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Review

Culture is not destiny, for reading: highlighting variable routes to literacy within writing systems

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Cross–writing system research in psychology and cognitive neuroscience has yielded important findings regarding how a writing system's structure can influence the cognitive challenges of learning to read and the neural underpinnings of literacy. The current paper reviews these differences and extends the findings to demonstrate diversity in how skilled reading is accomplished within a single writing system, English. We argue that broad clusters of behavioral and neural patterns found across writing systems can also be found within subpopulations who display atypical routes to skilled English reading, subpopulations including Chinese–English bilinguals, deaf native signers, compensated readers, and distortion-sensitive readers. The patterns of interest include a tradeoff between the degree of reliance on phonological and morphological processing for skilled reading, a shift in attentional focus from smaller to larger orthographic units, and enhanced bilaterality of neural processing during word reading. Lastly, we consider how understanding atypical routes to reading may apply to other writing systems.

Keywords: reading; writing systems; cross-linguistic; individual differences; phonology

Part 1: Reading diversity across writing systems

There is an old debate among reading scientists as to whether skilled readers access the meanings of words directly from their spellings, or whether there is an interim step in which the spelling triggers the phonology of the word.[1] Dual-route models propose a horse race of sorts between these alternatives, which the orthography-meaning route wins when words are high frequency or have irregular spellings and the orthography–phonology–meaning route wins when words are low frequency or spellings are regular. Damage to the phonologically mediated route in a dual-route computational model of reading English produced reading behavior consistent with that seen in a subtype of dyslexia.[2,3] Connectionist computational models assume the two pathways are not involved in a race, but rather negotiate a division of labor guided by the affordances of the writing system and individual differences in relevant cognitive and linguistic abilities. Thus, readers of Chinese lean more heavily on the orthography-meaning pathway than readers of alphabets, because cues to sublexical phonology in Chinese writing are unavailable or unreliable.[4] Mild, moderate, and severe damage to the phonologically mediated pathway in a connectionist simulation of reading English also produced reading behaviors consistent with different subtypes of dyslexia.[5]

It is, therefore, generally assumed that there is an optimal level of reliance on each route or division of labor for a particular writing system, and deviations from this balance by an individual result in or reflect disordered reading. In English, overreliance on meaning for word identification is traditionally associated with dyslexia. Recently, however, subpopulations have come to light that defy the typical division of labor for English, achieving high levels of

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reading skill despite heavier-than-usual reliance on meaning. A discussion of these subpopulations and their unlikely success with this atypical route to literacy is the focus of Part 2 of this review. First, however, we review the dimensions along which writing systems differ and the typical effects of this variability on the brains and behavior of readers.

Dimensions of writing system diversity

A glance at the diverse dimensions along which writing systems vary makes salient the multitude of factors that influence the brains of readers. To begin, all writing systems that have been adopted by human societies have conformed to one of three mapping principles by which visual symbols relate to the spoken language they encode.[a,6,7] These are: grapheme-to-phoneme (including alphabets, like English and Russian, and abjads, like Hebrew and Arabic); grapheme-to-syllable, including syllabaries, like Cherokee and Japanese *kana*, and alphasyllabaries/abugidas, like Thai and Devanagari, which involves representation at both the phoneme and syllable levels;[8] and grapheme-to-morpheme, including morphosyllabaries/logographies, like Japanese *kanji* and Chinese.[9] The mapping principle adopted over time by a given culture tends to be suited to the phonology and morphology of the spoken language. Thus, Mandarin Chinese uses logographs (characters) to differentiate between its extraordinary number of homophonic morphemes, which are often distinguished by tones in the spoken language; Arabic uses an abjad (in which graphemes represent consonant-only phonemes) to reveal its morpheme roots, composed of distributed consonants.[10] Additionally, both the number of graphemes and the perceptual complexity of those graphemes are tightly correlated with the type of mapping principle, where alphabets have few and less visually complex graphemes, whereas Chinese has thousands of characters with high visual complexity.[9]

Within writing systems, there are a multitude of scripts (e.g., the Cyrillic, Latin, and Korean *hangul* scripts are all alphabets), and scripts can be implemented with a variety of orthographies (e.g., English and Spanish orthographies are different implementations of the Latin script; Russian and Serbian are different implementations of Cyrillic). Orthographies can vary considerably in the transparency/opacity, or depth, of their mapping to spoken language. In transparent (shallow) orthographies, such as Korean and Finnish, there is near one-to-one consistent correspondence of graphemes and phonemes: a letter or group of letters has a single pronunciation, and vice versa. Conversely, English is an especially deep orthography in which a single phoneme can be represented with as many as 11 graphemes, and a single grapheme can correspond to upward of 22 phonemes.[11,12]

Behavioral implications of writing system diversity

The universality of reading behaviors and their neural underpinnings has been an ongoing topic of debate in the reading literature. On the one hand, there is considerable evidence for a universal core reading network[13] that includes the left mid-fusiform gyrus, inferior frontal gyrus, superior and middle temporal gyrus, and the inferior parietal lobule. Moreover, connectionist models of reading demonstrate the same computational architecture can give rise to the reading behaviors observed across different writing systems.[4,14,15] On the other hand, variation of orthographies along each of the dimensions discussed above (mapping principle, transparency, and perceptual complexity) leads to different behavioral and neural demands on the individuals reading them. In other words, different orthographies lend themselves to different reading challenges and strategies for dealing with these challenges, which ultimately lead to differences in the degree of activation of areas of the reading network. In terms of behavioral consequences of writing system diversity, in this paper we mostly focus on two clusters of patterns: (1) a tradeoff between reliance on phonological/phonemic and morphological/semantic processing to support skilled reading, with a natural extension of such a tradeoff being (2) attentional focus on different-sized orthographic units (phonemes/small units versus syllables/morphemes/larger units).

