Selective disorders of reading?

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Over the past few decades, refined cognitive architectures with highly specific components have been proposed to explain apparently selective disorders of reading, resulting from brain disease or injury, in previously literate adults. Recent analysis of the more general linguistic and cognitive abilities supported by neural systems damaged in the various forms of alexia favours a rather different view of reading and the kinds of models sufficient to account for its acquisition, skilled performance and disruption.

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Abbreviations

L-by-L	letter-by-letter
O→P	orthography-to-phonology
PET	positron emission tomography
S→P	semantics-to-phonology

Introduction

Cognitive neuropsychologists who study acquired disorders of reading (alexia) have usually paid scant attention to the neuroanatomical basis for these disorders, and even less to the likely presence or significance of associated deficits. The prevailing view seems to be that a brain lesion can disrupt some component of the reading process without touching other cognitive functions. This view entails the assumption — almost never explicitly stated — that there are brain regions dedicated to reading processes.

In this review, we demonstrate how and why this tacit assumption is now being challenged. The cognitive skill of reading is acquired late and only with instruction. Other domains of cognitive function germane to reading, in particular the abilities to comprehend and produce spoken language and to make rapid visual discriminations, have typically reached substantial levels of competence before the brain confronts the problem of reading. Recent evidence suggests that disorders of reading may rarely, if ever, occur in isolation, that is, without impairment to these ontogenetically earlier capacities of language or visual processing. The hypothesis under consideration is that for each of the major patterns of acquired alexia, there is a consistent accompanying impairment in another cognitive domain, and that the nature of both the reading and the associated nonreading disorder is predictable from the location of the brain lesion.

Three distinctive patterns of alexia

Although a number of patterns of alexia have been described, we restrict our review to three patterns that have standardly been treated as 'selective' disorders of reading: phonological alexia, surface alexia, and pure alexia or letter-by-letter (L-by-L) reading. Each disorder will be summarised in terms of both the variable that has the largest impact on the patients' success in reading single words aloud and the characteristic type of reading error.

Phonological alexia

Phonological alexia is most sensitive to the lexical status of the letter string. Familiar words are usually read correctly, though success may be modulated by word class (e.g. content words such as *inn* or *bee* are read more successfully than grammatical function words such as *in* or *be*) [1] and/or by word imageability (i.e. words with concrete referents such as *tart* are read more successfully than abstract words such as *tact*) [2]. The striking deficit appears for unfamiliar letter strings or nonwords; to these, the patients typically produce either no response or an orthographically and/or phonologically similar real word, such as 'cake' or 'date' for *dake* [3]. Another disorder of reading, known as deep dyslexia [4,5], received considerable attention from researchers especially a decade or so ago. More recently, deep dyslexia has been characterised as an extreme version of phonological alexia rather than as a separate, independent disorder [6]. We share this view and therefore will not devote additional space here to the deep dyslexic pattern of reading.

