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Writing Systems, Reading, and Language

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RUNNING HEAD: WRITING SYSTEMS, READING, AND LANGUAGE

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Abstract

Skilled reading reflects an accumulation of experience with written language. Written language is typically viewed as an expression of spoken language, and this perspective has motivated approaches to understanding reading and reading acquisition. However, in this article I develop the proposal that written language has diverged from spoken language in important ways that maximise the transmission of meaningful information, and that this divergence has been central to the development of rapid, skilled reading. I use English as an example to show that weaknesses in the relationship between spelling and sound can give rise to strong regularities between spelling and meaning that are critical for the rapid analysis of printed words. I conclude by arguing that the nature of the reading system is a reflection of the writing system, and that a deep understanding of reading can be obtained only through a deep understanding of written language.

Reading is one of our primary means of gathering and analysing information as we interact with the world. It provides access to knowledge, employment, social benefits and services, and allows us to participate in democracy. Modern society places intense literacy demands on individuals. Thus, low literacy is a major contributor to inequality, separating nations from one another, and segmenting populations within societies. But reading is also a fascinating scientific problem. Decades of research have shown that reading is rapid, and arises without intention (e.g. Stroop, 1935) or even conscious awareness (e.g. Forster & Davis, 1984; Marcel, 1983). It is in this context that reading is especially interesting, because unlike the other cognitive abilities that guide us through the world, reading is not a universal part of human experience. Instead, it is a learned *skill* dependent on the reorganisation of brain circuits designed for other purposes (e.g. Dehaene & Cohen, 2007). Thus, in addition to its impact on the outcomes of individuals, societies and nations, reading provides a model system for asking questions about how the brain learns a new body of knowledge, and how the emerging system is shaped by information in the environment, pre-existing knowledge structures, and more general constraints on human learning.

The ubiquity of reading in contemporary society contrasts sharply with the fact that it is such a recent cultural invention. For thousands of years of human history, nobody could read or write. Then, through the emergence of writing and its antecedents over the past 10,000 years (e.g. Schmandt-Besserat, 1992), and through the continuous improvement of materials on which to write (e.g. Sproat, 2010, de Hamel, 2016), reading became a device available to the most privileged. The phenomenon of mass literacy that we know today has arisen within a timescale of generations. It is often said that the emergence of writing represents a threshold of human history – allowing civilization to accumulate knowledge, to record history, to establish laws, and therefore to depart from an oral culture based on the 'here and now' (Sproat, 2010) – and indeed, there is no doubt that writing allows us to make the most of spoken language. But as I will argue in this paper, writing is more than a record of spoken language, and this turns out to have profound consequences for reading and reading acquisition.

Spoken Language Basis of Reading and Writing

The concept of *primacy* dominates virtually all scholarly thinking about reading and writing. In the discipline of linguistics, spoken language is characterised as having primacy over written language (e.g. Saussure, 1966; Sapir, 1921). Written languages are viewed as reflections of spoken languages, as emerging from spoken languages, and have even been characterised as a form of language technology (Sproat, 2010), of little theoretical interest in their own right. Indeed, spoken languages are found in all societies, sometimes with and sometimes without written language, but the reverse never occurs. Similarly, in the domain of cognitive psychology, reading is characterised as an “accessory that must be painstakingly bolted on” to the spoken language system (Pinker, 1997, p. ix). Babies are born with the ability to acquire spoken language, but children learn to read only through years of formal instruction and practice. Even when the reading skill is fully acquired, leading scholars characterise it in terms of spoken language – “language at the speed of sight” (Seidenberg, 2017).

The notion that reading is dependent on spoken language has been at the heart of psychological approaches to understanding reading since its first treatment as a scientific phenomenon. Huey (1908) described silent reading as involving “inner speech” (p.117) and of words being “mentally pronounced” (p. 118). In contemporary research, the most influential theories posit that ‘decoding’ the printed word to a spoken language representation is an essential component of successful reading comprehension (e.g. Gough & Tunmer, 1986). On this perspective, the decoding process allows the reader to activate an existing spoken language representation, and to derive meaning on the basis of that pre-existing vocabulary knowledge. Thousands of articles have been devoted to understanding the impact of phonological decoding ability on reading success (e.g. Lervåg, Hulme, & Melby- Lervåg, 2017), the impact of restricted access to spoken language representations on deaf children learning to read (e.g. Marschark & Harris, 1996), how irregularity in the spelling-to-sound mapping poses challenges for reading acquisition (e.g. Seymour et al., 2003), and how best to teach phonological decoding skills (e.g. Johnston & Watson, 2005). Similarly, debate in the skilled reading literature has focused on how phonological decoding impacts on reading comprehension (e.g. Van Orden, 1987), whether phonological decoding is obligatory (e.g. Frost, 1998) or 'fast' (e.g. Rastle & Brysbaert, 2006), and the mechanisms that underpin the translation of letters into sounds (Coltheart et al., 2001; Plaut et al., 1996).

The conceptualisation of reading and reading acquisition in terms of the primacy model is to a certain extent appropriate. There is a broad consensus that reading acquisition in alphabetic writing systems is strongly determined by a child's ability to decode the printed word to a spoken language representation (see e.g. Castles, Rastle & Nation, 2018, for discussion), and there is no doubt that such representations are computed and influence word recognition and comprehension in skilled readers (e.g. Leinenger, 2014, for review). Similarly, evidence from functional MRI reveals that brain systems underlying print and speech processing converge in very similar ways across a wide spectrum of contrasting languages, suggesting that reading acquisition may be constrained by the organisation of the brain network underlying speech (Rueckl et al., 2015). But I will argue that by viewing reading through the primacy lens, we miss much of what there is to see in written language; and we fail to appreciate fully how the challenge of skilled, rapid reading is met.

Divergence of Written and Spoken Language in Antiquity

One theme of this article is that writing has diverged from spoken language – that it communicates different information to spoken language – and that this is key to understanding the problem of skilled reading. In antiquity, writing was seen as a direct representation of spoken language. Classical Greek and late Classical Latin texts were written in *scriptura continua*, mimicking the nature of spoken language, with no spacing between words or other graphic conventions (Saenger, 1997). Within the stream of text there was a very high degree of transparency between the sounds of the spoken language and the symbols used to write those sounds. These texts were typically read aloud, in groups or individually in a soft voice (Saenger, 1997). Reading in this period thus consisted of overt translation to the spoken language, and because writing consisted of such a high fidelity record of the spoken language, it was thought to facilitate this translation.

However, slowly the graphic conventions apparent in modern writing did emerge, including spaces between words, punctuation, and experimentation with the visual layout of text (Parkes, 1992). Palaeographic study reveals that the emergence of spacing and other graphic conventions began around the 7th century, and it has been argued that that this coincided with the emergence of silent reading (Saenger, 1997). It is not possible to find causal data linking these two milestones. However, the introduction of spacing to mark word boundaries is rather perplexing if written language is a simple record of spoken language. Indeed, the introduction of spacing *actually broke the very tight link* between written and spoken language, as word boundaries are not present in continuous speech. Thus, this innovation in writing practice introduced inconsistency in the mapping between spelling and sound, in what was otherwise a highly-transparent relationship.

