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Universal and specific reading mechanisms across different writing systems

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Abstract | Reading of alphabetic writing systems, such as English, has been extensively studied and most theories and models of reading are based on findings from these studies. This practice raises a practical question regarding whether findings from alphabetic writing systems can be extended to other writing systems, such as Korean or Chinese, and a more fundamental question about the universality of reading mechanisms. In this Review, we discuss how findings from different writing systems contribute to an understanding of the universal mechanisms of reading. We first describe the unique properties of different writing systems. Then we review evidence that points to universal mechanisms common to all writing systems, followed by evidence suggesting that readers of different writing systems develop specific perceptual and cognitive mechanisms for efficient reading. These findings suggest that computational models developed for alphabetic reading cannot always account for reading in other scripts. We conclude that studies in non-alphabetic writing systems are valuable in understanding the universal and script-specific mechanisms of reading.

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Inspired by the trend in the field of psycholinguistics to search for universality in language processing[1], reading researchers have tried to find universal cognitive mechanisms applied to reading in all writing systems[2,3]. A writing system is a method of visually representing spoken language using written letters or characters. Reading of alphabetic scripts (such as English) has been extensively studied, and most models and theories of reading are based on these studies[4,5]. However, conclusions obtained from studies of alphabetic scripts cannot necessarily be extended to other writing systems, which vary in appearance and in how visual symbols are mapped to sounds and meanings. Whereas alphabetic scripts such as English recode spoken language at the level of individual sounds, syllabic scripts such as Korean do so at the syllable level. By contrast, logographic scripts such as Chinese can represent word meanings without recourse to spoken language.

Researchers have investigated whether differences in writing systems are accompanied by differences in readers' cognitive mechanisms, or whether the mechanisms are universal regardless of writing system. The search for universal cognitive mechanisms of reading often takes the form of seeking computational models of reading that can apply across writing systems. Many models have been developed to explain core aspects of reading, such as word processing[6–8], sentence processing[9,10] and eye-movement control[11–13]. These models have inspired further studies and advanced the field's understanding of reading mechanisms. However, most of these models were developed to account for findings in English reading and no model to date has been systematically tested in different writing systems. Although some attempts have been made to extend alphabetic models to explain findings in other writing systems, most of these attempts made only minor changes to fit a small set of data from other languages[14], hoping to show that the model is sufficiently powerful to generalize to all languages. It remains unclear whether these models can indeed be used to capture reading of qualitatively distinct scripts. With the accumulation of studies in different languages, especially with findings from writing systems that are qualitatively different from alphabetic scripts (for example, logographic writing systems such as Chinese)[15,16], this question can now be addressed more extensively.

In this Review, we compare reading mechanisms across different writing systems, focusing mainly on word identification and eye movements during reading. We first delineate key properties that differentiate writing systems from each other. Then we review general principles of cognitive reading processes that are common across writing systems, followed by processes unique to different writing systems. Finally, we argue that studying reading mechanisms in non-alphabetic

a Mapping to phonology

Finnish	kissa	Letters represent phonemes
Korean	고양이	Characters represent syllables, each symbol within a character represents a phoneme
Chinese	猫	Characters represent syllables

b Grapheme forms

English	A a	uppercase lowercase
Arabic	قط ق	connected isolated
Arabic	بـ ـبـ ـب	letter at word initial, middle or end
Japanese	胃 い	kanji kana

c Word boundaries

English	lovely cat
Hindi	काली बिल्ली
Arabic	قطة جميلة
Japanese	素敵な猫
Chinese	可爱的猫

d Morphemes

English	post office
Finnish	postitoimisto
Chinese	邮局

Fig. 1 | **Unique properties of writing systems. a** | Examples of alphabetic, syllabic and logographic writing systems. All words mean 'cat'. **b** | Visual forms in different writing systems. The symbols in each line are different forms of the same letter, as indicated by the colours. **c** | Different ways that writing systems mark word boundaries. All examples mean 'lovely cat' and word boundaries, where present, are highlighted in blue. **d** | Morphemes in different writing systems. The first morpheme is highlighted in blue, and the second morpheme is highlighted in yellow.

writing systems is both necessary and extremely valuable. We conclude that although there are universal processing principles common to all writing systems, readers of different writing systems naturally adapt to a given script so that they can efficiently comprehend written text.

Unique properties of writing systems

There are more than seven thousand languages in the world and hundreds of them also appear in a written, or orthographic, format (http://www.ethnologue.com/). All writing systems use a script comprised of a collection of written symbols known as graphemes to represent spoken language. Writing systems are categorized as alphabetic, syllabic, or logographic according to how the graphemes map to spoken language[17–19] (FIG. 1a). Alphabetic writing systems, used to write languages such as English, French and Finnish, encode sound mainly at the phoneme level, enabling readers to pronounce a written word even if they do not know its meaning. Alphabetic scripts contain a small number of letters (according to one survey, from 16 to 166 letters, with an average of 36 letters)[20], with each phoneme usually represented by one or two letters (such as 's', 'oo'). By contrast, syllabic writing systems, such as Korean hangul and Japanese kana, represent spoken language at the syllable level with one character per syllable.

Logographic scripts such as Chinese, Japanese kanji, and Korean hanja mainly represent semantic information. In logographic writing systems, each character usually corresponds to a unit of semantic meaning, or morpheme. Thus, morphemes are the primary unit of these scripts. Each logographic character corresponds to a syllable, but the pronunciation of the character cannot be assembled from parts of the character as in alphabetic writing systems. Thus, readers of logographic scripts must memorize the pronunciation of each character.