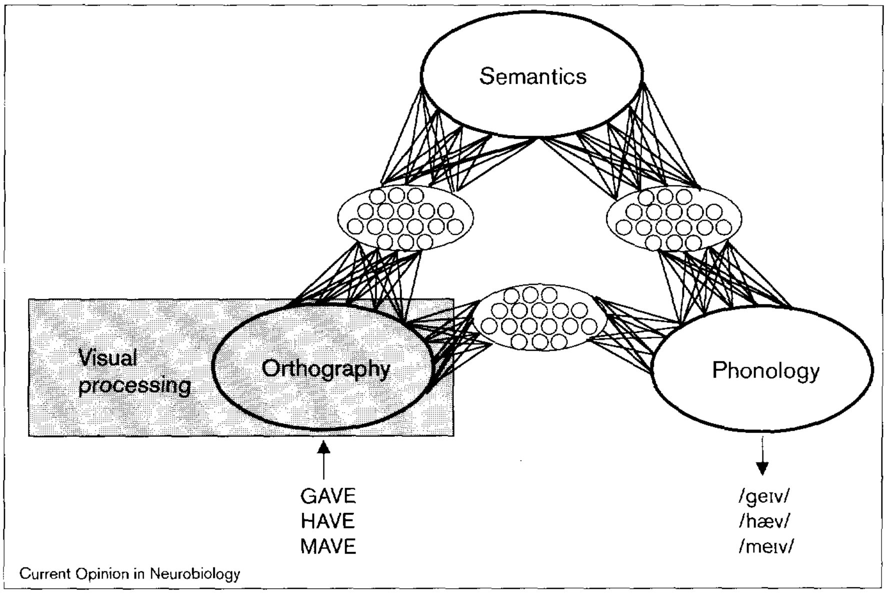
Surface alexia

Surface alexia is most sensitive to the predictability of the relationship between a word's spelling and its pronunciation. Words for which this relationship is consistent with most other similar words (e.g. *mint* and *print*), are read aloud correctly, and similar nonwords (such as *rint*) are assigned an appropriate pronunciation. The deficit is seen for words with an atypical spelling–sound relationship, especially lower-frequency exception words, which the patients 'regularise' (e.g. *pint* is pronounced to rhyme with 'mint') [7,8].

Letter-by-letter reading

L-by-L reading is abnormally slow and sensitive to word length. Asked to read aloud a familiar written word, normal adult readers respond within about half a second of seeing it [9]. L-by-L readers require several or even tens of seconds, and show a striking monotonic relationship between word length and response time [10••]. Incorrect responses arise from letter identification errors characterised by visual similarity to the target (e.g. the word *bone* might be read as 'done' or 'bore') [10••].

Figure 1



A framework for single-word processing, drawn from the connectionist networks developed by Seidenberg and McClelland [13] and Plaut *et al.* [12]. This version of the framework is a slightly revised version of Figure 1 in Plaut [11••]; it differs only in attempting to reflect the hypothesis that orthographic knowledge is a component of general visual processing.

A 'triangle' interpretation of the alexias

Figure 1 is a slightly revised depiction of some recent connectionist models of single-word reading [11••,12,13]. In this 'triangle' framework, the computation from orthography to phonology (O→P) is accomplished primarily by three interconnected pools of units: orthographic and phonological elements, and a set of hidden units between them. The weights on the connections between units are determined partly by whole-word frequency, because words that appear more frequently during learning have a larger impact on the weight settings, but also by subword structure, because words with partially overlapping structure produce similar patterns of activation. The network achieves efficient computations for common words (e.g. *have*) and for words with common subword correspondences (e.g. *gave*), and also supports generalisation to nonword letter strings (e.g. *mave*). Only words that are uncommon at the level of both whole and subword correspondences (e.g. *pint*) remain somewhat slow and/or susceptible to error in the direct O→P computation.

The triangle framework assumes interactivity amongst the various components; thus, semantic representations for familiar words provide an additional source of constraint on activation of the correct pronunciation in reading aloud [14]. Although additional semantic activation occurs for all words, it is considered to play an especially important role in determining the correct outcome for lower-frequency irregular words, which have the least efficient direct O→P computation [12]. Furthermore, it has been claimed that the additional semantic input to phonology (S→P) will be modulated by the richness of a word's semantic features, with concrete content words having richer representations than abstract content words or function words [15,16].

In this triangle framework, phonological alexia is attributed to a general phonological deficit, perhaps in the form of abnormally low activation of units in the phonological system, affecting any task that requires speech output [17,18]. This deficit will have a disproportionate effect on the production of nonword responses because weak activation can be boosted only for familiar patterns (i.e. real words) by feedback amongst co-occurring phonological units (i.e. phonological 'attractors') [19••] and by additional S→P activation [20]. The influence of S→P on reading aloud also provides an account for the advantage of high over low imageability words and of content over function words.

Surface alexia is attributed to reduced strength of activation from S→P, arising either from a central semantic deficit [8] or from degraded S→P connectivity [21]. These impairments have substantial consequences for tasks other than reading (especially for speech production) but should also impair the reading of lower-frequency exception words, which depend on additional S→P activation. According to this model, direct O→P translation is sufficient on its own to activate the correct pronunciation for high-frequency words and for words (or nonwords) with typical, shared correspondences.

L-by-L reading is attributed to a deficit in orthographic processing, which is just one manifestation of a general visual processing impairment [22]. Word recognition requires the reader to discriminate amongst visual symbols and identify them rapidly, and in parallel, and therefore might be especially vulnerable to even a mild deficit of visual processing.

These interpretations are controversial partly because they differ from accounts of reading disorders in more popular 'dual-route' conceptions of reading (we do not have space to summarise this debate here; see [11••,23] for some recent discussion). More apposite to our current focus, these interpretations are controversial because they predict that each form of alexia should be accompanied by a significant deficit outside the domain of reading. In other words, this approach challenges the notion of selective disorders of reading.

