Eye Movements in Arabic Reading

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Abstract

Measures of eye movements provide a moment-by-moment account of the visual and cognitive processes that underlie normal reading. These measures have been used to develop detailed sophisticated computational models of eye movement control during reading, primarily based on research conducted with Latinate languages such as English and German. However, relatively little is known about the mechanisms underlying eye movement control during reading for Semitic languages, such as Arabic, that have very different visual and linguistic characteristics. In this chapter, we provide an overview of eye movement research on reading, including research conducted to date on eye movements in Arabic reading. We consider whether current computational models can account for these findings and outline key theoretical questions that remain to be examined.
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empirically.
1. Introduction

Over the past 40 years, research on eye movements in reading has been instrumental in developing our understanding of cognitive mechanisms underpinning the ability to read and understand text in real-time (for a review, see Rayner, 2009). This is because eye movements are intrinsic to reading and allow researchers to examine the behaviour while it is carried out naturally. It is also because there is a close correspondence between the movements of the eyes and underlying cognitive processes, so that quantitative measures of eye movements can provide a richly-detailed, moment-by-moment account of the underlying cognitive activity (Rayner, 1998, 2009). This contrasts with other methods for studying reading, which typically require participants to read text in unnatural formats (e.g., in studies using electroencephalography, i.e., EEG / ERP methods, for a recent review, see Bornkessel-Schlesewsky, Staub, & Schlesewsky, 2016; Swaab, Ledoux, Camblin & Boudewyn, 2012; see also Dimigena, Sommer, Hohlfeld, Jacobs, & Kliegl, 2011) or that lack the temporal resolution required to describe underlying neural processes in real-time (e.g., in studies using functional magnetic resonance imaging, i.e., fMRI; e.g., Skeide & Friederici, 2018).

It is argued, in particular, that the process of word identification is the engine that drives the forward movement of the eyes through text, such
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that how quickly the reader can identify a word will determine when and where the eyes move (Reichle, Pollatsek, Fisher, & Rayner, 1998). Research investigating variables affecting this dynamic eye movement behaviour has led to the development of sophisticated computational models that provide a current framework for investigating the cognitive basis of reading (e.g., Engbert, Nuthmann, Richter, & Kliegl, 2005; Reichle et al., 1998; Reichle, Rayner, & Pollatsek, 2003). However, much of this research has been conducted in Latinate languages, principally English and German, and so it is of increasing importance to examine the effects of these variables in other languages, to establish the extent to which the models apply cross-linguistically. The focus of the present chapter is on Arabic reading, as surprisingly little eye movement research had been conducted in this language. This is despite Arabic being one of the most widely-used alphabetic writing systems globally (second only to English), while possessing visual and linguistic characteristics very different from those of Latinate languages. Conducting eye movement research on Arabic reading (and the reading of other non-Latinate languages) is therefore important for establishing the extent to which mechanisms that are thought to account for eye movement control when reading Latinate languages might also apply cross-linguistically. Accordingly, with the present chapter, we will (1) summarise eye movement research in Latinate languages and briefly review those studies
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conducted in Arabic to date; (2) provide an overview of the Arabic writing system, focusing on characteristics likely to be of interest to eye movement researchers; and (3) outline key research questions that should be addressed to better understand the mechanisms of eye movement control in Arabic reading.

2. Mechanisms of Eye Movement Control in Reading

When reading, our eyes move by making a series of saccades (rapid eye movements lasting 20-30 milliseconds) separated by brief fixational pauses (see, e.g., Rayner, 1998, 2009). This behaviour is a consequence of limitations in retinal acuity, which is greatest within a narrow region at the centre of gaze (extending no more than about 1°), and declines sharply with increasing eccentricity from this location even within central vision (e.g., Hilz & Cavonius, 1974). As a result, only a very small portion of text (corresponding to no more than about 4-5 letters of normal-sized text) can be processed in high resolution on each fixation, so that readers must move their eyes and make multiple fixations to process a line of text. Crucially, from the perspective of the eye movement researcher, quantitative measures of these eye movements can provide valuable information about how a reader processes text. In particular, while each
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fixation lasts about 250 milliseconds on average (when reading Latinate languages like English or German), there is considerable variability in their actual duration, and precisely how long the reader’s eyes dwells on a word has been shown to closely reflect the difficulty experienced in processing that word (see Rayner, 2009). There is also considerable variability in the length of saccades. Typically, these traverse about 7-9 character spaces, roughly equivalent to the distance between the midpoints of adjacent words in text in English. However, saccades can be much shorter and cover as little as one character space, such as when the readers make corrective saccades to re-fixate words optimally (Bowers & Polletti, 2017; Nuthmann, Engbert, & Kliegl, 2005); or much longer, such as during a return sweep, where the reader makes a saccade that carries their gaze from roughly the end of one line of text to the beginning of the next (Parker, Nikolova, Slattery, Liversedge, & Kirkby, 2019; Slattery & Vasilev, 2019). Readers will also sometimes make a forward saccade that skips a word, so that the word is not fixated before the reader looks at the next words along in the text (e.g., Brysbaert, & Vitu, 1998; Drieghe, Rayner, & Pollatsek, 2005; Rayner, Slattery, Drieghe, & Liversedge, 2011; see also Rayner, 1998, 2009). Such behaviour is important as it suggests that saccade planning is sensitive to parafoveal processing (i.e., the pre-processing of upcoming words in a text).
3. The Perceptual Span for Reading