In Chinese, there are more than 6,000 characters[21], and most characters represent a morpheme. Japanese kanji has more than 2,000 characters, borrowed from Chinese, used to write content words such as nouns[22]. Each Chinese character is presented within a box-like square, and is composed of one or more radicals, each of which is composed of one or more strokes. Some radicals are characters by themselves. In modern Chinese, about 66% of frequently used characters include one radical that represents the pronunciation of the characters to a certain extent (phonetic radical), with the other radicals representing the meaning of the characters[23]. However, the phonetic radical often does not have the same pronunciation as the whole character.

Cutting across these differences in how phonology is represented, many writing systems have multiple forms of each grapheme that map onto the same pronunciation (FIG. 1b). In alphabetic scripts, letters appear in upper and lower case (for example, 'A' and 'a'). In other scripts, such as Arabic, letters are written differently when they appear at different positions within a word and when they appear in isolation[24]. In syllabic scripts such as Japanese, a syllable can be represented by both the kana and the kanji forms[25].

Writing systems also differ with respect to the physical layout of words and sentences. Although graphemes are always arranged linearly, the direction varies across languages. Most languages are read from left to right, but some are read from right to left (Arabic and Hebrew) or from top to bottom (traditional Mongolian, currently used in Inner Mongolia, China). Writing systems also differ with regard to how the boundaries between words are marked. Most writing systems use inter-word spaces and/or other visual cues to mark word boundaries (FIG. 1c). By contrast, other writing systems, including Chinese, do not contain explicit demarcation of word boundaries and instead characters belonging to different words are presented contiguously with small spaces between characters.

Languages also vary in how morphemes are combined into words. For instance, word compounding enables construction of new words out of existing ones (FIG. 1d). For example, 'football' is comprised of two morphemes 'foot' and 'ball', with a meaning that derives from both morphemes. In some languages, such as Chinese, most words are compounds of two or more characters[26]. By comparison, the percentage of compound words is much smaller in English[26]. Whereas morphemes are a salient unit for logographic scripts, the number of letters that constitutes a morpheme varies across words in alphabetic scripts and there are no explicit markers to signal morpheme boundaries for most compound words.

In alphabetic and logographic writing systems, morphemes are attached to each other linearly; 'foot' is directly followed by 'ball' in 'football.' However, in some systems, including Hebrew and Arabic, morphemes are intermixed. In Hebrew, many words are composed

Graphemes
The smallest written units that represent sound (such as letters or letter strings that represent phonemes in alphabetic writing systems and characters in syllabic and logographic writing systems).

Phoneme
The smallest sound unit in a language that makes a word differ from other words.

Morphemes
The smallest meaning-bearing linguistic units (for example, 'baseball' contains the morphemes 'base' and 'ball' and 'cats' contains the morphemes 'cat' and 's').

of two morphemes: roots and word-patterns[27]. Roots usually consist of three consonants and carry the core meaning of the word. Word-patterns are other letters that together create variations on the meaning of roots. Neither roots nor word-patterns are independent words; only their interleaved combination forms a word. To illustrate this with English letters, the root 'g_d_l' can combine with the word pattern '_a_a_' to form the word 'gadal' (meaning 'he grew'). In standard written Hebrew and Arabic, vowels are omitted. Thus, despite being alphabetic scripts, the pronunciation of words is not fully represented in these written forms.

To sum up, different writing systems vary in how graphemes encode sounds, the visual forms of graphemes, physical layout and morphology. To successfully comprehend text in a particular writing system, readers have to take into account the unique properties of that system. Accordingly, these unique script properties may give rise to script-specific perceptual and cognitive processing mechanisms. In the next section, we first outline processes common to reading different scripts, which form the common basis of reading mechanisms.

Universal reading mechanisms

At a broad level, the structure of the cognitive processes for reading is similar across writing systems (FIG. 2). Readers interactively use knowledge stored in long-term memory (such as lexical, syntactic, semantic and world knowledge) and bottom-up input from the world (visual information) to comprehend words, sentences and texts[6,15].

Visual input is first encoded using the visual processing system, which detects the visual features of text, such as strokes of Chinese characters. Words are then identified by integrating visual information with stored knowledge about the visual forms of words. The identified word is further processed by the language processing system to access the associated stored meaning[29].

General cognitive functions such as visual processing, working memory, long-term memory and executive control, which are universal across languages, are used in reading[18]. Because of the constraints of visual perceptual acuity and working memory capacity, when reading any script, text is processed chunk by chunk with the help of attention[30]. Both overt and covert attention are involved. Overt attention involves selectively focusing on one location at the expense of others by moving the eyes to that location; covert attention involves doing so without an eye movement.

Studies have shown that words act as the basic processing units in all languages[18,31], even though writing systems differ in their physical layout and word boundaries are not always explicitly marked. Even in unspaced scripts such as Chinese, there is strong evidence that words are processed as holistic units[32–34]. Some studies have shown that disrupting words being processed as a whole slowed down Chinese reading[33,34]. During sentence reading, word length[35] and word frequency[36] have been found to influence word identification similarly across different languages[37], with words of shorter length and/or higher frequency being faster to read. Word predictability, which is the probability of guessing an upcoming word given the prior words, also influences reading so that highly predictable words are read more quickly[38,39]. Similar effects of word frequency and word length have also been reported in studies on single word identification[40]. The importance of words during reading has also been supported by eye-movement studies demonstrating that word properties affect eye movements in a similar way across languages[30,41].

The initial part of a word is more important than its final part in word identification in both logographic and alphabetic writing systems[42–44]. Moreover, when only part of a character is shown in Chinese, readers are less likely to recognize it if the initial strokes are removed compared with when the final strokes are removed[45,46]. Similarly, in English or in Korean hangul, readers recognize a word faster and more accurately when the upper half is shown than when only the bottom half is shown[47,48], suggesting that the upper half of a word is also more important for word identification than the bottom half.

