Trends in Cognitive Sciences

Opinion

A Vision of Reading

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Different fields of research within the cognitive sciences have investigated basic processes in reading, but progress has been hampered by limited cross-fertilization. We propose a theoretical framework aimed at facilitating integration of findings obtained via these different approaches with respect to the impact of visual factors on reading. We describe a specialized system for parallel letter processing that assigns letter identities to different locations along the horizontal meridian within the limits imposed by visual acuity and crowding. Spatial attention is used to set up this system during reading development, and difficulty in doing so has repercussions in terms of efficient translation of the orthographic code into its phonological counterpart, and fast access to semantics from print.

Trends

Processing of orthographic information begins with scale-invariant gaze-centered letter detectors that conjunctively encode letter identity and letter location. Visual acuity, crowding, and spatial attention conjointly determine activity in these gaze-centered letter detectors.

Location-invariant orthographic processing involves the computation of orthographic chunks and orthographic features. Orthographic chunks encode highly co-occurring letter combinations using precise information about letter order. Orthographic features encode diagnostic information with respect to word identity using more flexible letter position information.

Orthographic processing operates in parallel across multiple words and is pooled into a single processing channel, hence allowing orthographic overlap across neighboring words in a sentence to exert a mutually facilitatory influence.

Visual Constraints on Reading

What are the visual constraints on reading, how do they impact on orthographic processing in skilled readers, and how do they influence the development of this skill in beginning readers? Until recently, these questions have been addressed within relatively independent fields of research, including the psychophysics of reading, investigations of single word reading, research on eye movements and reading, studies of reading development, and computational modeling of reading. Today, important progress has been made in integrating the findings across these different domains, and particularly with respect to improving our understanding of the role of visual factors in skilled reading, reading development, and reading disorders. The goal of the present article is to describe a theoretical framework aimed at facilitating such cross-domain integration of empirical results.

The integrative framework is shown in Figure 1. It summarizes basic processes in reading for languages that use an alphabetic script. The framework builds on prior theoretical work [1–3] and the widely accepted assumption that words are the building blocks of reading, and letters are the building blocks of words [4,5]. In this theoretical framework, parallel processing of letter strings is performed by **gaze-centered** (see Glossary) letter detectors that conjunctively code for letter identity and letter location [2,6]. For languages that use a horizontally aligned alphabetic script, these gaze-centered letter detectors are aligned along the horizontal meridian. They are scale-invariant such that their location from fixation is measured in letter units rather than degrees of visual angle [7]. Furthermore, although they are hypothesized to have sufficient shape-invariance to be able to handle different fonts and forms [8,9], it is thought that letter case information is retained at this level of processing. Availability of case information can be used to inform higher-level processing, such as sentence parsing mechanisms and the recognition of proper names.

Visual and attentional factors have their main impact on reading at this first level of orthographic processing. Acuity, **crowding**, and spatial attention influence activity in gaze-centered letter detectors. These three factors conjointly determine how letter visibility varies as a function of distance from fixation, the number of flanking letters (i.e., the number of spaces surrounding the letter: 0, 1, or 2), and the deployment of spatial attention. The closer a letter is to fixation the more