Do the three forms of alexia represent selective disorders of reading?

In 1996, a special issue of the journal *Cognitive Neuropsychology* reported investigations of 17 different cases of phonological alexia [1,2,17,18,24,25]. All cases were assessed on phonological tests that involved no orthographic processing (e.g. repeating spoken nonwords, removing or adding phonemic segments from or to spoken words or nonwords). No phonological alexic subject achieved performance within the normal range on all of these nonreading phonological tasks. Furthermore, manipulations of the lexical status of the spoken response — for example, in tasks such as blending, where the correct outcome may be a word (/st + ep/= 'step') or a nonword (/st + eg/= 'steg') — yielded significantly lower scores for nonword than for word targets [17,18,24,25]. These results demonstrate a strikingly consistent association between phonological alexia and a more general phonological deficit, and suggest that the lexicality effect in reading (considered the hallmark of phonological alexia) is the product of a lexicality effect in speech production.

Behrmann, Plaut and Nelson [10••] have reviewed 57 published cases of L-by-L reading: 50 of the 57 cases showed frank deficits in single-letter identification, at least in speed/efficiency if not in accuracy; for the remaining seven, there was insufficient evidence to rule out an impairment in this rather peripheral aspect of the reading process. Not all of these cases were assessed on tasks with non-orthographic stimuli that might tax visual discrimination/identification as heavily as word reading does; however, in studies where this kind of careful empirical assessment was included [22], the patients were impaired on these tasks as well. Farah, having previously argued for the *non*selectivity of reading disorders [2,26], subsequently questioned this conclusion [27••] on the grounds that L-by-L readers may be significantly better at identifying numbers than letters. This observation certainly warrants attention and further investigation; however, at least some well-documented L-by-L readers are significantly impaired in identifying numbers [28], musical notation [29] and faces [30] as well as letters/words. There is considerable and mounting evidence that L-by-L reading (which used to be called 'pure' alexia because the patients are alexic but not agraphic) is anything but pure, and is just one manifestation of a visual-processing deficit.

Surface alexia is the acquired disorder of reading whose interpretation is currently most controversial. Suffice it to say that surface alexia is almost invariably observed in conjunction with significant anomic aphasia (i.e. impaired word finding in spontaneous speech and in object naming). Anomia can be caused by either a deficit of central semantic representations [31] or an impairment in communication from S→P [32]; and since the triangle interpretation of surface alexia is reduced S→P activation [33], this constitutes our working hypothesis of the nonselectivity of surface alexia.

Additional considerations

Neuroanatomy of alexia

As emphasised by several authors [34,35••], extensive behavioural investigations of alexia and well-specified neuroanatomical investigations of alexia tend to 'dissociate' in the literature. It is therefore not yet possible to draw firm conclusions as to whether the lesions yielding the various forms of alexia are consistently located in regions that would be expected to produce the hypothesised associated impairments. Evidence from many decades of lesion studies and also from more recent functional imaging results does at least seem consistent with the proposals under consideration here. Typical lesion sites in L-by-L reading include left occipital and/or left posterior temporal cortex, which are known to be involved in visual processing and object recognition [35••]. Lesions producing phonological alexia very often disrupt left frontal regions known to support phonological processing [36••,37••]. All of the most striking cases of surface alexia have had damage to inferolateral left temporal regions, which are considered essential for semantic processing [37••,38••,39].

Cross-linguistic comparisons

The world's languages have arrived at a variety of solutions to the problem of how to represent the sounds and meanings of words in writing. Consider the extreme differences in these relationships between say Chinese (or Japanese Kanji) and English. If there were orthography-specific brain regions, one might expect reading disorders in these highly discrepant writing systems to be characterised both by different behavioural patterns and by different lesion locations. What (little) is known so far, however, suggests striking similarities rather than contrasts across writing systems [17,40–42]. We would argue that the human brain has arrived at a consistent solution to the problem of reading, and that this is because, much earlier in its evolutionary history, it had sorted out consistent neural systems for visual processing, speaking and comprehending spoken language, on to which reading processes are grafted.