Another universal processing mechanism in reading is that different grapheme forms map onto the same abstract orthographic word representation. Abstract orthographic representations are supported by the finding that recognizing a letter is faster when a letter with the same identity was recognized just before. This priming effect is comparable between visually dissimilar prime-target pairs (for example, a and A) and visually similar pairs (for example, c and C) in English[49,50]. Similar findings have been found for Arabic letters[51], Japanese kana[22,25,52] and Chinese radicals[51]. Abstract orthographic encoding enables readers to read scripts printed in different formats, as well as to contend with individual differences in handwriting styles.

Reading is an incremental process in that newly perceived information is integrated with existing information as soon as it becomes available[10]. Readers try to immediately integrate the perceived word into the evolving sentence structure to build a coherent representation of the text[53]. Readers also make inferences and predictions based on prior text information and their world knowledge[53,54]. As a result, reading times are influenced by the ambiguity and plausibility of word meanings

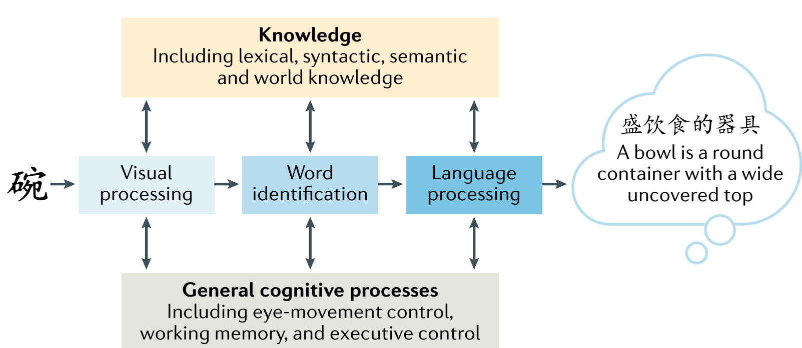

Fig. 2 | **Main processes of reading.** Readers of all scripts transform written language into a code that can be used by the language processing system to comprehend text. Readers use both top-down information (such as lexical, syntactic, semantic and world knowledge stored in long-term memory) and bottom-up information (visual information) interactively. General cognitive processes such as visual processing, eye-movement control, working memory and executive control are also used.

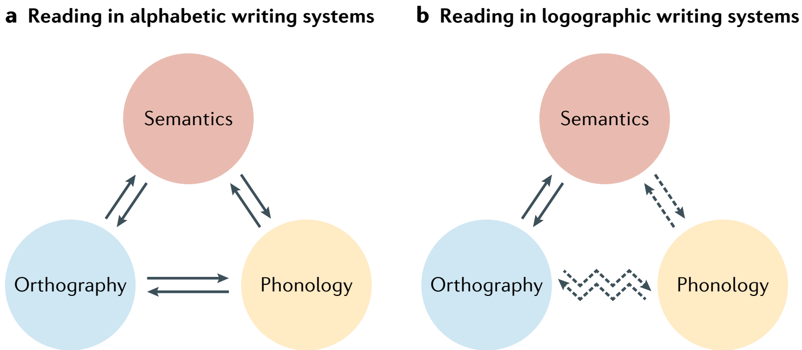

Fig. 3 | **Routes from visual forms to semantics for different scripts. a** | For alphabetic writing systems, information between the orthographic and phonological levels is cascaded so that the activation of orthographic units propagates continuously to phonological units, making use of both the direct semantic route and the phonologically mediated route (solid arrows). **b** | For logographic writing systems, the corresponding phonological units are activated only once a character is identified (stepped arrows); the role played by the phonologically mediated route is minimal for adult readers (dashed straight arrows).

and/or sentence structures[55,56]. In both alphabetic[9] and logographic languages[57], when a sentence structure is mis-parsed or a comprehension difficulty is encountered, eye-movement measures reveal that readers regress back to previous parts of text to resolve the confusion.

In summary, many aspects of the perceptual and cognitive mechanisms of reading are universal. Two factors might underlie these universal mechanisms. First, many features of written texts (for example the linear arrangement of text) are similar across scripts. Second, general cognitive processes (such as visual perception, working memory and long-term memory) that support reading are shared. These shared script features and language-independent perceptual and cognitive processes might have resulted in universal mechanisms of reading. Understanding universal reading mechanisms is important for a comprehensive picture of reading mechanisms, as well as providing a scaffold for understanding script-specific mechanisms.

Script-specific mechanisms

As described above, writing systems differ in terms of how they represent spoken languages, in their physical layout, in the way they demarcate words and in morphology. These differences affect how the perceptual and cognitive systems process different writing systems.

Routes from visual form to semantics

Readers process words in different ways based on how the writing system encodes spoken language. Most reading models assume that word identification includes the computation of orthographic (visual), phonological (sound), and semantic (meaning) codes based on the visual input, with the ultimate goal of accessing the meaning of words and text[7,8]. One influential word processing model, the triangle model, assumes that the meaning of a word be accessed through two routes. The direct semantic route encodes orthography directly into semantics, whereas the phonologically mediated route first encodes the orthography to phonology, and then encodes phonology to semantics[7].

For alphabetic writing systems, the two routes work simultaneously and interactively during reading[7,8,58,59] (FIG. 3a). The network consisting of the direct sematic route and the network consisting of the phonologically mediated route cooperatively compute semantics from visual form. In a cascaded fashion, word-level phonological units begin to activate before the complete specification of all letter units. Therefore, the phonologically mediated route can work cooperatively with the direct semantic route to activate semantic units when processing alphabetic scripts[59]. For syllabic scripts such as Korean hangul, whose relationship between orthography and phonology is unambiguous and direct, both the direct semantic route and the phonologically mediated route are used to access semantics[60,61].

