Literacy advantages beyond reading: Prediction of spoken language

Falk Huettig[1,2] & Martin J. Pickering[3]

[1]*Max Planck Institute for Psycholinguistics, The Netherlands*

[2] *Centre for Language Studies, Radboud University, Nijmegen, The Netherlands*

[3] *University of Edinburgh, United Kingdom*

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Correspondence**:** falk.huettig@mpi.nl (F. Huettig)

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Abstract

Literacy has many obvious benefits—it exposes the reader to a wealth of new information and enhances syntactic knowledge. However, we argue that literacy has an additional, often overlooked, benefit: it enhances people's ability to predict spoken language thereby aiding comprehension. Readers are under pressure to process information more quickly than listeners, and reading provides excellent conditions, in particular a stable environment, for training the predictive system. It also leads to increased awareness of words as linguistic units, and more fine-grained phonological and additional orthographic representations, which sharpen lexical representations and facilitate predicted representations to be retrieved. Thus, reading trains core processes and representations involved in language prediction that are common to both reading and listening.

Literacy and Prediction

Learning to read during childhood or adulthood transforms people's lives. It gives readers access to a wealth of new information, for instance through novels, factual articles, and public notices [1]. 'Book language' is also different from conversational speech because the more sophisticated language of written text involves more complex grammar than typical every day speech interactions [2]. For this reason, exposure to written language enhances syntactic knowledge. The frequency of shared reading with parents at 24 months, for instance, predicts children's comprehension of syntactically complex sentences at 30 months [3]. **Literacy** (see Glossary) improves memory [4], visual search [5] and mirror image discrimination abilities [6], and changes cortical [7, 8] and subcortical [9] brain networks. But we argue here that literacy has an important additional benefit: It causes people to predict spoken language and thereby aids understanding. People predict extensively during both spoken (e.g., [10, 11]) and written (e.g. [12, 13]) language comprehension, and such **prediction** facilitates comprehension (e.g. [14, 15). We do not suggest that people always predict (but see [16, 17]) but they may predict aspects of language such as meaning or grammar (e.g., a noun referring to something edible) even if the word itself is unpredictable. They pre-activate predictable upcoming information and use it to reduce processing load if the upcoming information is subsequently encountered. In other words, they can focus on checking for matches between it and the input.

In this paper, we argue that literacy enhances prediction and that this ability to predict transfers to the comprehension of spoken language. Literacy enhances background knowledge and thus in part reflects *secondary* influences of reading acquisition. We define secondary influences as indirect consequences of book language – that is, those influences on prediction that can also be acquired by exposure to audio books (e.g., learning the more elaborate language and complex grammar, and extensive vocabulary of written text). But literacy also has *primary* influences on prediction because people develop predictive skills through reading and these skills transfer from reading to language processing as a whole. We define primary influences of reading as those that are directly linked to the physical act of reading (e.g., the timing and regularity of saccadic eye movements during reading, exposure to printed word forms, and a word bias created by encountering word separation in written language). The assessment of benefits of literacy beyond reading is an important and timely issue. It has been suggested that rather than teaching illiterates in developing countries how to read (or **functional illiterates** across the world how to read better and more), artificial intelligence voice recognition and voice assistants provide an answer to dealing with low literacy [18]. The arguments outlined below suggest that such a strategy might be counterproductive and have some unintended far-reaching consequences.

Literacy Influences Prediction in Spoken Language Processing

Several studies have shown effects of literacy on prediction in spoken language processing. Eye-tracking studies have shown that adults who are proficient readers predict objects in their surroundings whose names are predictable following a sentence context but low literate adults do not [19]. Similarly, children who are good readers were better at predicting the reference of concurrent speech in their visual environment than less proficient readers and word reading scores were a robust predictor of anticipatory looks [20]. These studies involved different types of participant populations (low and high proficient adult readers, low and high proficient developing readers), different types of spoken language materials (adjective-particle-noun constructions, thematic arguments consistent with a verb's selectional restrictions) and used different languages (Hindi, German), thereby providing converging evidence for effects of literacy on speech prediction. Even college students in the US with higher literacy (as assessed in author recognition, vocabulary knowledge, word reading, reading habits, and weekly reading times) predict more upcoming spoken language than US college students with lower literacy [21]. Moreover, a recent electrophysiological study has shown that higher reading proficiency in adults is associated with a reduced negativity over anterior channels as early as 170-300ms after target onset when listening to a strongly predictable spoken target word compared to adults with lower reading proficiency [22]. It is important to stress here that this does not mean that without reading experience listeners make no predictions. Indeed, two-year-olds make some predictions about up-coming spoken language [11, 23] (though 4-5 year olds do not seem to predict the form of upcoming words [24]). But literate adults become better and often extremely skilled predictors.

