Brain & Language 134 (2014) 44–67

Contents lists available at ScienceDirect

Brain & Language

journal homepage: www.elsevier.com/locate/b&l

The anatomical foundations of acquired reading disorders: A neuropsychological verification of the dual-route model of reading

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ARTICLE INFO

Article history:
Accepted 1 April 2014
Available online 9 May 2014

Keywords:
Acquired reading disorders
Lesion-symptom mapping

ABSTRACT

In this study we investigated the neural correlates of acquired reading disorders through an anatomo-correlative procedure of the lesions of 59 focal brain damaged patients suffering from acquired surface, phonological, deep, undifferentiated dyslexia and pure alexia. Two reading tasks, one of words and nonwords and one of words with unpredictable stress position, were used for this study. We found that surface dyslexia was predominantly associated with left temporal lesions, while in phonological dyslexia the lesions overlapped in the left insula and the left inferior frontal gyrus (pars opercularis) and that pure alexia was associated with lesions in the left fusiform gyrus. A number of areas and white matter tracts, which seemed to involve processing along both the lexical and the sublexical routes, were identified for undifferentiated dyslexia. Two cases of deep dyslexia with relatively dissimilar anatomical correlates were studied, one compatible with Coltheart's right-hemisphere hypothesis (1980) whereas the other could be interpreted in the context of Morton and Patterson's (1980), multiply-damaged left-hemisphere hypothesis. In brief, the results of this study are only partially consistent with the current state of the art, and propose new and stimulating challenges; indeed, based on these results we suggest that different types of acquired dyslexia may ensue after different cortical damage, but white matter disconnection may play a crucial role in some cases.

1. Introduction

The main objective of this paper is to examine the neural correlates of the principal acquired reading impairments in brain damaged patients. Although numerous studies have been conducted on these impairments and documented in detail in the literature, the neuroanatomical foundation of the cognitive behavior of the patients involved is not totally clear as studies were done principally on single-case studies, with only a few group studies being published.

In this section we will review the main cognitive aspects of the acquired reading impairments, while the following section will be dedicated to an assessment of the state of the art in the literature, with the objective of localizing neuropsychological symptoms and describing the functional anatomy of the normal cognitive functions, also in connection with some of the key findings deriving from functional neuroimaging studies. Finally, we will report the main methods employed for drawing inferences from the lesion data obtained from post-mortem analyses of the brain-damaged tissue to voxel-based lesion-symptom mapping.

1.1. Psycholinguistic models and acquired reading disorders

Prior to the mid-1950s, the classical framework established by the French neurologist Joseph-Jules Dejerine was used to interpret acquired reading disorders. In 1891, he reported the case of a 63-year-old man who was afflicted by reading and spelling impairments (*cécité verbale avec agraphie*, i.e., verbal blindness with agraphia), but had no other language impairment and, in particular, no object-naming deficit. The post-mortem examination on this patient revealed cerebral damage to the left parietal lobe (including the angular gyrus). In 1892, he described the case of another brain-damaged patient with a reading impairment, but no associated spelling or oral language deficit (*cécité verbale pure*, i.e., pure alexia, also

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http://dx.doi.org/10.1016/j.bandl.2014.04.001
0093-934X/

known as alexia without agraphia). The patient presented a right homonymous hemianopia but did not have any difficulty in naming either objects or colors. In this case the autopsy revealed an occipital and inferior temporal lesion extending to the retroventricular white matter, which had caused a functional disconnection of the trans-callosal pathways. Dejerine suggested that pure alexia was caused by left-hemisphere blindness (due to right hemianopia), right-hemisphere processing of the written stimuli and disconnection of this information from the intact left-hemisphere store of "optical images of letters and words" in the angular gyrus. As Coslett (2000) observed, Dejerine's ground-breaking accounts of acquired dyslexia – although considered somewhat limited nowadays – are in some aspects the forerunners of contemporary cognitive psychological theories. In his pioneering model of reading, Dejerine assumed the existence of a written word-form area in the left angular gyrus while the right hemisphere is conceived to be word-blind, so that the visual images of words would have to reach the left angular gyrus to match stored orthographic representations. His anatomo-functional account of written language remained undisputed until the second half of the twentieth century (when it was contested by Marshall & Newcombe's seminal papers, 1966, 1973), and continues to be considered as the major point of reference for the clinical description of isolated reading (or reading and writing) disorders after brain damage. However, Dejerine's taxonomy does not account for several aspects of reading disorders that may occur in patients with acquired dyslexia following left-hemisphere lesions, left hemispherectomy or complete cerebral commissurotomy (split-brain patients). These aspects include the emergence of semantic, visual and morphological errors; grammatical class (nouns are read better than verbs and than function words), imageability and word frequency effects. Furthermore, his model cannot account for the dissociated ability to read irregular words or nonwords commonly found in dyslexic patients (surface dyslexia, phonological dyslexia and deep dyslexia).

