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Phonological processing deficit—a culprit behind developmental dyslexia?

1. Introduction

This article endeavours to discuss the issue of phonological processing and its relation with developmental dyslexia from several angles. It attempts to define it, analyzes its complex relationship with other manifestations of cognitive functions, such as memory and processing speed, and investigates its contribution to reading in reading-disabled and unimpaired reading cases. Additionally, it offers a wide spectrum of data from behavioural, cognitive and neurobiological studies. Developmental dyslexia has been a focal point of cross-disciplinary research, and for a good reason, as for the last decades, depending on the criteria and statistical data, it has been estimated to range from 6 to 15 per cent within the school population (Bogdanowicz 2004, Habib 2004). However, in order to proceed to discussing the matter and its various implications in terms of reading-writing acquisition, it is essential to create the context which begins with the utmost refinement of the cognitive development of the human capacity to think and express those thoughts—speech.

2. Speech and writing

The idea that spoken language arises spontaneously, even in extremely adverse conditions, is comforting (Petitto and Marentete 1991). And it arose, from the 21st century's perspective, in somewhat adverse conditions approximately 30,000 years BC (Coulmas 1999). From then on speech has capitalized on the neurocognitive modules placed at the junction of the frontal and parietal lobes, and the temporal lobe in the left hemisphere in right-handed people. It is entertaining to think that somewhere around the year 2000 BC there was a moment, technically the last in history, when people who carried a particular gene predisposing them for dyslexia never had to be burdened by its consequences. They might have felt a little forgetful or distracted, or in some cases particularly expressive in artistic domains, but they were not necessitated to confront their genes with print. That came later, with the arrival of writing to Northern Syria (Schoolcraft 1851 in McDougall 2010), more precisely the first consonantal scripts, or perhaps just a tiny bit later when the transition to alphabetic writing occurred with these scripts having been adopted for use in Greek (McDougal et al. 2010). It is of course a great generalization, as literacy had not been regulated, promoted, nor made use of on a larger scale until around a hundred years back. Had it been more popular, life would have been more difficult for the dyslexics much sooner. However, it marked a "psychological and epistemological revolution" in the development of Western culture (Havelock 1976: 49). On the other hand, writing has never been imposed on people. It has spread quickly and through many cultures (Paulesu, Brunshwick and Paganelli 2010). Ever since, it has granted us access to educational and cultural resources and its consequences can never be overvalued. Humankind began a tradition of storing and passing on knowledge which has diversified amongst others, into Science, religion, and the internet.

3. Reading versus speech

An attentive observer may notice that, although writing is secondary to speech, and although there is no other way to acquire it but through instruction, almost everyone is granted a disposition that compels them to read anything they see, and do it fluently (Havelock 1976, Paulesu et al. 2010). Almost everyone. But we shall return to this point later. Firstly, it is worth examining reading fluency and its relation to speech. Meyer and Felton (1999: 284) characterize reading fluency as "the ability to read connected text rapidly, smoothly, effortlessly and automatically with little attention to the mechanisms of reading such as decoding". This mechanism that allows for fluent decoding of written symbols into meaningful messages is based on the brain's ability to segment speech and map the segmented units onto corresponding graphic symbols (Goswami 2010). Usha Goswami (2010: 23) points out that we cannot forget that the brain is evolutionarily wired to comprehend speech, not the written word, which is of an arbitrary nature. Thus, in her words, the orthographic lexicon is "parasitic on the speech processing system". It is now absurdly easy to confirm this statement as data from behavioural studies are verifiable by neuroimaging studies and the results reveal that, in reading, a mandatory phonological activation occurs both in apprentice readers and efficient, skilled readers (Cohen and Dehaene 2004). The activation of Broca's area in all types of readers is the sign of the brain's adaptation to understand communicative messages, even though it might have seemed that skilled readers absorb information straight from the graphic form of words. (Zeigler and Goswami 2005). Interestingly, the reading system in a mature brain is relatively independent of other brain systems. In 2010 Paulesu and colleagues carried out a study involving neuroimaging techniques and proved that reading and writing have capitalized on already existing neurocognitive modules, other than those used for oral language, leaving reading with a quasi-autonomous space within the cognitive system.

