Neuropsychologia 48 (2010) 863–872

Contents lists available at ScienceDirect

Neuropsychologia

journal homepage: www.elsevier.com/locate/neuropsychologia

Different underlying neurocognitive deficits in developmental dyslexia: A comparative study

D. Menghini[a,b], A. Finzi[a], M. Benassi[c], R. Bolzani[c], A. Facoetti[d,e], S. Giovagnoli[c], M. Ruffino[d,e], S. Vicari[a,b,*]

[a] Neuroscience Department, "Children's Hospital Bambino Gesù", Research Hospital, Rome, Italy
[b] Psychology Department, European University, Rome, Italy
[c] Psychology Department, University of Bologna, Italy
[d] General Psychology Department, University of Padova, Italy
[e] Cognitive Psychology Unit, "E. Medea" Scientific Institute, Bosisio Parini (Lecco), Italy

ARTICLE INFO

Article history:
Received 2 March 2009
Received in revised form 2 November 2009
Accepted 5 November 2009
Available online 10 November 2009

Keywords:
Phonological processing
Visual-spatial processing
Attention
Implicit learning
Executive functions

ABSTRACT

The aim of this study was to investigate the role of several specific neurocognitive functions in developmental dyslexia (DD). The performances of 60 dyslexic children and 65 age-matched normally reading children were compared on tests of phonological abilities, visual processing, selective and sustained attention, implicit learning, and executive functions. Results documented deficits in dyslexics on both phonological and non-phonological tasks. More stringently, in dyslexic children individual differences in non-phonological abilities accounted for 23.3% of unique variance in word reading and for 19.3% in non-word reading after controlling for age, IQ and phonological skills. These findings are in accordance with the hypothesis that DD is a multifactorial deficit and suggest that neurocognitive developmental dysfunctions in DD may not be limited to the linguistic brain area, but may involve a more multifocal cortical system.

1. Introduction

Learning to read is a highly complex and integrative neurocognitive process. Reading acquisition requires precise visual recognition of letters and letter combinations to convert the visual forms into their appropriate sounds using primary grapheme-phoneme mapping (e.g., Share, 1995).

In addition to phonological short term memory and to phonological awareness for sounding out syllables and phonemes (for a review see Ramus, 2004), this visual-to-auditory conversion also requires selective attention to visual sub-lexical units (e.g., Cestnik & Coltheart, 1999; Facoetti, Ruffino, Peru, Paganoni, & Chelazzi, 2008; see for a recent review Perry, Ziegler, & Zorzi, 2007). This highly integrative process depends on reliable multi-faceted visual and auditory sensory processing that includes, for example, motion detection, and object discrimination in the visual domain (for a recent review see Boden & Giaschi, 2007) and sequential processing in the auditory domain (for a review see Wright, Bowen, & Zecker, 2000).

The complexity of reading behaviour becomes apparent especially when we analyse a clinical condition such as developmental dyslexia (DD). The DSM-IV-TR explains DD as a reading achievement that falls substantially below expected levels given an individual's age and education. The reading deficit should be sufficiently severe as to interfere with everyday activities requiring reading. Finally, the reading deficit cannot be strictly due to a sensory disorder (American Psychiatric Association, 2000).

Although this definition is generally well accepted, the different underlying neurocognitive deficits in DD are still a matter of debate. There is now a strong consensus that the central difficulty in DD reflects a deficit within the language system and, more particularly, in a lower level component, phonology, which has been defined as the ability to access the underlying sound structure of words (Ramus et al., 2003; Scarborough, 1990; Shaywitz & Shaywitz, 2005; Shaywitz et al., 1998; Shaywitz, 1996; Snowling, 2000; Swan & Goswami, 1997; Wagner and Torgesen, 1987). Results from different populations with reading disability confirm that in children a deficit in phonologic analysis represents the most reliable (Fletcher et al., 1994; Stanovich & Siegel, 1994) and specific (Morris et al., 1998) correlate of DD. Phonological deficits have been also suggested to account for the phonological working memory deficits, often reported in individuals with DD (see for example Gathercole, Willi, Baddeley, & Emslie, 1994).

