button if the letter string was a real word in Arabic and to refrain from responding if the letter string was not a word in Arabic. Participants were instructed to make this decision as quickly and as accurately as possible, and none of them reported (after the experiment) conscious knowledge of the existence of any prime.

Data analyses

The results comprised 15,120 data points (84 participants × 180 stimulus items). Incorrect responses (4.43%) and RTs less than 100 ms or greater than 2,000 ms (4.49% of the data) were excluded from the latency analysis. We adapted the same approach as in Experiment 1 by using the unrelated baseline as the reference condition, fitting a model with the maximal random slopes and random intercepts, and pruning until the model fully converged.

Results and discussion

Mean lexical latencies, standard errors of the mean, percent error, and magnitude of priming are displayed in Table 3. Inferential statistics results showed the response times in the orthographically similar condition that kept the WP intact to be significantly faster than the unrelated baseline, $t(14435) = -3.04$, $p = .002$; $b = -0.05$, 95% CI [−0.09, −0.02]). Similarly, the orthographically related condition that did not keep the WP revealed significantly faster response times than the baseline condition, $t(14435) = -3.56$, $p < .001$; $b = -0.06$, 95% CI [−0.10, −0.03]). The error data analysis revealed no significant effects.

The presence of orthographic priming with the go/no-go LDT provides further evidence that the integrity of the root and the WP are not prerequisites for successful lexical access in a Semitic language, Arabic. Instead, the orthographic similarity between pairs of items is enough to guide lexical access. Notably, the magnitude of form priming in the present experiment was not modulated by the presence/absence of the WP, suggesting that this facilitation is driven purely by orthographic similarity. Overall, these findings align Arabic with the rest of the world's languages and rule out the absence of orthographic priming in previous masked form priming experiments as the basis for qualitative cross-linguistic differences.

Table 3 Mean response times (in ms) standard errors (*SE*) in parentheses, percent error rates, and magnitude of priming (in ms) in Experiment 2, go–no-go task

Lexicality	Condition	RT (*SE*)	%Error	Priming
Word	One LD+WP	767 (3.68)	4.50	13*
	One LD-WP	766 (3.78)	4.44	14*
	Baseline	780 (3.73)	4.34	

Note. One LD+WP = One Letter Different, same Word Pattern; One LD-WP = One Letter Different, different Word Pattern; * =

General discussion

Current theories of visual word recognition acknowledge that the different domains of linguistic knowledge, such as phonology, orthography, morphology, and semantics, may be differentially weighted across languages, leading to measurable quantitative rather than qualitative differences (Davis, 2012; Grainger & Ziegler, 2011; Norris & Kinoshita, 2010; Whitney, 2012). However, this assumption is at variance with several key findings in Semitic languages, in which the integrity of the root and WP appear to play a role over and above orthography. This has led some researchers to contend that the difference in lexical space between word representations in Semitic and Indo-European languages is qualitative (Frost, 2012).

To test these opposing views, we conducted two orthographic priming experiments that investigated whether the root's or the WP's integrity was essential for lexical processes in a Semitic language, Arabic. On the one hand, we found facilitation between nonword-word prime–target pairs differing by one letter from the root but sharing the WP compared with an unrelated priming condition, replicating Perea et al. (2014). More importantly, we also found facilitation when the nonword-word prime–target pairs differed by one letter from the root without sharing the WP. This is the first demonstration that neither the integrity of the root nor the presence of the WP is indispensable for lexical processing in Arabic. This novel result potentially has far-reaching theoretical implications.

The first implication is that the lexical space in Arabic is not solely determined by morphological relations. Instead, this space can also be defined by an orthographic dimension, where orthographically similar words are grouped together. How can it be otherwise? After all, when speakers of Semitic languages learn to read and write, they can use orthographic knowledge that potentially modulates visual word processing. The second implication is that Semitic languages are not fundamentally different from Indo-European languages; instead, any differences may be quantitative rather than qualitative (e.g., morphological effects may be more pronounced in Semitic languages, whereas orthographic effects may be more salient in Indo-European languages). This view is consistent with the idea that the internal representations supporting different linguistic domains (e.g., orthography, morphology) may universally depend on co-occurrence statistics (Lelonkiewicz et al., 2023). The main differences between these families of languages may arise from the linguistic environment provided to this statistical learning mechanism and the generalizations it subsequently extracts. Therefore, benchmark orthographic and morphological effects in word recognition can occur, to varying degrees in both language families, and, in principle, current neurobiologically inspired models of word recognition developed for Indo-European languages can be modified to accommodate Semitic languages.