Given the limitations in retinal acuity, it is important to understand how much information can be acquired on each fixation. This has been addressed using gaze-contingent moving window paradigms (e.g., McConkie & Rayner, 1975, 1976; for a review, see Rayner, 2014). In these, the text is presented entirely as normal within a small region (window) at the point of fixation, while text outside the window is masked (by, for example, replacing letters in words with X strings). The window is yoked to the reader’s eye movements so that when they move their eyes to fixate a new location, text within the window at this new location is shown normally and text at the previous fixation location masked. This requires high-speed computing and displays with very fast refresh rates to ensure that changes to text displays are made sufficiently rapidly (typically within 10 ms of fixation), so that the reader’s phenomenological experience is that the window moves in synchrony with their eyes. In addition, the size of the moving window often is varied across an experiment, following the logic that windows that produce reading rates similar to when the text is shown entirely as normal must contain all the information required for normal reading.

The area of text that encompasses this information is described as
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the reader’s *perceptual span*. For skilled young adult readers of languages like English, this extends approximately 3-4 characters to the left of the fixated word (and so includes the beginning of the currently fixated word) and about 14-15 characters (or approximately two words) to the right (e.g., McConkie & Rayner, 1975, 1976; Rayner, Well, & Pollatsek, 1980). The perceptual span (for languages like English) is therefore asymmetric. This asymmetry is not solely a function of acuity, however, but widely believed to reflect greater allocation of attention in the direction of reading to facilitate the pre-processing of words and to guide decisions about where next to move the eyes (Balota, Pollatsek, & Rayner, 1985; Briihl & Inhoff, 1995; Drieghe, Rayner, & Pollatsek, 2005; McConkie & Rayner, 1975; Rayner, 1975a; Rayner, Well, Pollatsek, & Bertera, 1982; White, Johnson, Liversedge, & Rayner, 2008; for a review, see Schotter, Angele, & Rayner, 2012).

As this asymmetry is believed to be a function of reading direction, several studies have investigated whether it changes for languages, such as Arabic, Hebrew and Urdu that are read from right to left compared to languages like English that are read from left to right. Such studies have investigated the perceptual span of bilingual readers who are native readers of a right to left language and proficient in English. A seminal study by Pollatsek, Bolozky, Well, and Rayner (1981) examined the perceptual span for a small sample (*N*=6) of Hebrew-English bilinguals.
They used a paradigm similar to that used in previous perceptual span studies, and compared effects for moving windows that extended asymmetrically to the right or left of fixation (where letters in words outside the windows were replaced with ‘x’s) with text shown entirely as normal. The results revealed that the perceptual span for English extended asymmetrically to the right, as observed previously for native English readers. However, for Hebrew, this asymmetry was reversed, so that the perceptual span extended asymmetrically to the left of fixation, consistent with greater allocation of attention in the direction of reading.

A subsequent study by Jordan et al. (2014) addressed this same question but with a larger sample size ($N=12$) of readers who were bilingual in Arabic and English (and a follow-up study by Paterson et al., 2014, investigated the same issue with Urdu-English bilinguals). In this study, native Arabic-speaking participants with good English abilities read sentences in Arabic or English (in separate sessions). The sentences were displayed either entirely normally or text was presented as normal only within gaze-contingent moving windows. By contrast with previous studies, however, Jordan et al. used a blurring technique rather than letter substitutions to mask words outside the moving windows. They took this approach because it is standard for Arabic to be written in a proportional font as cursive text (i.e., where letters join together in words) and substituting letters in words would disrupt the normal visual appearance of
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the text. The blurring, by comparison, allowed them to effectively mask the identities of words while preserving the approximate orthographic properties of words and their layout in the text, thereby preserving the normal visual appearance of text. The findings from this study broadly replicated those reported by Pollatsek et al. (1981), showing that the perceptual span extends asymmetrically to the right in English, and asymmetrically to the left in Arabic, for this bilingual population, providing further evidence that perceptual span asymmetries are a function of reading direction.

4. Word Factors Affecting the Spatial and Temporal Characteristics of Eye Movements

Research on the spatial and temporal characteristics of eye movements in reading has been crucial for revealing the influence of the visual and linguistic characteristics of a text on when and where the eyes move (Rayner, 1998, 2009), and central to the development of models of eye movement control (e.g., Engbert et al., 2005; Pollatsek et al., 2006; Reichle et al., 1998, 2003). This research provides compelling evidence that eye movements are under cognitive control, such that processing difficulty associated with the characteristics of words directly influences
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eye movement behaviour (see, e.g., Rayner, Sereno, & Rayney, 1996). The central claim is that three variables (a word’s length, familiarity, operationalized as the frequency of its written usage, and its contextual predictability) primarily guide eye movements during reading, by influencing the time spent fixating words and the likelihood of skipping these words.