* Corresponding author at: Neuroscience Department, "Children's Hospital Bambino Gesù", Research Hospital, Piazza Sant'Onofrio 4, I-00165, Rome, Italy. Tel.: +39 06 68592475; fax: +39 06 68592450.
E-mail address: vicari@opbg.net (S. Vicari).

0028-3932/$ – see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.neuropsychologia.2009.11.003

Phonological deficits in DD are also supported by a large number of anatomical and neuroimaging studies that report brain abnormalities located mainly in the left posterior temporal areas (Galaburda, Sherman, Rosen, Aboitiz, & Geschwind, 1985; Geschwind & Galaburda, 1985; Paulesu et al., 1996, 2001; for a review see Ramus, 2004).

In addition to the phonological deficit, several studies have provided evidence for further cognitive impairments associated with DD (see Stein & Walsh, 1997 for a review; Nicolson, Fawcett, & Dean, 2001). In particular, visual-spatial deficits have been found in DD, as documented by deficits in visual recognition tasks (Geiger et al., 2008) or in mental rotation tasks (Rüsseler, Scholz, Jordan, & Quaiser-Pohl, 2005). Furthermore, impaired perceptual performance in different motion detection tasks has been reported in dyslexics (e.g., Cornelissen, Richardson, Mason, Fowler, & Stein, 1995; Demb, Boynton, Best, & Heeger, 1998; Eden et al., 1996), thus suggesting a possible magnocellular-dorsal (MD) pathway impairment in DD (see for a recent review, Boden & Giaschi, 2007). However, it should also be recognized that physiological and psychophysical findings have been failures to replicate (see for a review, Skottun, 2000) and the hypothesis for a MD pathway deficit in DD remains controversial.

Reading acquisition (i.e., phonological decoding) is an attention demanding process even in skilled adult readers (Reynolds & Besner, 2006). In particular, graphemic parsing, that is the segmentation of a letter string into its constituent graphemes (Perry et al., 2007), requires an efficient orienting of visual-spatial attention (Cestnik & Coltheart, 1999; Facoetti et al., 2006; for a review see, Hari & Renvall, 2001). Moreover, auditory attention is an essential component to focus resources on relevant acoustic information during phoneme–grapheme conversion processes. Notably, impaired visual-spatial attention and auditory attention have been repeatedly described in DD (e.g., Bosse, Tainturier, & Valdois, 2007; Cestnik & Coltheart, 1999; Facoetti et al., 2003, 2006; Geiger et al., 2008). In particular, deficits have been found in DD when dyslexics with non-word reading impairment performed visual serial search tasks (Buchholz & McKone, 2004; Jones, Branigan, & Kelly, 2008; Roach & Hogben, 2007) or during tasks involving attention to auditory stimuli (Dufor, Serniclaes, Sprenger-Charolles, & Démonet, 2007).

Behavioural studies in individuals with DD have also documented deficits in implicit and procedural learning abilities (Bennett, Romano, Howard, & Howard, 2008; Stoodley, Ray, Jack, & Stein, 2008; Vicari, Marotta, Menghini, Molinari, & Petrosini, 2003; Vicari et al., 2005). Similarly, an automaticity deficit has also been demonstrated in dyslexics (Nicolson & Fawcett, 1990; Nicolson et al., 2001). Neuroimaging studies exploring brain activity in dyslexics performing implicit learning and automatization tasks have been documented notable cerebellar dysfunctions in these individuals (Menghini, Hagberg, Caltagirone, Petrosini, & Vicari, 2006; Nicolson et al., 1999). Moreover, Nicolson and Fawcett (2007) recently systematized findings on this topic into a “neural system” approach. They suggested that in DD the procedural learning system, which is sustained by prefrontal language areas, basal ganglia, parietal and cerebellar regions, is specifically impaired.