[a]In theory, a pure ideography—in which meaning is derived directly from symbols without the mediation of language—is possible, but none has succeeded on a significant scale in human society. It appears that writing systems must map to sounds to be successful. Even Chinese characters, which do map to morphemes, also (simultaneously) map to syllables.

Evidence for the first behavioral pattern cluster, a tradeoff between reliance on phonological/phonemic and morphological/semantic processing to support skilled reading, comes from research that has focused on the influence of some aspect of graphic-linguistic correspondences in writing systems (i.e., mapping principle and transparency). In general, if an orthography is alphabetic and transparent, readers rely more heavily on phonological information for word identification,[16] whereas readers tend to rely relatively more on morphological or lexical strategies if an orthography is deep and logographic. For instance, in orthographically opaque Chinese, readers access phonology concurrent with (not prior to) word identification,[17] and morphological processing plays a greater role in reading than in most alphabetic writing systems. Moreover, although phonological awareness in Chinese children predicts character recognition and later reading ability,[18,19] it is awareness of larger-size phonological units, such as onset-rimes[20] and syllables,[21] rather than phonemes, that predict reading skill. In contrast to transparent alphabets, morphological awareness is also more strongly associated with reading skill than is phonological awareness in Chinese[22] and is substantially more important than in English.[23] Furthermore, reports of extremely early semantic influence on word recognition[24] are consistent with a qualitatively different role of meaning in Chinese reading compared to transparent alphabets. The visuospatial complexity of Chinese characters also causes reading and word learning to be associated with a number of ostensibly nonlinguistic factors, including basic visual processing,[20,25] copying skill,[26,27] handwriting practice,[28,29] and handwriting quality.[30] Perhaps not surprisingly, perceptual expertise predicts reading in Chinese dyslexic readers[31,32] along with morphological processing.[33,34]

The contrast between reliance on phonology versus morphology in transparent alphabets and Chinese is consistent with the second behavioral pattern cluster: orthographic processing differences. Seymour and colleagues, studying children learning to read 13 different European orthographies, noted that reading development was impeded when languages were syllabically complex or orthographically deep.[35] This finding inspired the psycholinguistic grain size theory,[36] which posits that children implicitly learn the grain size mapping most appropriate to their orthography and form psycholinguistic units accordingly. The appropriate grain size mapping emerges as a function of both grain size of the mapping principle and transparency of the graphic-linguistic correspondence. For example, learners of transparent alphabets can focus exclusively on the level of phonemes/letters. However, when the phoneme-level grain size is inconsistent or unavailable in a writing system (as in Chinese), readers must additionally focus on larger orthographic units, such as syllables, rhymes, or whole words.[37]

The English writing system occupies an interesting middle ground between highly transparent alphabets and opaque logographies because, while it is an alphabet, it employs an extremely deep/opaque orthography. Unlike transparent alphabets, English phoneme–grapheme and grapheme–phoneme mappings are inconsistent (e.g., /oʊ/ is not always spelled <ow>, and <ow> is not always pronounced /oʊ/), and several letters often represent a single phoneme (as with <ough> in *dough*). Unlike Chinese, English represents individual phonemes, so decoding words at the subsyllabic level is possible. Thus, although phonological awareness,[38,39] and more specifically phonemic awareness,[40] is overwhelmingly considered a strong predictor of reading outcomes in English, English readers tend to lean on morphological processing more heavily than readers of relatively more transparent alphabetic orthographies like Italian, French, and German.[41]

Neural implications of writing system diversity

In addition to differences in the broader reading network across writing systems,[42,43] cognitive neuroscientists of reading have devoted particular attention to one area in the left mid-fusiform gyrus, the putative visual word form area (VWFA). This area has been shown to play a crucial role in skilled word reading, based on converging evidence that it develops over time during literacy acquisition,[44,45] leads to reading impairments when focally damaged,[46–49] and displays functional differences in developmental disorders.[50,51]

Although the classic anatomical location of the VWFA is in the left hemisphere, cross-linguistic research provides support for the existence of variability in the laterality of this region.[43,52] This brings us to the third pattern cluster seen across

Table 1. **Clusters of behavioral and neural patterns observed across different writing systems**

