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Insights from the study of Arabic reading

Ehab W. Hermena[1] | **Erik D. Reichle**[2]

[1]Department of Psychology, Cognition and Neuroscience Research Laboratory, College of Natural and Health Sciences, Zayed University, Dubai, UAE

[2]Department of Psychology, Macquarie University Center for Reading, Macquarie University, Sydney, Australia

Correspondence
Ehab W. Hermena, Cognition and Neuroscience Research Laboratory, Department of Psychology, College of Natural and Health Sciences, Zayed University, Academic City, PO Box 19282, Dubai, UAE.
Email: Ehab.Hermena@zu.ac.ae

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Abstract

Current reading models were largely designed to explain findings from experiments of the reading of English and other European languages (Reichle, 2020, *Computational models of reading: A handbook*). Recent evidence from studies of other languages and writing systems (e.g., Chinese) has demonstrated the need to critically evaluate the assumptions of these models, and whether they are sufficient to explain the full range of findings related to reading, as required, for example, to understand the universal and specific cognitive principles that support reading. In this article, we review the recent behavioural and cognitive-neuroscience research on the reading of Arabic, a world language that until recently has received scant attention despite the fact that its writing system poses fundamental challenges for current models of reading. We also highlight the points of convergence and difference between what has been learned about the reading of Arabic and the reading of another, more widely studied Semitic language, Hebrew. We then discuss the theoretical implications of these findings for existing models of reading.

1 | INTRODUCTION

Computational models of reading have been primarily designed to explain empirical findings obtained from studying the reading of English and other European languages (Rayner & Reichle, 2010; Reichle, 2015, 2020; cf, Reichle & Yu, 2018). But recent research on other languages suggests that the assumptions of these models might not accurately describe the

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Direction of Reading Arabic

← ← ←

(a)

صِف خَلقَ خَودِ كَمِثلِ الشَمسِ إِذ بَزَغَت — يَحظى الضَجيعُ بِها نَجلاءَ مِعطارِ

(A poem by Al Farāhīdi)

(b)

Letter	End	Middle	Initial
ع	ـــع	ـــعـــ	عـــ

(c)

Orthography	قدر	قُدِّرَ	قَدَّرَ	قَدَرٌ	قَدْرٌ	قِدْرٌ
Phonology	/qdr/	/q^{u}d^{di}r^{a}/	/q^{a}d^{da}r^{a}/	/q^{a}d^{a}r^{un}/	/q^{a}dr^{un}/	/q^{i}dr^{un}/
Syntactic case	?	Verb past – passive	Verb past	Noun	Noun	Noun
Meaning	?	[was] estimated / destined	estimated / destined	fate	amount	vessel / pot
Disambiguating sentence	ركل الولد الكرة فتحطم القدر الخزفي الجميل.					
Translation	The boy kicked the ball so the beautiful ceramic vessel got smashed.					

(d)

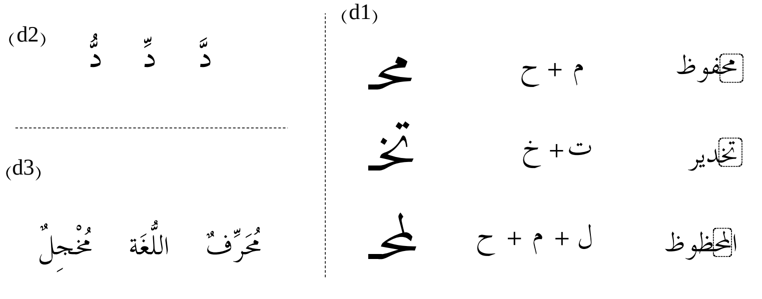

FIGURE 1 Legend on next page

perceptual and cognitive processes engaged during the reading of non-European writing systems (Frost, 2012). This research has questioned the degree to which the mental processes that support reading are universal. The present review will not resolve this issue but will add to the discussion by using, as a case study, a world language that has only recently received attention from reading researchers—Arabic. Our goals will be to first summarize the main characteristics of the Arabic language and writing system, and then describe key findings that have important

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theoretical implications for our understanding of the mental processes involved in reading. Importantly, this review will also compare these findings with what has been learned about a similar but more extensively studied language, Hebrew. We will then conclude by discussing the implications of these findings for existing models of reading, and how those models might have to be augmented to explain these findings.

2 | THE ARABIC LANGUAGE AND WRITING SYSTEM

Arabic is spoken and read by approximately 310 million people, with steadily growing numbers of both native and learner readers (almost another 300 million Arabic second-language readers). Arabic belongs to the family of Semitic languages that also includes Hebrew, Amharic and Maltese. As Figure 1a shows, Arabic is written and read from the right to left using a continuous cursive script comprises 28 alphabetic letters. This script allows 22 of its letters to be connected to spatially adjacent letters via ligatures, but the remaining letters (i.e., ا, د, ذ, ر, ز and و) to be connected only to their preceding letters. This system results in the letters of many Arabic words being completely connected (e.g., سقطت $/sqat^{ʕ}t/$ or *[she] fell*) but for some words to contain inter-letter spaces (e.g., مفتوح /mftuħ/ or *open*), including a few with spaces between all letters (e.g., رِزْق /rzq/ or *daily bread*; Khateb, Taha, Elias, & Ibrahim, 2013). The script also uses some common fonts that allow two or more consonants to be 'stacked' within the same vertical space (Figure 1d, also Hermena, Liversedge, & Drieghe, 2017). And as Figure 1b illustrates, the allographic forms of letters can actually vary significantly as a function of their within-word position (i.e., beginning vs. middle vs. end).

The Arabic alphabet is considered to be an *abjad* writing system because most letters are consonantal. Exceptions to this are the letter ا /alif/ representing the vowel /a:/, and the letters و /w/ and ي /y/ representing the semi-vowels /u:/ and /i:/, respectively (Holes, 2004; see also Saiegh-Haddad, 2017; Saiegh-Haddad & Henkin-Roitfarb, 2014). The writing system also uses small marks, called *diacritics* (Abu-Rabia, 1997, 2001), to convey vowel information and thereby fully specify the pronunciations of consonants (e.g., ب /b/ can be pronounced بَ $/b^a/$, بِ$/b^i/$, or بُ $/b^u/$). Diacritics can also convey the doubling of the consonantal sound, known as *tashdeed* (e.g., دّ /dd/ in قَدَّرَ $/q^a d^{da} r^a/$, which in this example is followed by the diacritical mark *fat'ha*

FIGURE 1 (a) Arabic alphabet pangram in the form of a poetic verse. The text features typical Arabic cursive script, with some letters carrying diacritics for illustration, and because poetry is often printed with diacritics to facilitate accurate pronunciation. (b) The Arabic letter ع and its allographs used as an example, printed as a single letter, and as it appears in the initial, middle (i.e., between other letters) and final locations of words. (c) A sample Arabic heterophonic-homograph, with the word pronunciation indicated by the various diacritics to indicate its correct syntactic category and meaning. The homographic word (underlined, with added ال meaning *the*) is placed in a disambiguating sentence, below. In the absence of diacritics or disambiguating context, determining the intended meaning of the word is not possible. (d) Sample of Arabic words to illustrate vertical stacking of letters and diacritics as appears in commonly used Arabic fonts and taught handwriting styles (see Hermena et al., 2017). (d1) shows vertical stacks of two and three letters are shown. The stacked letters (in dotted box) and the letters that make up the stack are listed to the left. The right-to-left letter order becomes top-to-bottom. (d2) shows the letter د /d/ printed in a vertical stack of one letter + two diacritics, from right to left: With *shedda* for doubling the consonant sound, and the shedda is followed by *fat'ha* /a/ on top, *dumma* /u/ also on top, whereas the final example shows the shedda followed by *kesra* /i/ which is typically placed underneath it. (d3) shows words containing various vertical stacks of letters and diacritics (Note that the final two words of the Arabic sentence in section (c) also contain vertical letter stacking)