The study of brain-damaged patients started to play a central role in cognitive neuropsychology with the series of seminal papers such as those by Marshall and Newcombe mentioned above (1966, 1973). These authors made a fundamental contribution to the study of acquired reading disorders with their dual-route processing model, proposed both from a psycholinguistic and a neurolinguistic perspective – see also Morton (1969, 1980), Forster and Chambers (1973), and Morton and Patterson (1980) – suggesting that reading is underpinned by two distinct cognitive procedures, i.e., the lexical and sublexical routes (see Coltheart, Curtis, Atkins, & Haller, 1993 for a review and a comparison with other models). In recent years several single-case and multiple single-case studies have been published, reporting clear-cut dissociations in support of dual-route reading models (e.g., Toraldo, Cattani, Zonca, Saletta, & Luzzatti, 2006). In addition, a computational realization of the dual-route theory of reading, known as the dual-route cascaded (DRC) model, was proposed by Coltheart, Rastle, Perry, Langdon, and Ziegler (2001). This model simulates a number of effects that other computational models of reading were unable to reproduce.

The main difference between Dejerine's original model and the dual-route models of reading is that the latter provide for the existence of independent input and output orthographic representations, and the process of reading aloud is based on two independent pathways. After an initial visual analysis, letter strings would be processed by an orthographic recognition system, which specifies the abstract letter identity (i.e., non-dependent on letter case or font information) and the position of each letter within the target word. This orthographic information can be converted into the phonological word form by means of three routes of processing running in parallel. Firstly, letter strings are processed along the *sub-word-level routine* by means of grapheme-to-phoneme conversion rules. This is a serial procedure that can be successfully applied when reading regular words or nonwords but not with irregular words, since it would yield regularization errors. Secondly, words are read along the *lexical-semantic route* through a three-step procedure, from the orthographic input lexicon to the cognitive system and to the phonological output lexicon. The lexical route provides for successful reading of regular and irregular words and allows access to stored conceptual knowledge (Coltheart et al., 1993, 2001). This procedure is only suitable with words whose orthography is stored at lexical level, i.e. cannot process nonwords, and is the only procedure available when reading irregular words. Thirdly, Schwartz, Saffran, and Marin (1980), basing their assumption on the study of a patient who could name irregular words correctly but with no comprehension of their meaning, suggested a direct lexical pathway connecting the orthographic input lexicon and the phonological output lexicon, but bypassing the conceptual system.

It is worth noting that, in normal readers, the nonlexical route is activated in parallel with the lexical routes also when reading irregular words, and this *interaction* effect leads to longer RTs for low-frequency words (Paap & Noel, 1991; Seidenberg, Waters, Barnes, & Tanenhaus, 1984; Taraban & McClelland, 1987). Such interference manifests in the phonological buffer, which is fed by parallel activation of two conflicting phonological strings derived along either the lexical or the sub-word-level reading procedure, and this leads to an RT increase (see Coltheart et al., 2001, p. 221). The same line of reasoning is also valid for the lexical route, which is also activated when reading nonwords, thus leading to a facilitation effect in naming nonwords with large number of orthographic neighbors (Laxon, Masterson, Pool, & Keating, 1992; McCann & Besner, 1987; Peereman & Content, 1995; see Coltheart et al., 2001).

1.1.1. Central dyslexias

From a cognitive neuropsychological perspective, several cases characterized by dissociation (either classical, strong or trend dissociations, see Shallice, 1988) in their reading performance between irregular words and nonwords have been reported (see Hillis, 2008, 2010; Lambon Ralph & Patterson, 2005 for reviews).

Surface dyslexia is the term used to denote selective damage in reading irregular words (e.g., "yacht", "island", "colonel"), despite preserved ability in reading both regular words and nonwords along the grapheme-to-phoneme conversion routine (e.g., Behrmann & Bub, 1992; Marshall & Newcombe, 1973; Shallice & Warrington, 1980; Shallice, Warrington, & McCarthy, 1983; Temple, 1985; Weekes & Coltheart, 1996 – see Coltheart, Masterson, Byng, Prior, & Riddoch, 1983 for a review). Furthermore, it has been observed that the performance of surface dyslexics might be highly variable both with regard to accuracy and to reading latencies. In opaque orthography languages such as English, the rate of successful reading of words with irregular orthography-to-phonology mapping is a direct measure of the integrity of the lexical route. In Italian and other shallow orthography languages, irregular words are virtually absent in reading, but the position of the major stress in three or more syllable words is ambiguous. This information is not predictable and not diacritically marked, so that it can only be accessed along the lexical and not the sublexical route. Surface dyslexia may be associated with fluent aphasia (as Wernicke's aphasia, transcortical sensory or anomic aphasia), and it has often been found in conjunction with cases of semantic dementia (Funnell, 1996; Hodges, Patterson, Oxbury, & Funnell, 1992; Jeffries, Lambon Ralph, Jones, Bateman, & Patterson, 2004; Patterson & Hodges, 1992; Shallice et al., 1983; Warrington, 1975, but see Blazely, Coltheart, & Casey, 2005 for a comparison of two patients with semantic dementia, one with and the other without surface dyslexia; see also Woollams, Lambon Ralph, Plaut, & Patterson, 2007 for a detailed review of the association between semantic dementia and surface dyslexia).