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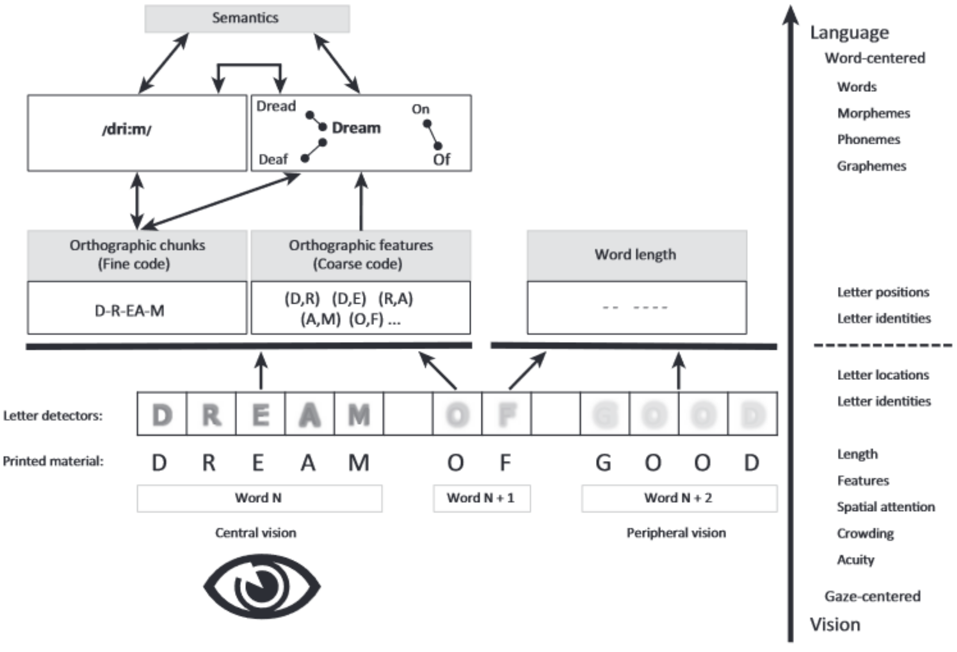

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Figure 1. An Architecture for Orthographic Processing During Reading, and How this Connects with Phonology and Semantics. Eye fixation on word N enables extraction of detailed orthographic information from this word, and this is used to generate orthographic features for fast access to semantics, and orthographic chunks for accurate sublexical translation of spelling-to-sound (not shown) and subsequent access to whole-word phonology. Orthographic information from word N + 1 is processed in parallel with word N by gaze-centered letter detectors, and integrated into a single channel for subsequent orthographic processing and word identification [55]. Lower spatial frequencies in peripheral vision enable extraction of word length information that is used to guide eye movements and constrain potential word candidates [56]. Not shown in Figure 1 is the hypothesized increase in the horizontal extent of the receptive fields of gaze-centered letter detectors with increasing eccentricity, and the greater overlap in receptive fields that accompanies this increase in size (see [1,57–59] for similar ideas). Acuity determines bottom-up input to gaze-centered letter detectors; their receptive field size determines lateral interactions (crowding), and spatial attention modulates the combined effects of acuity and crowding.

visible it is (acuity), the more spaces surrounding a letter the more visible it is (crowding), and the closer a letter is to the focus of spatial attention the more visible it is. When a string of letters is presented centered on fixation, then the combined effects of acuity and crowding generate the typical W-shaped serial position function for letter-in-string identification accuracy (Box 1). The central letter benefits from maximal acuity, and the two outer letters benefit from reduced crowding. Serial position functions are also often characterized by a first-letter advantage, with letters at the initial position in a string being identified with greater levels of accuracy than final letters [10,11]. Furthermore, visual and attentional factors operating on gaze-centered letter detectors determine the span of effective vision in reading (Box 2).

Within this theoretical framework, one of the keys to becoming a skilled reader involves adaptation of basic visual object identification processes to optimize parallel processing of letter identities. These adaptations are therefore thought to mainly concern processing at the level of gaze-centered letter detectors. One hypothesized adaptation involves a reduction in the receptive field size of such letter detectors to reduce inter-letter interference during reading. In line with this hypothesis, there is evidence that, in adult readers, letters are less affected by crowding than other types of stimuli [12]. Importantly, one recent study demonstrated that the letter advantage is obtained for horizontally arranged strings but not for vertically arranged strings [13]. It has also been hypothesized that, as well as a change in size, adaptive

Glossary

Crowding: impaired processing of visual information owing to clutter. The negative impact of nearby flanking elements increases linearly with eccentricity and is scale-invariant.

Gaze-centered coordinates: scale-invariant coordinate system for defining location with respect to eye fixation. When applied to word stimuli, distance from fixation is measured in letter units (i.e., number of letters from fixation) rather than in degrees of visual angle.

Phonological decoding: the operation by which beginning readers can recover the pronunciation of any pronounceable string of letters by using knowledge about the associations between graphemes (letters and letter clusters) and phonemes (e.g., 'B' → /b/; 'SH' → /ʃ/).