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Direction of Reading Arabic
← ← ←

(a)

/fʕl/	كتب	/ktb/
Ten Verbal Patterns	(Predominantly) meanings related to ‘writing’	
فَعَلَ /f^{a}ʕ^{a}l^a/	كَتَبَ	/k^{a}t^{a}b^a/
فَعَّلَ /f^{a}ʕ^{ʕa}l^a/	كَتَّبَ	/k^{a}t^{ta}b^a/
فاعَلَ /f^{a}aʕ^{a}l^a/	كَاتَبَ	/k^{a}at^{a}b^a/
أَفْعَلَ /afʕ^{a}l^a/	أَكْتَبَ	/akt^{a}b^a/
تَفَعَّلَ /t^{a}f^{a}ʕ^{ʕa}l^a/	تَكَتَّبَ	/t^{a}k^{a}t^{ta}b^a/
تَفَاعَلَ /t^{a}f^{a}aʕ^{a}l^a/	تَكَاتَبَ	/t^{a}k^{a}at^{a}b^a/
اِنْفَعَلَ /inf^{a}ʕ^{a}l^a/	اِنْكَتَبَ	/ink^{a}t^{a}b^a/
اِفْتَعَلَ /ift^{a}ʕ^{a}l^a/	اِكْتَتَبَ	/ikt^{a}t^{a}b^a/
اِفْعَلَّ /ifʕ^{a}l^{la}/	اِفْعَلَّ	/ifʕ^{a}l^{la}/
اِسْتَفْعَلَ /ist^{a}fʕ^{a}l^a/	اِسْتَكْتَبَ	/ist^{a}kt^{a}b^a/

/fʕl/	علم	/ʕlm/
Seven Derivational Nominal Patterns	Meanings related to ‘learning’ & ‘science’	
Active Participle فَاعِل /f^{a}ʕ^{i}l/	عَالِم	/ʕ^{a}al^{i}m/
Passive Participle مَفْعُول /m^{a}fʕ^{u}l/	مَعْلُوْم	/m^{a}ʕl^{u}um/
Nouns of intensity فَعِيل /f^{a}ʕ^{i}il/	عَلِيْم	/ʕ^{a}l^{i}m/
Adjective مَفْعُول /m^{a}fʕ^{u}l/	مَعْلُوْم	/m^{a}ʕl^{u}um/
Elative أَفْعَل /a^{a}fʕ^{a}l/	أَعْلَم	/a^{a}ʕl^{a}m/
Nouns of place and time مَفْعَل /m^{a}fʕ^{a}l/	مَعْلَم	/m^{a}ʕl^{a}m/
Nouns of instrument / vessel مُفَعِّل /m^{u}f^{a}ʕ^{ʕi}l/	مُعَلِّم	/m^{u}ʕ^{a}l^{li}m/

FIGURE 2 Legend on next page

denoting the short vowel /a/). Diacritics can also denote the absence of vowelization altogether, known as *sukun* (e.g., دْ /d/ in قِدْرٌ /q^{i}dr^{un}/). In this last example, the /^{un}/ sound at the end of the word is conveyed by another diacritic (on the last letter, رٌ), known as *tanween*, that conveys morpho-syntactic information (mainly about nouns).

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The similarity of how Arabic and Hebrew use additional marks, diacritics and pointing, respectively, to represent vowels is remarkable (e.g., Frost, 1994, 1995). Arabic and Hebrew orthographies are thus considered semi-transparent because, although consonants have a single pronunciation (e.g., د is always pronounced as /d/), their exact vowelized pronunciations (e.g., /d^a/, /d^i/ or /d^u/) are not fully specified when diacritics are absent. As Figure 1c shows, the precise pronunciation, syntactic category and meaning of a word can often only be determined if each consonant is fully diacritized, or if the word is embedded within the disambiguating context of a sentence (Abu-Rabia, 2001). Notably, only children's texts and formal writings (e.g., religious books) are printed with diacritics. Readers older than 8–9 years of age are typically given texts without diacritics, and so as they become skilled readers, they learn to use context to disambiguate homographic words (Abu-Rabia, 1997, 1998, 2001). The same applies to Hebrew, and Hebrew readers, who are also dependent on context for disambiguating unpointed Hebrew letter strings (e.g., Bentin & Frost, 1987). Arabic diacritics, thereafter, are only printed on single ambiguous words in printed texts where the context in which that word is embedded does not sufficiently disambiguate it (Hermena, Drieghe, Hellmuth, & Liversedge, 2015). We will return to the implications of this later when we consider reading development in Arabic, and the development of models of word identification and reading that would accommodate Semitic abjads such as Arabic and Hebrew.

Another key feature of Arabic and other Semitic languages is their root-derived word composition, wherein root and pattern morphemes are interwoven (i.e., infixed, See Figure 2a and b). In the context of Arabic, *root morphemes* are predominantly three-consonant strings

FIGURE 2 (a) A list of the 10 commonly used verbal patterns and the seven nominal derived patterns. For both, the pattern letters and diacritics are presented on the left accompanying the trilitral string fʕl that is typically used to represent the three letters of the root when representing the abstract form of the word (known as الوزن or *wazn*). The letters and diacritics of the pattern are represented on the right accompanying the real roots كتب and علم that are used in the examples. Note that the ninth (penultimate) verbal pattern /ifʕ^{al}l^{la}/ is rarely used except for colouring (e.g., اِخْضَرَّ /ixd^{a}r^{ra}/, or *became green*). Note also that in the nominal patterns, the root علم /ʕlm/ is rarely used in the form presented for the nouns of place and time, where the places of learning and science (مدرسة school, or جامعة university and so on) employ different roots. (b) An example of a very common Arabic root and its semantic representation. The second row of the table shows the root infixed with the letter and diacritics of the pattern morpheme, making up the whole word. The letters and diacritics of the pattern are shown in grey colour to make them easier to distinguish from the root letters shown in black. As it can be seen in the (i) to (v) examples, the phonological (pronunciation), syntactic and semantic representations of the word vary depending on the exact pattern, that is, added to the root letters. Note that in all examples except (iv), the pattern morpheme comprises both letters and diacritics, whereas in (iv), it consists only of diacritics. Also, without diacritics, the example (iv) is indistinguishable from the plain root, and would require sentence context to disambiguate it. In examples (i) and (iii), the root letters كتب *ktb* are interrupted (or infixed) by pattern letters. In example (ii), the initial pattern letter ت/t/ indicates the tense and gender of the verb (would have been a يـ /y/ for a present tense masculine-inflicted verb, as in example [v]). Finally, in example (v), the final two letters ون /un/ indicate the plural status of the masculine-inflicted verb. It is thus clear that pattern morphemes add the phono-syntactic information that serve to fully specify Arabic words