If written language is an expression of spoken language, and if reading is built on a spoken language foundation, then why should introducing inconsistency in the relationship between print and sound have occurred, and been sufficiently successful to be retained? To answer this question, we need to consider more carefully the proposal that meaning can be derived from text through translation to spoken language representations. In particular, on considering the nature of the spoken language representations that can be accessed through a decoding process, it is immediately apparent that these are highly impoverished relative to the rich information characteristic of actual spoken language. When we compute meaning from spoken language, we take advantage of coarticulatory cues to predict upcoming sounds (e.g. McMurray & Jongman, 2016; Salverda, Kleinschmidt, & Tanenhaus, 2014), prosodic and intonation cues to predict aspects of meaning in sentences (e.g. Grosjean & Gee, 1987) and single words (e.g. Soto, Sebastian-Galles & Cutler, 2001), information about the context and intent of the speaker (e.g. McQueen, 2007, for discussion), along with audio-visual (McGurk & MacDonald, 1976) and gesture (Kita, 2000) cues. No matter how tight the link between written and spoken language, these forms of information will *always* be absent in text.

This discussion reveals the weakness of viewing reading and writing through the primacy lens. The classical *scriptura continua* manuscripts provided the closest possible link between written and spoken language. But a simple analysis exposes the paucity of information in writing. Translating the written language back to sound-based representations presents the reader with many of the challenges of understanding spoken language, but without any of the usual cues that support this process. Though this form of analysis might allow slow, overt reading aloud by trained orators, it is unlikely that it could support the rapid analysis of text that characterises modern, skilled reading.

This insight suggests that while weakening the link between spoken and written language, perhaps the introduction of graphic conventions was related to the development of a more advanced form of reading. Indeed, we know from modern research that word spacing has a powerful impact on eye-movement control and word identification. Unsurprisingly, removing word spacing in typically-spaced formats such as English sentences slows reading (Rayner, Fischer, & Pollatsek 1998). But conversely, introducing word spacing to typically non-spaced formats such as Japanese Hiragana (Sainio, Hyönä, Bingushi, & Bertram, 2007) and Thai (Kohsom & Gobet, 1997) speeds reading. More recent research on Chinese (another non-spaced script) suggests that the addition of spacing facilitates word identification by reducing fixation time as well as the number of refixations in child and adult readers (Zang, Liang, Bai, Yan, & Liversedge, 2013), perhaps because physical demarcation of word boundaries influences the computation of the next fixation location (Zhou, Wang, Shu, Kliegl, & Yan, 2018). Spacing also assists children to learn new vocabulary words printed within Chinese sentences (Blythe et al, 2012).

Our consideration of the limits of information within the classical *scriptura continua* texts also helps to explain the geographical distribution of the introduction of spacing and other graphic conventions. Paleographic analysis suggests that the introduction of these conventions began in Ireland before spreading to the European continent (Parkes, 1992). This is significant because for the Irish monks who had embraced Christianity, Latin was a foreign language (Parkes, 1992). In the absence of lexical knowledge to guide segmentation of the text, seeking to access meaning even through overt reading aloud would have presented a very serious challenge indeed. The introduction of word spacing in these texts probably made reading possible, and as such, also provided a scaffold for these monks to begin to learn the spoken language.

This brief introduction to the development of graphic conventions in antiquity serves two purposes. First, it reveals that breaking the link between spoken and written language may have been *functional* in the development of skilled, silent reading. This position is contrary to much of the recent theoretical work on reading acquisition, which posits that the convergence between spelling and sound in a writing system is a major determinant of reading success (e.g. Seymour et al., 2003; Spencer & Hanley, 2003). Second, it provides a simple example of how written language communicates different information to spoken language. Indeed, I have argued that these additional graphic conventions may have been *necessary* to overcome the paucity of information in the written signal, as reading transitioned from use in public oration to the silent, rapid analysis of printed text associated with contemporary usage (see also Saenger, 1997).

The Information in English Writing

The central challenge of reading is learning the relationship between visual symbols and their meanings. Recent empirical and theoretical work suggests that precisely how this challenge is met may depend on the writing system (Frost, 2012). Thus, achieving an understanding of reading and reading acquisition requires reference to the nature of information available *in a particular writing system*. In this article, I describe the relationship between the writing system and the reading system with reference to English. One might argue that this is an example of Anglocentricity in reading research (Share, 2008); and I do not disagree that the trajectory of reading research has been driven to some extent by the accessibility of English within research-intensive universities. However, as I hope will become clear, achieving an understanding of the reading system requires a *deep* understanding of the writing system, and the focus on a single writing system provides an opportunity to develop and address a number of issues of theoretical importance. Further, English is particularly interesting to study because it is a self-organising system, allowed to vary freely over time (Berg & Aronoff, 2017). This contrasts with many major writing systems (e.g. Dutch, French, Welsh, Norwegian, Malay, Portuguese, English braille), in which spellings have been standardised by national or supra-national bodies. The self-organising nature of English writing may mean that it transmits information in a more complex or nuanced manner than in more regulated systems in which particular forms of information are deliberately emphasised. If reading systems are closely linked to writing systems, then this may have demonstrable consequences for reading and reading acquisition. However, although I focus on English, I hope to draw out more general lessons about the relationship between writing systems, reading, and language, in a manner that can be evaluated in future research.

Writing systems are all expressions of spoken language, but they vary considerably, even amongst the alphabetic writing systems that are the focus of this article (see e.g. Daniels, 2018). Drawing from the primacy model, a great deal of research concerned with alphabetic writing systems has focused on the consequences of *orthographic depth* (Katz & Frost, 1992). Orthographic depth refers to the transparency with which visual symbols relate to sounds in a writing system. Writing systems with high transparency between spelling and sound (e.g. Spanish) are known as shallow orthographies, while writing systems with low transparency (e.g. English) are known as deep orthographies. However, it is worth remembering that even shallow orthographies consist of additional information not available in the acoustic signal. For example, Korean has very high transparency between symbols and sounds, but the written language physically demarcates word and syllable boundaries, and the shapes of the letters themselves depict the articulatory organs that would be needed to pronounce them.

The characterisation of writing systems in terms of spelling-to-sound transparency has had a profound impact on reading research. Research has been concerned with how orthographic depth influences the trajectory of reading acquisition (e.g. Caravolas et al., 2012; Seymour et al., 2003), the nature of the representations acquired (e.g. Ziegler & Goswami, 2005), and the development of the reading network in the brain (e.g. Paulesu et al., 2000; Rueckl et al., 2015). In particular, decades of research have been devoted to challenges associated with the very low degree of spelling-sound transparency in English, in which there are multiple possible pronunciations for particular letters, and multiple possible spellings for particular sounds (e.g. Baron & Strawson, 1976; Ziegler, Stone, & Jacobs, 1997). This phenomenon has been a driving force in defining the shape of the most important theoretical approaches to reading (e.g. Coltheart et al., 2001; Perry, Ziegler, & Zorzi, 2007; Plaut, McClelland, Seidenberg & Patterson, 1996; Seidenberg & McClelland, 1989; see also Share, 2008; Castles et al., 2018, for discussion). The classification of words based on spelling-sound transparency has also been central to initial work on the genetic (Bates et al., 2007) and neural (Taylor et al., 2013) underpinnings of reading.