Numerous studies show the influence of these factors when reading Latinate languages. First, short words tend to be read more quickly and skipped more often than longer words (e.g., Joseph, Liversedge, Blythe, White, & Rayner, 2009; Juhasz & Rayner, 2003; Kliegl, Grabner, Rolfs, & Engbert, 2004; Paterson, McGowan, & Jordan, 2013; Rayner & McConkie, 1976; Rayner, Sereno, & Raney, 1996; Rayner, Slattery, Drieghe, & Liversedge, 2011; Vitu, O’Regan, Inhoff, & Topolski, 1995). Moreover, words that have a high lexical frequency are read more quickly and skipped more often than lower frequency words (e.g., Inhoff & Rayner, 1986; Rayner & Duffy, 1986; Rayner, Sereno, & Raney, 1996). Finally, words that are more predictable from the preceding sentence context are read faster and skipped more often than words that are less predictable (Balota et al., 1985; Brothers, Swaab, & Traxler, 2015; Brothers, Swaab, & Traxler, 2017; Ehrlich & Rayner, 1981; Rayner & Well, 1996; Staub, 2015). Taken together, such findings show that the movements of the eyes during reading are strongly influenced by the
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visual, lexical and contextual characteristics of words.

Other studies point to word-based influences on where saccades tend to land during reading. Most end in fixations on words rather than the spaces between words, suggesting that the oculomotor system aims saccades towards words using low spatial frequency cues to word boundaries (i.e., word-shaped blobs separated by spaces). Saccades towards upcoming words in text also exhibit a systematic tendency to land at a so-called preferred viewing location (PVL) between the word’s beginning and middle letters, certainly in Latinate languages like English (Rayner, 1979). This further suggests that low spatial frequency cues are used to target saccades towards the centre of words but that these often fall short of this location. This is attributed to random error in oculomotor control and also the range effect, which is a tendency to overshoot close targets and undershoot more distant targets (McConkie, Kerr, Reddix, & Zola, 1988). Consequently, not all saccades land at the PVL, and saccades often will land further to the left in longer words and sometimes overshoot the centre of short words (Joseph et al., 2009; McConkie, Kerr, Reddix, & Zola, 1988; Paterson et al., 2013). Other evidence that readers benefit from saccades that land at the PVL comes from the finding that readers tend to make longer fixation and are less likely to re-fixate a word (i.e., make more than one fixation on it) when the landing position is at the PVL than the beginning or end of words (e.g., Nuthmann, Engbert & Kliegl, 2005;
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Rayner et al., 1996; Vitu, McConkie, Kerr & O’Regan, 2001).

These findings suggest that words are recognized most efficiently when fixated at the PVL and that readers will make a corrective eye movement when saccades land at sub-optimal locations towards the beginning or ends of words. This has also led to the widespread belief that there must be some correspondence between the PVL and the optimal viewing position (OVP) effect reported in studies of isolated word recognition (e.g., Hyönä & Bertram, 201; Jordan, Paterson, Kurtev, & Xu, 2010; Li et al. 2017; O'Regan, 1980; O'Regan & Jacobs, 1992; O'Regan, Lévy-Schoen, Pynte, & Brugaillerè, 1984; Vitu, O'Regan, & Mittau, 1990). In these studies, words are displayed to participants at different horizontal offsets relative to a specific screen location that participants are instructed to fixate, so that the participant initially will fixate a specific inter-word position (e.g., the first, middle, or end letter). The standard finding from studies conducted in Latinate languages is that participants are quicker to recognize words (measured by word naming or lexical decision latencies, or the duration of fixations on the words) when these are fixated at locations between their beginning and middle letters. Based on the similarity between the OVP and the PVL, it often is assumed that this shows that saccades are targeted towards the PVL in textual reading to optimize word recognition.

This view is also relevant when considering OVP and PVL effects
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for Semitic languages like Arabic and Hebrew. Studies of OVP effects shows that, in contrast with effects for Latinate languages, words in these languages generally are recognized most efficiently when fixated at their centre rather than between the beginning and middle letters of words (Deutsch & Rayner, 1999; Farid & Grainger, 1996; Jordan, Almabruk, McGowan, & Paterson, 2011). Various explanations of this difference in OVP effects have been proposed, including that it reflects morphological structure, and therefore the location of information about the core meaning of a word, which differs for Semitic languages like Arabic and Hebrew compared to Latinate languages like English (see Stevens & Grainger, 2003). We will return to this issue when we discuss the characteristics of the Arabic writing system.