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(b)					
Root	كتب /ktb/				
Root + Pattern Examples	(i) كاتِب	(ii) تَكتُبُ	(iii) مكاتِب	(iv) كُتُبٌ	(v) يَكتُبون
Phonology	/kat^{i}b/	/t^{a}kt^{u}b^{u}/	/mkat^{i}b/	/k^{u}t^{u}b^{un}/	/y^{a}kt^{u}bun/
Syntactic case	Noun, singular, masculine	Verb, present, singular, feminine	Noun, plural, masculine	Noun, plural, masculine	Verb, present, plural, masculine
Meaning	writer	[she] writes	offices / desks	books	[they] write

FIGURE 2 (Continued)

that convey the semantic family to which the word belongs. Some roots are more productive than others (e.g., the root علم /ʕlm/ is a constituent of more than 40 forms, whereas وبخ /wbx/ is a constituent of only three forms); however, there are an estimated 5000–6000 roots in Arabic (Ryding, 2005; see also; Boudelaa, Norris, Mahfoudhi, & Kinoshita, 2019). In contrast, *pattern morphemes* are abstract phonological structures consisting of vowels (letters and/or diacritics) or vowels and consonants that are interwoven with root letters. Figure 2b gives an example of a common Arabic root, كتب /ktb/ (its meaning predominantly relates to writing) infixed with various letter- and diacritics-based pattern morphemes (see also Figure 1c). The core meaning represented by the root morpheme is further specified with the phono-syntactic information supplied by the pattern morpheme, allowing the word to be identified. On some occasions (e.g., Figure 2b, example [iv], or Figure 1c), if the diacritics are not printed, the pattern morphemes must be inferred from the text context, thus resolving the homographic ambiguity.

To illustrate this homographic ambiguity, consider that an equivalent example in English is the word *lead*, which depending upon the context of its use, can refer to a noun that names a common metal or a verb that denotes leadership, with different pronunciations to denote each meaning. But in contrast to English, where such heterophonic-homographs are rare, these ambiguities are extremely common in Arabic (every second or third word in printed Arabic; Abu-Rabia, 1998).

Finally, although it is common in the study of English and other European languages to distinguish between words that vary in terms of the regularity (Coltheart, 1978) or consistency (Glushko, 1979) of their grapheme-to-phoneme correspondences, a central distinction in the study of Arabic is between words that have familiar (or fully lexicalized) versus unfamiliar forms (Share, 2008). This distinction is critical because, when native Arabic learners first learn the written form of Arabic, there are many linguistic discrepancies between the local dialect

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they speak and hear and the standard formal written variety, *Modern Standard Arabic* (*MSA*; see Saiegh-Haddad, 2003). These discrepancies are extensive and include lexical and grammatical differences. The presence of colloquial and formal forms of the language is known as *diglossia* (Ferguson, 1959; Saiegh-Haddad, 2012).

In the sections that follow, we will review recent empirical findings that indicate how the properties of the Arabic language and writing system that were just reviewed affect the skilled identification of Arabic words, the development of this skill in beginning readers, and the implications of these findings for our understanding of the perceptual, cognitive and motoric systems that support skilled reading (as studied using eye movements). We will then conclude by speculating about how the study of Arabic reading might guide future reading research and the development of more comprehensive models of reading.

2.1 | Arabic word identification

Evidence clearly indicates that the visual complexity of the Arabic writing system makes the identification of words difficult because it requires the accurate identification and/or counting of small dots above or below the letters (e.g., to discriminate ـبـ /b/ from ـيـ /y/) and small curves and strokes (e.g., ـمـ /m/ vs. ـعـ /ʕ/, or ـفـ /f/ vs. ـغـ /ɣ/, and so on; see Boudelaa, Perea, & Carreiras, 2020 for a recent systematic survey of Arabic letter similarity; also Asaad & Eviatar, 2014). Despite the previously discussed similarities between Arabic and Hebrew (e.g., their diacritics-based vowel representation, the resulting semi-transparent orthography and lexical ambiguity, and thus the need to rely upon disambiguating context), the visual complexity of Arabic script and its effect on language learning and processing is one main area where Arabic and Hebrew diverge markedly. As will be discussed in more detail below, converging research findings indicate that the visual complexity of Arabic script is responsible for significantly slower mastery of reading Arabic in native learners, even compared to these learners' second language (e.g., Ibrahim, Shibel, & Hertz-Lazarowitz, 2014).

Evidence also shows that both word-identification behaviours and their neural correlates are affected by the presence or absence of diacritics. For example, Bourisly, Haynesd, Bourisly, and Mody (2013) used fMRI to examine the neural correlates of diacritics processing when participants made lexical decisions about Arabic letter strings. The key findings of this study were that responses to non-diacritized words were faster and induced more hippocampus and middle-temporal gyrus activation, whereas responses to diacritized words were slower and induced more insula and inferior frontal activation. This pattern was interpreted as showing that the decisions about non-diacritized words were informed by the direct retrieval of word-form information from lexical memory, whereas the decisions about diacritized words were informed by phonological and/or semantic processing of the fully specified (unambiguous) word forms.[1]

Other examples illustrating the role of diacritics in Arabic word identification come from a series of eye-movement experiments reported by Hermana and colleagues. The first study suggested that skilled readers only use diacritics if they are necessary to disambiguate a word; otherwise, the diacritics are treated as redundant information, with readers spending no extra processing time to analyse the diacritics (Hermena et al., 2015). The second study (Hermena, Liversedge, & Drieghe, 2016) examined the processing of diacritics on upcoming, parafoveal words[2] and showed that skilled readers actually develop expectations that, if the upcoming word lacks diacritics, its pronunciation will correspond to the most frequent one in print. This

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expectation was evident if the parafoveal word did not carry diacritics or if the fixation prior to the word was too distant to afford perception of the diacritics. Finally, the third study suggested that the inclusion of diacritics to increase a word's orthographic transparency does not modulate the influence of its frequency, length or predictability, as the diacritized words are read more slowly, being the recipients of more, longer fixations and inflated re-reading times (Hermena, Bouamama, Liversedge, & Drieghe, 2019). This pattern suggests that the presence of diacritics on a particular word will prompt readers to adopt a cautious reading strategy for the word and its surrounding region. This pattern can be contrasted to what happens if diacritics are added to the entire sentence, where they have no effect on reading (Hermena et al., 2015; Saiegh-Haddad & Schiff, 2016). Collectively, these findings suggest that, in contrast to English and other European languages, the skilled identification of Arabic words is less dependent on grapheme-phoneme decoding and diacritics-based vowel processing and is instead more dependent upon letter-based morpho-orthographic processing (Saiegh-Haddad, 2017). This conclusion is consistent with what has been observed with skilled readers of Hebrew: With the development of reading skill, phoneme-grapheme and pointing-based vowel processing gives way to more morphology- and context-mediated word identification and text processing (e.g., Koriat, 1984; Navon & Shimron, 1984; Ravid, 2005; Shimron, 1993).