4. Where reading takes place

At this point it seems valuable to revise the reading areas, their location in the brain, their purpose and also briefly mention some possible results of brain damage to these areas. Using functional magnetic resonance imaging (fMRI), neuroscientists have been able to identify and localize several interrelated left hemisphere neural networks in reading (Anderson and Gore 1997; Frackowiak et al. 2004, Jezzard et al. 2001), namely, Wernicke's area, Broca's area (BA 44), the Angular gyrus and Area BA 37. Although a brain activates around seventeen regions to a diversified extent during the reading process, these four areas have been acclaimed the reading areas (see Table 1). Typically, all are placed in the left hemisphere in the majority of right-handed people.

Table 1. The revision of the four main reading areas and their functions

	Area	Function	Damage
1.	Wernicke's area	Highly specialized for the detection of language signals Holds the records of phonemes and the phoneme sequences that make up words Recognizes language from background noise	Language input cannot be properly classified and recognized, and thereby meaning cannot be ascribed (Lishman 2010)
2.	Broca's area	Responsible for producing fluent speech (articulation) Assembling words according to syntax in order to transmit meaning Important in silent reading and naming (Fiez and Peterson 1998; Frackowiak et al. 2004)	Speech becomes slow and hesitant with faulty grammar
3.	Angular gyrus	Has special relevance to written language—critical to skilled, fluent reading Acts with Wernicke's area to give meaning to language which is visually perceived It maps visual images of printed words onto the phonological structure of language	Results in the loss of the ability to read and write/speak and understand speech
4.	BA 37	Gives access to our 'word dictionaries' and allows us to select the appropriate word to match a given perceived object	Reduced RAN capacity

With regard to reading-disabled cases, functional imaging studies indicate failure in the left hemisphere anterior systems, mainly the inferior frontal gyrus (Benson 1994, Brunswick et al. 1999, Corina et al. 2001, Georgiewa et al. 2002, Paulesu et al. 1996, Rumsey et al. 1997, Shaywitz et al. 1998), as well as the posterior systems while reading (Brunswick et al. 1999, Helenius et al.1999, Horwitz et al. 1998, Salmelin et al. 1996). Additionally, Shaywitz and her colleagues (2002: 459) argue that

> although dyslexic readers exhibit dysfunction in posterior reading systems, they appear to develop compensatory systems involving areas around the inferior frontal gyrus in both hemispheres, as well as the right hemisphere homologue of the left occipito-temporal word form area.

5. The impact of reading on the brain

One of the fascinating aspects of reading acquisition is that once it has been learnt, it changes the neural organization of the brain. It is symptomatic that literate individuals become aware of the sounds of language and the way they can be manipulated (Castro-Caldas et al. 1998). It clearly points to the bilateral relationship between phonemic awareness and reading. The relationship is further supported by the reverse cases of illiterate individuals who lack this awareness, which proves that phonemic awareness cannot develop without reading. Furthermore, reading cannot occur without a fully developed awareness of phonemes (1998).

6. The building blocks of fluent reading

The most general prerequisites for reading to become automatized and fluent are, according to Ellis (1993) phonological awareness, age-appropriate oral language skills a well-developed vocabulary and the ability to name objects rapidly and effortlessly (see RAN later on in the article), as well as early print awareness and letter recognition. The above factors are essential for the proper formation of phonological representations in the mental lexicon but in order for them to become refined, language production is mandatory (Scarborough 1998). To be more specific, for the mental representations of language sounds to sit comfortably in the mental lexicon, actual speech production, preferably as immaculate as possible, is essential. As a matter of fact, the key factor in reading acquisition is the development of mental representations of the alphabetic code. One more aspect is unveiling from the discussion, namely the fact that in reading and writing attention must be paid to phonological representations of sounds and not their co-articulated versions (Jule 1996). Speech sounds are incorporated in both the surrounding neighbours but to encode speech in the processes of writing, an entirely different set of sounds must be incorporated. The complexity of the phenomenon that literacy represents is probably underestimated. Its complexity, and frankly, the sheer fact of its existence is the very reason dyslexia is noticed in the first place.