5. Parafoveal Processing in Reading

As already noted, readers acquire parafoveal information from upcoming words to pre-process these words and guide saccade-targeting. This raises the question of what information is processed parafoveally and, indeed, whether words are processed serially, one at a time during reading, or in parallel. Evidence in answer to these questions generally comes from research using gaze-contingent boundary paradigms (Rayner, 1975a; for
reviews, see Hyönä, 2011; Schotter et al., 2012). In these, an invisible boundary is placed immediately in front of a specific target word in a sentence. Prior to the reader crossing the boundary, this word is shown entirely as normal (a valid preview) or changed (an invalid preview). The invalid preview can be created by changing all the letters in the word, typically while maintaining word length. When the participant makes a saccade that crosses the boundary, a display change is initiated so that the preview word is replaced by the target word. This display change requires high-performance computing and a display screen with a fast refresh-rate to ensure it is implemented quickly, ideally before the saccade ends (and so within 20-30 ms), and without the participant’s conscious awareness. To be certain about this, at the end of the experiment the participant is usually asked if they noticed any display changes. Trials in which display changes were noticed are removed from analyses, and the participant’s entire dataset may be excluded if they noticed too many changes.

The principal consideration in these experiments is whether a preview benefit is observed. This is a processing advantage for the target word (i.e., shorter reading times) when the preview is valid rather than invalid. Such a finding demonstrates that the readers acquired parafoveal preview information prior to the boundary change and that their reading performance was influenced by this preview information. It is also possible, by manipulating the relationship between the preview and the
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target word, to investigate what information is processed parafoveally. For instance, numerous studies show a preview benefit when the target word (e.g., song) and preview (e.g., sorp) share the same beginning letters and are similar in shape (Rayner, 1975a, 1978; Rayner, Balota, & Pollatsek, 1986; Rayner, McConkie, & Zola, 1980). This suggests readers acquire orthographic information parafoveally and that preserving the first couple of letters in words can facilitate target word recognition, presumably because this information helps initiate lexical access (Balota, Pollatsek, & Rayner, 1985; Briihl & Inhoff, 1995; Drieghe, Rayner, & Pollatsek, 2005; Inhoff, 1987, 1989a, 1989b, 1990; Inhoff & Tousman, 1990; Lima & Inhoff, 1985; Rayner, 1975b; White, Johnson, Liversedge, & Rayner, 2008). Other studies show that phonological information can also be acquired parafoveally, so that there is a preview benefit when the preview and target word sound similar but are composed of different letters (i.e., using either homophones such as bear and bare, or pseudohomophones such as brain and brane; e.g., Pollatsek, Lesch, Morris, & Rayner, 1992; see Schotter et al., 2012, for a review). Whether semantic information is processed parafoveally is more controversial. This does not appear to be the case in English, as no preview benefit is observed when the preview and target words are semantically related (e.g., tune & song; Rayner, Balota, & Pollatsek, 1986). However, such effects have been reported in German (Hohenstein, Laubrock, & Kliegl,
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2010) and Chinese (Yan, Richter, Shu, & Kliegl, 2009). Similarly, whereas evidence seems to suggest that Hebrew readers extract morphological information from upcoming words in the parafovea (Deutsch, Frost, Pelleg, Pollatsek, & Rayner, 2003; Deutsch, Frost, Pollatsek, & Rayner, 2000, 2005), investigations in English have failed to replicate the same findings (Inhoff, 1989; Juhasz, White, Liversedge, & Rayner, 2008; Kambe, 2004). This raises the possibility that the extent to which parafoveal processing is observed may vary cross-linguistically depending on the nature of the orthography and other characteristics of the writing system.

6. Models of Eye Movement Control in Reading

Research discussed in the above sections has been the basis for the development of computational models of eye movement control. These provide an explicit formalization of theoretical accounts that have used to simulate key findings in the literature and to generate and test theoretical predictions. Two currently dominant models, the E-Z Reader model (Pollatsek, Reichle & Rayner, 2006; Reichle et al. 1998; Reichle, Rayner, & Pollatsek, 2003) and the SWIFT model (Engbert & Kliegl, 2012; Engbert, Longtin, & Kliegl, 2002; Engbert, Nuthmann, Richter, & Kliegl,
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2005), build on an earlier generation of models that aimed to explain perceptual and attentional processes in reading, including the Morrison model (Morrison, 1984) and the Mr. Chips ideal-observer model (Legge, Klitz, & Tjan, 1997). We briefly outline these two models, along with the more recent OB1 model (Snell & Grainger, 2019; Snell, van Leipsig, Grainger, & Meeter, 2018).

All three models start from the assumption that readers acquire linguistic information from within a narrow region (the perceptual span) across which attention is distributed and that, due to acuity limits, words nearer fixation are seen most clearly. An important distinction between these models, however, relates to the extent to which words within the perceptual span are processed serially or in parallel. A key assumption of the E-Z Reader model is that words are identified serially, in the order in which they appear in the text. According to this model, an initial stage of pre-attentive visual processing informs a two-stage process of lexical identification, inspired by activation-verification models of word recognition (e.g., Paap, Newsome, McDonald, & Schvaneveldt, 1982). During the first stage, called the familiarity check (called L1), the system assesses if the currently fixated word is likely to be recognized imminently. This decision is influenced by information about word length, frequency and predictability, and is completed faster if the word is short, high frequency or highly predictable. Full lexical identification is slower,
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however, and only achieved following completion of a second stage of lexical identification (called L2), during which information about the word’s orthography, phonology and meaning is accessed. Once the familiarity check is complete, the system begins programming a saccade and shifts attention to the next word. As soon as attention is switched to the next word, this initiates a familiarity check for this word. If this is completed before saccade-programming finishes, the saccade is terminated and a new saccade program initiated that will skip the next word and target a word following it. The likelihood of this occurring is a function of the length, frequency, and predictability of the next word, so that the model uses sequential shifts in attention to account for parafoveal processing and word-skipping.