Why does Prediction in Reading Enhance Prediction in Spoken Language?

It is important at this juncture to note that there has been some controversy about the robustness of transfer effects in the cognitive sciences, but it mainly relates to replicability of so-called **far transfer effects** across domains [25], for example whether working memory training improves other distinct mental abilities such as fluid intelligence and attention [26, 27]. But there is little doubt about **near transfer effects** – that is, that training can affect subsequent performance in related abilities that did not receive additional training [28]. For example, working memory training improves reading because successful reading comprehension relies on working memory processes such as connecting different parts of a text and maintaining content-relevant information for construction of a situation model [29, 30, 31].

We suggest that there are two explanations for near transfer from literacy to spoken-language prediction. First, exposure or training within a particular domain affects core *processes* of the system that are shared. Some of the processes that are shared during reading and listening result in the forming of predictive dependencies, for example **associations** [32] or **error-based learning** of dependencies among representations [33, 34]. Second, reading experience transfers to speech because it exerts its effect on at least some identical *representations*. It is widely accepted that written and spoken language processing involve many shared representations (e.g. lexical; [35, 36]; syntactic; 37]) and those that are not shared (e.g., orthographic and phonetic/phonological representations) can directly impact each other (e.g., speech processing is affected by orthography [38]). We suggest that both secondary and primary influences of reading acquisition on prediction affect the core processes and representations.

Secondary Influences of Reading that Affect Predictive Comprehension

Vocabulary Knowledge

Preliterate children and illiterate adults learn words mostly from oral social interactions [39]. Eventually oral contexts however cease to help vocabulary development because everyday conversations rarely contain words beyond the most frequent ones [40]. Reading experience greatly improves vocabulary knowledge because the language of written texts exposes language users to new words. In addition, experimental evidence shows that more frequent encounters with words increase the depth of word understanding [41, 42]. Less skilled readers are less able to use context to derive the meaning of words [43]. There are dramatic differences in the number of words read per year with the most avid child readers (98th percentile rank) encountering over 4 million words a year and children who rarely read (10th percentile rank) encountering only about 50,000 words [44]. Importantly, there is evidence that reading habits contribute to vocabulary growth over and above general cognitive ability [45]. Thus, reading has specific and direct effects on vocabulary growth.

Secondary influences of reading such as increased vocabulary knowledge affect both processes and representations shared with spoken language. Greater and deeper vocabulary knowledge acquired from written sources, for instance, leads to more sophisticated interconnected networks of words (e.g. stronger associations among representations [46, 47]). Increased depth of word understanding, moreover, results in greater lexical precision, which facilitates activation of target lexical representations and minimizes the activation of competing alternatives [48, 49]. Such developments also benefit spoken language because most predictive (e.g., associative) dependencies and linguistic (e.g. semantic) representations are shared between written and spoken language [35, 36].

Importantly, studies with children [50, 11, 51] and adults [50, 52, 53] suggest that increased vocabulary knowledge enables increased prediction of spoken language. Crucially, studies have found that vocabulary knowledge robustly accounted for unique variance of prediction of spoken language beyond production fluency and non-verbal IQ (Raven's progressive matrices) [52,53].

Verbal Working Memory

Reading letters, newspapers, magazines, or novels requires the integration of information over several sentences, paragraphs, or often even pages and it requires keeping track of multiple entities and so enhances memory. Furthermore, the intensive practice of recoding skills during reading acquisition supports the development of short term memory functions, including subvocal rehearsal and, as a consequence, working memory for serial order information [4, 54]. Working memory according to influential models [e.g., 55; 56] is the ability to activate long-term memory representations and keep them active for online processing. An important feature of these models is that working memory capacity is mediated by an individual's expertise or experience and does not just reflect processing resources available for any task at hand but is specifically operationalised as memory for verbal material. Both reading and listening require verbal working memory, which is shared for written and spoken language [4]. Spoken language prediction relies on this common verbal working memory [57].