7. Orthographic depth and reading acquisition pathways

Another aspect, strongly echoed in the process of reading acquisition in normally-reading and reading-disabled individuals, is the type of orthographic regularity of a given language. Behavioural studies point to significant differences in the reading acquisition routes taken in languages with different spelling models. Most recent studies involving brain scans reveal that there are different patterns of brain activation depending on the type of regularity with which sounds correspond to letters, the divergence is noted both in normal and dyslexic readers (Frith et al. 1998, Seymour et al. 2003). An excellent example of the abovementioned link between a spelling pattern and reading acquisition is highlighted by Paulesu and his colleagues (2000). The Italian researchers compared two languages, Italian and English, which differ significantly in their grapheme-phoneme designs. The readers of the two languages were tested on reading three groups of words in their native languages, where one group consisted of high frequency words from their mother tongue, the other of non-words derived from these words, and the last one of international words that have the same meaning and spelling in both languages. For clear-cut results, half the words conformed to Italian orthography and the other half to the English one with regular spelling. The behavioural results converged in that the Italian group read their words faster than the English group, for reasons other than the spelling complexity of English words, as the word choice excluded that option. Neuropsychological studies confirmed differences in brain activation pointing to the variance in the emphasis on the subcomponents of the same reading system, which may be attributed to the specific demands of the particular orthographic code, in this case either Italian or English. More precisely, the Italian readers showed greater activation in the region associated with phonological processing (Demonet et al. 1994), whereas the English readers also activated areas linked with word retrieval, word naming and semantic processing (Poldrack 1999). This is to be expected as words like *island, yacht, women, bough, dough* do not allow one to retrieve the word sounds simply by phonological decoding.

8. The alphabetic principle

In the Foreword to an excellent review of the latest research on reading and dyslexia, Uta Frith (2010) claims the alphabet to be “one of the most elegant and simple solutions to turn spoken language into written language”. It is clearly a perspective of a non-dyslexic as 'dyslexia is evident when accurate and fluent reading and/or spelling is learnt very incompetently or with great difficulty', as Pumfrey and Reason state (1999: 18). It is evident that the alphabetic principle, which makes the world a literate place, is the reason why some 15 per cent of readers do not progress in reading (Habib 2004). Had it not been for the alphabetic principle, this article would have never come to life. A curious thought. Had all instruction and communication been performed orally, a vast potion of the problem would disappear. In the first official report following the first diagnosis of dyslexia, Pringle Morgan (1896) states that:

> The boy is of average intelligence in conversation. His eyes are normal and his eyesight good. The schoolmaster who has taught him for some years says that he would be the smartest lad in the school if the instruction were given in oral.

However, even though reading problems are at the heart of dyslexia, there is a whole set of symptoms that reflect disorders of various psychological processes:

- delayed speech acquisition and problems in early speech production (Scarborough 1990);
- object naming and word retrieval (Wolf 1991);
- poor verbal short-term memory (Shankweiller and Cain 1986);
- difficulty in segmenting phonemes (Khami and Catts 1986);
- poor non-word repetition (1987).

The common ground is still reading and writing. Nevertheless, in 1985, Ellis stated provocatively that "whatever dyslexia may turn out to be, it is not a reading disorder" (1985: 237). From the 1980s onwards there has been an incredible push in the search for the causes of dyslexia. Scientists in different centres across the world have taken different approaches from the biological to the cognitive, forming hypothesis such as the Magnocellular Theory (Stein 2001), Phonological Awareness Hypothesis (Goswami, Snowling 2004, Swan and Goswami 1997), Temporal Processing Hypothesis (De Martino et al. 2001; Tallal 1996), Cerebellum Theory (Fawcett and Nicolson 2001, 2004) and finally, Phonological Processing Deficit Theory (Stanovich 2001). And it is there where the story next takes us.

9. Phonological processing and reading

Phonological processing refers to 'the use of the sound structure of oral language in processing written and oral information'(Anthony et al. 2006: 239). It is broadly defined as 'the ability to process sounds of spoken language' (Johnson et al. 2001: 240). More precise phonological processing "entails the segmental analysis of words during ordinary speaking and listening" (van der Leij et al. 2001: 161). It is a construct covering three components: phonological awareness, phonological memory and phonological access to lexical storage, also referred to as RAN, and it has emerged as a result of almost four decades of research on the reading and writing skills in pre-school and school children.