English has an alphabetic writing system and so its primary regularities are indeed between spelling and sound (more specifically, between graphemes and phonemes). However, the ultimate goal of reading is not to map symbols to sounds, but to map symbols to meanings, and this consideration brings different forms of regularity into view. These regularities arise largely because of the morphological structure of English. That is, the vast majority of English words are built by combining a finite number of stem morphemes (e.g. book) with other stem morphemes (e.g. bookworm) or affix morphemes (e.g. bookish). This combinatorial organisation means that stems reoccur in words with similar meanings (e.g. kindness, unkind, kindly), and that affixes modify the meanings of stems in a predictable manner (e.g. kindness, darkness, shyness; Plaut & Gonnerman, 2000; Rastle et al., 2000). The computational models of reading described above have largely focused on single stems in which the only regularity is between spelling and sound; the relationship between spelling and meaning for such words is arbitrary (e.g. *pint* and *mint* share three quarters of their letters but do not overlap in meaning). It is perhaps for this reason that regularities between spelling and meaning have been underappreciated in the reading literature. But if we consider the whole lexicon, made primarily of words with more than one morpheme, then regularity between spelling and meaning is abundant. [1]

The characterisation of spelling—meaning (morphological) regularities in written language, and their impact on reading acquisition and skilled reading, has been treated as somewhat of a niche area of study. However, morphological regularity is intimately linked to the spelling—sound regularities that have been the focus of much of the work on reading. It has long been observed that meaningful information is more apparent in English spelling than in spoken language (e.g. Carney, 1994; Chomsky, 1970). For example, the words *herded*, *kicked*, and *snored* all relate to something that happened in the past, but the past-tense status of these words is far easier to appreciate in their spellings (i.e. the letters [-ed] denote the past tense) than in their spoken realisations (in which past tense is associated with three different sounds or sound sequences; /ɛd/, /t/, and /d/). Similarly, in words such as *magician* and *health,* it is far easier to extract meaningful components (i.e. that these words have something to do with *magic* and *heal*) from their spellings than from their spoken realisations. These examples show how written language can transmit meaningful information more effectively than spoken language. However, the consequence of preserving meaningful information in the spellings of these words is divergence between spelling and sound. That is, marking the past tense consistently through use of the word-final letters [-ed] *necessarily* means that the relationship between these letters and their corresponding sounds is inconsistent. If English writing were a perfect reflection of spoken language, the words *herded*, *kicked*, and *snored* might be spelled *herdid*, *kickt*, and *snord*; and the words *magician* and *health* might be spelled *majishun* and *helth*, losing the meaningful information that the English written forms convey. Thus, like the introduction of word spacing, these examples demonstrate how divergence from spoken language can be functional, by enhancing the transmission of meaningful information.

[1] Non-morphological regularities between print and meaning also occur, as in the case of phonaesthemes (e.g. '<u>sn</u>' is associated with the nose in <u>sn</u>out, <u>sn</u>eeze, <u>sn</u>ort, <u>sn</u>ore; and '<u>gl</u>' is associated with vision in <u>gl</u>immer, <u>gl</u>isten, <u>gl</u>itter, <u>gl</u>ow), but these are relatively rare (see e.g. Monaghan et al., 2014; Rastle et al., 2000 for discussion).

Anecdotal examples like these are often recounted as evidence of the visibility of meaningful information in English writing, but only recently has linguistic analysis begun to quantify the relationship between English spelling and meaning precisely. In their study of the past tense, Berg and colleagues noted that there are only 38 English words comprising a single morpheme that contain word-final [-ed]. Of these, 8 do not have a plausible stem (e.g. *bed*, *shed*) and 20 occur as part of a different vowel grapheme (e.g. *breed*, *feed*); there are only 10 instances that could support an erroneous morphemic reading (e.g. *wicked*, *hatred*, *moped*). The relative absence of this latter class of words means that the presence of [-ed] is a *highly-reliable* cue to past tense (Berg, Buchmann, Dybiec, & Fuhrhop, 2014). Berg et al. (2014) further noted that the high fidelity of information denoted by the spelling [-ed] is achieved because words comprising a single morpheme that could legitimately be spelled with [-ed] are typically spelled another way (e.g. *instead*, *salad*, *horrid*; Berg et al., 2014). Thus, the spelling [-ed] appears to have become *reserved* for communicating the past. Berg et al. (2014) reported similar findings for word-final [-s]: use of word-final [-s] is very rare in words comprising a single morpheme (e.g. *lens*); such words that could be spelled using [-s] are typically spelled another way (e.g. *please*, *sneeze*, *box*).

Berg and Aronoff (2017) articulated a similar relationship between spelling and grammatical class achieved in derivational suffixes. For example, they observed that there are many possible spellings for the word-final sound sequence /əs/ (e.g. *bonus*, *service*, *nervous*, *princess*), but that the spelling [-ous] is virtually always used if the word is an adjective. Further, while it could be that the spelling [-ous] is also used to indicate other grammatical classes, this is not the case; word-final spelling [-ous] *always* indicates adjective status (e.g. *nervous*, *joyous*, *famous*). Thus, as for the past tense marker, the suffix [-ous] appears to be reserved to communicate adjective status. Berg and Aronoff (2017) studied four suffixes and observed similar regularities across all of them. Further, a diachronic analysis revealed that these regularities appear to have become more visible over the last 1250 years of English spelling change.

Recent computational work demonstrates that this strong relationship between suffix spelling and grammatical class is a *general principle* of English suffixation (Ulicheva, Harvey, Aronoff, & Rastle, 2019). Ulicheva et al. (2019) studied the relationship between suffix spelling and grammatical class for over 150 English suffixes; this relationship is visualised in Figure 1 for two suffixes. The first example shows that there are many possible spellings of the word-final sound sequence /ləs/ (e.g. [-lace], [-less], [-liss]). But only one of those spellings is possible if the word is an adjective; and adjectives almost without exception are spelled with [-less] (e.g. *fearless*, *helpless*, *joyless*). The second example shows precisely the same pattern. There are many possible spellings of the word-final sound sequence /Ikəl/ (e.g. [-ickle], [-ycle], [-ickel], [-ical]), But again, with just a few exceptions, one spelling seems to be reserved for adjectives.

Insert Figure 1 about here

These examples give us pause to consider the relationship between English spelling-to-sound and spelling-to-meaning regularities. Specifically, discussion of English writing has typically focused on the apparent disorder created by the proliferation of spellings for particular sound sequences. But it is only through this fractionation that particular spellings can be used reliably to transmit meaningful information. Further, these meaningful regularities are *not present in the spoken language*; the very strong information about grammatical class arising through suffixation is present *only in the written language*. Thus, we can see that spelling—meaning regularity and spelling—sound irregularity are two sides of the same coin. The diversification of spelling maximises the transmission of meaningful information, but this comes at the cost of an absence of a tight link between spelling and spoken language.