Transposed-letter effect: an effect caused by the high level of orthographic similarity entertained between two letter strings (not necessarily words) that differ uniquely by a change in letter order, such as for the anagrams 'trial' and 'trail'.

Box 1. Acuity, Crowding, and Reading

Skilled readers use short saccadic eye movements to fixate the majority of the words in the text being read, and mostly only once. Fixating a word brings it into the fovea, the part of the retina that performs the most detailed visual analysis. Outside of the fovea, stimuli appear more blurred the further they are from fixation, as a result of the drop in visual acuity. Crowding also contributes to the drop in our ability to recognize words the further they are from fixation, owing to the approximately linear increase in crowding with eccentricity [60,61]. Acuity and crowding impact differently on how well we perceive objects in peripheral vision: loss of acuity causes blurred vision, whereas crowding leads to confused or 'jumbled' vision [62]. Larger receptive fields of gaze-centered letter detectors in peripheral vision explains why crowding and positional errors are greater in peripheral vision [57].

Acuity and crowding also affect the processing of words that are fixated. Serial position functions for letter-in-string identification in the fovea are accounted for by a combination of effects of acuity and crowding (Figure I). The fact that strings of symbols or simple shapes do not show a first- or last-position advantage relative to the second and penultimate positions [63] can be explained by single flankers causing greater crowding with these stimuli compared with letters or digits [12].

Can visual constraints on reading be counteracted by modifying the physical characteristics of text? There exists a critical print size (CPS) for maximal reading speed beyond which there is no further gain [64]. Thus, increasing print size in peripheral vision beyond the CPS does not help to counteract the drop in acuity. This is partly because increasing the size of text is accompanied by an increase in eccentricity, and the same holds for increases in inter-letter spacing [10]. There is nevertheless evidence that a small increase in inter-letter spacing is beneficial for reading [65], and particularly for dyslexic children [66,67]. Greater increases in inter-letter spacing will eventually interfere with reading [68], as does smaller than normal inter-letter spacing [69,70].

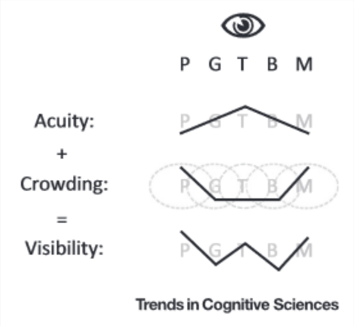

Figure I. Serial Position Function for Letter-In-String Identification. This is explained by the combined influence of acuity (linear drop from fixated letter to outer letters) and crowding (greatest for inner letters that are flanked by two letters, least for outer letters that are flanked by one letter).

modifications might also involve a change in the shape of the receptive fields. This would involve an exaggeration of the typical inward/outward asymmetry of the oval-shaped tangentially oriented crowding zone [14] for letter stimuli in the left visual field (for languages read from left to right). This hypothesized modification would cause a decreased sensitivity to interference from rightward flankers, and increased sensitivity to leftward flankers, for letters in the left visual field [12,15], and therefore provides one explanation for the first-letter advantage.

Evidence in favor of adaptation of visual processing induced by learning to read has been obtained by contrasting the brain responses of literate and illiterate adults in simple visual discrimination tasks (see [16] for review). A key finding is that literacy enhances retinotopic fMRI responses in early visual areas (V1), but only for horizontally aligned stimuli [17]. The fact that this enhancement occurs for stimuli other than letters suggests that learning to read leads to an improved parallel mapping of visual features onto location-specific shapes via extensive experience in the parallel mapping of visual features onto gaze-centered letter detectors. Crucially, it has also been shown in adult readers that random letter strings cause greater activation in bilateral retinotopic areas (V1, V2) than strings of rotated letters (non-letters), but only for horizontally arranged strings [18]. This increased activity would be caused by the mapping