Compared with E-Z Reader, SWIFT allows for multiple words to be processed in parallel and assumes that saccade programming is not directly informed by lexical identification. In this model, attention is allocated as a distributed gradient across words. This allows parallel lexical processing of several words at a time, although as the attention gradient allocates most attention to the fixated word and less to words further from fixation, words will be processed at different rates. Decisions about when to make a saccade are determined by a random timer, and saccades directed towards the word that is most active in the attention gradient but not yet lexically identified. Although these decisions are not
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triggered by word identification in the model, difficulty with lexical processing can interrupt this process to delay the system making a saccade. Finally, word-skipping occurs because of parallel lexical processing and takes place when the next word along has already been identified prior to the completion of a saccade programme so that the subsequent saccade is directed towards a later word in the sentence.

OB1 is a more recent example of a parallel-graded attention model that also incorporates the assumption that multiple words can be processed in parallel. Similarly to SWIFT, it also assumes that saccades are generated at a random pace but can be inhibited when word recognition is difficult, and that saccades are targeted towards words that are most active in the attention gradient but not yet identified. A distinctive feature of OB1 is that it includes an account of lexical and sub-lexical processing (at the level of letters and bigrams) while existing models do not incorporate specific mechanisms for word recognition.

Despite their differences, both E-Z Reader and SWIFT models can successfully predict visual and lexical influences on eye movements during reading (and see Reichle, Warren, & McConnell, 2009, for a version of the E-Z Reader model that tackles higher level language processing). An important concern for the present chapter is whether these models can, in principle, account for these influences on eye movement control during Arabic reading. This is important because it provides
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evidence for the cross-linguistic generalizability of the different models and creates a framework for future research.

7. The Arabic Writing System

Arabic belongs to the Semitic subgroup of Afro-Asiatic languages which include Hebrew and Maltese. It uses a phonemic alphabet with 28 letters (Abu-Rabia, 1997; Daniels, 2013). Some letters are visually similar, in the sense they share the same grapheme, and are distinguishable by the number and location of small dots (Alotaibi, 2007; Perea, Abu Mallouh, Mohammed, Khalifa & Carreiras, 2016). For example, the letters /b/ (ب), /t/ (ت), /θ/ or soft th (ث) share the same basic grapheme but differ in the numbers of dots above or below it. Text in this language is read horizontally from right to left and printed in cursive script in which most letters in words link with the letters to each side using short horizontal lines (called ligatures). There are six letters (ودزذرذ) that are exceptions to this. These link only to the preceding letter and so create spaces that divide words into separate parts. Some letter shapes change because of this linking between letters and their location in words (see Carreiras, Perea & Abu Mallouh, 2012; Daniels, 2013; see also Boudelaa, Norris, Mahfoudhi & Kinoshita, 2019). For instance, the letter ‘ayn’ can
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be written as ـع، ـع، or ـع depending on whether it occupies a beginning, medial or end location in words, and as ـع when it is not followed by another letter and follows one of the six exception letters that do not link with other letters. Finally, all letters in Arabic are phonemic consonants except for three (ا، و، ي) that can additionally serve as long vowels. Short vowels are occasionally represented using additional small diacritic mark above or below a consonant. For example, adding different diacritics to the consonants /k_t_b/ (كُتُب) changes the pronunciation and meaning to /kataba/ (كتاب) meaning “he wrote”, /koteba/ (كتبا) meaning “it’s written” and /kotobon/ (كتب) meaning “books”. Therefore, the presence of diacritics increases the transparency of the language by making the relationship between letters and the sounds they represent clearer (Abu-Rabia & Taha, 2005). However, other than in religious texts or books for children, diacritics are only rarely used in written Arabic and usually only to disambiguate words (Hermen et al., 2015; Lallier et al., 2018).