10. The components of phonological processing

Phonological awareness is the state of being conscious of the sounds of language and how they can be manipulated (Liberman and Shankweiler 1985). Phonological awareness involves knowledge about the sounds that constitute words. It is a metalinguistic skill with the awareness of rhymes at one end of the continuum and the ability to perform operations on phonemes on the other. Its existence has been verified, as the ability to count phonemes, divide words into phonemes, delete them or substitute them requires the most attention and proficiency in working with linguistic material (Adams 1990). Interestingly, on top of the developmental pathways for phonological skills, where rhymes come first, onset-rimes fall midway, and phonemes arrive last, particular points in a child's development have been pinpointed. Between the ages of three to four, syllable awareness develops. Only later, at the age of six, when the foundation for acquiring higher levels of metaphonological skills is ready, is the awareness of phonemes attained (Goswami and Bryant 1999). So by the late 1990s, a causal link between phonological deficit and reading difficulties in dyslexia was established (Bruck 1993; Elbro et al. 1994; Fawcett and Nicolson 1995a; Nicolson and Fawcett 1995; Shankweiler et al 1995; Snowling 1995; Wagner and Torgensen 1987 D and the Brain p. 2) (For a contrasting viewpoint see Savage, Blair and Rvachev 2006)

Phonological memory "refers to the coding of information in a sound-based representation system for temporary storage" (2006: 240). Phonological short-term memory involves storing distinct phonological features for short periods of time to be "read off" in the process of applying the alphabetic principle to word identification.

RAN is a measure of "retrieving phonological codes from memory" (2006: 240). Rapid naming of verbal material is a measure of the fluid access to verbal names, in isolation or as part of a series, and efficiency in activating name codes from memory (Wagner, Torgensen, & Rashotte 1999).

Data accumulating from research has been instrumental in pinpointing the three components and linking phonological deficit with poor reading performance, irrespective of IQ and language background (Elbro 1998). In order to store phonological information in memory (PM), there has to be a clear-cut mental representation of each of the sounds of spoken language (PA). By the same token, access to these representations can be granted on two conditions: the sound representations are distinct and clear, and they are comfortably sitting in the memory, available for retrieval at any time (RAN). However, there is still vagueness that pertains to the extent of correlation of PA, PM and RAN and their exact role in the advancement of literacy in learners wit and without dyslexia. Anthony (2006) accentuates the significance of the search for the answers to these questions, as they will delineate the efficiency of test batteries aimed at assessing children potentially at risk for reading difficulties and enable researchers and practitioners to mark the “potential loci of intervention” (Anthony 2006: 240).

11. Phonological distinctness

To accentuate the importance of phonological awareness, it is worth zooming in on the concept of quality of phonological representations (Elbro et al. 1998: 40), which is defined as “the degree of separation—that is the relative distance between a phonological representation and its neighbours”. It has been hypothesized that the difficulty in conversing grapheme to phoneme, and the reverse, lies in the insufficient distinctions between the representations of particular sounds, which hinders segmentation and other phonological tasks on such blurry forms (1998). These insufficiently distinct representations may serve their purpose for everyday communication but they fail to establish the basis for phonological operations. Snowling (2006) advocates the position that poorly specified phonological representations are the underlying reason of reading problems. She proposes that when phonological representations are blurry, the processing of auditory material is less efficient. The consequences are surprisingly grave, as manifested by converging data (Lyon 1995; Manis et al. 1993; Perfetti 1992; Rack et al. 1992; Share 1995; Stanovich and Siegel 1994; Vellutino and Scanon 1991):

- reduced verbal short term memory (phonological memory);
- poorer long-term verbal learning, sequential memory;
- reduced accurate and fluent word identification;
- insufficient application of a letter-sound knowledge to decode unfamiliar words.

Nonetheless, even though the evidence proclaiming phonological awareness to be the marker of developmental dyslexia is both extensive and convincing, Zeigler and Goswami (2005, 2006) undermined these results by their research in transparent orthographies. They demonstrated that in orthographies such as Greek, Italian, Spanish and German, unlike English, French or Danish, factors such as RAN and phonological memory proved to be more sensitive diagnostic measures of dyslexia. However, between Elbro’s research and that of Goswami and Zeigler’s, there resides a story of how the thought on phonological processing evolved in the context of reading acquisition and dyslexia. This brings us closer to a review of cognitive deficits in dyslexia.