Hebrew and Arabic are processed differently from other alphabetic writing systems[2,62,63] because phonology is not fully encoded. Thus, the exact pronunciation does not become available until the word is recognized. Because roots carry the core meanings of the word, some semantic information may be accessed before the activation of the full phonological representation, suggesting the use of the direct semantic route from orthography to semantics[64–66]. Only the combination of root and word-pattern morphemes yields the exact meaning for a specific word form, so word meaning can not be obtained by accessing the morphemes separately[63].

Unlike readers of alphabetic scripts, there is no clear evidence that adult readers of logographic scripts access word meanings through the phonologically mediated route[67–69] (yet phonology is still automatically activated)[68,70–75]. Studies in Chinese[67,76–78], Japanese kanji[79,80] and Korean hanja[60,61] have consistently shown that the direct semantic route from orthography to semantics has a dominant role in logographic reading and the phonologically mediated route plays a minimal part for adult readers (FIG. 3b).

The relationship between the direct semantic route and phonologically mediated route during single-word Chinese reading has been illustrated in a computational connectionist model[16]. In this model, the connections between the orthographic and phonological levels are activated on the basis of a threshold. That is, only when a certain orthographic threshold is reached are the corresponding phonological units activated[16,81]. This process for logographic languages corresponds to the fact that each spoken syllable in Chinese is mapped onto a whole character, and no part of the character corresponds to any subset of a syllable. Thus, it is impossible for a Chinese reader to know the pronunciation of a character before the character's lexical form is identified. Because the phonologically mediated route in logographic reading is much slower than the direct semantic route, it is highly unlikely that Chinese readers access word meanings through the phonologically mediated route. This threshold-style processing in Chinese reading contrasts with the cascade-style of information transformation between the orthographic and phonological levels in reading of alphabetic scripts[7,58].

These studies demonstrate that different routes from visual form to meaning are applied to the reading of different writing systems. For alphabetic and

Connectionist model
Neural-inspired computational network that propagates activation among simple units, also known as parallel distributed processing models.

syllabic writing systems, both the direct semantic route and the phonologically mediated route are used for converting visual form into meaning. For logographic writing systems, the direct semantic route is the major processing route.

Perceptual span and covert attention

The amount of information that can be processed when the eyes fixate on a single position in text is traditionally called the perceptual span, often measured in number of letters or characters around fixation. Readers must move their eyes to read text that is wider than the perceptual span. The width of the perceptual span is constrained by the general properties of the human visual processing system and covert visual attention. The foveal region, which has the highest-acuity vision, is narrow and is usually narrower than the width of perceptual span. The perceptual span is asymmetric; it is wider towards the right for scripts read from left to right (for English: 3–4 letters to the left of fixation and 14–15 letters to the right of fixation)[82–84] (FIG. 4). Two possible mechanisms have been proposed to account for the rightward asymmetry in the English perceptual span: hemispheric specialization and attentional bias[83].

The hemispheric specialization view suggests that the perceptual span asymmetry is due to the fact that information to the right of fixation is initially projected to the left hemisphere of the brain, which is specialized for language processing, thus generating wider span to the right of fixation. By contrast, the attentional bias view posits that attention is biased toward the reading direction, expanding the perceptual span to the right for scripts read from left to right. Studies on scripts written from right to left (Hebrew, Arabic, Uyghur and Urdu) revealed a perceptual span that is wider on the left, toward the reading direction[85–87], consistent with the attentional bias view[85]. Other studies have shown that the perceptual span is wider towards the bottom for languages read from top to bottom (traditional Mongolian and Japanese when read from top to bottom)[88,89]. For bilingual readers, the direction of the perceptual span asymmetry varies according to the properties of the particular language being read[85], suggesting that readers adapt to reading different scripts[90].

The perceptual span size also varies across scripts. As noted above, in English the perceptual span can extend up to 18–20 letters in total[82–84]. Cross-script variation in perceptual span width may reflect differences in the visual complexity of letters or characters[20]. Compared with English, the perceptual span is a bit narrower (18 letters in total) in reading Uyghur, which is written with Arabic letters, and even narrower (11–12 letters in total) for reading Tibetan[91], an alphabetic script containing letters that are visually more complex than the letters used in English. The perceptual span is also quite narrow (5 characters in total) in reading Chinese characters[84], supporting the hypothesis that script complexity influences span width.

Taken together, these findings suggest that readers adapt to their specific writing system by dynamically deploying attention[90]. The perceptual span is asymmetric toward the reading direction, indicating that visual attention is deployed preferentially toward the text that will be read next. Models of eye movements during reading make different assumptions regarding precisely how attention is deployed (BOX 1). Some models assume that attention is deployed serially, one word at a time, and attention shifts to the next word after the currently fixated word is identified[11]. According to E-Z Reader, for scripts read from left to right, attention typically shifts to the word on the right of fixation before the eyes move, resulting in a larger perceptual span toward right than left. Other models, such as SWIFT (Saccade-generation With Inhibition by Foveal Targets), assume that attention can be simultaneously deployed to multiple words[12,92]. According to SWIFT, because more attention is deployed to the right of fixation for scripts read from left to right, the size of perceptual span is bigger on the right side of fixation than left. Currently, there is support for both models and the exact mechanism of attention deployment during reading is still debated.