Latinate languages convey inflectional meaning by appended prefixes or suffixes to a word’s root. For instance, “print” can be inflected using suffixes to produce “printed” or “printer” and a prefix to produce “reprint”. By comparison, Arabic uses a non-concatenative morphology in which the root and inflectional parts of a word intermingle (Abu-Rabia, 2002; Boudelaa & Marslen-Wilson, 2001, 2004). The root in Arabic usually corresponds to three consonants, while the word pattern is a
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sequence of letters that provide inflectional meaning about word class, gender and number. These two units intermingle such that, while root letters retain their order, they are interspersed with the word pattern. For example, the verb /jaktubu/ (يَكِتُب) meaning “he writes”, the noun /keta:ba/ (كتبة) meaning “writing”, and the noun /ka:teb/ (كاتب) meaning “writer”, are all derived from the three-letter root /k_t_b_/ (كتب) by interweaving the root with different word patterns. Because of this interweaving, letters conveying the core meaning of a word are much less likely to appear at the beginning of a word in Arabic compared to concatenative languages like English. This is potentially important as these beginning letters can provide valuable parafoveal information when reading Latinate languages like English (e.g., Blanchard, Pollatsek, & Rayner, 1989; Rayner, McConkie, Zola, 1980; for a review, see Schotter, Angele, Rayner, 2012), and so the absence of this information in Arabic words may limit parafoveal processing when reading this language.

More generally, because of their morphology, Arabic words tend to be more linguistically dense compared to words in Latinate languages like English. They are generally short, with 90% of Arabic words between 4 and 8 letters long (Boudelaa & Marslen-Wilson, 2010), while often expressing complex meanings. For instance, the five-letter word /katabata/ (كتابات) translates as the four-word phrase “the two females wrote” in English. This greater complexity of orthography and morphology might
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increase the word decoding time, potentially resulting in slower reading speeds for Arabic compared to other languages (Brysbaert, 2019; Hermena et al., 2019; Roman & Pavard, 1987; see also Liversedge, Drieghe, Li, Yan, Bai & Hyönä, 2016).

8. Eye Movement Research on Arabic Reading

There is a growing body of research on Arabic word recognition (but see, Almabruk, Paterson, McGowan, & Jordan, 2011; Boudela, 2004; Boudela, Norris, Mahfoudhi, & Kinoshita, 2019; Boudela & Marslen-Wilson, 2001, 2004, 2005; Carreiras, Perea, & Abu Mallouh, 2012; Carreiras, Perea, Gil-López, Abu Mallouh, & Salillas, 2013; Duñabeitia, Kinoshita, Carreiras, & Norris, 2011; Farid & Grainger, 1996; Gómez, Ratcliff & Perea, 2008; Jordan, Paterson, & Almabruk, 2010; Jordan, Sheen, AlJassmi, & Paterson, 2015; Lallier et al., 2018; Perea, Abu Mallouh, García A-Orza & Carreiras, 2011; Perea, Abu Mallouh, Mohammed, Khalīfa, & Carreiras, 2016; Perea & Lupker, 2003; Perea, Mallouh & Carreiras, 2010; Perea, Mallouh, & Carreiras, 2013). However, there are surprisingly few studies of eye movement control even fewer studies have investigated mechanisms of eye movement control in Arabic reading, despite the very different features of this language compared to
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Latinate languages like English that have been the focus of research to date. In an earlier section, we outlined one of the few such studies, which reported an eye movement experiment on perceptual span effects in Arabic reading (Jordan et al., 2014). This showed that, as with Hebrew, the perceptual span is asymmetrically longer to the left of fixation in Arabic reading. Several other eye movement studies have investigated other aspects of word and sentence processing during Arabic reading, including factors, such as word length and lexical frequency, that have a central role in eye guidance in current models of eye movement control in reading.

One study that investigated word length effects examined eye movements while reading sentences containing either a 3-, 5-, or 7-letter target word (Paterson, Almabruk, McGowan, White & Jordan, 2015). These words were matched for contextual predictability and lexical frequency (using the Aralex database of Arabic word frequencies; Boudelaa & Marslen-Wilson, 2010), across the word lengths. Words in Arabic with the same number of letters can vary quite substantially in spatial length because individual letters vary in width. In this study, the words were carefully selected so that letter and spatial lengths were closely matched. Reading times were much longer than for the same length of words in Latinate languages like English (see Rayner, 2009), which may be a consequence of the greater information density of Arabic
words (e.g., Roman & Pavard, 1987). However, as with languages like English, longer letter length was also associated with increased reading times and higher re-fixation probabilities for words. Moreover, this effect was observed during the initial processing of the words (prior to the reader fixating words to the left and so later in the sentence), and so the study provided clear evidence that, as with Latinate languages, word length influences decisions about when to move the eyes in Arabic reading. Word length effect on word-skipping, by contrast, were restricted to the 3-letter words (with no difference between 5-letter and 7-letter words) and even then the skipping rates were much lower than reported for Latinate languages like English (only 10% for 3-letter words). Consequently, while word length also influenced decisions about when to move the eyes, skipping rates were generally very low and largely insensitive to word length. The study also looked at the landing positions of saccades on these words and found that these tended to land between the beginning and middle letters of the longer words (and so slightly to the right of word centre) and to slightly overshoot the centre of short words. This is essentially the same pattern as reported for Hebrew (Deutsch & Rayner, 1999), and opposite to that reported for Latinate languages, and so suggests that word length information is used for saccade-targeting similarly across these languages.