Verbal working memory capacity in children increases as a function of reading rate. A study with 8-, 10-, and 12-year-old children, for example, concluded that the developmental increase in working memory span is attributable fully to the increase in mean reading rate [58]. Deficits in verbal working memory in individuals with reading disorders are well-documented [59, 60, 61]. The notion that reduced and suboptimal reading experience at least partly explains the impairment in verbal working memory of individuals with reading disorders [62] is supported by many studies that have observed reduced verbal (but not spatial) working memory abilities in illiterate and low literate people (e.g., [63, 54]). Importantly, regression analyses show that verbal working memory contributes significantly more than non-verbal intelligence (as measured by performance in Raven's progressive matrices) to unique variance in speech prediction [57].

To conclude, substantial evidence links secondary influences of reading acquisition such as vocabulary knowledge and verbal working memory to enhanced spoken language prediction. The studies that also measured a general "g-factor" show that general intelligence does not account for the influence of vocabulary knowledge and verbal working memory on spoken language prediction. [52, 57, 53]. We now turn to the primary influences of reading on spoken language prediction.

Primary Influences of Reading that Affect Predictive Comprehension

A main reason for the differences in the tendency to predict between reading and listening relates to the speed of language processing. This is because of the different information processing bottlenecks in the two modalities. The bottleneck for processing spoken language is the speed of language production. Normal speech rates are 80 to 180 words per minute. But people can understand speech that is compressed to around twice this rate [64] so comprehension of normal speech, under good listening conditions at least, is well within comprehenders' abilities and bottom-up processing of the input typically suffices.

Reading, in contrast, is "self paced". Thus, when learning to read there is an incentive to learn to predict. Indeed, skilled readers tend to read texts much faster than they process spoken language – they read English prose at approximately 250 to 300 words per minute [65]. They (typically) have the goal of reading as fast as possible, primarily so that they can understand or act on what they encounter efficiently but also perhaps because they have a general tendency to maximize the rate of information processing. In fact, reading is pretty much as fast as it can be (given limits on **saccadic eye-movements** and speed of lexical access), and any attempt to read faster ("speed reading") impairs comprehension [66]. Readers do whatever they can to maximize and maintain this speed and therefore make use of predictive mechanisms (both in relation to upcoming words, i.e. general language predictions, and in relation to the specific written form, i.e. its shape and location), whenever they can if they give them even a small advantage.

Experimental evidence for the importance of prediction in reading comes, for instance, from **electrophysiological studies** that show that a strongly constraining context is needed to facilitate word processing in lower proficiency readers [67]. Moreover, the frontal positivity linked to predictive processing emerges only when reading rates are relatively fast [68].

Individuals who predict less in reading incur substantial processing costs for revising predictions [67].

Properties of the Reading Environment that Affect Predictive Comprehension: Processes

As a consequence of spending much of their lives comprehending regularly structured stimuli as fast as they can, literate people hone their ability to predict language. Prediction in reading is the result of learned relationships – between a word or broader context and a likely upcoming word, or between visual forms (i.e., orthography or word shape). So if I have repeatedly encountered *book* after *read the*, and I then encounter *read the*, I can then predict *book* – the lexical item "book", the sequence of letters, and the actual form on the page (e.g., its font and point size). Similar relationships hold of course for spoken language but reading is special in that it supports the forming of predictive relations in several ways.