Reading without inter-word spaces

Readers of most alphabetic writing systems are accustomed to reading text with spaces between the words; inter-word spaces are used to group letters into words (word segmentation) and to plan eye movements. Inter-word spaces are perceived using low-level visual information with parafoveal vision (vision outside the high-acuity foveal region) to group letters into words. The removal of spaces from typically spaced text greatly interferes with reading comprehension[93,94]. Readers of languages that do not use inter-word spaces to demarcate words use different methods to group contiguous

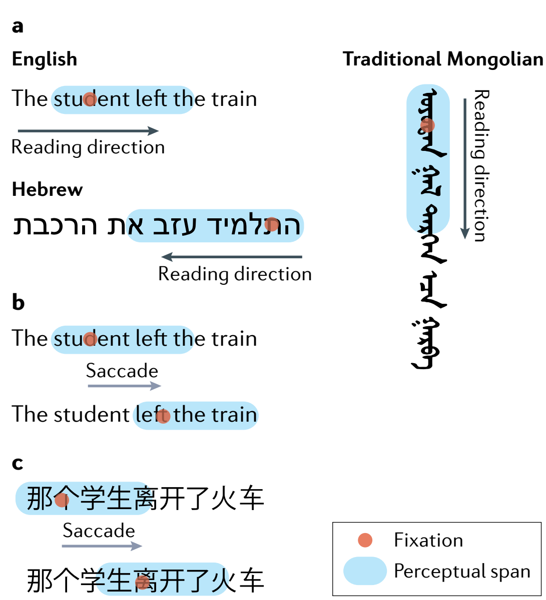

Fig. 4 | **Script physical properties influence attention and eye movements. a** | The perceptual span is asymmetric toward the reading direction (rightward for English, leftward for Hebrew, down for Mongolian). **b** | In English, a saccade is planned to the preferred viewing location of the next word, via parafoveal information from the current fixation. **c** | In Chinese, a saccade is planned to a location that contains novel information that has not yet been processed. All example sentences mean 'The student left the train'.

Visual complexity
The level of detail or intricacy contained within an image, reflecting the amount of psychological effort required to process the image.

Box 1 | **Models of eye-movement control during reading**

The first formal model of eye-movement control was E-Z Reader[11] (originally designed for English). This model assumes that only one word can be processed at any given time. After completing early processing of the fixated word, an eye movement is programmed to target the centre of the next word, with an eye movement executed after some delay. Only after the fixated word is fully identified, covert attention shifts to the next word and processing of next word starts. E-Z Reader has been used to simulate some findings in Chinese reading[14]. However, the Chinese version of E-Z Reader assumes that words are segmented as in the alphabetic writing system and that eye movements are controlled in a way that is similar to English reading. This model therefore fails to explain how words are segmented and how saccade targets are selected without the aid of inter-word spaces. However, the Chinese version of E-Z Reader still contributes to the understanding of Chinese reading even with this limitation (for example, the model made the word segmentation problem salient and therefore stimulated many studies on this topic)[101,106].

Other models assume that multiple words are processed in parallel[12,144]. One example is the SWIFT (Saccade-generation With Inhibition by Foveal Targets) model, originally developed for reading English and tested against German experimental data[12]. A challenge for parallel processing models is how word order is encoded during sentence reading. Encoding of word order is very important for comprehension; 'the boy kicked the girl' has a different meaning from 'the girl kicked the boy.' The OB1 Reader model was proposed to address word order encoding in alphabetic writing systems[13]. According to the OB1 Reader, readers use inter-word spaces available in parafoveal vision to perceive word length information of upcoming words, and then use word length information to determine the position of words within a sentence.

All these models are designed for alphabetic writing systems and do not offer solutions for reading unspaced scripts. By contrast, the CRM (Chinese Reading Model) was designed for Chinese reading to account for script properties unique to Chinese[15]. It integrates word processing, word segmentation and eye-movement control in a single model. The model has two modules: a word processing module and an eye-movement control module. The word processing module activates all possible word candidates comprised by the characters within the perceptual span. The activated (spatially overlapping) candidate words compete for activation. When a word wins the competition, it is simultaneously recognized and segmented. The eye-movement control module uses the activation information provided by the word-processing module to plan eye movements. The CRM posits that readers process as many characters as possible at a given fixation, and then move their eyes to a location containing novel information. The CRM successfully simulates many important findings in Chinese reading[99,111,113,145,146]. However, it is unknown whether the CRM can explain reading in other unspaced scripts.

No existing model can explain eye-movement and segmentation findings for both alphabetic and logographic writing systems. The question of whether words are processed serially or in parallel may take different forms for different writing systems. For scripts with explicit word boundaries, readers can segment words with parafoveal vision, and therefore it might be possible for them to process words serially (although debate continues[147–150]). Without inter-word spaces, readers do not know where the word boundaries are until the words within the perceptual span have been identified, so it is unlikely that they process only one word at a time. Accounting for findings in different writing systems seems to require a model that takes into account script-specific properties.

characters into words and to program eye movements between words. Thus, research using alphabetic scripts does not explain how words are visually processed in unspaced scripts[11,12].

Word segmentation. Some writing systems carry word boundary information even though they do not have inter-word spaces. In Thai, readers use misaligned vowels, relative letter frequency, and marks indicating tone to segment words during reading[28,95]. In Japanese, because kanji characters often appear at the beginning of words, this visually distinct character can indicate the start of a new word. When kana characters are surrounded by kanji characters, the kanji characters and following kana characters are more easily recognized as words, suggesting a role for kanji characters in word segmentation[96,97].

By contrast, Chinese text consists of continuous characters without any explicit word boundary information. This property sometimes leads to character strings that can be segmented in multiple ways[98–100]. For example, the three-character string '从小吃' can be segmented with the first two characters as a single word, to mean 'eat since childhood', or it can be segmented with the last two characters as a single word, to mean 'from snacks'. For successful text comprehension, readers must rely on word knowledge to segment words. A model called the Chinese Reading Model (CRM) has been proposed to explain how Chinese readers segment words without the aid of inter-word spaces[15,101] (BOX 1). According to the CRM, all possible word candidates within the perceptual span are activated, and these activated words compete for a winner. When a word 'wins' the competition, it is simultaneously identified and segmented from the surrounding text. Thus, word segmentation and word identification are a unified process in Chinese reading.