Hermenä, Liversedge and Drieghe (2017) expanded upon the
findings of Paterson et al. (2015) in a study that aimed to disentangle the effects of letter and spatial length on reading times and saccade-targeting. To do so, they exploited the natural variability in the spatial length of words containing the same number of letters when Arabic words are printed using a conventional proportional font in which letters are not equally wide. Hermena et al. selected a set of 5-letter and 7-letter target words that were matched for spatial length so that these sets of words occupied the same amount of horizontal space that was classified as either narrow or wide (wider 5- and 7-letter words were about 10 pixels wider than narrow 5- and 7-letter words). The researchers presented these words in sentences using a proportional Arabic font. Hermena et al. also found that reading rates were high and word-skipping rates were low compared to those of Latinate languages like English. However, their results also showed that number of letters rather than spatial length determined the reading times for words. However, saccadic control was influenced exclusively by the spatial length of words, so that word-skipping and saccade landing positions were influenced by spatial length and not the number of letters in words. Hermena et al. also examined the influence of initial bigram characteristics on saccade-targeting. Participants read sentences containing 6- or 7-letter target words with initial bigrams that were (a) very high frequency (ـﻟا, /al/, meaning the), (b) relatively high frequency (ـﻠﻟ, /lel/, meaning for the), or (c) low frequency, where initial
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bigrams belonged to the word stem. They found that landing positions were insensitive to the initial bigram frequency and that saccades always landed towards the centre of words, providing evidence that saccadic control is insensitive to word orthography in Arabic reading.

A further study by Hermena and his colleagues examined frequency effects on eye movements in Arabic reading (Hermena, Liversedge, Bouamama, & Drieghe, 2019). They did this by embedding in sentences words that were of high or low frequency but matched for length (i.e., number of letters and spatial length) and contextual predictability. Again, reading times were high and word-skipping rates were low compared to Latinate languages like English. However, readers made fewer fixations and had shorter reading times for the higher frequency words, as observed for Latinate languages. However, skipping rates for these words were low (less than 4%) and did not differ for high- compared to low-frequency words. This suggested that, in Arabic reading, readers are less likely to use information about the lexical frequency to skip words. With a follow-up experiment, Hermena et al. examined the influence of frequency of a word’s root (i.e., the consonantal trigram that conveys the core meaning of the word). They found no effect on reading times when words were matched for overall word frequency (as well as length and predictability) but had either a high or low root frequency, suggesting that familiarity with the core meaning of the word did not
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influence the process of lexical identification during reading. Studies conducted to date therefore provide evidence that two of the three principal factors that guide the lexical processing of words during reading in Latinate languages also influence reading times for words but have a much weaker influence of word-skipping in Arabic reading. It will also be important to establish whether contextual predictability influences eye movement control during Arabic reading and, in particular, whether it can facilitate parafoveal word recognition and so potentially increase skipping rates for words.

Several other eye movement studies have investigated the processing of diacritics during Arabic reading. These, as we described earlier, are small marks used to indicate vowel information that are placed above or below the consonants in the word. These are not widely used in modern writing, except in religious texts and children’s books, or occasionally in other texts to disambiguate words. One study, by Hermena, Drieghe, Hellmuth, & Liversedge (2015) investigated the processing of this information in normal reading by presenting participants with sentences that either contained no diacritics, were fully vowelized by including diacritics in every word, or where diacritics were used only to disambiguate a specific homographic verb (as passive) in the sentence. Compared to sentences containing no diacritics, the fully vowelized sentences took slightly (but reliably) longer time to read, as they had fewer
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fixations that were longer in duration. Hermena et al. explained this in terms of increased visual crowding due to the added diacritical marks. In addition, reading times were shorter when homographic words were disambiguated using diacritics compared to when not, indicating that skilled Arabic readers can make rapid use of diacritic information to disambiguate words. However, this benefit of diacritics was not observed when sentences were fully vowelized, indicating that the selective use of diacritics in most modern Arabic writing serves also to cue readers to the presence of an ambiguity. By comparison, this information may have been redundant in fully vowelized sentence and so no longer served as an effective cue to ambiguity.

A follow-up study by Hermena, Liversedge, and Drieghe (2016) investigated whether diacritics are processed parafoveally (that is, preprocessed before the word is fixated or skipped). They used the boundary paradigm described earlier. In the experiment, an invisible boundary was placed immediately before target word which was always a heterophonic homographic noun that had a dominant or subordinate meaning (based on the form of diacritization/ pronunciation). Three types of preview were created for words that were disambiguated in favour of the dominant meaning by the use of diacritics (e.g., as in ﺑُدْرُ /qadaru/, meaning destiny). In one, the preview provided the accurate diacritic information. In another, the preview provided inaccurate diacritics that
disambiguated the word in favour of an alternative meaning (e.g., ﻗَدْرَ), / qedru/, meaning pot). A third preview provided no diacritic marks so that the preview was ambiguous between the two meanings (e.g., ﻗَدْرَ, / qadaru/ or / qedru/, could mean destiny or pot). Compared to accurate previews, inaccurate previews produced longer reading times on these words, and the parafoveal processing effects of accurate or inaccurate previews were heavily modulated by the launch distance. Launch distance refers to the distance between the location of the fixation on the pretarget word, and the location of the initial fixation on the target word. In line with previous research findings, the obtained effects were greater for closer launch sites. The results therefore indicated that, subject to the quality of the parafoveal preview (as determined by launch distance), diacritic information can be processed parafoveally to facilitate word disambiguation.