Box 2. Span of Effective Vision for Reading

Estimates of the span of effective vision were first obtained using the moving window paradigm where the region of unaltered text around eye fixation is manipulated, and eye movements are recorded while reading the text [71]. Text that is replaced with Xs beyond 4 letter spaces to the left of fixation and 15 letter spaces to right was found to have no significant influence on eye-movement patterns (see [72,73] for review). Smaller estimates are obtained when non-word stimuli are used rather than Xs [74], and more recent research points to a greater leftward extension of the visual span than had been previously estimated [75]. The fact that the span of effective vision is scale-invariant [76] is in line with our hypothesis that it is determined by constraints on processing at the level of scale-invariant gaze-centered letter detectors. Another key finding is that the asymmetry in the span is known to depend on reading direction, such that skilled readers of Semitic languages, that are read from right to left, exhibit a perceptual span that extends more to the left of fixation than to the right [77,78]. This points to a key role for spatial attention in modulating bottom-up visual constraints, and further suggests that hemispheric specialization is not the main cause of the asymmetric span.

Estimates of the span of effective vision have also been obtained using a different paradigm, the ‘trigram method’ [79]. Percent correct trigram identification as a function of trigram eccentricity is used to plot a visual span profile (VSP). Similarly to estimates obtained using the moving window paradigm, the VSP extends further in the direction of reading. It is important to note, however, that the right visual field advantage of the VSP does not hold for the initial letter of trigrams, for which accuracy remains equally high in the left visual field as in the right visual field despite the greater eccentricity [79] (see [80] for this pattern with 5-letter strings). Does variation in the VSP determine individual differences in reading behavior? When measured using rapid serial visual presentation (RSVP, in which eye movements are minimized), faster readers have a wider VSP [70,81], and the same holds for reading speed for normal text reading [70] (see [82] for more details). Finally, the span of effective vision increases during reading development [74,83] and is reduced in dyslexic children [84].

of visual features onto location-specific letter detectors hypothesized in our approach. More generally, these results lend support to the idea that learning to process letters in parallel is accompanied by a change in status of letters, from being individual objects to becoming object parts [4].

From Letters to Sounds and Meaning

Gaze-centered letter detectors encode information about which letters are where with respect to eye fixation, but do not provide information about which letters are where in a given word (i.e., the order of letters in a word), and it is this type of word-centered orthographic information that is essential for reading. Information about the location of letter identities relative to eye fixation must be combined with information about the location of inter-word spaces to be able to infer the order of letters in a word. Adding a ‘space character’ detector to the bank of gaze-centered alphanumeric character detectors provides accurate information about the location of inter-word spaces, and enables a precise representation of letter positions relative to word beginnings and endings [19–22]. Within a dual-route architecture for reading [23], information about letter identities and within-word letter positions is primarily used for two tasks – to compute orthographic word identity (direct orthographic route) and to compute sublexical phonology (indirect phonological route). The use of diagnostic orthographic features (letters, and ordered but not necessarily contiguous letter combinations) in the direct route from orthography to semantics gives preference to speed over accuracy, whereas the use of more precisely position-coded letter identities in the indirect route gives preference to accuracy over speed in generating sound from print. More precise positional information enables an accurate representation of within-word letter order (necessary for accurate spelling, for example), which in turn enables chunking of frequently co-occurring contiguous letter combinations such as multi-letter graphemes and affixes [3]. This distinction between orthographic features and orthographic chunks could be applied to alternative schemes for letter position encoding, such as spatial coding [21].

As illustrated in Figure 1, the extent of the span of effective vision in reading enables parallel processing of orthographic information across multiple words, and follows the general approach advocated by models of eye-movement control in reading known as processing gradient models [24,25]. Although information about letter identities deteriorates in peripheral vision, clear information about the length of words is available, and this is primarily used to guide eye movements during reading (see [26,27] for reviews). As concerns the parallel processing of orthographic information across multiple words, the evidence at present suggests that mostly sublexical orthographic and phonological information is extracted during processing of word N + 1 (see [28,29] for reviews). This evidence has been mainly obtained using the gaze-contingent boundary technique [30] in which the letter string at location N + 1 is manipulated before fixation of that location, and this preview is replaced by the target word that forms a regular sentence the moment the reader's eyes cross an invisible boundary between word N and N + 1. Thus, parafoveal previews that share letters with the target word help readers process the target word when it is fixated, and parafoveal previews that share phonology with the target word also facilitate processing. In the theoretical framework shown in Figure 1, gaze-centered letter detectors capture information from the parafoveal stimulus, and this generates activity in word-centered sublexical orthographic and subsequently phonological representations. Activity in sublexical representations is maintained across fixation of word N and the target word N + 1, hence facilitating processing of the target word when this shares orthographic and/or phonological information with the preview.