	Cluster 1	Cluster 2
Natural writing system example	Transparent alphabet (e.g., Finnish)	Chinese
Relative reliance on phonology versus morphology	Relatively greater reliance on phonology	Relatively greater reliance on morphology
Orthographic attentional focus	Phoneme (fine)	Syllable/morpheme (coarse)
VWFA laterality	Left	Bilateral

writing systems (Table 1). Typically, readers of alphabetic writing systems exhibit strongly left-lateralized VWFA activation in response to printed words, consistent with the original work done primarily in French and English.[53–55] Readers of nonalphabetic writing systems, meanwhile, often exhibit bilateral engagement of the left-hemisphere VWFA and its right-hemisphere homologue.[43,52,56–60] The general pattern is a left-lateralized VWFA for readers of alphabets, which naturally promote sublexical analysis, and bilateral VWFA engagement for readers of Chinese, which naturally promotes attention to whole characters (for an alternative interpretation, see Ref. 61). This pattern is interestingly consistent with lateralization of function for visual processing in domains other than reading. Broadly, the left hemisphere is more associated with fine-grained, detailed, or analytic visual processing, whereas the right hemisphere is more associated with holistic or whole-object processing.[62,63]

Due to the limitations of comparing naturally occurring writing systems that vary along many dimensions (i.e., transparency, mapping principle, and visual complexity), researchers have recently turned to artificial orthographies[58,64–66] and computational modeling[67,68] to further explore the sources of VWFA laterality. Computational models sought to understand whether properties of visual lateralization (e.g., left bias for high spatial frequencies) could account for the lateralization differences across writing systems.[67,68] The models revealed that both visual complexity and mapping principle influenced VWFA laterality, with greater complexity and larger mapping principles leading to greater bilateral VWFA engagement. Visual complexity and mapping principle are also inherently difficult to disentangle in natural orthographies that have to represent an entire spoken language:[69] as the number of graphemes necessarily increases in nonalphabetic writing systems, visual similarity and complexity also increase. However, mini artificial orthography studies that used identical graphemes for both grapheme–phoneme mapping and grapheme–whole-word mapping still found greater bilateral engagement when the mapping principle was at the whole-word level compared to alphabetic,[58,64,65] supporting the notion of mapping principle as a driver of VWFA laterality. This pattern has also been observed in two artificial orthographies that compared an alphabetic and an alphasyllabic system;[66] the alphasyllabic system with the larger mapping principle engaged the right VWFA to a greater degree.

Xue and colleagues[70] developed a logographic artificial orthography and examined how different types of training influenced VWFA activity. They found increased bilateral VWFA activity after phonological training (i.e., learning the mapping between visual symbols and whole-morpheme phonology). Furthermore, participants who engaged in additional semantic training for the artificial logography showed increased activation in the right VWFA (and nowhere else) relative to participants who received the basic training. This finding highlights another example of graphemes that map onto a larger phonological unit (i.e., the syllable or morpheme) inherently containing more semantic information. Thus, it remains unclear whether the shift to greater bilateral VWFA engagement in readers of logographies is a result of using a larger phonological unit for the decoding process itself, or of using a different reading procedure that involves greater semantic and morphological processing.

Nevertheless, an interpretation consistent with natural and artificial orthography studies as well as computational modeling is that VWFA laterality is at least partly due to the mapping principle of the orthography to phonology. The general pattern is that writing systems that use ortho-phonemic mapping engage a left-lateralized VWFA, whereas writing systems that map orthography onto larger phonological units (i.e., syllables and morphemes) engage the VWFA more bilaterally.

Part 1 summary

To summarize, if phonological information is transparent in an alphabet, skilled readers primarily use it rather than morphological information or whole-word strategies for word identification; they focus mostly on the phonemic rather than the morphemic or syllabic grain size; and they display left-hemisphere-dominant rather than bilateral VWFA engagement. If an orthography is phonologically opaque with a larger mapping principle, the opposite pattern is observed: there is a relatively greater reliance on morphological information, a focus on larger grain size units, and greater bilateral VWFA engagement. English finds itself somewhere in the middle of the transparency spectrum such that the type of information (phonological and/or morphological) and grain size of attention most helpful for word identification vary across words. However, most accounts of skilled reading in English align it more with other alphabets (e.g., phonological—and more specifically, phonemic—deficits predict reading difficulty; VWFA engagement is left lateralized) than with nonalphabetic systems. While research on English has primarily shown left-hemisphere–dominant VWFA engagement, there has been some unexplained variability, as well. Part 2 explores and synthesizes recent research that increasingly suggests that although much literature largely aligns English with the first cluster of patterns (Table 1), there is a consistent alternative route to successful reading in English that aligns more closely with patterns observed in Chinese reading.

Part 2: Reading diversity within a writing system

While cross-linguistic research has been useful for learning about which aspects of reading are universal and which are writing system–dependent, it has generally assumed homogeneity within each population of readers in terms of what predicts skilled reading. Variability in skill level for word reading and comprehension and how it relates to differences in phonological versus morphological processing is well studied within a single writing system (e.g., English). However, similar variability in the degree of reliance on phonological versus morphological processing, attention to smaller versus larger orthographic units, and laterality of VWFA activation that contribute to similar levels of skilled reading within a writing system is not often acknowledged. Mounting evidence indicates that clusters of individual differences associated with high skill in another writing system are found within certain subpopulations of English readers. In short, group differences *within* a writing system can mirror those found *across* writing systems.