The extent to which this trade-off between phonology and morphology is characteristic of writing systems in general is an open question that requires investigation. Certainly, morphology is a feature of virtually all languages, and many languages have far richer morphology than English. But for the purposes of understanding reading and reading acquisition, we are interested in the visibility of meaningful information in the *writing*, not in the spoken language. I've argued that the high visibility of meaningful morphological information in English writing is a consequence of the fractionation of English spelling (i.e. multiple potential spellings for the same sound sequence). It is certainly possible to find examples of writing systems that are reasonably transparent in terms of the spelling–sound mapping, but which nevertheless convey morphological information in spelling. For example, the past–present distinction in Dutch is sometimes conveyed through spelling alterations in a manner that distinguishes homophonic words (as in zij betwisten [they dispute] versus zij betwistten [they disputed]; Brysbaert, Grondelaers, & Ratinckx, 2000), but this is not characteristic of Dutch spelling in general. Indeed, I would argue that the closer a writing system gets to a one-to-one mapping between spelling and sound, the less scope there is for highly reliable morphological cues to arise in the spelling, unless particular sound sequences themselves are reserved to communicate meaningful morphological information. However, this proposal is speculative; moving forward toward a more general understanding of how writing systems balance spelling–sound and spelling–meaning information will require much more detailed analyses of contrasting writing systems along the lines of those undertaken by Ulicheva et al. (2019).

More broadly, it seems almost inconceivable that the trajectory of reading acquisition, and the nature of representations characterising skilled reading, would not be substantially influenced by the nature of the information being learned (see also Frost, 2012). Yet, while there have been *decades* of research on reading and reading acquisition, research has only just begun to articulate the nature of information transmitted through the orthographies of the world's languages. I would argue that understanding more about how orthographies convey meaning – formulating quantitative models of the nature of information communicated in written languages – will be an essential part of developing a deeper knowledge of reading and reading acquisition into the future.

The Writing System Reflected in the Reading System

Becoming a skilled reader requires instruction and massive text experience over many years (see Castles et al., 2018, for review). Ultimately, all theories of skilled reading in alphabetic systems agree that the outcome of these years of text experience is a reading system whereby visual forms map onto meaning via two broad pathways (e.g. Coltheart et al., 2001; Harm & Seidenberg, 2004; Woollams et al., 2007). One pathway maps visual forms onto meanings via sound-based (phonological) representations, while the other pathway maps visual forms onto meanings directly. Recent neuroimaging studies suggest that this dual-pathway architecture is also observed in the brain, with a dorsal pathway representing spelling-to-sound (Taylor et al., 2013) and sound-to-meaning (Hoffman, Lambon-Ralph & Woollams, 2015) computations, and a ventral pathway representing direct access to meaning (e.g. Taylor et al., 2013; Fischer-Baum et al., 2017). In the following, I describe how the spelling-to-sound and spelling-to-meaning regularities that I have described in English writing are represented in these pathways, and the extent to which they contribute to skilled, silent reading.

Insert Figure 2 about here

<u>Spelling-Sound Knowledge and its Limits in English Skilled Reading</u>

There is a very substantial body of research investigating the role and nature of spelling—sound knowledge in reading and reading acquisition. Hundreds of research studies have demonstrated that the acquisition of spelling—sound knowledge provides a critical foundation in learning to read (see e.g. Castles et al., 2018; Melby-Lervåg, Lyster, & Hulme, 2013 for reviews), and this body of literature has motivated recommendations to teach this knowledge explicitly through phonics in the first years of reading instruction (e.g. National Reading Panel, 2000; Rose, 2006). Learning the relationship between spelling and sound allows children to access the meanings of printed words via their spoken language knowledge through a process of phonological decoding.

Though this process may be relatively slow and effortful, it is critical in bringing children to a degree of proficiency that they can begin to read independently, and thus begin to build up the vital text experience necessary to become a skilled reader (Share, 1995; Castles et al., 2018, for discussion). Recent work suggests that emphasis on spelling-sound knowledge also assists adults to learn to read and understand novel words (Taylor, Davis, & Rastle, 2017). Functional neuroimaging data suggest that this benefit is associated with a decrease in neural effort within the dorsal pathway brain regions thought to underpin spelling-sound knowledge (Taylor et al., 2013, 2017).

The acquisition of spelling—sound knowledge is vital in reading acquisition, but it is also well known that this knowledge continues to play a role in skilled, silent reading. The most persuasive evidence for this comes from studies of masked phonological priming, in which recognition of targets (e.g. MADE) are faster or more accurate when primed by a phonologically-identical nonword (e.g. mayd) than by an orthographic control (e.g. mard). This phenomenon has been observed across paradigms (e.g. perceptual identification: Perfetti, Bell & Delaney, 1988; visual lexical decision: Ferrand & Grainger, 1992; reading aloud: Lukatela & Turvey, 1994; text reading: Rayner, Sereno, Lesch & Pollatsek, 1995) and across alphabetic writing systems (e.g. French: Ferrand & Grainger, 1992; Dutch: Brysbaert, 2001; Korean: Kim & Davis, 2002). The fact that these effects emerge when primes are nonwords indicates that the spelling-sound knowledge being deployed is sublexical (i.e. not based on stored knowledge of known words). Further, the fact that these effects emerge despite the very short exposure durations of the primes has been taken as evidence that this spelling-sound knowledge is activated rapidly and plays a leading role in word recognition and comprehension. However, meta-analysis suggests that these effects are small, at least in English (Rastle & Brysbaert, 2006). We are yet to fully understand the nature of the phonological representations activated at these short durations, although research has shown that they also capture some prosodic information associated with stress assignment (Ashby & Clifton, 2005), suggesting that they may be reasonably detailed.

If reading acquisition involves learning the statistics of the writing system (Frost, 2012), then the spelling-sound knowledge of English skilled readers should ultimately mirror the spelling—sound relationship of the writing system, and this is exactly what has been observed in recent research. Mousikou and colleagues probed the nature of skilled readers' spelling—sound knowledge by asking 41 participants to read aloud 915 disyllabic nonwords such as *explave*, *laniff*, and *bamper (*Mousikou, Sadat, Lucas & Rastle, 2017). Despite the fact that nonwords were generated from existing disyllabic words, they found considerable variability in how the 41 participants pronounced these nonwords, with each nonword generating between 1 and 22 alternative pronunciations (see also Pritchard et al., 2012 for similar observations). Critically, regression analyses of the variability in pronunciation of the nonwords suggested that it was strongly attributable to the consistency with which orthographic units in the nonwords map onto sounds in the lexicon of English words. For example, the nonword *bamper* generated only a single pronunciation across participants; this result is consistent with the fact that the onset and rime units in each of its syllables ([b], [am], [p], [er]) have a very reliable association with their pronunciations (/b/, /æm/, /p/, /ə/). In contrast, the nonword *eluch* generated 22 different pronunciations; in this case, while the onset of the second syllable [l] is associated with only one pronunciation in English words, neither of the rime units [e] or [uch] are associated reliably with a single pronunciation. The strength with which the onset and rime units used in the disyllabic nonwords map reliably to particular stress patterns in English words also determined the degree to which stress was assigned consistently to the nonword stimuli (Mousikou et al., 2017).