Parafoveal preview benefits, however, are not necessarily evidence for orthographic processing operating across several words in parallel. This is because they can arise in a strictly one-word-at-a-time serial processing account of reading, by attention shifting to the parafoveal stimulus before an eye-movement, and hence enabling processing of the preview before it is fixated. This is the account offered by a family of models of eye-movement control in reading, known as sequential attention shift (SAS) models (e.g., [31]; see [32] for review). This strictly serial account has been relaxed in the face of evidence for parallel processing of orthographic information across multiple words [33]. Key evidence has been obtained in sentence-reading experiments applying the boundary technique to manipulate the orthographic overlap of stimulus N + 1 with word N (the word that is fixated). This research has shown that when N + 1 is orthographically related to word N, then fixation durations are shorter on that word compared with a condition where there is no orthographic overlap [33,34] (see [35,36] for additional evidence). This suggests that orthographic information extracted in parallel from word N and the stimulus at position N + 1 is integrated within a single processing channel, hence enabling facilitation when there is overlap between the two. A key question for future research therefore concerns how readers keep track of letter–word associations during sentence reading (see Outstanding Questions).

Development of orthographic processing

How does this proposed architecture for orthographic processing and reading evolve during reading development? Building on the seminal work of others [37,38], we have proposed that the slow, sequential process of **phonological decoding** used by beginning readers, when given the opportunity to do so, provides a simple and effective mechanism for supervised learning via an internal supervisor [39,40]. The internal supervisor is the whole-word phonological representation and its associated meaning that the child already knows. Upon presentation of a new word, knowledge of the alphabet and knowledge of grapheme–phoneme correspondences enables generation of a whole-word phonological representation via phonological decoding. Letter-level representations can then be associated with word meanings without any direct involvement of phonology. Thus, one of the keys to becoming a skilled reader lies initially in developing efficient access to lexical-level information from print. In line with this perspective, research on eye movements and reading in primary school children points to orthographic and lexical factors as the best predictors of changes in eye-movement behavior during reading development [41,42]. Furthermore, difficulties in learning to read arise principally from difficulties in single word reading, either due to impaired phonological decoding or from deficits related to basic orthographic processing (Box 3).

Box 3. Visual Deficits and Reading

Poor vision necessarily causes impaired reading unless it can be corrected. Low vision caused by aged-related macular degeneration seriously disrupts reading because of damage to the crucial central region of the retina [85]. Dyslexia is a reading disorder that arises in persons with normal vision, but there is increasing evidence that dyslexic children exhibit deficits in visuospatial processing (see [86,87] for reviews). While some of these deficits could be a direct consequence of a lack of reading exposure [88], recent studies suggest that visual search abilities in kindergarten predict future reading skills [89,90].

In our framework, spatial attention is necessary for phonological decoding in beginning readers. The guidance of attention is achieved through the dorsal stream, which receives its major input from the magnocellular system [91]. Hypothetically, the rapid dorsal route provides feedback to the ventral stream (including occipital and left occipitotemporal regions) about where to attend so as to identify letters and specify their order in a word. A recent fMRI study indeed found deficits both in the dorsal and the ventral stream for processing of strings of letters, digits, and symbols in dyslexic children [96]. We propose that reported magno/dorsal deficits in dyslexics [92] are linked to a diminished ability to use spatial attention for efficient phonological decoding, an operation that requires spatial attention in order to segment a letter string into graphemes [23]. Indeed, studies have shown that only phonological dyslexics, who are impaired in non-word reading, which requires precise letter position information, showed deficits in focused spatial attention [93,94]. Thus, for most dyslexics, visual-spatial attention deficits are associated with phonological decoding deficits. Deficient decoding in dyslexics hinders use of self-teaching to establish direct connections between orthography and meaning. However, there are subgroups of dyslexics who do not seem to have phonological decoding deficits but show specific problems with letter transpositions (e.g., reading 'slime' for 'smile'). This form of dyslexia is called letter-position dyslexia [95]. In our framework, this pattern can best be explained by an over-reliance on coarse-grained orthographic processing.