Saccade target selection. During sentence reading, readers of alphabetic writing systems target their eye movements (saccades) toward the word centre for short words and slightly left of the centre for long words (this target is known as the preferred viewing location (PVL))[102,103]. Fixating at the word centre is optimal for word processing because the maximal letters of the word fall on the fovea where visual acuity is best[102]. Fixation durations are usually longer when the eyes land at the word centre than when they land on word boundaries (known as the inverted optimal viewing position)[104,105]. The inverted optimal viewing position effect is caused by error-correction of mislocated fixations; when fixation is on a word boundary, readers immediately program a new saccade to a more optimal position, resulting in a shorter fixation for word boundary positions[105].

In comparison to alphabetic scripts, Chinese text does not have inter-word spaces. Thus, readers cannot pre-segment words using inter-word spaces in parafoveal vision and saccade to the centre of the next word. Indeed, there is no PVL around the word centre in Chinese reading[106]. Some studies have shown that the landing position of eye movements is more likely to be located at the word centre if there is only one fixation on the word than if there are multiple fixations[107,108]. A possible explanation is that if a reader's fixation happens to land on the word centre, they will not need another fixation within the same word. Some studies have provided evidence for this argument. First, a model that assumes that the eyes move a constant distance (with some variation) generates a very similar finding[106]. Second, reading of arbitrary character strings for which the neighbouring characters do not make up a word generates a very similar pattern of results[109]. In both cases, saccade programming is not word-based, so readers cannot attempt to saccade to the word centre. Therefore, the PVL peaking at the word centre during a single fixation cannot be treated as evidence that readers aim to saccade to the word centre. Taken together, there is no strong evidence suggesting that Chinese readers preferentially target the word centre when moving their eyes during reading.

Instead, Chinese readers might adopt a processing-based strategy for saccade target selection by processing as much information as possible at a given fixation and then moving their eyes to a location containing novel information[110]. According to this argument, saccade length will be longer when readers can process more characters to the right of fixation. This prediction was confirmed by the finding that foveal and parafoveal information both influence where the eyes move during Chinese reading[111]. During sentence reading, the properties of the fixated word, such as its length and frequency, influence the length of the next saccade[111–113]: easier processing in foveal vision leads to longer outgoing saccades. Moreover, the frequency of the fixated word does not influence saccade programming when parafoveal information is not available[112,113], which suggests a decisive role of parafoveal processing in saccade target selection. In sum, Chinese readers dynamically adjust their saccade lengths depending on how much information they have processed to the right of fixation.

There is evidence that readers of alphabetic writing systems use both a word-centre-based target selection strategy and a processing-based strategy to plan saccades. First, although the landing position distribution peaks at the word centre, there is a lot of variation and landing positions are systematically influenced by the distance between the location where the saccade originates (the saccade launch site) and the target word[114]. For scripts read from left to right, the distribution shifts to the left when the launch site is far away, and shifts to the right when it is close to the target. This finding reflects a processing-based strategy; when the launch site is close to the target word, readers might have processed more of the target word, so they can send their eyes further to the right. Second, readers of alphabetic scripts can process more information to the right of fixation when the currently fixated word is easy to process than when the word is difficult[115–118]. For instance, saccades leaving frequent English words are longer than those leaving infrequent words, suggesting that the amount of information processed with parafoveal vision impacts saccade programming[119].

In Thai (an unspaced alphabetic script) readers can use statistical information about the relative frequency of consonants in word-initial and word-final positions to guide a saccade toward the word centre[120,121]. When Japanese readers read mixed kanji–kana text, a preferred viewing location is only observed when a kanji character is located at the word beginning. In other words, readers employ a simple strategy of fixating on the kanji characters[96,122]. No difference in saccade landing position is found between the initial and middle word positions for reading pure kana text[96]. Therefore, Thai and Japanese readers can make use of physical word boundary cues other than inter-word spaces in saccade target selection.

Taken together, these findings show that word processing is an important factor in eye-movement control and that inter-word spaces are important in the processing of alphabetic writing systems[30]. In some unspaced writing systems such as Japanese and Thai, readers utilize other available information and cues to program saccades so that they can process words efficiently. For other unspaced writing systems such as Chinese, readers use a processing-based strategy to program saccades. As a consequence, readers develop different mechanisms of eye-movement control adapted to their writing system[123].

Reading compound words

Compound words exist across a wide variety of qualitatively different scripts. A key question in reading research has been to determine the extent to which compound words are processed as holistic units versus via their component morphemes. To investigate this, the frequency of the component morphemes and that of the whole word are independently manipulated[124]. For example, the compound word 'headstand' is a relatively infrequent word but its first component ('head') occurs frequently as a separate word. If component frequency exerts an effect during word identification, it is taken as evidence for processing via the components. An effect of whole-word frequency is interpreted as evidence that the representation of the whole compound word is activated during reading. Eye-tracking studies demonstrate that in alphabetic writing systems, both component frequency and whole-word frequency affect word recognition[125]. The pattern of results gives rise to a parallel dual-route race model, in which word identification takes place by simultaneously accessing the representations of the component morphemes and the whole word. Whichever route completes earlier wins the race for providing a lexical representation for the compound word[125].

Evidence from Finnish, an alphabetic language, suggests that compound word length modifies the race between the two processing routes[126–128]. The foveal area covers all or most letters of short compound words (for example, 'etuovi' meaning 'front door'), enabling the whole word to obtain priority. However, the foveal area covers only a subset of the letters of long compound words (for example, 'postitoimisto' meaning 'post office'), lending priority to the components in the initial stages of word processing and accessing whole-word representations takes place relatively later in the processing timeline (BOX 2).