With regards to resolving the ubiquitous ambiguity in Arabic print, eye-tracking research suggests that the different pronunciations of Arabic words are somehow represented and accessed from memory in terms of their relative frequency of occurrence (Hermena et al., 2016). Readers also rely upon the sentence context that surrounds the ambiguous word to compensate for the under-specified nature of the lexical information that is available in print; this claim is supported by experiments using both eye tracking (Hermena et al., 2015) and other measures (Abu-Rabia, 1997, 1998, 2001; Taouk & Coltheart, 2004).

Another important aspect of Arabic words is that they constitute a remarkably dense lexical ‘space’ wherein letter transpositions within tri- or quadriliteral roots often results in other known roots (e.g., بعيد /bʕeed/, meaning *far*, becomes عبيد /ʕbeed/, meaning *slaves*). Boudelaa et al. (2019) estimated that this happens about 54% of the time for the commonly used Arabic roots, compared to only 7% of the time for English three-letter words. Not surprisingly, numerous studies in Arabic and Hebrew have shown that facilitation from root-preserving primes or parafoveal previews (e.g., the preview تقسيمات for the target الأقسام, both containing the root قسم /qsm/) is eliminated if root-letter order is not preserved (e.g., if the parafoveal preview is either الأسقام or الأمساق where root letter transposition created the root سقم /sqm/ or the pseudo root مسق /msq/, respectively, for the target of الأقسام; Hermena, Juma, & AlJassmi, in preparation; see also Perea, Abu Mallouh, & Carreiras, 2010; Velan & Frost, 2007, 2009, 2011 for similar results in other tasks in both Arabic and Hebrew). These findings stand in stark contrast to findings from English and other European languages where primes or parafoveal previews containing *transposed-letter (TL)* pairs (e.g., *golve* as a prime for the target *glove*) typically facilitate target-word processing relative to primes or previews containing *substituted-letter (SL)* pairs (e.g., *gatve–glove*; see Brysbaert, 2001; Dunabeitia, Perea, & Carreiras, 2007; Johnson, Perea, & Rayner, 2007; Kinoshita & Norris, 2009; Perea & Carreiras, 2006, 2006, 2008; Perea & Lupker, 2003). These findings suggest that the cognitive systems mediating letter-order perception can adapt to accommodate Semitic versus European writing systems (e.g., Frost, 2012, 2015), with rigid letter-position coding for Semitic languages and a more flexible letter-position coding for European languages. The strongest evidence supporting this notion comes from studies demonstrating the capacity to switch between ‘rigid’ versus ‘flexible’ letter-position coding within bilingual readers, with those readers adopting rigid letter coding when processing

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Hebrew with Semitic roots, but adopting flexible letter coding when processing either Hebrew with no Semitic roots or English (Frost, Kugler, Deutsch, & Forster, 2005; Velan, Deutsch, & Frost, 2013; Velan & Frost, 2011).

However, task demands also determine if rigid or flexible letter-position coding is deployed. Whereas Velan and Frost (2011) reported no root-TL priming benefit for Hebrew target words in lexical decision, Kinoshita, Norris, and Siegelman (2012) found a clear benefit from root-TL primes in a word-matching task using the same stimuli. This same pattern was also reported in Arabic: Boudelaa et al. (2019) replicated the absence of root-TL priming benefit in lexical decision (Experiment 1) while obtaining root-TL priming benefit in a matching task using the same stimuli (Experiments 2 & 3). The explanation for these findings is that, because lexical decisions entail lexical access, task performance reflects the statistical properties of the lexicon being accessed. Thus, lexical decisions about Arabic or Hebrew letter strings are influenced by the dense orthography and the rigid letter-position coding that supports morphological decomposition and processing. In contrast, because the word-matching task only requires participants to indicate whether or not a target word matches some reference word, the task can be performed using pre-lexical (abstract) letter codes as the basis of comparison (e.g., Kinoshita, Gayed, & Norris, 2018; Kinoshita & Norris, 2009), so that task performance is unaffected by the properties of the Arabic or Hebrew lexicons. By this account, primes containing TL-root letters should produce the priming benefits reported in languages with non-Semitic morphology. And by extending this account, one might infer that the operations required to access a word from the mental lexicon are subject to a variety of constraints, including the properties of the linguistic environment, the neurobiological constraints that support lexical processing and the demands of the task being performed.

2.2 | Morphological processing in Arabic

Several studies have documented the special cognitive status of Semitic roots by examining their neural correlates. For example, several case studies of Arabic- and Hebrew-speaking aphasic patients (Barkai, 1980; Idrissi, Prunet, & Béland, 2008; Prunet, Béland, & Idrissi, 2000) have documented selective impairments of either root (consonant) or pattern (vowel) production. Experimental evidence for the dissociated processing of root versus pattern information comes from an electro-physiological study reported by Boudelaa, Pulvermüller, Hauk, Shtyrov, and Marslen-Wilson (2010). This study showed that the processing of root information elicited a symmetrical, fronto-central distribution of brain activity (similar to what is observed with the processing of English content words), but that the processing of pattern information elicited a left-lateralized, perisylvian distribution of brain activity (similar to what is observed with the processing of English function words). Variability in root information also elicited activity 160 ms post-stimulus presentation, whereas variability in pattern information elicited activity 250 ms post-stimulus presentation, suggesting both a *temporal* and spatial distinction of root versus pattern processing (see also Gwilliams & Marantz, 2015). Together, these findings indicate that the neural systems engaged during Semitic word processing are sensitive to the morphological distinction between roots and patterns.

In addition to the neuropsychological evidence discussed above, behavioural evidence indicates that Semitic roots play an important role in both word identification (e.g., Boudelaa & Marslen-Wilson, 2000, 2001) and the organization of the lexicon (Boudelaa, 2014; Boudelaa & Marslen-Wilson, 2015). For example, root-preserving primes facilitate Arabic and Hebrew word

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processing more than orthographically controlled primes (Boudelaa & Marslen-Wilson, 2000, 2001, 2005; Frost, Deutsch, & Forster, 2000; Frost, Forster, & Deutsch, 1997). Similar priming was reported for root-preserving parafoveal previews in both Arabic and Hebrew (Deutsch, Frost, Pelleg, Pollatsek, & Rayner, 2003; Deutsch, Frost, Pollatsek, & Rayner, 2000; Hermena et al., in preparation). This root-based facilitation was not contingent on mediation from orthography (i.e., on sharing root letters; Boudelaa & Marslen-Wilson, 2004) or semantically transparent prime-target relationships (Boudelaa & Marslen-Wilson, 2000, 2001; for evidence from Hebrew, see; Deutsch, 2016; Frost, Deutsch, Gilboa, Tannenbaum, & Marslen-Wilson, 2000).