The nonword reading aloud data of Mousikou et al. (2017) suggest that skilled readers' spelling—sound knowledge is a reflection of the strength of the spelling—sound mapping in English words. Knowledge is precise when the spelling—sound mapping is highly consistent in the lexicon of English words, and imprecise when the spelling—sound mapping is highly inconsistent. This conclusion fits with the notion that the process of reading acquisition is a process of learning the statistical structure of writing system (Frost, 2012). However, the results described above relate to variation *across* participants. It could be that participants individually have very precise knowledge, perhaps expressed in the form of rules (e.g. Coltheart et al., 2001), but that this knowledge differs across participants as a result of differences in reading experience. Mousikou et al. (2017) considered and rejected this possibility, on the basis that there is also a high degree of inconsistency *within* participants in the pronunciations and stress given to highly-inconsistent orthographic units (see also Ktori, Mousikou, & Rastle, 2018). Overall, the findings of Mousikou et al. (2017) suggest that even in a sample of highly-skilled adult readers with considerable experience of English writing, there is a *high degree of uncertainty* in areas of the spelling—sound mapping. This uncertainty reflects the fact that English writing offers relatively imprecise information about the sounds of spoken language.

To summarise, there is strong evidence that learning to appreciate the relationship between spelling and sound is critical in learning to read an alphabetic writing system because it brings children to a level in which they can begin to gain text experience (see Castles et al., 2018). There is also strong evidence that spelling—sound knowledge is activated in skilled, silent reading (Rastle & Brysbaert, 2006, for review), and that this knowledge is represented in dorsal pathway brain regions (Taylor et al., 2013, 2017). Finally, when we probe skilled readers' knowledge of the spelling—sound relationship, there is evidence that it is a mirror of the spelling—sound relationship in the writing system (Mouskiou et al., 2017).   The fact that spelling—sound knowledge is a mirror of the writing system has consequences for the extent to which this form of knowledge can be relied upon. For a writing system like Korean in which there is a near one-to-one mapping between spelling and sound, the visual symbols of the writing system provide a direct line into spoken language. But for a writing system like English in which the mapping between spelling and sound is imprecise, and in which adults with many years of reading experience show considerable uncertainty, it is unlikely that phonological decoding on its own could support rapid word recognition and text comprehension.

Spelling—Meaning (Morphological) Regularities and Orthographic Learning

I have argued that the acquisition of spelling—sound knowledge is necessary in reading acquisition in alphabetic writing systems, but that it is unlikely that this knowledge alone could support skilled, silent reading in English. Instead, contemporary theories of skilled reading propose that readers must also acquire a direct mapping between printed words and their meanings (e.g. Coltheart et al., 2001; Harm & Seidenberg, 2004; Woollams et al., 2007). This direct mapping is represented in ventral pathway brain regions (Taylor et al., 2013), which become increasingly tuned to printed words as readers develop greater skill (Dehaene-Lambertz et al., 2018), certainly into the period of adolescence (Ben-Shachar et al., 2011). Much less is known about the acquisition of direct links between spelling and meaning, but it is thought that this process of "orthographic learning" arises through an accumulation of experience with printed text (e.g. Castles & Nation, 2006; Nation, 2017), as a child uses their spelling-sound knowledge as a self-teaching device (Share, 1995). The self-teaching theory proposes that successful, repeated decoding of an unfamiliar word into a spoken language representation provides a mechanism through which to establish the orthographic lexical representations necessary for rapid word recognition (Share, 1995).

Most of the research on the acquisition of the direct pathway linking spellings to meanings has focused on item-level effects – the journey of a particular word to one that can be recognized rapidly (Castles & Nation, 2006; Nation, 2017). Indeed, theoretical work in this area suggests that at any point in time, there will be some words that a child can recognize rapidly in an item-based manner, while recognition of other words will require an analytic decoding process (Castles et al., 2018). Simulation models have investigated how this orthographic learning might arise within a self-teaching framework (Pritchard, Coltheart, Marinus, & Castles, 2018; Ziegler, Perry, & Zorzi, 2014). In the developmental model of Ziegler et al. (2014), rudimentary knowledge of a small set of grapheme-phoneme relationships is used to decode novel words; if a decoded pronunciation matches a representation in the phonological lexicon, a representation in the orthographic lexicon is learned, and the successful decoding experience is used as an internal teacher to improve grapheme-phoneme knowledge. The model of Pritchard et al. (2018) went on to explore the impact of *context* on orthographic learning under a variety of circumstances. However, though these models provide proof-of-concept that orthographic representations can be acquired through a self-teaching mechanism, they do not address the question of how these orthographic representations map onto semantic contents. This would seem to be a difficult problem in English (as in other alphabetic languages) because of the sheer scale of the challenge: it is estimated that the average 20-year-old English reader can recognize around 70,000 unique words (Brysbaert, Stevens, Mandera, & Keuleers, 2016). One counterargument might be that this type of item-based learning is similar to what is involved in learning Chinese characters.[2] However, estimates of the number of characters that must be learned for full adult literacy in Chinese are an order of magnitude less than the requirement for English, ranging from 4,300 characters (Katz & Frost, 1992) to between 7,000 and 9,000 characters (Pine, Ping'an, & Song, 2003).

It turns out that the problem of how English readers can possibly acquire item-specific knowledge of so many tens of thousands of words is somewhat of a red herring, because the English writing system is structured such that orthographic learning does not need to arise in an item-based manner. That is, the challenge of learning the spelling-meaning mapping is dramatically reduced if the learner has an appreciation of how morphological relationships are expressed in the writing. This principle is illustrated in Figure 3. The first panel of the figure lists 15 unique English words; however, if the learner has an understanding of morphology, then these 15 words become variations of a single word. It is unlikely that these words would need to be learned in an item-specific manner, one at a time, because learning the meaning of one word assists learning the others. In fact, in the estimates of vocabulary size recently published by Brysbaert et al. (2016), the number of unique words that the average 20-year-old can recognize drops from 71,000 to 42,000 if inflections (e.g. *develops*, *developing*, *developed*) are not counted as unique; and this number drops

[2] There is a limited degree of regularity between the components of Chinese characters (phonetic and semantic *radicals*) and the sounds and meanings associated with them. However, there are many hundreds of these radicals that must be learned, and some have low reliability. Thus, although not wholly arbitrary, the learning of Chinese characters offers only limited capacity for generalisation.

further to a much more manageable 11,100 if derivations (e.g. *developer*, *redevelop*) are not counted as unique. It seems important that this basic fact about the writing system should feature in theories of orthographic learning.