It is unclear how compound words are processed in Chinese. In isolated word-identification tasks, a facilitative effect has been observed for high-frequency components (characters)[129,130]; a high-frequency component results in shorter reaction times to the compound word than a low-frequency component. In sentence reading, different studies have found a facilitative component-frequency effect[131,132], no component-frequency effect[37,133–135], and an inverted component-frequency effect[135,136]. However, reliable effects of whole-word frequency (shorter reading times on frequent compound words than infrequent compound words) have been obtained[109,131,136]. Eye-tracking studies have shown that semantic information about individual characters is not activated during Chinese reading if the single character forms a part of a two-character compound word[137–139]. Taken together, these mixed results challenge a categorical distinction between holistic and decompositional processing; it is probably an oversimplification to describe Chinese compound word recognition as using either holistic units or components. The CRM model provides an alternative explanation for compound word processing[15]. According to the CRM, when a multi-character word falls within the perceptual span, both the compound word and the embedded words constituted by the individual characters are activated. For a compound word, the whole word is more likely to win the competition than its components, because it receives activation from multiple characters.

Contradictory findings related to character frequency effects in compound word processing might have occurred because studies did not distinguish between character frequency and word frequency for single-character words. According to the CRM, character frequency and word frequency of single-character words influence word processing time at two different levels and in opposite directions. At the character level, high-frequency characters produce facilitatory feedforward activation to the words they constitute, resulting in faster word processing. But at the word level, a high-frequency single-character word competes more strongly with the whole word, resulting in longer reading times. Because previous studies did not distinguish between the two types of frequency, the balance of opposite effects at the character and word levels is likely to result in different patterns of results across studies.

Box 2 | **Writing format influences compound word reading**

Compound words appear either in concatenated ('doorbell'), hyphenated ('high-speed'), or spaced format ('tennis ball'). The following predictions may be made regarding the effects of writing format on compound word reading. On one hand, visually marking the morpheme boundary by a hyphen or space may aid in splitting the word into morphemes. On the other hand, these demarcations encourage the use of the decomposition route in cases when holistic processing is a viable option, as is the case with short compound words whose letters fit within the fovea. Finally, the illegal insertion of a space ('door bell') or hyphen ('door-bell') might slow down reading, owing to the unfamiliar visual appearance of the word.

Illegally adding a space in concatenated compound words in alphabetic scripts (German or English) seems to facilitate reading of long compound words[151] but to disrupt reading of short compound words[152]. Adding a space within compound words in Chinese, an unspaced logographic script, disrupts reading[153]. Finally, deleting the space at the morpheme boundary ('tennisball') has no discernible effect on reading short spaced English compound words[152].

Two studies in Finnish suggest that when the use of hyphen is obligatory (such as when the same vowel spans the morpheme boundary), long hyphenated compound words ('vaihto-ohjelma', meaning 'exchange programme') are read faster but short hyphenated compound words ('palo-ovi' meaning 'fire door') are read more slowly than the same words without a hyphen[127,154]. By contrast, illegally adding a hyphen at a morpheme boundary disrupts reading of long Finnish and Dutch compound words[155]. Similarly, adding an optional and legal, but non-preferred, hyphen in compound words in Hebrew disrupts reading[156].

In sum, current evidence suggests that the illegal insertion of a space (but not a hyphen) facilitates compound word reading when morphological segmentation is demanding owing to word length in alphabetic scripts. However, visual marking of morpheme boundaries (by space or hyphen) hampers reading of compound words in logographic scripts and short compound words in alphabetic scripts. The manipulations that disrupt reading might do so because the format interferes with holistic processing, as suggested by the dual-route race model and the CRM model.

In summary, the parallel dual-route race model can explain findings of multi-morphemic word processing in alphabetic writing systems and the CRM can explain findings in logographic writing systems. Differences in the features of compound words might result in partly different processing mechanisms across writing systems. First, the visual length of words is usually greater and the variance bigger in alphabetic than logographic writings systems. Thus, word length might be a more important factor in processing compound words in alphabetic scripts. Second, in alphabetic scripts, morpheme length in compound words varies greatly, with no spaces between morphemes, whereas in logographic scripts one character usually represents a morpheme with a small space separating characters from each other. As a result, morpheme segmentation may be easier in logographic than alphabetic writing systems.

Processing differences across scripts

In this section, we reviewed evidence demonstrating how perceptual and cognitive reading mechanisms vary across different writing systems (TABLE 1). These differences are caused mainly by script-specific features such as the phonological encoding method, physical layout, and properties of word compounding. Categorizing processing into universal versus script-specific mechanisms can be done at multiple levels. Different aspects of processing may employ universal or script-specific mechanisms. For example, readers of logographic scripts usually do not use the phonologically mediated route to access word meaning, demonstrating script-specific processing. By contrast, phonology is still automatically activated when reading logographic scripts, demonstrating that it is a universal feature. Furthermore, some mechanisms may be not universal across all scripts, but shared only among a subset of scripts. For example, even though PVL effects are typically not observed in Chinese, they are observed in spaced and some unspaced scripts with some physical word boundary cues (such as Japanese and Thai). Thus, it can be said that the PVL effect is universal across scripts as long as the script contains explicit word-boundary cues. In summary, although research into universal and script-specific reading processes is valuable, the distinction is not categorical.

Lessons from non-alphabetic scripts

Although some reading-related cognitive processes are universal across different writing systems, others are unique to specific writing systems. The findings from different writing systems are valuable in enhancing understanding of the universal and script-specific mechanisms of reading and provide important insights for formal models of reading.