The available evidence also suggests that the privileged role of morphological processing in Semitic languages is not due to root morphemes conveying semantic information, suggesting that morphological and semantic processing are largely independent. For example, an fMRI experiment reported by Bick, Goelman, and Frost (2011) identified a common network of cortical areas that were engaged during the processing of English and Hebrew words in the brains of English-Hebrew bilinguals—a network comprises the left inferior-frontal, middle-frontal and occipital-temporal regions. But there were also language-specific differences in the observed patterns of brain activity; although the activation observed during the processing of Hebrew words was unaffected by the semantic relatedness of the words, the inferior- and middle-frontal activation decreased when processing morphologically and semantically related English words (see also Bick, Frost, & Goelman, 2010; Bick, Goelman, & Frost, 2008). Essentially, in contrast to the root and pattern composition of Semitic words (see Figure 2a and b), where the root conveys the core meaning and the infixed pattern morpheme adds the specific phono-syntactic information necessary for word identification, English word stems—the equivalents of Semitic roots—are identifiable words (e.g., the stem *light* is a word, independent of the word *lighter*). In addition, and whereas pattern morphemes in Arabic and Hebrew are identifiable and follow a set of rules for creating verbal and noun word forms, English has no clear rules for specifying when a given cluster of letters is a prefix (e.g., *im-* in *improper* vs. *impugn*) or a suffix (e.g., *-er* in *stronger* vs. *letter*). By this account, the processing of the simpler, linear English morphology is modulated by semantic processing because the intended meaning of a whole letter string clarifies the status of any encompassed letter clusters (Bick et al., 2011).

The results discussed in the previous paragraph were also interpreted as evidence that Semitic words are rapidly and obligatorily decomposed into their root and pattern morphemes in order to achieve complete word identification, and that this decomposition is not modulated by orthographic or semantic processing (Boudelaa, 2014; Frost et al., 1997; Hermena, Liversedge, Bouamama, & Drieghe, 2019). More support for the obligatory morphological decomposition of Semitic words into roots and patterns (e.g., Boudelaa, 2014; Frost et al., 1997), and for the delineation of the processes that take place after the morphological decomposition came from a recent study of Arabic word- and root-frequency effects. Whereas Hermena et al. (2019) replicated the word-frequency effect observed in many world languages (see Rayner, 2009), frequency effects associated with Arabic roots were modulated by how often the roots occurred in combination with a particular pattern morpheme. Specifically, combining high-frequency roots with patterns to produce low-frequency words obliterated the potential benefit that might have otherwise been evident in the fixation durations during the reading of a high-frequency root. Furthermore, the root-frequency effects were actually reversed in a lexical-decision task, with pseudowords containing high-frequency roots yielding inflated response times and lower accuracy rates. These findings replicated previous results for English word bases (Taft, 2004) and further support the hypothesis that, following morphological decomposition, re-combination is performed, and that, depending on the characteristics of the constituents being

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re-combined (e.g., a high-frequency base/root being combined to produce an unusual or low-frequency form), the processing cost may be sizeable.

Despite these recent advances in our understanding of morpho-lexical processing, much remains to be learned about *how* pattern morphemes affect Arabic word identification. For example, there are seven nominal patterns corresponding to classes of nominal derivatives (Schulz, 2004; for other classifications, see Holes, 2004; Ryding, 2005), and 15 verbal patterns, only 10 of which are still in common use (Boudelaa & Marslen-Wilson, 2005; Holes, 2004; see Figure 2a for examples). Each of the patterns can be further expanded by morpho-syntactic inflectional patterns to indicate tense, number, gender and mood (see examples in Figure 2b). Although lexical processing appears to be facilitated by the presence of these patterns (e.g., in primes), the time course for processing nominal versus verbal patterns seems to be different (Boudelaa & Marslen-Wilson, 2005). Additionally, the amount of facilitation from pattern morphemes is modulated by root-related variables such as productivity (Boudelaa & Marslen-Wilson, 2011). Interestingly, recent evidence suggests that, despite the facilitation observed with priming, pattern-preserving parafoveal previews do not produce facilitation (Hermena et al., in preparation). These findings echo Boudelaa's (2015), where vowel-based pattern morpheme primes did not produce facilitation compared to consonantal-based root morpheme primes. Boudelaa and Marslen-Wilson (2011) suggested that processing roots and patterns in Arabic are influenced by the fact that pattern morphemes are largely represented by diacritics and thus typically absent from Arabic print (see Figure 2a and b). Clearly, much remains to be understood about pattern morpheme processing in Arabic reading.

Moreover, processing pattern morphemes is an area where Arabic and Hebrew data diverge for reasons that are not fully understood. Specifically, Frost et al. (1997) (and for a recent MEG imaging study, see Kastner, Pylkkanen, & Marantz, 2018) found that Hebrew readers benefited from primes that preserve verbal pattern morphemes, while Arabic readers benefited from primes preserving both verbal and nominal patterns (e.g., Boudelaa & Marslen-Wilson, 2000, 2001, 2005, 2015; Shimron, 2006). To explain the absence of benefit from primes that preserved Hebrew nominal pattern morphemes compared to verbal pattern morphemes, it was suggested that the smaller number of the latter (Hebrew has only seven verb patterns compared to the 15 in Arabic) facilitates the winnowing down of possible word candidates, thereby enhancing the efficiency of word identification (e.g., Deutsch, Frost, & Forster, 1998). However, recent findings from Hebrew (Deutsch, Hadas, & Michaly, 2018) suggested that nominal-pattern previews are beneficial for target-word processing. The effect occurs very early, is small in magnitude, and is subject to interference from the effects of root violations (i.e., by definition, preserving the pattern only entails changing the identity of the other letters in the word, viz., the root). Replicating these findings in Arabic would be a good first step towards a better understanding of the time course of pattern morpheme processing in Semitic languages given that the currently available evidence regarding pattern morpheme processing in Arabic can be summarized as follows: (a) There is an inconsistency between the time course of processing verbal and nominal pattern processing and the resulting priming benefit (e.g., Boudelaa & Marslen-Wilson, 2005); (b) There is an apparent dependence of pattern-based priming benefit on root-related variables (e.g., Boudelaa & Marslen-Wilson, 2011) and (c) Recent findings show no parafoveal pre-processing benefits when the root information is disrupted in parafoveal previews that preserve pattern morpheme (Hermena et al., in preparation). These findings, together with the apparent inconsistency between findings in Hebrew and Arabic, indicate that a more comprehensive understanding of the role of pattern morphemes in word identification and lexical organization in Semitic languages is necessary.

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2.3 | Eye movements in Arabic reading

The properties of the Arabic writing system also provide an opportunity to examine the cognitive systems and variables that inform the decisions of *where* and *when* readers move the eyes. For example, the *perceptual span*, or the region of effective visual processing during reading, is limited in spatial extent and extends asymmetrically to the right in languages that are read from left to right (for reviews, see Rayner, 1998, 2009). The evidence also indicates that the perceptual span when reading Arabic and Hebrew (which are both read from right to left) exhibits a leftward asymmetry (Jordan et al., 2014; Pollatsek, Bolozky, Well, & Rayner, 1981). These asymmetries thus reflect how attention is allocated towards upcoming words in the service of identifying printed words during reading—leftwards in Arabic and Hebrew and rightwards in English and other European languages.