Insert Figure 3 about here

Taking advantage of these regularities requires that the reader have an understanding of morphological relationships. But what does this mean in mechanistic terms? It means that the orthographic input needs to be structured in such a way that reveals that they share the same stem [develop], as illustrated in the second panel of the figure. Yet, in order to acquire overlapping representations of this nature, the reader must appreciate that the letter groups at the beginnings and endings of these words are somehow significant, and should be separated from the stem [develop] in a way that would not occur for other cases in which words are embedded in other words (e.g. *shallow*, *formula*). To understand how this might be achieved, we again need to go back to the information available in the writing system, and specifically to the observation that the large number of English spellings for particular sound sequences permits some spellings (affixes) to become reserved to communicate particular meanings. If learners become sensitive to this highly-reliable information about the functions of particular letters and letter groups, then that ultimately will allow them to structure orthographic representations in such a way that captures the meaningful relationships between words (as in the second panel of Figure 3; see also Rastle & Davis, 2008). It seems plausible that limited morphological knowledge may act as a schema with which to interpret new words; and conversely, that appropriately-structured orthographic representations of these new words may further strengthen morphological knowledge. In this way, knowledge of this feature of the writing system may support a form of *morphological self-teaching* that facilitates ongoing orthographic learning, as readers encounter increasingly complex derivations through their text experience. However, further computational modelling work is required to develop this proposal, and of course it is also subject to empirical evidence.

Recent work using laboratory acquisition paradigms has begun to articulate *how* readers might discover this powerful morphological information (e.g. Tamminen, Davis & Rastle, 2015). In these laboratory experiments, adult participants are taught novel vocabularies with a morphological structure (e.g. *sleepnule*, *buildnule*, *teachnule*), and then probed some days later in a variety of ways to assess their knowledge of the novel affix (e.g. [-nule]), including online tasks requiring generalisation to untrained items (e.g. *sailnule*). Tamminen et al. (2015) reported that learning of the novel affix is dependent on (a) the consistency with which the affix spelling maps to a particular meaning; and (b) the number of unique stems to which the affix attaches (i.e. family size). These findings suggest that we acquire knowledge of spellings that consistently signify particular meanings across multiple diverse contexts. This conclusion seems consistent with work investigating morphological representation in skilled readers (e.g. Ford, Davis, & Marslen-Wilson, 2010) but further work is required to assess the validity of these predictions fully. More generally, the development of a theory of how we acquire this form of knowledge will be enriched through contact with research on other forms of language learning, including statistical learning (e.g. Gomez, 2002) and novel word learning (e.g. Nation, 2017; Joseph & Nation, 2018), as well as research on the impact of explicit instruction on the development of long-term knowledge (e.g. Kirschner, Sweller & Clark, 2006).

Spelling—Meaning (Morphological) Regularities in Skilled Reading

I have argued that coming to appreciate morphological information in the writing system may underpin acquisition of the direct mapping between spelling and meaning necessary for rapid, skilled reading. Though this proposal requires further evidence, it is consistent with new research investigating the relationship between microstructural properties of white matter pathways used in reading and aspects of reading behaviour (Yablonski, Rastle, Taylor & Ben Shachar, 2019). Yablonski et al. (2019) used diffusion MRI (dMRI) to identify the major ventral and dorsal reading pathways in a group of 45 adult English readers, who had also completed a behavioural battery assessing morphological and phonological processing skill in reading. They found significant correlations between white matter properties of the left-hemisphere ventral (but not dorsal) reading pathway and morphological processing skill. This relationship remained significant even after accounting for phonological processing skill. This study demonstrates that variation in white matter properties of the ventral (spelling-to-meaning) reading pathway is associated with variation in morphological processing ability. Although we cannot draw causal inferences from this association, it does indicate that sensitivity to morphological information in reading is a ventral (spelling-to-meaning) capacity (see also Rastle, 2018).

Once the reading skill has been acquired, it is clear that adults capitalise on the meaningful morphological information conveyed by the writing system, to facilitate rapid word recognition. There is now substantial evidence that skilled readers analyse the morphological structure of printed words very early in visual word recognition. Research using masked priming demonstrated almost 20 years ago that subliminal presentation of derivations facilitates recognition of related stems (e.g. dreamer-DREAM), and that this facilitation cannot be attributed to a simple summation of the semantic and orthographic overlap characteristic of morphological relatives (Rastle et al., 2000). Further work over the subsequent decade, and involving multiple replications, revealed the surprising finding that these masked priming effects actually arise whenever items *appear* to be morphologically related (e.g. corner-CORN, [-er] is an English suffix but *corner* is not related to *corn*), and critically, are larger than those obtained on the basis of simple letter overlap (e.g. brothel-broth; [-el] is not an English suffix; Rastle, Davis & New, 2004; see Rastle & Davis, 2008, Davis & Rastle, 2010 for reviews). More recent work using the temporal precision of ERPs has shown that this form of morphological analysis arises within the initial 200 ms of visual word recognition, and is rapidly followed by semantic analysis and integration. It is during this latter stage that any incorrect analyses from the initial stage (e.g. for items like *corner*) are resolved (Lavric, Elchlepp, & Rastle, 2012; see also Whiting, Shtyrov, & Marslen-Wilson, 2014). Research probing the nature of this morphemic knowledge further suggests again that it is a mirror of the writing system: suffixes that are strongly indicative of aspects of meaning are more strongly represented in the skilled reading system than suffixes that are more weakly associated with aspects of meaning (Ulicheva et al., 2019). Reading experience into adolescence continues to shape this form of analysis (e.g. Beyersmann, Castles & Coltheart, 2012; Dawson, Rastle & Ricketts, 2017).

This body of research suggests that skilled readers have acquired an understanding of how particular letter groups convey meaningful information and deploy this knowledge rapidly in visual word recognition. This analysis is rapid precisely because it is superficial, based only on the *apparent* presence of morphological structure. But why should skilled readers conduct an analysis that will lead to an incorrect interpretation for words like *corner* (i.e. that a *corner* is someone who *corns*)? The answer lies again in the information transmitted by the writing system. Indeed, words like *corner* that appear incorrectly to be morphologically complex are very rare in English spelling, because (as discussed previously) they use letter groups that are reserved as affixes to communicate particular meanings. Typically, words with a single morpheme like *corner* would be spelled in a way that does not make use of these letters (e.g. as in *martyr*, *sulphur*, *fibre*); words like *corner* are exceptions because their spellings do not convey the appropriate meaning (Ulicheva et al., 2019). Thus, the writing system provides a very simple way of computing the meanings of a large number of words with only a small degree of failure; and the outcome of years of text experience is a reading system that capitalises on this feature of the writing system.

To summarize, the English writing system communicates highly-visible information about meaning through spelling, information that arises only because of imprecision in the relationship between spelling and sound. Thus, just as the introduction of word spacing in *scriptura continua* texts allowed information to be transmitted “directly to the mind through the eye” rather than the ear (Parkes, 1992, p. 1), the divergence from spoken language allows English writing to communicate high-fidelity meaningful information. It appears that this information is acquired through an accumulation of experience with printed words into the period of adolescence (e.g. Beyersmann et al., 2012), and that our sensitivity to this information is reflected in the ventral stream brain regions that underpin the direct mapping between spelling and meaning (Yablonski et al., 2019). Finally, this form of information in the writing system shapes the process of skilled reading, making it possible to identify the meaningful components of printed words reliably and at great speed. In essence, the writing system has evolved to support skilled, silent reading; and the knowledge represented in the skilled reading system reflects information available in the written language.