12. Cognitive level

The cognitive level, according to Nicolson (2008) "provides a valuable descriptive level between brain and behaviour", and in a way bridges the neurobiological level we are unaware of with its daily, behavioural manifestations. Below is an outline of Cognitive Psychology's approach to the causes of dyslexia within this framework.

13. Phonological Deficit Hypothesis

The 1980s brought a then-leading theory to an abrupt halt. For a decade, dyslexic problems had been attributed to visual problems, also including motor skill problems. It was Vellutino who, in 1979, argued that the problem lay in language rather than vision, and that the visual difficulties experienced by some readers are symptomatic of a deficit of a linguistic nature. From then on, the phonological deficit hypothesis received much attention and has dominated research on developmental dyslexia (Snowling 1987; Stanovich 1988a; Vellutino 1979). Bradley and Bryant (1978) in the UK, and Lundberg, Olofsson and Wall (1980) in Scandinavia established that phonological awareness was the most powerful predictor of later reading and writing success. Later intervention studies (Bradley and Bryant 1983; Kundberg, Frost and Peterson 1988) validated the assumption in a study of a group of preschoolers with low phonological skills who received training in that very aspect, and achieved better results in tests of reading performance, when compared with a group who received nonphonological training, and at the onset was equally deficient in phonological skills. Throughout the 1980s and 90s converging evidence accumulated, continuously confirming phonological type difficulties in children and adult readers with dyslexia (Bruck 1993; Elbro, Nielsen and Petersen 1994; Fawcett and Nicolson 1995a, 1995b; Shankweiler et al.1995; Snowling 1995, Wagner and Torgensen 1987). Further studies have elaborated on the earlier findings and demonstrated that the facilitation of phonological awareness and letter-sound mappings exerted a positive influence on word identification, spelling and reading ability in general (Foorman et al. 1991, 1998; Lundberg, Frost and Peterson 1988; Rack 1985; Torgesen et al. 1999; Vellutino and Scanlon 1987).

14. Phonological-core variable-difference

Another step forward was made by Stanovich (1988) who proposed the first cognitive model of developmental dyslexia, which he termed phonological-core variable difference. Phonological deficit had been a central focal point in dyslexia research (Morris and Manis 1983) but it was in the late 1980s when an exhaustive model was formulated. Stanovich elaborated on the "assumption of specificity" of the phonological deficiency in dyslexic readers, and he concluded that it was a contained deficit. Consequently, when moving away from a dyslexic area and down the IQ continuum, the deficit, Stanovich construed, would spread into wider areas of cognitive domains. According to this model, moving along the continuum, the deficit in phonological skills remained, but further down it was accompanied by an increasing number of other deficits, notwithstanding reading, to arrive at 'garden variety poor readers'. The explanation attracted much attention but it also raised doubts, as some researchers claimed it failed to encompass the vastness of the dyslexic landscape (Gathercole 1995). The phonological deficit, despite extensive research, as Uta Frith once put it, "remains tantalizingly elusive" (1997: 11).

15. Double deficit

A broader perspective was drawn when the speed of processing was also taken into account. The earliest studies include those by Dencla and Rudel (1976) on the Rapid Automatized Naming technique. They demonstrated that dyslexic children reacted significantly slower when their choice reaction to any kind of stimuli was measured, be it auditory tone, visual flash or either of the two in a linguistic format (Nicolson and Fawcett 1994). Further analysis came from van der Leij and van Daal (1993) who demonstrated that dyslexic readers require longer exposure to recognize known words in comparison to their normally-reading counterparts, matched for reading age not chronological age. They hypothesized that the speed processing limitations are the core impediment of automatization of word recognition skills. Wolf (2001: 125) recognized that some children may have "fundamental difficulties in developing sufficiently rapid processing rates in the components necessary for fluent reading and writing". Serial naming speed embraced the problems with a deficient processing rate. The first RAN (rapid automatized naming) tests allowed Denckla and Rudel (1976) to establish that it is the speed of naming that distinguishes children with dyslexia from the normally-reading peers, as well as other LD students. The finding, coupled with the phonological awareness data, has proved to account for a vast majority of cases.