Moreover, Arabic text is usually printed in proportional fonts, so that words comprise different numbers of letters can occupy the same spatial extent. Eye-movement experiments have exploited this property of Arabic to show that readers' decisions about *where* to move their eyes are primarily influenced by the spatial extent of words and letters, and not the number of letters contained therein or the frequency of the initial bigram (Hermena et al., 2017). By contrast, as is true with other languages (Rayner, 1998, 2009), the best predictors of *when* the eyes move are linguistic variables such as word frequency (Hermena et al., 2019), cloze predictability (Hermena, Bouamama, Liversedge, & Drieghe, in press) and the number of letters within a word (Hermena et al., 2017, Experiment 2; see also Paterson, Almabruk, McGowan, White, & Jordan, 2015). Interestingly, because most Arabic words are 6–9 letters long, they typically receive more, longer fixations (e.g., Hermena et al., 2015; Hermena et al., 2017; Hermena et al., in press) than is observed in the reading of English, where average word length is approximately five letters (Brysbaert, 2019; Johns & Dye, 2019). These results support a clear dissociation between the factors that determine where readers move their eyes (e.g., visual acuity and saccade-programming parameters, as modulated by the spatial layout of a text) and the factors that determine when readers move their eyes (e.g., rate of lexical processing as modulated by a variety of linguistic properties of the text).

However, perhaps the most important variable affecting when the eyes move and thus reading rates is the informational density of Arabic. Because it employs a non-concatenated morphology (i.e., root and pattern infixes), a large amount of information can be conveyed to the reader using a relatively small number of letters. For example, the word سيتعلمان is a verb indicated by the tri-literal root /علـ/ that has a meaning related to *learning*. This verb carries a future tense inflection at its beginning /سـ/, followed by a masculine determiner /يـ/, and a continuous tense infliction /تـ/, and ends with number marker /ان/ that indicates dual agents. This eight-letter word thus translates into the phrase *they will be learning*. In a comprehensive meta-analysis of reading rates in multiple world languages, Brysbaert (2019) reported that a 1000-word English text can (on average) be translated into Arabic using only 822 words. In other words, Arabic text conveys the same amount of information, but using fewer, more informationally dense and morphologically complex words. This increase in informational density also results in Arabic words receiving more and longer fixations than words in English. This conjecture that informational density influences eye-movement behaviours is also supported by reading studies that have controlled the informational content of text but used different languages. These studies showed no significant differences in text reading times between languages as different as English and Hebrew (Kuperman, Siegelman, & Frost, 2019), or English, Chinese and Finnish (Liversedge et al., 2016). Finally, the increased processing time for

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Arabic words, given their informational density, is also reflected in average reading speed (i.e., words per minute, or *WPM*). Brysbaert (2019) reported rates of 181 WPM for silent reading of Arabic, compared to 236 WPM for English, and a rate of 142 WPM for reading aloud Arabic, compared to 190 WPM for English.[3]

Given the findings reviewed so far, it is perhaps not surprising that the increased visual and informational density of Arabic jointly attenuate the parafoveal processing of Arabic words. This is best evidenced by the fact that, whereas readers of English and other European languages skip approximately 30% of the words in a given text (e.g., Rayner, 2009; Rayner & Pollatsek, 1981), readers of Arabic exhibit only modest word-skipping rates (on average 8%; Hermena et al., 2015, 2016, 2017; Hermana, et al., in press). Similarly, the magnitude and reliability of the effects that reflect parafoveal processing are more limited to spatially proximal pre-target fixation positions (Hermena et al., 2016), presumably because these positions afford the high visual acuity required to identify the small features of Arabic words.

Somewhat paradoxical to what was just indicated, however, is recent demonstrations that Arabic readers actually extract root morphology and semantic information from parafoveal previews of target words that are synonymous with those words (Hermena et al., in preparation). Although such findings appear contrary to the reduced parafoveal processing discussed previously, it should not be surprising that, second only to root morphology, skilled readers prioritize semantic information because, as already discussed, readers of Arabic rely upon sentence context to disambiguate homographs. The fact that Arabic orthography is semi-transparent likely facilitates rapid access to semantic information for identifying printed words (see Schotter, 2013).

The idea of early access to semantic information, and that this semantic processing can influence and facilitate word identification should not be surprising given that some existing models of reading already incorporate (mostly underspecified) semantic feedback routes to phonology and orthography, as will be discussed in more detail below. Compelling empirical evidence also exists: Schmidtke, Van Dyke, and Kuperman (2018) reported very early effects of semantic transparency of morphologically complex English compound words on eye movements during sentence reading. The results suggested that semantic processing started almost simultaneously with the (typically early) processing of orthography. Of particular relevance to the current discussion, the authors (p. 435) argued that these early effects call into question theoretical accounts that exclude semantic processing from early morphological decomposition (e.g., Taft, 2004, see above), and by extension, the interpretations of findings that suggest considerable separation of root morphology and semantics processing (e.g., Bick et al., 2011; Boudelaa & Marslen-Wilson, 2000, 2001, see above). The exact nature of the relationship between morphology and semantic processing thus clearly requires further delineation and clarification. Semitic morphology, as exemplified in Arabic and Hebrew, provides a fertile ground for future examination of this question.

2.4 | Learning to read Arabic

The studies reviewed in the previous section have provided clues about the cognitive processes supporting the skilled reading of Arabic. The studies reported here provide additional clues by examining how beginning readers of Arabic (typically children) acquire this important skill. For example, Ibrahim, Eviatar, and Aharon-Peretz (2002) (see also Asaad & Eviatar, 2013; Eviatar, Ibrahim, & Ghanayim, 2004) found that, in Arabic-Hebrew bilingual children, letter identification was faster and more accurate in Hebrew, their second language, than in Arabic, their

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native language. This was attributed to the complexity of Arabic letter visual representations, including letter connectedness. However, a series of experiments have also indicated that, for skilled Arabic readers, the identification of words containing semi-connected letters is more prone to error than words containing connected letters (Ganayim, 2015; Khateb et al., 2013; Taha, Ibrahim, & Khateb, 2013). These latter findings suggest that, although semi-connected letters might be visually simpler, ligatures facilitate word identification accuracy. Finally, a study by Khateb, Khateb-Abdelgani, Taha, and Ibrahim (2014) found that the most skilled readers in the sample (i.e., 9th graders) showed no differences in either the speed or accuracy of identifying words containing connected versus unconnected letters. The inconsistency of these results may reflect the fact that connected letters occur more often than semi-connected (Al-Muhtaseb, Mahmoud, & Qahwaji, 2009), with such differences also possibly influencing an early stage of abstract letter encoding (Ganayim, 2015).

In addition to difficulties associated with the characteristics of the Arabic writing system, children learning Arabic makes two major transitions as they begin learning to read. The first of these is when they are introduced to the formal variety of written Arabic, *MSA*, which as mentioned above, differs widely from their spoken varieties. Consistent evidence suggests that diglossia causes difficulty for children who are learning to read. For example, Ibrahim et al. (2014) found that 3rd and 4th grade children were slower reading MSA than Hebrew (see also Eviatar & Ibrahim, 2001; Ibrahim, Eviatar, & Aharon Peretz, 2007). Others have likewise shown that problems with phonological-awareness tasks, short-term memory tasks and reading and spelling persist in native Arabic-speaking children throughout primary education (up to the age of 11 years, e.g., Azzam, 1993; Brosh & Attili, 2009; Ibrahim, 2011; Saiegh-Haddad & Haj, 2018; Saiegh-Haddad & Schiff, 2016; Schiff & Saiegh-Haddad, 2018; Taha, 2017), even after those children have presumably attained some degree of fluency with MSA. These difficulties were particularly pronounced in Arabic children with specific language impairment (Saiegh-Haddad & Ghawi-Dakwar, 2017) and dyslexia (Schiff & Saiegh-Haddad, 2017) and can include deficits in semantic and syntactic processing (Khamis-Dakwar, Froud, & Gordon, 2012; Leikin, Ibrahim, & Eghbaria, 2013).