Before closing, one report by Frost et al. (2005, Experiment 5) deserves consideration. These authors compared priming among Arabic words that differed by one letter and either shared the root (e.g., حنين-حنان 'HanAn'-'Hanyn' *tenderness-longing*) or not (e.g., حنين-حزين 'Hazyn'-'Hanyn' *sad-longing*). They found priming among root-related but not orthographically related words, concluding that orthographic factors are irrelevant to the organization of the Semitic lexicon. One key difference between the present experiments and Frost et al.'s (2005) Experiment 5 is that the primes were invariably words; ours were nonwords. This resonates with Forster and Veres's (1998) finding of masked orthographic priming effects being reliable with nonword primes (e.g., *anivorse-UNIVERSE*) but not with word primes (e.g., *contrast-CONTRACT*; see also Andrews & Lo, 2012; Duñabeitia et al., 2009, for a similar dissociation for masked orthographic priming with word and nonword primes). If priming is a process in which evidence sampled from a prime and target is combined to decide on the target (Gomez et al., 2007; Norris & Kinoshita, 2008), when the prime and target are existing words (e.g., '$aryf'-'Earyf'), the perceptual evidence supplied by the prime is more consistent with the prime itself and may contribute little evidence to identifying the target. In contrast, when the prime is a nonword (e.g., 'garyf'), the evidence it provides is most consistent with the target (e.g., '$aryf'). Hence, priming can arise among orthographically related nonword–word pairs, but these effects may be elusive for word–word pairs. Notably, when using nonword primes in Hebrew, Frost et al. (2005, Experiment 7) found an advantage of 9 ms and 1.6% in the orthographically related priming condition over the unrelated priming condition. While these priming effects were reported as nonsignificant, the number of observations per condition was small (576; 48 participants, 12 items/condition) and could have been a Type II error (see Brysbaert & Stevens, 2018, for a systematic analysis of statistical power in masked priming).

In conclusion, the evidence that Semitic languages engage similar processing mechanisms as the rest of the world's languages is accumulating, and the consensus that reading models should be constrained by general principles of visual processing and object recognition is gaining momentum (see Gomez & Silin, 2012; Grainger & Hannagan, 2012; Janini et al., 2022; Lelonkiewicz et al., 2023). Here, we have provided a novel finding that supports this general view, demonstrating that purely orthographic effects (i.e., in the absence of shared roots or WPs) are sizeable in a Semitic language, Arabic (cf. Perea et al., 2012). Note, however, that this demonstration does not play down the importance of morphological structure in Semitic languages. On the contrary, it highlights the underlying cross-linguistic similarities that help advance our understanding of language processing. Future research into Semitic languages must take these findings further by exploring the full breadth of orthographic processing and whether they behave in Semitic like they do in the rest of the world's languages.

Author contribution Sami Boudelaa: Conceptualization, Methodology, Investigation, Formal analysis, Software, Data curation, Project administration, Writing–review & editing. Manuel Carreiras: Conceptualization, Writing–review & editing. Manuel Carreiras: Conceptualization, Formal analysis, Writing–review & editing.

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Code availability The analysis scripts used in the current study and the raw data are available in the Open Science Framework (https://osf.io/zhg5m/).

Declarations

Conflicts of interest The authors declare no conflicts of interest with respect to the authorship or the publication of this article.

Ethics approval All procedures involving human participants were in accordance with the ethical standards of the 1964 Helsinki Declaration and its later amendments or comparable ethical standards.

Consent to participate Informed consent was obtained from all individual participants included in the study.

Consent for publication Not applicable.

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