9. Final Comments and Future Directions

In the present chapter, we outlined the approach taken to investigating eye movements during reading in Latinate languages and described the relatively few studies that have investigated eye movement control during Arabic reading. These show that, like readers of Latinate languages, Arabic readers make similar use of letter length and lexical frequency to
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recognise words as readers of Latinate languages. Moreover, studies examining effects of word length on saccade-targeting show that Arabic readers use information about spatial length but not letter length to target their saccades towards the centre, which due to oculomotor error often land to the right of centre of longer words and land near the centre of short words. Such findings suggest that factors shown to be fundamental to eye movement control in Latinate language reading are also likely to have a key influence on eye movement control during Arabic reading.

Other aspects of the findings obtained to date also reveal interesting differences in eye movement behaviour when reading Arabic rather than Latinate languages like English and German. First, reading times tend to be longer in Arabic compared to Latinate languages, indicating that readers have greater difficulty identifying these words, potentially because of their greater informational density (e.g., Roman & Pavard, 1987). At the same time, whereas skipping rates for words in English can be 15% or higher depending on the difficulty of the text and expertise of the reader, skipping rates appear much lower in Arabic (typically less than 10%). Moreover, word-skipping is only weakly affected by word length (Paterson et al., 2015) and largely unaffected by the lexical frequency of words (Hermen et al., 2019), while saccade-targeting in general appears to be unaffected by the presence of highly familiar orthographic information at word boundaries (Hermen et al.,
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2017). Such findings point to more limited parafoveal processing during reading for Arabic compared to Latinate languages. It therefore will be important for research to determine why parafoveal processing is more limited in this language and to establish the boundary conditions under which parafoveal processing effects might be observed in Arabic reading.

Studies of the influence of diacritics on word recognition might provide the first insights into this. These are used occasionally in everyday text to disambiguate words and research by Hermena et al. (2016) shows that Arabic readers are sensitive to this information and have faster reading times when the presence of diacritics disambiguate words. However, there is little evidence that even this information is used extensively in parafoveal processing as the benefit of receiving accurate rather than inaccurate or no diacritic parafoveal previews of words was observed only when the prior fixation was very close to the word. This may be because these important cues to word identity are only visible to readers when the prior fixation is close to the word. Other aspects of the Arabic orthography also mitigate against observing clear parafoveal processing effects. In particular, because Arabic uses a non-concatenative morphology, those letters that convey the core meaning of a word are less likely to appear near the beginning of words in Arabic compared to in Latinate languages, and so also may be less visible to readers during parafoveal processing. Alternatively, reduced parafoveal processing and
lower skipping rates in Arabic reading may reflect both the greater complexity and ambiguity of Arabic words. The greater complexity is also a consequence of the morphological structure of the language. In particular, unlike in English, grammatical information about gender and number is included within the word rather than as a separate function word, with the consequence that Arabic words convey complex grammatical information that is unlikely to be processed parafoveally and may require that words are fixated more frequently during reading. Moreover, because vowels are not marked orthographically, and readers must use context to determine the meaning and pronunciation of words, this ambiguity in the orthographic form of a word may also require readers to fixate words more frequently. The characteristics of the Arabic script may also limit parafoveal processing during reading, resulting in lower skipping rates and longer reading times for words. Evidence from studies using cursive text suggests the use of cursive script slows the recognition of words (Roldán, Marcet, Perea, 2018; see also Yakup, Abliz, Sereno, & Perea, 2015). This may slow the recognition of fixated words and impede parafoveal processing during Arabic reading, while such effects are likely to be aggravated by the variability in letter shape depending on the location of letters in words and the characteristics of adjacent letters.

An obvious first step in addressing this question will involve examining the effects of contextual predictability on word recognition.
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This will be valuable for establishing the extent to which parafoveal processing is limited by other factors influencing the pre-processing of upcoming words. In particular, if the findings show that highly predictable words are skipped only when these are very short and grammatically very simple, this will provide good evidence that the grammatical complexity of Arabic words mitigates against these being easily recognised during parafoveal processing. It will also be important, however, for future eye movement research to consider the consequences of the characteristics of the Arabic writing system for different populations of readers, including developing child readers, older adult readers, and groups with specific visual or reading impairments.

Finally, it will be important to determine whether current models of eye movement control during reading can account for Arabic reading behaviour. Research to date certainly suggests that key variables implemented in these models to account for reading in Latinate languages are also important for modelling Arabic reading behaviour. However, it also seems likely that parameters in the models governing lexical processing and saccade-targeting will be required to account for longer reading times, reduced word-skipping and decreased parafoveal processing in this language. Such work nevertheless will be valuable for extending the reach of these models and understanding mechanisms of eye movement control for reading across different writing systems.
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