The timing and regularity of eye-movements during reading

Eye movements during reading involve a highly regular pattern of **fixations** and **saccades**, with readers learning to optimize their eye movements based on very few parameters (essentially, fixation duration and location [69]). Their ability to process information (how much is taken in during a fixation) is a consequence of this behaviour, and the physiological limits of the eye. The timing of skilled readers' eye movements comes about as a result of satisfying the goals of reading as fast as possible while maintaining a good level of comprehension [70]. Through years of practice, skilled readers determine an optimal time to start programing a saccadic eye movement, so as to avoid remaining fixated on an already identified word for too long, while also not leaving a word prematurely. Simulations suggest that readers tune word identification and eye movement systems in such a way that saccades from one word to the next are initiated before the fixated word is completely identified but which takes account of how much longer the word will take to identify [71, 72], thus ensuring that fixation time is optimized. In other words, readers use a number of cues to predict how quickly a word will be identified and thus determine the optimal time to begin programming a saccade. We suggest that these dynamics of eye movement behaviour during reading, in particular the decision to initiate a saccade to the next word before the fixated word is fully identified, encourage readers to predict how long that word might take to identify (see Box 1). The developing reader of course gets regular feedback about the success or otherwise of such predictions (e.g., have I moved my eye too early or too late relative to word identification?) and can learn successful predictive behaviour (e.g., determining how early to begin programming a saccade). Readers thus learn the predictive dependencies between written input and, crucially (because lexical [35, 36] and syntactic [37] representations between written and spoken language are shared), predictive dependencies are also increased for prediction of spoken language as a function of reading proficiency.

Extreme form-invariance of printed forms

Not only is reading behaviour regular, but printed texts are regular too. Almost all tokens of an individual word within a text are practically identical (apart from capitalizing of the first letter of a sentence in written English). Intentional exceptions such as italics, cross-line hyphenations, changes in font size, and whole-word capitalization are rare, as are unintentional exceptions such as misspellings, typos, and smudges (or computer glitches) in most proof-read texts (though word-spacing is a partial exception.) Even differences between texts (related to font) are systematic and regular (Figure 1A). Hence written form is highly predictable. If readers can predict the upcoming word, then they can also predict the form of the word – exactly what shapes to expect on the next few centimetres of the page or screen. Moreover, the form of the prior context is also entirely regular (e.g., the form and location of *The boy is flying his is* regular, just as much as *kite*). Such regularity allows readers to set up consistent predictive models (particular written context form predicts particular written target form). There is good experimental evidence for such prediction of visual form (see Box 2).

Parallel processing of multiple letters in written word recognition

Written input allows for much more parallel processing than speech input. Parallel processing of multiple letters when reading means that readers get almost immediately a ‘snapshot’ of the **morpheme** (in long words), the whole word form, or even the whole form of **compound words** (Figure 1B). Thus there is a clear (one-step) mapping between a ‘snapshot’ form and its associated representation (e.g., meaning), and so the process of learning the predictive relationship takes place in a regular manner at a specific time. The temporal unfolding of spoken word recognition is very different from the temporal dynamics of reading. In spoken word recognition the uniqueness point – the point at which only one remaining spoken word is compatible with the input – has an important influence on spoken word recognition [73]. In contrast, there is no evidence for a uniqueness point in written word recognition. A consequence of this is that spoken language is more geared towards prediction within a word (e.g., on the basis of a cohort; cf. [74]), while written language places more emphasis on prediction of relations between words (see Outstanding Questions).

There is strong experimental evidence for parallel processing of large units in written word recognition [75, 76]. Readers process two-character compounds in Chinese using a "whole-word" route [77] but even readers of alphabetic writing systems typically engage in morphemic or whole-word reading rather than sequential **grapheme-phoneme** conversion [75]. (This is the case for skilled readers and contrasts with the slow left-to-right grapheme-to-phoneme conversion strategy of the beginning reader [78]). In conclusion, proficient readers typically process morphemes or even the whole word form at once and therefore learn to use these large units as the basis for prediction. Importantly, processes such as associative learning and/or error-based learning are shared between reading text and listening to speech and result in the forming of predictive dependencies between shared (lexical and syntactic) representations that also enhance spoken language prediction.