Conclusions and Emerging Questions

In this discussion, I have put forward the view that the study of reading and reading acquisition is the study of how information transmitted through writing becomes represented in the minds and brains of individuals, through an accumulation of instruction and text experience. This broad perspective seems uncontroversial, and yet, it is striking how little we understand of the nature of information transmitted through writing. Written language is an expression of spoken language, but the nature of information transmitted through these forms of language differs. Examples going back to antiquity show how written language has diverged from spoken language in ways that support skilled, silent reading. Understanding any aspect of reading acquisition requires a deep appreciation of what it is that is being learned; this knowledge provides the foundation for asking the right questions and helps us to make sense of behaviour. Yet, our field has produced thousands of journal articles and monographs on the problem of reading and reading acquisition, including differences in these processes across languages, while only just scratching the surface of characterising written language(s) in a quantitative manner. Addressing this gap presents a major challenge for future research.

I have conceptualised English writing (and therefore, reading) as reflecting a trade-off between spelling-sound regularity and spelling-meaning regularity. It is well known that English writing is a relatively poor reflection of English spoken language. Indeed, this theme has driven much of the scholarly thinking on reading instruction, reading acquisition, and skilled reading. However, I've argued here that spelling-sound irregularity and spelling-meaning regularity are two sides of the same coin. The former is a necessary condition of the latter. The proliferation of spellings for English sound sequences weakens the relationship between spelling and sound, but permits some spellings to become reserved for the transmission of specific aspects of meaning (Berg & Aronoff, 2017; Ulicheva et al., 2019). The transmission of this highly-consistent meaningful information would not be possible if English spelling were a totally faithful record of the spoken language with a one-to-one mapping between spellings and sounds. I have argued that English readers capitalise on both of these forms of regularity, though in different ways, at different time points in the process of reading acquisition, and underpinned by different brain pathways. This perspective turns the dominant narrative of English reading and writing on its head. The disorder of the English spelling–sound mapping is not some nasty feature of the writing to be overcome, but a consequence of order in the English spelling–meaning mapping. I've argued that this order in the spelling–meaning mapping may be vital for orthographic learning as text experience accumulates through the period of adolescence and beyond, and for rapid word recognition in skilled, silent reading.

The proposal that systematicity in the spelling–meaning mapping may be particularly important in supporting skilled, silent reading in English raises an interesting question about whether readers of writing systems that prioritise systematicity in the spelling–sound mapping might somehow be at a disadvantage. It is tempting to argue that the answer is 'no', for the reason that writing systems all provide optimal solutions to representing spoken language – that "most languages get the orthography they deserve" (Katz & Frost, 1992, p. 67). On this view, although writing systems may differ widely, every writing system itself provides the most efficient path into the spoken language that it represents. The reading system then becomes tuned to the specific solution for that language through the process of reading acquisition. Various examples of the ways in which writing systems are optimally tuned to represent spoken language were described by Frost (2012). This is an attractive proposal, and it is easy to find examples that offer broad support. However, it is also easy to find examples in which writing systems do not provide optimal solutions for representing spoken language, and we therefore need to be cautious about accepting this proposal uncritically.

One particularly interesting example of the latter situation is found in English braille. The most common form of English braille is *contracted braille*, in which highly familiar words and letter clusters (e.g. EA, ST, ED) are represented in a single cell (a cell is the 2x3 matrix of raised dots that constitutes the basic unit of braille writing). Though *uncontracted braille* (a writing system that does not use contractions) is used in the very early stages of learning to read, contracted braille is preferred because it saves space in printing and is also thought to permit more rapid reading (see Fischer-Baum & Englebretson, 2016 for discussion). Braille contractions are language specific, and in English, are regulated by the International Council of English Braille (see e.g. Simpson, 2013). However, Fischer-Baum and Englebretson (2016) identified a potential problem with these contractions: they often straddle and thus obscure morpheme boundaries (e.g. miSTrust, rERun, milEAge; in these examples the letters in capitals are expressed in a single Braille cell). Fischer-Baum and Englebretson (2016) went on to show that the obscuring of the morpheme boundary in these forms disrupts word recognition. Thus, here we have a case in which the writing system is clearly non-optimal in the way that it expresses spoken language. Of course, one could argue that this is an unusual case due to the intense regulation of English braille. But writing systems are altered through human intervention frequently and for many reasons, and it is unlikely that those alterations always lead to more efficient transmission of meaning.

Moving forward, a number of emerging questions come into view. Becoming a skilled reader requires case-specific but also general knowledge of regularities in the writing system being learned. This latter aspect of the acquisition process permits the learner to deal with unfamiliar words – to read new words aloud (e.g. *blog*), to determine the meanings of new words (e.g. *untweetable*), and to spell new words in a plausible manner (e.g. that word-final [-less] should not be used to spell a noun). The extent to which a learner comes to appreciate the item-specific and general information available in a writing system depends on text experience over many years, along with the nature of any instruction provided (e.g. training on spelling-sound relationships via systematic phonics). However, we do not have a good understanding of how these factors come together to impact on adult reading skill. Research has begun to address these questions – how the knowledge underpinning reading builds up over time (e.g. Monaghan & Ellis, 2010), whether certain learning experiences are more important than others (e.g. Zevin & Seidenberg, 2002; Joseph & Nation, 2018), whether explicit training on aspects of a writing system improves learning (Powell, Plaut & Funnell, 2006), and how pre-existing language ability may modulate the impact of that explicit training (Chang, Taylor, Rastle & Monaghan, 2017). However, much further work on these dimensions of experience needs to be conducted to understand reading acquisition. This work would also need to include contact with the memory literature (e.g. McClelland, McNaughton, & O'Reilly, 1995) to ensure that theories of the accumulation of knowledge in reading acquisition are consistent with what is known of the nature of short- and long-term learning processes.

Finally, while I have discussed how the information in writing impacts on reading and reading acquisition, an interesting question is whether this relationship also goes in the reverse direction. Is it possible that cognitive constraints on reading acquisition impact on the evolution of writing systems? No doubt, there are multiple social, historical, and political forces that can give rise to spelling change. However, the proposal that cognitive constraints might also impact the evolution of spelling seems worthy of consideration, particularly given research suggesting that properties of human learning may impact on the structure of spoken languages (e.g. Christiansen & Chater, 2008; Smith et al., 2017). I have already described how writing in antiquity may have changed due to (a) lack of familiarity with the spoken language used in early Christian texts; and (b) the change in the use of reading to a private, silent activity (see Parkes, 1992; Saenger, 1997). It seems possible that the introduction of spacing and other graphic conventions was driven by these cognitive challenges. The extent to which cognitive constraints may impact on the evolution of *modern* writing systems is an open question. However, emerging evidence suggests that English spelling has changed in such a way as to make regularities between spelling and meaning more visible (Berg & Aronoff, 2017), regularities that I have suggested are critical for the rapid analysis of English words. This insight suggests that perhaps English spelling has evolved to facilitate skilled reading – and in a manner that permits greater efficiency in accessing meaning than if the spelling had been reformed to present a more direct representation of spoken language. Understanding how information transmitted through written language impacts on how the brain solves the problem of reading, and understanding whether the challenge of reading drives evolution of written language are important areas for future discovery.

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Figure Captions

Figure 1. Illustration of how English spelling communicates meaningful information. There are multiple possible spellings for the word-final sound sequences /ləs/ and /Ikəl/ but one spelling in each case reliably indicates adjective status.