In this section, we provide evidence that four diverse subgroups have success with atypical (and often less efficient) reading procedures in English that share properties with typical Chinese reading, that is, less reliance on phonological sublexical processing and greater engagement of the right VWFA. We present evidence from English readers and speculate on why these subgroups achieve high levels of skill, how much within-writing-system variability is possible in other languages or writing systems, and how common success with these atypical routes to high levels of literacy may be.

Differences in the four subgroups along two main dimensions provide evidence to support this notion that within-writing-system (i.e., English) variability mirrors that found between writing systems (i.e., transparent alphabets and Chinese). The first dimension has to do with phonological processing abilities. There are individuals with biological constraints that make phonological processing more difficult, such as compensated readers (sometimes termed *high-functioning dyslexics* or *resilient readers*) and profoundly deaf native signers. Other individuals have no inherent deficits in phonological processing yet display some similar patterns in reading procedures to those who do. These include native English readers biased toward an attentional focus on larger units of orthographic analysis (newly termed *orientation-sensitive* or, more generally, *distortion-sensitive* readers[71]) and Chinese–English bilinguals (Table 2). The second dimension along which the four subgroups vary is whether English is their native language. English is the native language of distortion-sensitive readers and compensated readers discussed in this paper, but it is not the native language of Chinese–English bilinguals and profoundly deaf native signers. Thus, the four subgroups fill out a 2 × 2 grid, completely crossing these two dimensions.

Table 2. Subgroups that exhibit atypical reading procedures in English

	Higher (typical) skilled phonological processing	Lower skilled phonological processing
Non-native English speakers	Chinese–English bilinguals	Profoundly deaf native signers
Native English speakers	Distortion-sensitive readers	Compensated readers

Chinese–English bilinguals

Chinese–English bilinguals may be the least surprising subgroup to display atypical reading of English. There is a large body of evidence that one's first-language (L1) reading experience influences second-language (L2) reading, both behaviorally and neurally.[72–75] A growing body of work suggests that L2 reading acquisition is facilitated if one's L1 and L2 share underlying linguistic structures.[75–78] However, if one's L1 and L2 are structurally distinct, there are two likely patterns for L2 processing: accommodation or assimilation. For example, English and Chinese are structured differently, yet it has been argued that while dominant English reading procedures (e.g., phonological decoding) cannot be applied to Chinese, Chinese reading procedures *can* be applied to English.[79] Thus, native English speakers reading Chinese must accommodate the reading procedures of native Chinese readers, resulting in separate L1 and L2 procedures, but native Chinese speakers reading English can assimilate their L2 reading procedures into their L1 reading procedures. The following section reviews both behavioral and neural evidence for this pattern of assimilation in Chinese–English bilingual readers, which includes several clusters of patterns seen in native Chinese reading.

Behavioral patterns in Chinese–English bilinguals. As we discussed in Part 1 above, Chinese does not allow for segmental phonological assembly and thus cannot be broken down or analyzed as alphabets can. Although there is evidence for some degree of analytical processing in Chinese reading in the form of submorphemic (i.e., phonological or semantic) radical processing in adults[80] and children,[81] comparatively speaking, Chinese must be processed to some large extent at the level of the whole character or word. Further support for the notion that Chinese orthography is in a class all its own comes from the observation that orthographic knowledge in Chinese does not transfer to support the reading of other writing systems.[82] However, the absence of direct transfer of Chinese orthographic knowledge does not preclude it from influencing how Chinese individuals read another script. To examine behavioral consequences of having Chinese L1 on reading English, it has been productive and informative to compare the English reading procedures of Chinese–English bilinguals to those of Korean–English bilinguals within the same study.[72,83–88] Korean *hangul* is an alphabet whose letters are organized into syllable blocks that spatially resemble Chinese characters. The overlap of Korean writing with Chinese writing in terms of visuospatial demands and English writing in terms of mapping principle has been leveraged to more directly measure the effects of L1 writing system on L2 reading.

Evidence supports the idea that the unique orthographic analysis in native L1 Chinese readers contributes to distinct word-level processing in English for Chinese–English bilinguals compared to Korean–English bilinguals. Recent research examining L1 influence on L2 reading has used a measure of orthographic coding style derived from the face processing literature, where it was developed to distinguish between holistic versus analytic styles of face processing. The extent to which an individual holistically processes a face or object can be measured by observing the effect of disrupting the typical presentation on identification. Faces are thought to be processed more holistically than other objects in part because it takes longer or is harder to identify them when they are inverted.[89] This technique has been applied to visual word processing to probe the cross-linguistic and individual differences in orthographic attentional focus reviewed in Part 1. Altering the typical visual presentation of words by inverting them or presenting them in alternating cases can reveal whether readers focus on smaller/fine-grained units (i.e., take an analytical approach to word identification) or larger/coarse-grained units (i.e., take a holistic approach to word identification). Several studies have shown that Chinese–English bilinguals are more affected by such distortions than are Korean–English bilinguals when reading their English L2,[84–88] suggesting that Chinese–English bilinguals process English in a relatively more holistic manner than Korean–English bilinguals.