Saiegh-Haddad, Levin, Hende, and Ziv (2011) further document the problem of diglossia by showing that native Arabic children often exhibit problems with the phonology of MSA from their entry into kindergarten. And even after 2 years of instruction, children still find the phonemes of MSA more difficult to isolate than phonemes in their spoken dialect (Saiegh-Haddad, 2003; also, Saiegh-Haddad, 2004, 2005, 2007). However, children who were exposed to MSA during preschool (via daily dialogue and games) exhibited better phoneme-isolation performance 2 years later (Abu-Rabia, 2000). These findings suggest that, for native Arabic-speaking children, learning to decode MSA involves the mapping of corresponding spoken and written representations that often differ from each other to a degree that is almost equivalent to learning a second language (see Abou-Ghazaleh, Khateb, & Nevat, 2018; Ibrahim, 2009; Ibrahim & Aharon-Peretz, 2005). This hypothesis is consistent with results showing that remedial interventions targeting phonological competence in MSA is beneficial (Taha & Saiegh-Haddad, 2016). And although skilled college-aged Arabic readers can attain equivalent fluency in both informal and standard varieties of Arabic (Abu-Melhim, 2014), much remains to be learned about how this happens.

The second transition takes place as children become about 8–9 years of age, as noted above, when the orthography used to represent the formal variety of Arabic (MSA) becomes a deep one as diacritics are dropped from print (see Figure 1c; Abu-Rabia, 1998, 2001). Evidence suggests that in the earlier stages of learning an abjad writing system like Arabic, diacritics facilitate the pronunciation and acquisition of vocabulary, reading accuracy and

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comprehension (e.g., Abu-Rabia, 2001 and the same applies to Hebrew with its equivalent pointing system, e.g., Abu-Rabia, 1998; Share, 2008, p. 601; Share & Bar-On, 2017). As also noted earlier, at the later stages of development and thereafter, Arabic readers are depending progressively more on letter-based morpho-orthographic processing, rather than grapheme-phoneme decoding (Saiegh-Haddad, 2017), as well as context, rather than diacritic-facilitated lexical disambiguation (Abu-Rabia, 1997, 1998).

2.5 | Computational modeling

The preceding sections discussed key findings related to the identification of Arabic words, and how properties of the Arabic language and writing system influence morphological processing and eye-movement control during reading, as well as some of the difficulties faced by children who are learning to read Arabic. These discussions indicated that there are aspects of the reading of Arabic that differ markedly from the reading of English and other European languages, and that these differences pose challenges for computational models that have been designed to explain the latter (see Reichle, 2020). Examples of a few of these challenges will be discussed here.

2.5.1 | Word identification

The evidence suggests that the identification of Arabic words is made difficult by the visual complexity of the writing system (e.g., small diacritics and distinguishing features of letters, the cursive script and the allographic variety of Arabic letters), combined with the adoption of 'rigid' letter-order encoding required to identify the root versus pattern morphemes in words. Although some of the reported findings might be accommodated by augmenting an existing word-identification model with the array of orthographic features that are necessary for representing Arabic letters and diacritics, the theoretical assumptions about letter-order perception warrant consideration.

As indicated previously, most word-identification models assume a 'slot-based' encoding of letters wherein the features of the first letter in a word are encoded in the first letter position, and so on, so that, for the word *cat*, the features for the letters *C*, *A* and *T* are encoded in the first, second and third letter positions. The limitations of this simple scheme (e.g., it cannot explain the transposed letter effects reviewed earlier) motivated the development of alternative schemes, including the use of open-bigram (letter-pair) representations (Grainger & van Heuven, 2003), or letter positions are represented with uncertainty (Gomez, Ratcliff, & Perea, 2008) or via converting spatial positions to time-based codes (Davis, 1999, 2010; Whitney, 2001, 2008; Whitney & Cornelissen, 2008). Although there are no demonstrations that any of these ways of representing letter order might be successfully adapted to Arabic, we would argue that the common vertical stacking of Arabic letters (see Figure 1d) and the use of diacritics above and below letters is problematic for most of the aforementioned schemes. For example, it is unclear when beginning or skilled readers encounter diacritics, how diacritic information would be representing using open bigrams. And the conversion of letter and diacritic position to time codes would require their positions to be represented along two temporal dimensions to represent their horizontal and vertical spatial arrangement (e.g., one diacritic being above another, e.g., the shedda, on the letter د /d/ in this example, دّ for doubling consonant sounds, followed by the diacritics for /a/, /i/, or /u/ vowels, see Figure 1d). Only the assumption that the

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positions of letters and diacritics are represented with some amount of uncertainty (along two spatial dimensions) seems to provide a ready account of, for example, the vertical arrangement of diacritics and letters. However, adapting this approach to Arabic would still require the spatial positions of letters and diacritics to be represented with greater fidelity than is assumed in English, thereby allowing letter positions to be encoded in a 'rigid' manner in Arabic and a more 'flexible' manner in English.

Finally, as discussed, the underspecified nature of written Arabic means that lexical ambiguity is prevalent, and that skilled readers of the language must use sentence context to rapidly disambiguate the meanings of many ambiguous words. Precisely how this happens remains unclear, but what is clear is that most existing models of word identification say little about the role of whole sentence- and context-based semantics (see Reichle, 2020; however, for one interesting counter example, see also; Plaut, McClelland, Seidenberg, & Patterson, 1996). The role of semantics has primarily been restricted to word-level, as when it provides feedback for disambiguating pronunciations from homophonic competitors (e.g., the Triangle Model of Harm & Seidenberg, 2004; also Seidenberg & McClelland, 1989; see also Yang, Shu, McCandliss, & Zevin, 2013, for similar suggestions as applied to the training a variant of the triangle model to read Chinese vs. English words; see also Rueckl, 2016). Similarly, other models postulate feedback from semantic processing to orthographic output (i.e., a spelling-checking mechanism, e.g., Van Orden, Pennington, & Stone, 1990; also utilized by the triangle model). The inclusion of semantic feedback allows these models to accommodate findings which suggest that accessing the semantic representation of a letter string facilitates its identification, particularly for low-frequency letter strings (e.g., Strain, Patterson, & Seidenberg, 1995), morphologically complex and/or compound words (e.g., Schmidtke, Dyke, & Kuperman, 2018), and when impaired semantic processing impacts performance in patients (e.g., semantic dementia/surface dyslexia, see Woollams, Ralph, Plaut, & Patterson, 2007). However, most of the currently available models (e.g., Harm & Seidenberg, 2004, p. 711) acknowledge that the role played by word-based semantic processing is underspecified and give virtually no mention to the role of context-based semantic information utilized by readers of undiacritized Arabic or unpointed Hebrew. These models would therefore have to be augmented with some type of meaning-based representations to support the convergence of information made available from the orthographic features of a word and the overall meaning of a sentence. Such an account would likely require assumptions about sentence processing and how the overall meaning of a sentence is constructed and then used to guide the interpretation of each word as it is identified.