Studies across different writing systems enhance understanding of the universal mechanisms of reading. First, comparing findings from different writing systems can help researchers draw conclusions that are not possible from single-language studies[2]. For example, it would have been impossible to reach the conclusion that reading direction influences the perceptual span asymmetry by studying a single language. Second, studying reading across qualitatively distinct writing systems can bring to the fore research questions that may be disguised in

Table 1 | **Universal mechanisms and script-specific implementations**

Universal principle	Writing system	Script-specific considerations	Script-specific implementation
Eyes move forward in the reading direction so that text is processed chunk by chunk	Alphabetic	English: blank spaces between words	Saccades targeted to the centre of the word[103]
	Syllabic	Japanese: different character types mark word beginnings	Saccades targeted to kanji character[96]
	Logographic	Chinese: continuous characters	Saccades targeted to novel information regardless of word position[106]
Word meaning is extracted from visual form	Alphabetic	Phonology can be easily extracted from form	Phonological and semantic routes are used[7,8,58]
	Syllabic	Phonology can be easily extracted from form	Phonological and semantic routes are used[60,61]
	Logographic	Form does not indicate phonology	Direct semantic route is used primarily[67,76–78]
Compound words can be processed by components or holistically	Alphabetic	Word length varies greatly, and there are no spaces to mark morpheme boundaries for compound words written in concatenated form	Short compound words are processed holistically, whereas the recognition of long compound words takes place initially via components[126–128]
	Logographic	Each character usually represents a morpheme, and most words are short in visual extent	Both the compound word and the embedded words are activated during reading, and they compete for a winner[15]

single-language studies. Indeed, some researchers concluded that research on non-alphabetic writing systems can define and shape some of the key unanswered questions of reading comprehension[140]. For example, studies on Chinese reading can help reveal how readers segment words and how readers' eye movements are guided through the text without the aid of inter-word spaces. Finally, findings from non-alphabetic writing systems may provide possible solutions to research questions relevant to alphabetic writing systems. For example, the CRM can explain how compound words are processed during Chinese reading and may also be able to explain findings of compound word identification in alphabetic writing systems (such as German or Finnish)[15].

Some reading mechanisms are universal across languages, but most universal mechanisms are general and abstract in nature and how they are implemented varies across writing systems (TABLE 1). Thus, it seems that there are different ways to implement these general processing mechanisms. This point can be illustrated in studies of word identification. The first step of reading in all scripts is to transform visual text into a code that can be processed by the language processing system. However, this process is implemented differently in alphabetic and logographic reading[16,19]. Although both the phonologically mediated and the direct semantic routes are used by readers of alphabetic languages, adult readers of the logographic script mainly use the direct semantic route to access the meaning of words[16,19,141].

Script-unique properties make it very difficult to build a universal model to explain reading across qualitatively distinct scripts. For example, the lack of inter-word spaces in logographic scripts challenges models built based on alphabetic scripts (BOX 1). Some computational models have been proposed for logographic reading, but it remains unclear whether these models can explain phenomena in alphabetic reading. Currently, no model exists that explains reading across qualitatively different scripts.

The fact that no reading models to date are universal has important implications for researchers of reading in non-alphabetic scripts. Researchers should seriously consider whether an existing model can be applied to a specific script before using it to guide their research. For example, E-Z Reader and SWIFT are two influential models of eye-movement control in the reading of alphabetic writing systems, but neither model provides a straightforward solution to address the word segmentation problem in Chinese reading. However, for convenience, some studies (including some of our own) have used these models to motivate studies and explain findings in Chinese reading. Therefore, conclusions reached by those studies should be interpreted with caution.

Summary and future directions

In this Review, we have shown that different writing systems differ in their phonological encoding method, grapheme forms, physical layout and morphology. Even with these notable differences, some cognitive reading mechanisms are universal. Readers of all scripts transform written text into a code that can be used by the language processing system, use top-down information and bottom-up information interactively to achieve meaning, and process text incrementally as they move their eyes. Distinct features of writing systems also result in some script-specific mechanisms of reading. Owing to differences in phonological encoding, readers of alphabetic and logographic writing systems use distinct routes to access word meanings. Owing to differences in physical layout, readers of different scripts use script-specific ways to segment words and guide their eye movements. Taken together, the study of reading in different writing systems is both necessary and valuable.

Although much progress has been made in the study of reading in different writing systems, many interesting questions remain unanswered. More research should investigate how script-specific properties encourage readers to develop cognitive mechanisms unique to reading that specific script. For example, an interesting question is how readers of languages such as Chinese parse and comprehend sentences without the aid of inflectional morphemes (such as tense, person, gender, number, and case), which are present in many other languages.

For future studies, when trying to use a model developed for a specific script, researchers should analyse and justify whether the model can be applied to a new script. Moreover, if a researcher makes predictions using an untested model, script-unique properties should be carefully considered when drawing conclusions. Furthermore, when publishing new models, authors should extensively discuss the conditions and writing systems for which the model is applicable. It will be interesting to explore whether models developed for non-alphabetic writing systems can be extended to alphabetic writing systems. Models developed for non-alphabetic scripts may focus on questions less pertinent to alphabetic writing systems. For example, the CRM uses a processing-based strategy to select saccade targets. Perhaps this model can be extended to alphabetic reading to investigate how the processing-based strategy may be combined with the word-centre-based strategy to simulate eye movements during alphabetic reading.

Another set of questions involves cross-language studies. For example, it remains to be seen whether the application of the direct semantic route is similar for readers of alphabetic and logographic writing systems. Although the direct semantic route is used to access word meaning in both writing systems, characters of logographic writing system carry semantic information, whereas letters of alphabetic writing systems do not. This difference is very likely to result in different usage of the direct semantic route in different writing systems. To directly compare cognitive mechanisms across different writing systems, the reading mechanisms of different scripts should be compared within the same study[142,143]. Research on different writing systems contributes to our understanding of the perceptual and cognitive processes that support reading in general and how differences in script give rise to script-specific reading processes.

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Author contributions
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