In addition to visual orthographic analysis itself, the manner of orthographic analysis has also been linked with lexical versus sublexical biases in word identification.[88,90] Chinese–English bilinguals, who were more sensitive to distortion than Korean–English bilinguals, were also biased more toward lexical-level psycholinguistic measures like frequency, and less toward sublexical-level phonological measures like consistency.[88] Compared to Korean–English bilinguals, Chinese–English bilinguals display relatively less reliance on phonological sublexical processing in the service of word identification[73,74,91,92] and comprehension,[91] despite equivalent skill on sublexical phonological measures like nonword decoding. These patterns of differential reliance on sublexical and lexical processing in Korean–English bilinguals and Chinese–English bilinguals have also been supported by differences in broader reading networks.[93]

General patterns across writing systems suggest that if Chinese–English bilinguals do not rely as much on sublexical phonological knowledge to achieve high levels of literacy in English, they may rely instead on morphological knowledge. Unlike orthographic knowledge, which does not transfer from Chinese to English, recent work suggests that morphological knowledge does transfer.[94,95] Moreover, morphological knowledge explains unique variance in both word processing and comprehension in Chinese–English bilinguals reading English.[96,97]

Neural pattern in Chinese–English bilinguals. Consistent with the idea of neural accommodation and assimilation in L2 reading, VWFA activation in L1 English-L2 Chinese readers tends to be left lateralized when they read English but bilateral when they read Chinese to accommodate the processing demands of that writing system.[52,57] Similar patterns have been observed in Korean–Chinese bilinguals, whose L1 is also alphabetic.[98] Conversely, Chinese–English bilingual readers can assimilate English reading into the reading network used for Chinese reading, and engage bilateral VWFA when reading both Chinese and English.[52,79]

Profoundly deaf native signers

Profoundly deaf native signers are another interesting subgroup because, like Chinese–English bilinguals, English is not their L1. Deaf native signers tend to have deaf parents and acquire a sign language (such as American Sign Language or British Sign Language) as their first language. Because these signed languages are distinct from spoken English (and each other) in terms of grammar and vocabulary, deaf native signers learn to read a language they likely do not speak. This distinction between profoundly deaf native signers and other deaf individuals is important to make, since the deaf population is highly heterogeneous in terms of onset of deafness, degree of deafness, degree of oral communication, and so on. Unlike Chinese–English bilinguals, profoundly deaf native signers' phonological processing is less skilled or qualitatively different than that of native hearing English speakers.[99,100] Thus, it is not surprising that, on average, deaf readers do not reach the same levels of reading proficiency as their hearing peers, but some do. The following section focuses on these deaf native signers who are skilled readers.

Behavioral patterns in profoundly deaf native signers. It makes sense that deaf individuals are less in tune to the phonological properties of a spoken language than hearing individuals. Unlike in hearing individuals, however, a close link between phonological processing skill and reading outcomes in alphabetic writing systems is not seen in deaf individuals.[100,101] Although some deaf native signers perform well on adapted tasks that assess speech-based phonology (e.g., identifying rimes), such tasks are not the best predictor of their reading outcomes (a pattern similar to that seen in Chinese–English bilinguals; see Ref. 91). Since deaf native signers are not as sensitive as hearing individuals to phonological codes,[101,102] it has been proposed that they might compensate by becoming more sensitive to semantic codes.[103] That is precisely what has been observed. Free recall memory,[100] which is associated with semantic processing, and top-down strategies like real world knowledge and context[104,105] are better predictors of reading skill in deaf native signers than is phonological awareness.

In addition to being less sensitive to phonological codes, deaf native signers who are skilled readers have also been shown to have a larger perceptual span while reading than their hearing counterparts. Compared to skilled hearing readers, whose reading span is 14 characters to the right of fixation, skilled deaf native signing readers' span is, on average, 18 characters.[106] Furthermore, skilled deaf native signing readers made relatively fewer regressions back in the text (i.e., needed to reread less). The authors interpreted this greater efficiency (larger perceptual span with fewer regressions) as suggesting that deaf readers may form tighter connections between orthography and semantics[103] to be able to achieve equal levels of comprehension to hearing readers. A greater perceptual span could potentially contribute to a greater reliance on holistic orthographic analysis, but future research is needed to provide evidence to support this hypothesis.

Neural patterns in profoundly deaf native signers. There are mixed reports on laterality of the VWFA in deaf readers of English. Several studies of deaf readers using functional magnetic resonance imaging (fMRI) have reported left-lateralized patterns similar to those of hearing readers.[107,108] However, recent research reported that greater bilateral N170, the event-related potential component associated with orthographic processing and the VWFA,[109] might be a hallmark of skilled reading in deaf native signing readers compared to hearing readers.[110] The left-hemisphere N170, like left-lateralized VWFA activity, is associated with skilled reading in hearing individuals. However, Emmorey and colleagues found better deaf readers displayed a larger right N170, whereas better hearing readers had a smaller right N170. Another study that specifically examined differences in reading proficiency in deaf native signing readers found greater VWFA activation in both hemispheres in more proficient readers.[111] Most recently, Glezer and colleagues also reported that both left and right VWFA were selective to whole-word orthography in deaf skilled signers, further supporting the idea that sensitivity to phonological processing may have little impact on reading success for deaf adults.[112] These findings of a tenuous link between phonological processing and reading success in deaf readers complement data suggesting that highly skilled deaf readers are more sensitive to semantic errors in sentences, measured by the amplitude of the N400, compared to hearing readers.[113] Taken together, behavioral data and neuroimaging evidence suggest that deaf native signers utilize greater holistic orthographic analysis or, at the very least, engage in less phonological analysis than typical hearing English readers.