Neural plasticity

Recent research in neuroscience has demonstrated a dramatic degree of neural plasticity in response to changing circumstances, either physical or environmental [43,44]. The neural and cognitive organisation of language, classically thought to be determined primarily by innate, genetic mechanisms, is now being significantly redescribed in terms of shaping by experience [45••–47••]. This view might seem to conflict with the hypothesis that reading acquisition creates no new specialised brain areas but merely utilises neural mechanisms already adapted for other pertinent functions; however, we think not. Changes in the organisation and function of brain regions as a result of learning to read, in particular the elaboration and refinement of the phonological system [19••,48••], are undeniable. Such plasticity does not, however, require reading mechanisms to be independent of other cognitive functions. Nobre and Plunkett [46••] argue that neural systems for spoken language are determined to a significant degree by learning and experience, but are not independent of other, nonlinguistic cognitive abilities. Anyone persuaded (as we are) by Nobre and Plunkett's argument for speech will surely find this hypothesis plausible for the case of reading.

Conclusions

For many years, reading and its disorders were studied in a kind of vacuum, isolated from considerations of the brain regions involved in reading and of the other cognitive abilities supported by these neural systems. Emergence from this isolation is being prompted by significant developments in cognitive neuroscience, including connectionist modelling and more sophisticated structural and functional brain imaging. Importantly, there is also an increasing awareness within neuropsychology that dissociations do not necessarily reflect independent modules [11••,46••]. We believe that future studies of alexia, enriched by imaging, computational modelling, cross-linguistic comparisons and more sensitive assessments of the patients' performance in related nonreading tasks, will add weight to the conclusion of Neville and Bavelier [45••]: "the functional role of the language-related areas is more accurately characterized in terms of ... systems, such as phonology, syntax and semantics, than in terms of activities, such as speaking, repeating, reading and listening".

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Papers of particular interest, published within the annual period of review, have been highlighted as:

- • of special interest
- •• of outstanding interest

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Summarises 57 published cases of L-by-L reading and presents new analyses from seven cases studied by the authors. This comprehensive review establishes unequivocal evidence for an early visual-processing deficit in L-by-L reading, but also provides an interactive account of word processing that reconciles the peripheral deficit with demonstrations of lexical and/or semantic effects in some L-by-L readers.

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The author describes the connectionist 'triangle' model of word processing, involving distributed representations of written and spoken words and their meanings. In this model, distinctions between words and nonwords, and between words with regular versus exceptional spelling–sound correspondences, arise from degrees of systematicity in the mappings between domains rather than separate representations or processes. The author presents two simulation experiments that provide accounts of phenomena that have been thought to challenge the connectionist approach.

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The authors present a connectionist model of reading based essentially on the 'triangle' model but improving on both its plausibility and sophistication with the introduction of a phonological attractor structure that is learned before any exposure to orthography. This paper breaks new ground in accounting for different patterns of developmental dyslexia and for the effects of reading acquisition on phonological knowledge and processing.

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•• **Neuropsychological and computational investigations.** In *Converging Methods for Understanding Reading and Dyslexia.* Edited by Klein R, McMullen PA. Cambridge, Massachusetts: MIT Press; 1999:in press.
In this chapter, the author questions whether learning to read creates a new brain region specialised for visual word recognition. The source of evidence is studies of L-by-L reading. The author concludes by rejecting both of the simple dichotomised views – that L-by-L reading is a pure reading deficit or that it reflects a general visual-processing deficit. Her preferred interpretation is that, within the neural system dedicated to rapid encoding of multiple shapes, there is a further specialised subregion for recognising letters and perhaps for representing abstract letter identities.

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Results are reported for seven L-by-L readers, all of whom achieved above-chance performance on forced choice lexical and semantic decision tasks, with printed words presented at exposure durations at which the patients could explicitly identify very few or none of the words. The authors argue persuasively that the lesion in L-by-L readers prevents direct access from orthographic information to the left hemisphere, that the slow, serial reading process arises from the attempt of the left hemisphere to identify letters on the basis of information transmitted by the right hemisphere, and that the above-chance lexical and semantic decisions observed with brief presentations are attributable to a separate right-hemisphere reading system.

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This paper reviews recent developments in our understanding of the neural basis of language, not only from functional imaging techniques but also from connectionist modelling. The important conclusions emphasised by the authors include the claims that brain systems apparently specialised for language are not in fact independent of those responsible for related, nonlinguistic cognitive behaviour, and that experience is crucial to the organisation of language in the brain.

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