Properties of the Reading Environment that Affect Predictive Comprehension: Representations

Increased awareness of the compositional nature of speech units

In order to be able to read, people must map graphemes onto the corresponding sound units of spoken language. Proficient reading thus requires the knowledge that speech can be decomposed into smaller segments (Figure 1C). Without awareness that words in alphabetic scripts can also be decomposed into graphemes, readers cannot efficiently perform this mapping. Early forms of phonological knowledge and segmental awareness such as syllable onset and rhyme awareness can develop without any explicit teaching before reading instruction [79] but (pre-literate) children and (illiterate) adults do not acquire more fine-grained segmental awareness unless they learn to read [80]. Phonemic awareness is something children and adult illiterates have to learn in the early stages of reading acquisition and it develops from larger to smaller speech units [81, 82]. This 'reading-induced' increased awareness of the compositional nature of speech makes words more salient as a whole (i.e. it creates a word bias) also during the processing of spoken language [82]. We will discuss the relevance of this after the next (related) point concerning word separation in written language.

Word separation in written language

A consequence of morphemic and whole word-form processing and word separation in written language (see Box 3) is that the input in written language creates a word-bias that is not the same as for spoken language processing (Figure 1D) [83]. The concept of a 'word' is an invention of the literate mind and a notion that is extremely difficult to grasp for illiterate people [82]. Illiterates are unable to divide utterances into words [82]. They also tend to produce whole sentences when asked to produce one long word [84, 82]. Preliterate children and illiterates adults also repeat the whole sentence when asked to repeat only the last word of a spoken sentence [85]. Thus, it is well established that word separation in written language creates a stronger word bias than in continuous speech streams leading to more precise word representations. Enhanced lexical quality (i.e. sharpened representations) results in increased accuracy and fluency of word identification, retrieval of word meaning, the ability to learn new words, and integration of words within discourse representations ([49] for review) thus making prediction during language processing much more viable, both when reading and when listening.

More fine-grained (phonological) and additional (orthographic) representations

Reading acquisition creates new neuronal connections between phonological and orthographic representations [86, 87]. There is also evidence for lexical restructuring of phonological representations as a function of learning to read [88-90]. Recent behavioural and neuroimaging studies suggest that reading can affect speech processing both via activation of (additional) orthographic knowledge and more fine-grained phonetic/phonological representations [8]. Illiterates also have been observed to be less precise in phoneme discriminations tasks than literates [82]. Representations that are more precise reduce ambiguity and permit prediction that is more precise. Relatedly, there is experimental evidence that reading acquisition directly leads to faster retrieval of phonological representations [91]. Faster retrieval of representations permits faster prediction.

Concluding Remarks

Learning to read encourages people to learn to predict. 'Book language' has secondary effects on prediction in spoken language because it increases vocabulary knowledge and working memory capacity. Reading also has primary influences on speech prediction. It provides excellent conditions, in particular a stable environment, for training the predictive system. The regularity of eye-movement behaviour in conjunction with the extreme regularity and form-invariance of printed forms and the parallel processing of multiple letters in written text means that prediction can be precisely honed. Reading leads to increased awareness of the compositional nature of speech units, word separation in written language, and more fine-grained phonological and additional orthographic representations, which sharpen lexical representations and facilitate predicted representations to be retrieved. Thus, reading trains core processes and representations involved in language prediction that are common to both reading and listening.

What kind of research and experimental evidence should be considered crucial to further test the account we have put forward here (see Outstanding Questions)? It is important that experimental studies more precisely quantify how much people actually read and that such studies assess rigorously the quality and type of people's reading experience (including home literacy environments and social media reading experience [92-94]). Correlational evidence from cross-sectional studies will remain useful but it is important to recognise their limitations with regard to confirming causal explanations. Computational modelling can play a role for testing mechanisms and representations explicitly. Results and hypotheses derived from cross-sectional studies and computational modelling must be confirmed by longitudinal intervention studies. The gold standard, we suggest, is tightly controlled large-scale longitudinal studies with both developing and mature readers (see Box 4) that meticulously monitor reading experience throughout the study assessing its impact on spoken language prediction.