Compensated readers

The next subgroup, compensated readers, is similar to deaf native signers in their impaired phonological processing, but unlike Chinese–English bilinguals or deaf native signers, they learn to read their native spoken language. Also like some deaf native signers, they can achieve high reading outcomes despite deficits in phonological processing ability, which typically predict poor reading skill at the word and comprehension levels.[114–119] Other terms, such as *resilient readers* (who have poor phonological skills as adults but were never identified with a reading disability) or *high-functioning dyslexics* (who were identified with dyslexia as children but attain reading skills sufficient to succeed in college), have been used to refer to readers who have impaired, low-level phonological processing but typical skilled comprehension. For the sake of this review, we group these literatures as theoretically similar and use the single term *compensated readers* to refer to all groups that fit the basic criterion of a discrepancy between phonological processing ability and reading comprehension.

Behavioral patterns in compensated readers. The underlying reading procedures of compensated readers have been examined at the word and comprehension levels. Because, by definition, compensated readers have impaired phonological processing with preserved comprehension skill, it may be assumed that semantic processing is preserved and at the root of any compensation mechanism. Indeed, Welcome and colleagues found no significant differences between compensated readers and typical proficient readers in word-level tasks that tapped into semantic processing. However, the compensated readers showed a persistent deficit in tasks that relied heavily on phonological processing, like pseudoword naming and basic word identification, suggesting that they rely more on semantic than phonological representations.[115,116] These findings are consistent with the general pattern observed in Chinese–English bilinguals and deaf native signers. They are also consistent with the hypothesis that a greater reliance on semantic representations or the available context can facilitate compensation for deficits in phonological decoding[120] at the word level and be the mechanism by which normal comprehension can be achieved.[114,115]

More specifically, several recent studies have examined morphological processing in compensated readers. Morphological awareness is associated with both visual word recognition and text reading comprehension skills during literacy acquisition[121,122] and thus provides a reasonable framework in which to explore possible mechanisms of compensation in reading. Unsurprisingly, studies have shown that compensated readers have preserved morphological knowledge.[123–127] However, Cavalli and colleagues found that a larger difference between morphological and phonological knowledge was a predictor of higher overall reading level,[118] supporting the idea that at the word level, morphological knowledge can counteract persistent deficits in phonological processing in compensated readers. Similarly, Law and colleagues found that compensated readers performed better on morphological tasks than noncompensated readers, and that it was a better predictor of overall reading for the compensated readers than controls.[125,126] Lastly, a study using morphophonemic training suggested that this technique produces gains in word identification in adult struggling readers of English.[128] Despite the heterogeneous population, compensated readers as a subgroup show the pattern of relying less on phonological information and more on morphological and semantic information to support skilled reading.

Neural patterns in compensated readers. Studying the neural substrates of compensated readers is challenging due to the inherent complexity of reading disorders. There are arguably many subtypes of reading disorders that could have multiple neural mechanisms underlying similar behavioral manifestations.[129,130] Nevertheless, differences between compensated readers and typical proficient readers have emerged from studying the neural substrates of compensated readers: namely, differences in asymmetry,[117,131–134] and in the extent of top-down frontal engagement.[135,136]

While there is significant support for irregular VWFA activity in dyslexic readers,[50,137] it is unclear whether VWFA activity in compensated readers bears a greater resemblance to that of typical proficient readers (i.e., strongly left lateralized) or dyslexics (i.e., bilateral). There is some evidence that compensated readers engage right posterior regions to make up for irregular involvement of the left posterior reading network (including the VWFA). They may also develop greater connectivity between the right angular gyrus and visual areas.[131,138] One proposal is that right posterior regions may serve a compensatory role in mediating phonological performance, although greater right posterior engagement could be indicative of atypical cerebral lateralization independent of reading acquisition. Indeed, using functional transcranial Doppler ultrasound, compensated readers displayed general reduced left asymmetry for language processing during a word-generation task, suggesting that compensated readers' language processing may inherently be less left lateralized.[117] This result is consistent with the phonological mapping hypothesis,[139] which posits that the characteristic left-lateralization for reading is the result of the need to map left-lateralized phonological information to visual information. This hypothesis predicts less left lateralization with lower phonological skill levels. However, opposite accounts of atypical asymmetry have also been reported, such that compensated readers have greater left asymmetry[116] or no differences in asymmetry at all.[115,140] Ultimately, these inconsistent findings may be a result of a heterogeneous population.

Another interesting finding and interpretation of irregular VWFA activity in compensated readers builds off the finding that there is a functional gradient in the fusiform gyrus as it relates to visual word processing,[141–144] with more anterior portions being more sensitive to semantic properties of words.[143,144] There is evidence that in compensated readers, prelexical morphological processing occurs in the anterior part of the left fusiform gyrus around 400–500 ms after encountering a word, anterior to the classic VWFA but along the functional gradient mentioned above.[145] The authors argue that compensated readers might rely more on larger (i.e., morpheme sized) orthographic units than on smaller units (i.e., graphemes), which may explain their continued irregular or reduced activation in the more classic and posterior areas in the fusiform gyrus.