Finally, it has been suggested that executive function deficits are present in DD. For example, deficits in both verbal and figural fluency ability (Reiter, Reiter, Tucha, & Lange, 2005), in response inhibition (Kelly, Best, & Kirk, 1989; Reiter et al., 2005) and in the Wisconsin Card Sorting Test (Helland & Asbjørnsen, 2000) have been documented in individuals with DD.

In sum, a multiple neurocognitive deficit model seems necessary to understand DD (Pennington, 2006). Although many studies have proved the existence of individual neurocognitive deficits in DD, only a few have tested these different deficits simultaneously in a single study. For example, a paradigmatic study was conducted by Ramus et al. (2003) to test the phonological, magnocellular, and cerebellar theories of DD. All 16 adults with DD included in the study showed phonological deficits related to literacy impairments. Other disorders, when present, were interpreted as a mere aggravation, and only associated with the basic phonological deficits. The same research group replicated the previous study on 23 children with DD using similar tasks (White et al., 2006). Phonological deficits were reported by 50% of children with DD and only visual difficulties were present in a small subgroup of children.

In these two studies the authors focused on individual variations in DD and used measures taken from a wide range of theories. However, many theoretical and methodological criticisms were advanced (Bishop, 2006; Nicolson & Fawcett, 2006; Tallal, 2006). In particular, the tasks chosen to assess the different cognitive abilities were not uniformly distributed. For instance, while the phonological theory was extensively tested, the cerebellar theory was investigated in only a few basic tasks. Moreover, the hypothesis of attentional-parietal deficits in DD was not evaluated in these two studies (Ramus et al., 2003; White et al., 2006). It is worth noting that in their first work Ramus et al. (2003) tested 16 university students who could have compensated their deficit and whose reading could have been very different from that of children. Instead, in the second study (White et al., 2006) phonological and sensorimotor abilities were investigated in a sample of 23 children with DD. This sample may have been too small to test so many different neuropsychological domains.

Based on the above, the role of phonological deficits in DD is still unclear. Indeed, as Castles and Coltheart state in their recent review, “no study has provided unequivocal evidence that there is a causal link from competence in phonological awareness to success in reading” (Castles & Coltheart, 2004, pp. 77).

The present study was designed to verify this multifactorial hypothesis by simultaneously testing different neurocognitive domains in the same sample of children using numerous tasks. In particular, we assessed participants' neuropsychological profile by evaluating phonological and non-phonological skills. Regarding phonological capacities, the ability to access the sound structure of words has been evaluated using a measure of phonological fluency, a spoonerism task and a non-word repetition task. Tasks exploring spatial perception, spatial rotation and motion coherence as well as spatial and auditory attention have been also included in the study. Implicit learning abilities have been studied using a serial reaction time task. Finally, to assess executive functions a categorical fluency task and a widely used task, Wisconsin Card Sorting Test, have been utilized.

Starting from the consideration that each task used in this study required multiple cognitive abilities that were not limited to a single area, we used general linear model analysis (GLM) to analyse differences between groups, taking into account the reciprocal interaction between cognitive domains. In addition, to obtain more representative results we extended our investigation to a large sample of children with DD in different phases of development. Moreover, we investigated the predictive value of non-phonological cognitive functions with respect to word and non-word reading in dyslexic children. If non-phonological cognitive functions were independent non-speech mechanisms involved in sub-lexical processing, then measures of these non-phonological cognitive functions should predict non-word reading even when age, IQ and phonological skills are controlled for.

2. Methods

2.1. Participants

The study included 125 children and adolescents: 60 with DD and 65 normal readers (NR). Demographic data, global cognitive profile, and reading abilities of both groups are reported in Table 1. An inefficiency reading index, calculated as