16. Double-deficit—alternative viewpoints

At the turn of the 21st century, Wolf and Bowers (1999) proposed a variation of the double-deficit hypothesis, which holds that phonological awareness and naming-speed (RAN) are both independent sources of reading difficulties. However, they hypothesized the complexity of the characteristics of different dyslexic readers comes from the fact that they struggle with one of the three types, or variations, of the above components. For the purpose of clarification, Wolf and Bowers (1999) created three separate subtypes that cause reading problems: one with a phonological deficit only, the other with just the naming speed and the last one with a combination of the above. The last group proved to be the most severely impaired and the most treatment resistant (Torgensen, Wagner and Rashotte 1994). When it comes to their distribution across the dyslexic population, it is worth noting that it differs according to the language under examination. A study by Lovett et al. (2000) in a group of severely impaired English-speaking dyslexic readers allotted the double deficit to a whole 50 per cent of participants, with the other half equally divided between the RAN deficit and phonological deficit as separate subtypes. The same study carried out in a group of Hebrew speakers revealed that 96 per cent of cases fell within the double deficit, and the remaining 4 per cent within the phonological deficit. Recent research, however, has provided data pointing to the fact that the phonological deficit and speed-naming deficit tend to co-occur and it has been inferred that the phonological deficit may not be independent (Pennington et al. 2001; Schatschneider et al. 2002). Proponents of this theory (Waber, Forbes, Wolf and Weiller 2004) promote a notion that both phonological and naming-speed deficit are incorporated within a single reading difficulty. This line of thought is justified by the outcome of their study, in which all of the reading disabled participants who displayed a phonological deficit also showed a naming-speed deficit, but there was no case with a reversed pattern. Vellutino et al. (2004) claims that the assumption that there is a pure naming speed deficit causing reading problems in dyslexia is wrong. Rasmus (2003) agrees that at least two factors exist which cause reading problems in dyslexia, apart from phonological awareness deficit, and they are deficient speed-naming skills and faulty working-memory. He concludes that “phonology does not reduce to awareness, naming and memory; consequently many aspects of dyslexic phonology remain to be investigated”. The double deficit theory recognized that it is a combination of the phonological awareness and verbal working memory, as well as the ability to name objects rapidly, that contributes to the specific nature of the dyslexic reading problems. All in all, studies have led to the three-fold categorization of the reading difficulties, with the last category being the most frequent:

- Phonologial deficit alone,
- RAN deficit alone,
- Phonological and RAN.

Interestingly enough, both the speed of processing and working memory “are normally considered as fundamental cognitive attributes rather than derivatives of phonology” (Nicolson 2010: 28).

17. Neurobiological research

The recognition of dyslexia as a neurobiological disorder is fairly recent (Frith 1999; Habib 2000). Nonetheless, it marks a watershed in the history of research in developmental dyslexia. First and foremost, within just over a decade, for the first time in history, researchers have been able to carry out experiments on live brains as opposed to the post mortem examinations (Galaburda et al. 1985). And even Galaburda examined only four dyslexic brains. What that entails is a staggering number of opportunities which include examinations of the brain structure and brain activity of dyslexic readers of all ages (Eden et al. 1996; Shaywitz et al. 1998; Shaywitz and Shaywitz 2001; Pugh et al. 2000a, b, 2001; Simons et al. 2000a, b; Temple 2002; Temple et al. 2001; Habib and Demonet 2000; Paulesu et al. 2001). It is at last possible to perform longitudinal studies with behavioural data shifted to the background. The availability of PET scans and MRI scans has transformed the type of studies in the way that it is possible to diagnose, measure and compare how different brains respond to different tasks. Last but not the least, they provide an insight which shows beyond a doubt what is actually happening in the reading brain.

18. Structural brain investigation

In 2000 Eliez et al. performed a MRI study on a group of 16 dyslexic readers, aged 18-40, and on 14 controls, all right handed. Not only was the study of enormous scientific consequence, but it was one that struck a nostalgic note within the scientific community. It compared the measurements and structure of both brain types—a task first attempted some 20 years earlier without the elaborate equipment. The study also centered on *planum temporale*, an area situated in the temporal lobe, which is of utmost significance with regard to language. Galaburda et al. (1985) discovered that in the brain of dyslexic readers, the typical asymmetry of the planum temporale was absent. It is worth noting that in normally-reading brains this region is more pronounced, even as much as five times more so than its right-hemisphere counterpart (Galaburda 1985). What became evident from the study by Eliez et al. was that in dyslexic brains both temporal lobes were reduced in size with an additional 12 per cent reduction of the left. The study validated Galaburda's earlier finding and concluded that the impaired activation noted in the left temporal lobe of dyslexic readers may be linked to the structural difference.