2.5.2 | Morphological processing

Current models of reading also say very little about the role of morphology in word identification, with many word-identification models focussing on single-morpheme words or simply assuming that polymorphemic words are represented as whole units in the lexicon (see Reichle, 2020). To explain the role of root and pattern morphemes in Arabic, the models might require the capacity to use compound cues, in the form of the letters and diacritics that comprise root and pattern morphemes, to activate the compositional meaning of a given word. The models also need to be able to accommodate the transition, later on when only partial pattern information is present, when diacritics are removed from print. On a general level, this more compositional conceptualization of word identification is broadly consistent with models in which patterns of orthographic features are mapped onto their corresponding phonological

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and/or semantic patterns (e.g., Seidenberg & McClelland, 1989) rather than, for example, more static (lexicalized) representations of pronunciation and meaning (e.g., Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001). Another approach that would lend itself to this compositional conceptualization of lexical retrieval is the instance-based model of Ans, Carbonnel, and Valdois (1998); by this account, a configuration of features corresponding to root and pattern morphemes could be used to retrieve specific memory traces containing those morphemes, or in the absence of the traces, to construct a composite pattern of features that provides the 'best guess' about the composite meaning of the morphemes.

2.5.3 | Eye-movement control

Arabic is like English and most other alphabetic writing systems (cf., Thai) in that blank spaces separate individual words. This allows word-based saccade targeting wherein the centre of the next word in a sentence is normally selected as the saccade target[4] (e.g., Engbert, Nuthmann, Richter, & Kliegl, 2005; Reichle, Pollatsek, & Rayner, 2012). Existing default-targeting models of eye-movement control should therefore (in principle) explain the patterns of eye movements observed during the reading of Arabic, although the parameter values of these models would need to be adjusted to accommodate the right-to-left movement of the eyes, the leftward perceptual span and decreased skipping rates observed during the reading of Arabic.

2.5.4 | Reading acquisition

Two main aspects of Arabic reading must be accommodated to understand its development: The prevalence of diglossia and how this affects the initial mapping of the spoken forms encountered in local dialects and the formal forms in MSA, and how the subsequent removal of diacritics influences the final lexical representations that are acquired by skilled readers. Both factors reduce the consistency of the orthographic-to-phonological mappings, and by conjecture, might ultimately enhance the mapping between orthography and semantics in skilled readers. As already discussed, the latter would presumably facilitate the reading of Arabic because it would allow readers to use sentence context to help rapidly disambiguate the lexical ambiguities that are highly prevalent in written Arabic. We suspect, however, that such an account will require a more comprehensive model of reading than those currently available, in that the model would presumably need to simulate both word identification and sentence processing; that is, such a model would need to explain how the meanings of words are combined to generate the meaning of a sentence, and how the latter is then used to guide the interpretation of each word as it is identified. If our speculation here is correct, then we suspect that the reading of Arabic will provide an interesting new arena for evaluating both the feasibility and theoretical scope of future models of reading.

To conclude, our discussion above attempted to summarize the key findings and complexities of Arabic word identification and sentence reading. As with other languages, the mental processes involved in reading Arabic entails the orchestration of visual, orthographic, phonological, morphological, semantic and contextual information. Semitic languages like Arabic and Hebrew, however, provide an especially fertile ground for studying complex, non-linear morphological processing as conveyed by an underspecified and semi-shallow but

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dense orthographic representation. In particular, the prevalence of lexical ambiguity, in combination with a dense informational content per word, makes the study of morphological processing and both word- and context-based semantic processing necessary precursors for understanding how readers identify Semitic words. As compared to Hebrew and other Semitic languages, Arabic adds a few uniquely challenging features, including diglossia and visual complexity, which impact both the earliest stage of reading acquisition and the later transition from diacritized to undiacritized print. Despite recent advances, future research is required to better understand: (a) the processing of pattern morphemes and the processing time course of their phono-syntactic information, (b) the nature of morpho-semantic processing and integration and (c) the effects of visual complexity and diglossia on reading acquisition and performance in Arabic. The use of eye tracking is proving to be a highly effective method for addressing these issues, and we predict that the findings from future studies using this method will prove invaluable for guiding the development of more comprehensive models of reading—models that are sufficient to handle the complexities of Arabic.

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ORCID

Ehab W. Hermena https://orcid.org/0000-0002-3338-7980

ENDNOTES

[1] Although these results are interesting, they are seemingly at odds with behavioural results showing that diacritics-based vowel phonology is less important for lexical-decision than word-naming tasks (e.g., Bentin, Bargai, & Katz, 1984; Frost, 1995; Koriat, 1984). This discrepancy may reflect differences in task demands because, although phonological analysis is not necessary for discriminating words from non-words, it is for pronouncing words. It is also worth noting that the poor temporal resolution of fMRI likely resulted in the inclusion of brain activity associated with post-lexical decision processes.

[2] The *fovea*, or region of highest visual acuity, encompasses the central 2° of the visual field, with the *parafovea* then extending into the visual field out to 5°.

[3] In surveying about a dozen world languages, Brysbaert (2019) reported strong positive correlations between *expansion index*, or the number of words required to translate a 1000-word piece of English text into another language, and reading speed: The higher the expansion index, the higher the rate of both reading silently ($r = 0.59$) and reading aloud ($r = 0.82$).

[4] This scheme contrasts with the dynamic adjustment of saccade length that has been posited during the reading of Chinese; due to the lack of clear word boundaries, the length of an upcoming saccade is adjusted in a manner that reflects the lexical-processing difficulty of the upcoming characters, with the saccades being shortened to the degree that the processing is difficult; for example, see Liu et al. (2019).

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AUTHOR BIOGRAPHIES

Ehab W. Hermena is a cognitive psychologist with strong interest in language processing, eye tracking methodology, and related topics such as language acquisition, Semitic morphology and reading difficulties. Ehab qualified as a doctor in educational psychology and was later awarded a Ph.D. in cognitive psychology, both from the university of Southampton, UK. He is currently an assistant professor at Zayed University (Dubai, UAE), where he serves as an assistant chair of the department of psychology and heads the Cognition and Neuroscience Research Laboratory. Ehab has been the successful recipient of numerous research grants, as PI or co-investigator, from ESRC (K), Leverhulme Trust (UK), BPS (UK), as well as Zayed University (UAE).

Erik D. Reichle is currently a Professor and Head of the Department of Psychology at Macquarie University. His research uses computational modelling, eye-movement experiments and other methods (e.g., ERP) to understand the perceptual, cognitive and motor processes involved in reading. He authored more than 60 articles on these topics in international journals, including Brain and Behavioral Sciences, Psychological Review and Psychological Science. He also received fellowships from the Hanse Institute of Advanced Studies (Germany), the Leverhulme Trust (UK) and the National 1000 Talents Award (China). His forthcoming book, entitled Computational Models of Reading: A Handbook, provides a comprehensive review of models that are used to understand the mental processes involved in reading.

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