Literate children and adults predict more in spoken language comprehension than non-literate and low literate children and adults. An important consequence is that individuals with suboptimal reading behaviour such as people with **dyslexia** and related reading impairments or healthy readers with low literacy due to infrequent reading practice are also less proficient oral language comprehenders [95, 19]. For individuals with dyslexia and related reading disorders, this means that relatively minor impairments that may cause dyslexia can result in greatly exacerbated effects if they result in long-term suboptimal reading experience. Suboptimal reading acquisition and reading practice then results in less sharp representations and hence the formation of fewer and less strong predictive relationships. As a consequence, impaired readers predict less when reading and listening. Healthy individuals with low literacy or illiterate people will suffer similar detriments as impaired readers as a consequence of reduced or (in the case of complete illiterates) absent reading experience. Interventions targeted at both healthy low literates and impaired readers thus must at least partly focus on increasing and optimizing the quantitative and qualitative reading experience. Our arguments provide one more reason why more efforts should be undertaken to teach the hundreds of millions of illiterates in developing countries and functional illiterates across the world how to read (or to read better) and why a focus on artificial intelligence voice recognition and voice assistants to overcome literacy-related problems has its dangers.

Glossary

Associations: a mental connection between two mental concepts, states, or events due to experience

Compound words: two (originally independent) words used together to yield a new meaning (e.g. daydream, however, nobody)

Dyslexia: a reading disorder in which affected individuals show impaired reading abilities despite normal levels of intelligence

Electrophysiological studies: experimental studies that monitor the electrical activity of the brain over a period of time

Error-based learning: an instance of learning by which the system that supports learning readjusts itself when encountering an error to improve performance at the next encounter

Far transfer effects: training in a particular domain that impacts (typically improves) abilities across domains (e.g., music training increasing general intelligence)

Fixations: maintaining of eye gaze on a single location

Functional illiterates: individuals who show inadequate reading abilities despite having received some reading instruction

Grapheme: smallest unit of a writing system of a language

Literacy: knowledge and competence in reading and writing (though it can be extended to other areas)

Magnetoencephalography: a neuroimaging technique of measuring brain activity by recording magnetic fields produced by electric currents in the brain

Morpheme: smallest grammatical unit in a language

Near transfer effects: training in a particular domain that impacts (typically improves) domain-specific abilities (e.g., working memory training improving performance in tasks that partly rely on working memory)

Phoneme: a unit of sound that distinguishes spoken words in a language (e.g. /p/ in pat vs. /b/ in bat)

Prediction: pre-activation of upcoming information

Saccades: rapid eye movements with large amplitude used to change the direction of gaze

Saccadic eye movements: eye movements that involve quick jumps in eye gaze (saccades) between two or more periods of relative stability (fixations)

Box 1: The Timing of Saccadic Eye Movements During Reading

Readers of English and related languages/scripts take between 175-200ms to program and execute a saccadic eye movement [96]. Readers on average fixate a word between 200-250ms before shifting eye gaze to the next word, with fixation durations being strongly influenced by a word's lexical characteristics. Beginning to program the saccade to the next word thus typically happens early during the processing of the currently fixated word. Word frequency affects the timing of the decision to initiate saccade programming [97; 98], implying that readers are in some way able to predict the difficulty of processing a word on the basis of relatively little 'bottom-up' information. Importantly, word frequency effects on saccade programming are unlikely explained by orthographic form familiarity effects independent of lexical access [99].

The regularity of saccadic eye movements means that a predictive strategy for when to begin programming a saccade can be learned and optimized – all that is necessary is to determine when the saccade should be programmed and where it should be directed. The question of when to program the saccade is captured by models such as E-Z Reader [69] which assume that the decision must take place early, specifically before word identification is complete (on completion of the so-called L1 phase). The precise process by which this occurs is unclear – Schotter [100] pointed out that such saccade planning is based on partial word recognition, and is supported by partial information extracted from context [101]. But importantly we can be confident that readers engage in some form of prediction in order to facilitate eye movements in reading.

Recent evidence also suggests a role for prediction in how readers target their saccades to a specific location within a word [102]. According to this work, readers predict how long a saccade from the word to the right of fixation to the word beyond this would need to be so as to land in the centre of the second word prior to either word being directly fixated. Upon fixation of the first word, this prediction is updated with information about the distance between the current fixation location and the centre of the following word. The early prediction of the saccade length may speed up how quickly readers are able to move between words.