19. Functional brain imaging

Another interesting finding was carried out by a group of Italian researchers (Paulesau et al. 1996). The PET scans of dyslexic brains revealed the severely restricted activation of their relevant functional areas on performing phonological tasks. In the rhyming task, dyslexic readers activated Broca's but not Wernicke's area. Interestingly, in the memory task, their brains assumed a reversed pattern of activation. Additionally, Paulesau and colleagues observed a significantly reduced harmony in the activation of all reading areas. Finally, a surprising lack of activation of the insula, the region that lies between the anterior and posterior areas, was noted. This data was then compared with the well-known behavioural level of the disorder. The authors believe that brain's failure to connect different reading areas in the process of reading mirrors their failure to read fluently. Dyslexic readers experience difficulty associating between the different codes required for reading such as the sounds of a heard word with the sight of a written word and the articulation of the word. This may all be accounted for by lack of harmony in brain activation. Shaywitz (1998) designed an experiment measuring brain function on performing phonological processing tasks of increasing difficulty. The study revealed differences in the type of regions activated in the cognitively varying tasks. In controls, an increasing activation of Wernicke's area and the angular gyrus was observed, whereas the dyslexic group showed an overactivation of the Broca's areas in response to the phonological demands. It has been concluded that the functional differences between the brains of the dyslexic and skilled readers reflect an imperfectly functioning system for segmenting words into their phonological constituents in disabled readers, which is verified by the overactivation of the Broca's area. The disrupted system also includes the angular gyrus, which is pivotal in mapping the visual images of print on to the phonological structures of language. The finding supports the critical role of impaired phonological analysis in developmental dyslexia. Yet another study in word recognition points to the discrepancies in brain activation between dyslexic readers and the controls. In 1998, Brunshwick et al. observed both groups of readers. In the normally reading participants, activation in their visual cortex, the left tempoparietal receptive language areas and the articulatory Broca's area occurs. Although both groups showed activation in Broca's area, it was greater in the dyslexic group in comparison to the control group. The rest of the regions in the dyslexic brains showed a decreased activation.

20. The final note on the orthographic depth

Let us return to the issue of the effects of language depth and manifestation of dyslexia in the framework of neurobiological studies. Paulesau et al. (2001) compared English, French and Italian adults with dyslexia with controls from these countries. PET scans revealed that in the brain of the dyslexic readers from all countries, activation in the key brain regions was significantly reduced when compared with the normally-reading counterparts. Paulesau et al. came to the conclusion that all dyslexics, irrespective of their language experience and the severity with which dyslexia is manifested in a particular language, were equivalently impaired on phonological tasks. It has been inferred that phonological processing deficit, not phonological awareness deficit, appears to be a universal basis for dyslexia in all three languages. In shallow orthographies, though, the impact is less.

21. Conclusion

On the basis of behavioural and neuroimaging studies, it can be inferred that, at the cognitive level, it is the phonological domain of language that is critically affected. Despite differences in manifestation, namely the less opaque the language, the less severe the dyslexia, as confirmed by Oren and Breznitz (2005), phonological processing seems to be the culprit behind developmental dyslexia. Lundberg and Hoien (2001) reviewed the most characteristic symptoms accompanying an individual with phonological deficits across their lifespan and they are:

- problems in segmenting words into phonemes;
- problems in keeping linguistic material (strings of sounds or letters) in short-term memory;
- problems on repeating back long non-words;
- slow naming of colours, numbers, letters and objects in the pictures;
- problems in playing word games.

It would be an appropriate way to end this article with the words of Sinali et al. (2005: 2459) who pinpointed the very reason all the above mentioned studies are carried out:

> The coexistence of local cortical changes together with abnormality of cortico-cortical connectivity within the language network offers a more realistic description of the neurology of dyslexia (...) and may explain why (...) reading (...), which requires the integration of multiple visual, phonological and articulatory codes, is sensitive in revealing a dyslexic brain to teachers and parents.

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