Figure 2. Dual-pathway architecture of skilled reading and its neural underpinnings.

Figure 3. Illustration of the impact of morphological knowledge on orthographic learning and orthographic representation. Knowledge of morphology allows readers to recognize that these fifteen words are actually variations of the same word.

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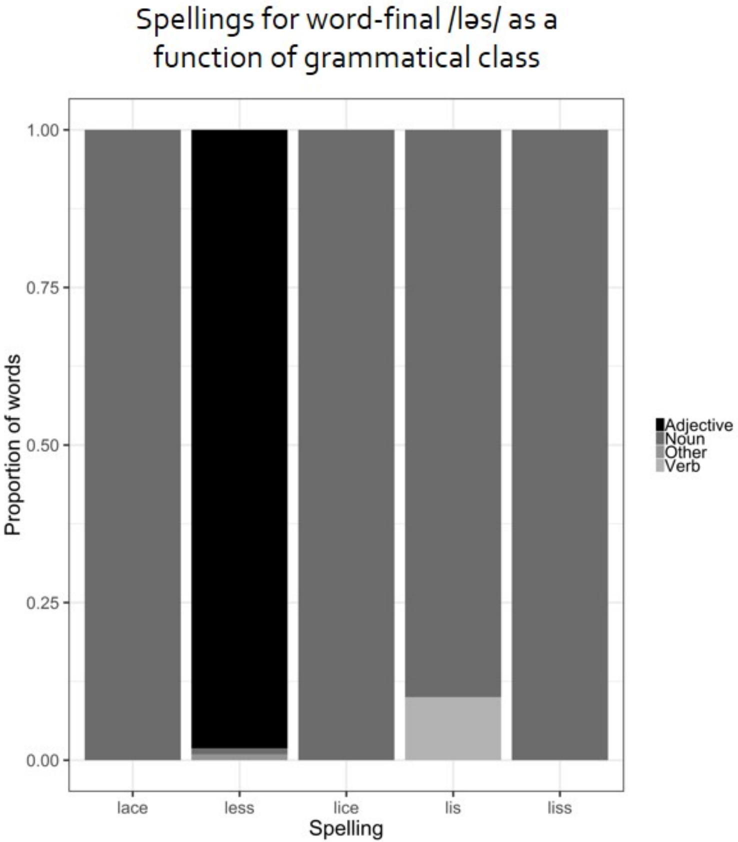
Spellings for word-final /ləs/ as a function of grammatical class
Proportion of words
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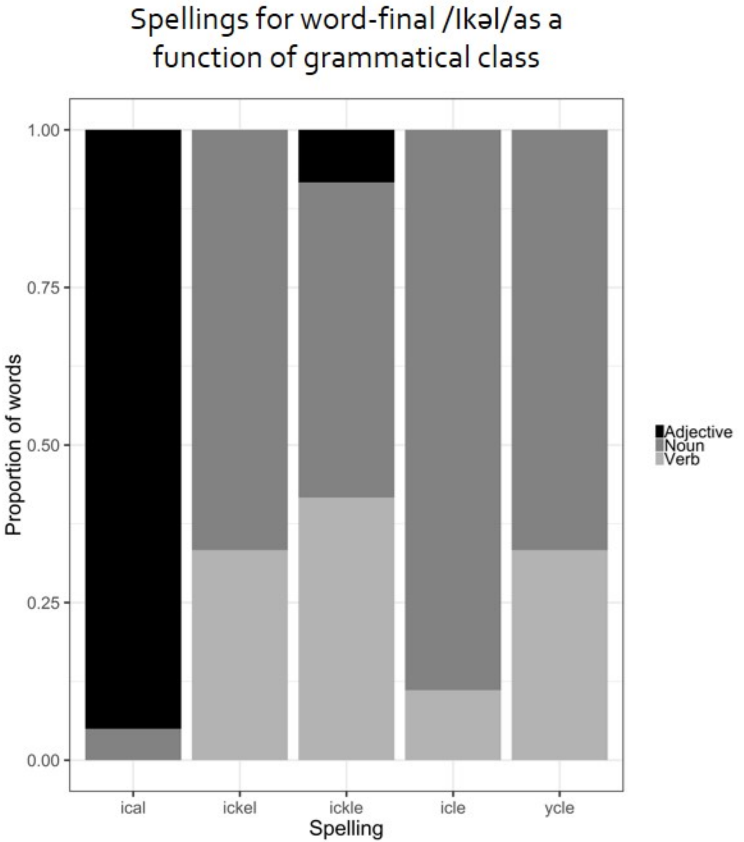
Spellings for word-final /Ikəl/as a function of grammatical class
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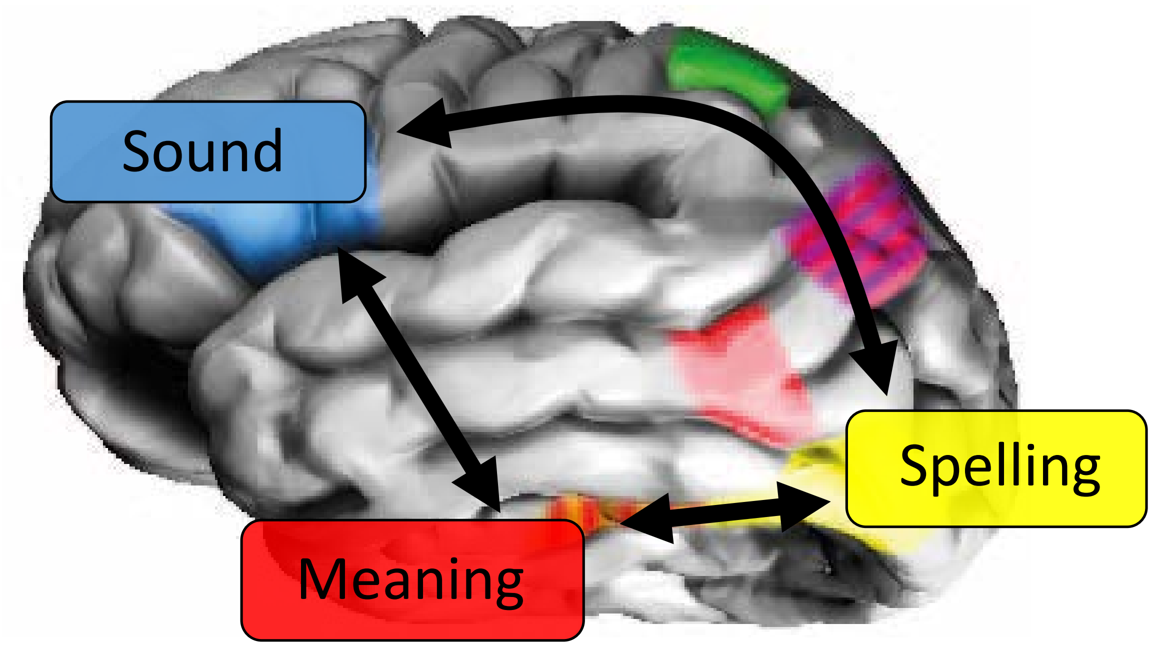
Sound
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