An important specificity of our approach to reading development is the hypothesis that becoming a skilled reader involves an increasing use of more flexible orthographic representations, which enable more efficient whole-word identification via diagnostic orthographic features. This hypothesis was put to test in a study examining the developmental trajectory of **transposed-letter** priming effects [43]. When measured with a z-score transformation of response times (RT) or a reciprocal RT transformation to remove the overall large influence of reading level on lexical decision RTs, it was found that the size of transposed-letter priming effects did increase significantly with reading level. Most important is that a benchmark measure of phonological influences on word recognition, pseudo-homophone priming [44], was found not to change significantly with reading level. In line with these findings, another recent study [45] has shown that parafoveal preview benefits from transposed-letter previews are greater in adults than for children aged 8 years, whereas pseudo-homophone preview benefits were only present in children (but see [46] for no difference in transposed-letter effects between children aged 8–10 years and adults, suggesting that single-word reading efficiency might already be optimal at around 10 years of age). Importantly, a longitudinal investigation of beginning readers using the same-different matching task with random consonant strings [47] revealed robust transposed-letter effects only in children who had acquired basic literacy skills (but see [48] for contradictory evidence), in line with the observation that illiterate adults do not show transposed-letter effects in this task [49]. In any case, given that transposition effects can be obtained with non-letter stimuli in humans [50–52], and with letter stimuli in monkeys [53], future research should compare these transposed-letter effects with effects obtained with strings of non-letter stimuli as a function of reading ability.

Further evidence in support of our approach to reading development was provided in a study that examined sentence reading in Finnish first- and second-graders using eye-movement recordings [54]. It was reported that introducing hyphens between syllables caused slower reading in these children compared with normal unhyphenated text, even though the use of hyphens to indicate syllable boundaries is commonly used in Finnish reading instruction. Furthermore, the disruptive effect of hyphenation was found to be greater for second-graders than for first-graders. The authors argued that hyphens disrupt whole-word orthographic processing and that, although the use of syllables is important for phonological decoding in Finnish, beginning readers rapidly adopt a parallel, whole-word processing route for more efficient reading.

Concluding Remarks

We have presented a theoretical framework for visual and orthographic processing in reading with the aim to facilitate the integration of findings obtained via the multiple facets of current reading research. In the proposed framework, gaze-centered letter detectors perform parallel letter processing across multiple words within the limits imposed by acuity and crowding, and modulated by spatial attention. Activity in gaze-centered letter detectors feeds into a single channel for word identification and semantic processing, with multiple routes operating within the single channel. Successful development of reading skills involves the use of spatial attention to implement parallel letter processing and the efficient conversion of letters and letter combinations into their corresponding sounds. Developing mechanisms for computing letter identities, their location (relative to fixation) and their position within a word is therefore thought to be one of the keys to becoming a skilled reader.

Outstanding Questions

Given the evidence for parallel processing of orthographic information spanning several words, how do readers keep track of which letters belong to which words? Is information about word order simply provided by the order in which words are identified, as hypothesized in our single-channel model?

Are there visual/attentional processing deficits in dyslexics that are specific to alphanumeric stimuli? Future research should aim to clarify the situations in which dyslexics show deficits specifically related to the processing of alphanumeric stimuli, and those situations where the observed deficits also apply to other types of visual stimuli.

Do visual factors have a different impact on reading in languages that use a logographic writing system, such as Chinese? Future research should compare the influence of visual constraints on reading in alphabetic and logographic scripts, in both monoscriptal and biscriptal readers of these languages.

How do visual factors influence learning to read in profoundly deaf children with no knowledge of the spoken version of the language they are leaning to read? A comparison of the impact of visual constraints on orthographic processing in deaf and hearing readers should help to specify the nature of the underlying mechanisms.

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