Box 2: Visual Form is Predicted

The reader predicts a specific word form (including its size and font, not merely an orthographic representation) based on the context; or uses such a form to predict a meaning. If the reader is incorrect, then the reader can use error-based learning to adjust subsequent predictions. If correct, the prediction is strengthened. Over time prediction during reading becomes very precise, as a consequence of its form-invariance, and because some representations between written and spoken language are shared, predictive dependencies are also increased for prediction of spoken language.

In a key study [103], participants with written context that biased towards predicting a syntactic category (noun or verb participle) and a target noun with visual form features that were typical (e.g., soda) or atypical (e.g., infant) of nouns. Enhanced activity in the visual cortex using **magnetoencephalography** (an M100) was observed for the difference between the typical noun in the verb-biasing context and the typical noun in the noun-biasing context but not for atypical nouns (thus the effect occurred only when there was a mismatch between the syntactic category and the visual form of the target word). An M100 effect is considered to be too early to be influenced by lexical access (syntactic category information in this case). This suggests that participants predicted the upcoming word’s syntactic category and its visual form. The finding that the effect was localized to the visual cortex further implicates visual form prediction.

Box 3: Word Separation in Written Language

Words in most (though not all; e.g., Chinese and Thai) of the world's modern writing systems are separated by empty space. Though some ancient texts were separated by either space or interpuncts, most Greek and Roman texts were written continuously without any punctuation or intratextual space [104]. This made reading very challenging and led to a habit of oral reading and delegation of reading and writing to skilled slaves who served as professional readers. The modern habit of word separation in written language only became standard practice in Renaissance Italy and France and encouraged silent reading at a much faster pace [105]. In fact, modern readers consider text without space (or punctuation) extremely difficult. Unspaced text slows down reading and encourages oral reading and/or subvocal processing [106]. It also leads to a greatly reduced perceptual span of peripheral vision [107] and many more regressive eye movements [108] compared with spaced text. Most importantly, word separation creates a strong word bias when parsing text. Indeed, experimental evidence suggests that word spacing facilitates word recognition even in writing systems that do not standardly use them such as Thai [109] and Chinese [110].

Box 4: Prediction in Older Adults

Older adults typically have decades of additional reading experience and often have larger vocabularies than younger adults [111]. Yet many studies suggest that older adults predict less than younger adults during reading ([112, 113]). There are also studies that suggest that older readers adopt a 'riskier' reading strategy than younger adult readers (older readers skip words more often [114; cf. 115; 116]), consistent with the notion that they rely more on predictions what the next word will be. One interpretation of such findings is that older adults predict more (or are more likely to act on a prediction) than younger adults to compensate for age-related cognitive decline (in line with evidence that older adults develop strategic differences in reading to overcome age-related differences in processing resources [117]). Indeed, a recent study investigating prediction in spoken language observed that age was positively related to predictive processing [57]. Interestingly, this effect only emerged in the regression analysis after accounting for age effects on working memory and processing speed (simple correlations suggested a negative relationship between older age and prediction). In other words, older adults' increased lifelong (reading) experience is likely to play a positive role in predictive processing but this may often be set off by age-related cognitive decline in other cognitive abilities such as working memory and processing speed. Future research needs to investigate more systematically the interaction of (reading) experience and cognitive decline on prediction in language processing (ideally in a longitudinal design).