The other neural difference between compensated readers and typical proficient readers is greater frontal neural engagement in both left and right hemispheres for compensated readers.[123,131,135,136,145] While Patael and colleagues attributed greater left frontal activity in compensated readers to general cognitive processes like cognitive control and working memory, Cavalli and colleagues found that greater frontal engagement was linked with earlier morphological processing (i.e., within 200 milliseconds). Cavalli and colleagues proposed that increased connectivity between frontal and posterior areas in these readers might reflect top-down influences on the fusiform gyrus, based on the relative timing of morphological processing in the two regions.[145] Independent of the exact location of neural engagement in compensated readers, the fact that they may be linked with increased morphological/semantic reliance is consistent with the other subgroups reviewed here.

Distortion-sensitive readers

Lastly, recent exploratory research has identified a subgroup of skilled native English readers with striking neural and behavioral similarities to the previous three subgroups.[71,146] The discovery of distortion-sensitive readers was inspired by a desire to understand understudied individual differences in the laterality of the VWFA of readers *within* a writing system: English. Although the general trend is for readers of alphabets to have a strong left lateralization of the VWFA, considerable variability in VWFA laterality had also been observed, including among alphabetic readers without apparent phonological difficulties[53,147–149] Based on patterns observed in the broader literature reviewed in this paper, it was hypothesized that atypical and more bilateral VWFA engagement in English could be a sign of a more holistic approach to reading, which the position of English in the middle of the transparency spectrum affords. Building off of the inversion effect in the face processing literature,[89] Hirshorn, Fiez, and colleagues set out to understand the variability in VWFA laterality by assessing readers' sensitivity to inverted words. Because other researchers have used manipulations other than inversion to tap into holistic visual processing of words,[84–88] we refer to the general phenomenon of greater sensitivity (i.e., slower processing) to any visual distortion of a word as *distortion sensitivity*. The overarching hypothesis for the subgroup of distortion-sensitive readers is their holistic approach to word processing should be accompanied by less reliance on phonological processing and a more bilateral VWFA engagement, similar to the other subgroups examined here.

Behavioral patterns in distortion-sensitive readers. Behavioral investigation of distortion-sensitive readers has supported the hypothesis that they should show less reliance on phonological or sublexical processing and a weaker connection between phonological decoding skill and overall word reading or comprehension relative to non–distortion-sensitive readers. When comparing high- and low-sensitivity readers matched in word knowledge and sentence comprehension in an overt word-reading task, high-sensitivity readers' reading speed was more affected by length than that of low-sensitivity readers when words were inverted.[71] The authors interpreted this finding as support for the idea that, among distortion-sensitive readers, visual distortion leads to the requirement for a more effortful sublexical approach in word identification, leading to longer reading times for longer words. The fact that the length effect for atypically oriented words was larger for readers sensitive to distortion suggests that they are less efficient at utilizing the sublexical/analytical approach and typically rely on a more holistic/lexical reading procedure. Further, marginal effects were in the predicted directions, such that distortion-sensitive readers were marginally more affected by the lexical-level factor of imageability, whereas they were relatively less affected by the sublexical-level factor of biphone frequency. These patterns support the idea that there are distinct reading procedures utilized by a set of skilled English readers that would otherwise not be distinguishable based on standardized measures. A recent study replicated this finding; readers more and less sensitive to distortion did not differ in reading comprehension or phonological decoding, yet differed dramatically in how the two measurements were correlated. Readers less sensitive to distortion had a strong correlation between phonological decoding and comprehension, which is the typical pattern in the literature, while readers highly sensitive to distortion had no significant correlation between the two measures.[150]

Neural patterns in distortion-sensitive readers. An examination of the VWFA laterality of distortion-sensitive readers also supported the hypothesis that greater sensitivity to visual word distortion should translate to greater bilateral VWFA engagement.[146] Distortion-sensitive readers were run in a simple fMRI localizer in which they saw pictures of words, letter strings, faces, houses, and patterns. Using a new multivariate method that uses machine learning, the authors found that the extent of sensitivity to visual distortion predicted classification accuracy for words and letter strings in the left and right VWFA. Low-sensitivity readers had significantly greater classification accuracy in the left VWFA, compared with the right, whereas high-sensitivity readers' classification accuracy did not differ between the left and right VWFA. These results begin to shed some light on sources of individual differences in VWFA laterality in the general population and suggest that it could serve as a meaningful marker of a distinct reading profile among skilled English readers.

Understanding atypical clusters: conclusions and implications

Taken together, this body of work highlights how the brain can, in certain circumstances, deviate from the typically optimal division of labor and achieve skilled reading, at least in English. While the typical pattern of successful reading in English includes the high reliance on phonemic processing and left-lateralized VWFA observed in other alphabets, there are subpopulations of English readers who share atypical patterns that still support skilled reading. These atypical patterns include relatively less reliance on phonological processing and more on morphological and semantic processing, greater attentional focus on larger orthographic units, and greater bilateral VWFA engagement. There remain important differences between the four subgroups, but the fact that these patterns persist seems to point to a consistent atypical route to successful reading.