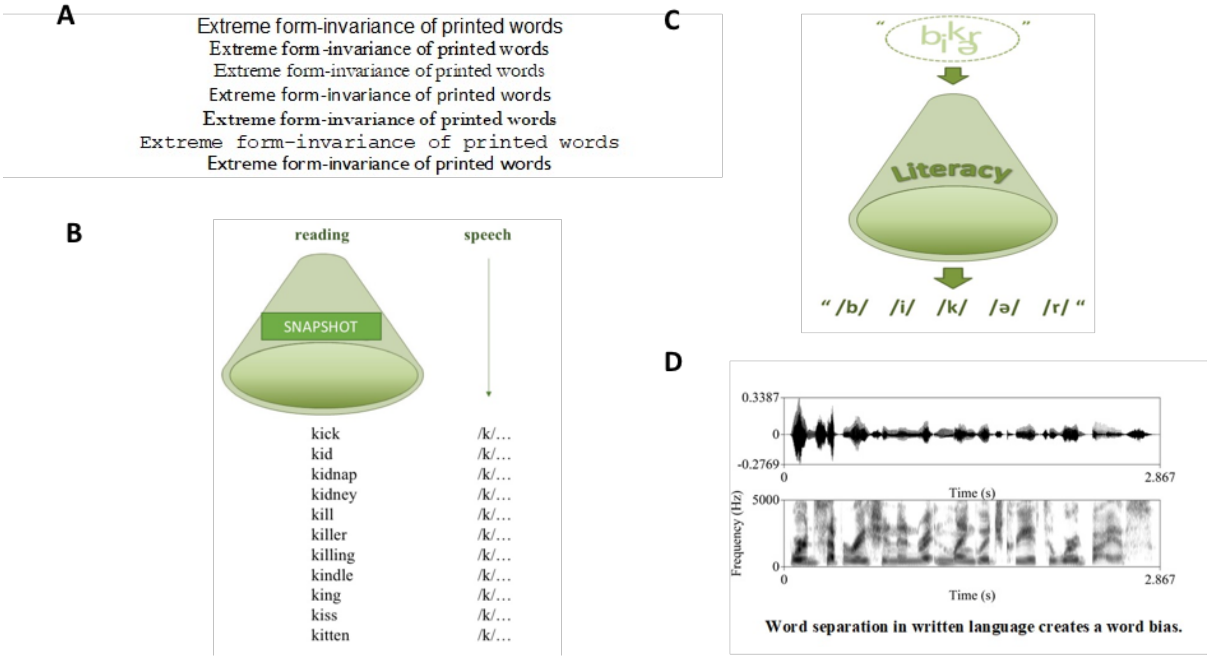

Figure 1, Key Figure: Properties of the reading environment that affect prediction

(A) Printed words are extremely form-invariant: Seven of the most used print fonts (Arial, Times, Garamond, Calibri, Bodoni MT, Courier New, Gill Sans MT). In contrast, more than 60% of words in speech corpora deviate from their citation form [118]. Written form is therefore much more predictable than spoken form. This extreme regularity allows readers to set up consistent predictive models as particular written context forms predict particular written target forms. (B) Parallel processing of multiple letters when reading means there is a clear one-step mapping between a 'snapshot' form and its associated representation (e.g., meaning), and thus the process of learning predictive relationships takes place in a regular manner at a specific time. (C) Learning to read leads to increased awareness of the compositional nature of of speech and also makes words more salient as a unit. (D) The sentence "Word separation in written language creates a word bias" represented as a speech wave form and spectrogram and as printed sentence. The speech wave form and spectrogram reveal no clear 'pauses' between words and there are sometimes 'pauses' within the spoken words. Word separation in written language creates a stronger word bias than in continuous speech streams, making prediction during language processing much more viable. In sharp contrast, casual speech to which listeners are exposed in everyday life contains a huge amount of phonological reduction [119]. Casual speech is also full of disfluencies, as well as incomplete utterances and speech errors, which lead to low consistency [119]. Reductions are thus another source of variability that does not occur in written language (e.g., we do not change the printed letter 'e' to a schwa symbol). In fact, the presence of reduced forms in weakly constraining contexts increases the likelihood that word recognition will fail rather than that listeners compensate by trying to predict [120].

Outstanding Questions

- Are listeners particularly good at predictions involving those words that they have encountered during reading (in which case the predictions will be more specific in nature; for instance, learning the printed form "considerable" to predict the meaning CONSIDERABLE might generalize that knowledge to prediction about the spoken form "considerable").
- Is spoken language (comparatively) more geared towards the prediction of relations within a word than the prediction of relations between words?
- Fully justified text has irregular inter-word space. Does reading fully justified text with variable word-spacing impair predictive learning?
- Changing font style improves success of proof-reading. Font style influences distraction when reading under conditions of environmental noise. Does changing fonts (mid-text or between texts) make prediction more challenging because of the reduced regularity of the written symbols that support the precision of prediction?
- Are people worse at predicting handwriting because of its greater variation in symbol forms?
- Social media appear to encourage more variation (e.g., 'sloppy' spelling) than traditional print media. Do increased social media reading habits result in less predictive learning?

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