What is additionally striking about the four subgroups reviewed is that the atypical patterns they exhibit (e.g., greater reliance on morphological processing) are commonly linked with impaired or less-skilled reading. For example, it was found that children who have stronger associations between print and meaning have weaker reading skills than those with relatively stronger associations between print and speech/phonology in a word-naming task.[151] Further, when individual differences in semantic processing (e.g., differences in the effects of imageability and semantic priming, specifically for reading exception words) are studied in typical readers, reliance on semantic processes is usually a liability. Unlike distortion-sensitive readers, who perform equally to non–distortion-sensitive readers on phonological tasks, high-semantic-reliance readers show weaker performance on phonological tasks.[152] By pointing out subgroups that have had unexpected reading success relying on a holistic approach to word identification, we do not mean to appear to be in support of the whole-word method or whole-language instructional approaches that do not involve phonics instruction, as they have overwhelmingly been refuted.[153] It is likely that for most English speakers, a phonological approach to reading is more effective than a holistic or semantic approach because visual memory is not up to the task of storing tens or hundreds of thousands of unique strings of symbols. (We say "likely" because the precise number of individuals who become skilled readers using this seemingly atypical route is unknown: skilled readers do not often demand the attention of researchers.) Explicitly teaching children to read this way, therefore, is not recommended. We do feel the existence of our four subpopulations is worth noting, however, and encourage future research on variable routes to skilled English reading.

As to why these subpopulations present skilled outcomes with less reliance on phonological and sublexical measures, we can only speculate at present. It is possible that they share a protective factor that allows them to achieve high levels of reading skill despite reliance on a potentially less-than-optimal route. Chinese–English bilinguals make sense to consider first, as their atypical English reading is likely a product of their L1 reading procedures. It has been proposed that there are natural tradeoffs between writing systems with different grain sizes, such that alphabets encourage reliance on phonological decoding, whereas Chinese places demands on visual memory to recall thousands of unique but similar characters.[69] There is evidence that readers exposed to more visually complex traditional Chinese characters (used in Taiwan and Hong Kong) display greater visual discrimination than those exposed to less visually complex simplified characters (used in mainland China) in a same–different perceptual judgment of characters varying in visual complexity.[154] Presumably, intensive visual discrimination enhances one's ability to encode visual memories for characters and creates more robust visual memories. For example, once Chinese readers' visual memory processes have been shaped by these cultural conditions of their writing system, it is possible that they could apply them to identifying English words.

Consistent with the conjecture that success with atypical routes is possible for individuals with highly developed visual memory skills, stronger visual memory has been linked with compensation in dyslexic readers of English.[155] And although skilled deaf native signing readers do not necessarily have better visual memory per se, they have increased visual attention in the periphery. While Bélanger and colleagues[103] reasoned that the greater visual span was linked with greater semantic processing, there is additional evidence that deaf native signers are biased toward encoding information in the visual domain in short-term memory.[156] Perhaps deaf readers who are naturally biased to rely more on visual information encoding attend to larger orthographic units that allow for more direct semantic processing. As for distortion-sensitive readers, they have only begun to be studied. Investigating visual long-term memory in this population could help identify protective factors that better situate individuals in our four subgroups to successfully use this atypical route to successful reading. Whether bilateral VWFA lateralization proceeds from or contributes to reliance on the atypical route in these subpopulations is also a subject for future research. In the absence of longitudinal data in these subgroups, it is difficult at present to determine the causal connection between brain-based differences in VWFA lateralization and reading patterns.

Whether the atypical clusters we have reviewed have implications for best teaching practices for the four subgroups discussed above is an open question. Research has demonstrated that the method of instruction[157] (e.g., phonics versus text-centered approach) or the writing system itself[158] can affect reading strategies and focus attention on different-sized units. For example, readers of an alphasyllabary found it easier to blend larger grain size units in the process of word recognition than those who used smaller units.[158] If the subgroups of readers discussed in this paper achieve success naturally attending to larger units, it is possible an instructional approach that facilitates this use of attention may benefit these readers more than instruction that guides attention to smaller units. Future research is needed to assess whether additional protective factors, such as increased visual memory capacity, would be needed for this route to be successful.

Generalizations to other writing systems

One last natural extension of this review is to ask whether the patterns observed in the alternative routes to skilled reading in English generalize to other writing systems. Successful deviation from the optimal division of labor observed in subpopulations of English readers could apply to readers of other orthographies that are both alphabetic and opaque, such as French or Danish, or alphasyllabaries, such as Hindi, which also afford analysis at multiple grain sizes. There is even some evidence that, just as certain subpopulations of English readers adopt strategies more common in logographic languages, certain populations of Chinese readers adopt strategies more common to readers of alphabets. Thus, phonetic strategies for character learning may remain intact for Chinese children with dyslexia,[159] and English L1 readers of Chinese tend to benefit from more analytic than holistic strategies for word reading.[160,161] Whether these characteristics reliably describe subgroups or rather reflect normal variation among individuals within cultures is a subject for future research. However, it seems unlikely that English is the only orthography for which there are subpopulations who reliably hit upon an alternative route to literacy.

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Author contributions

E.A.H. contributed the initial proposed topic and scope of the paper; both authors contributed to the background research, writing, and editing of the paper.

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