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Procedural Learning and Dyslexia

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Three major 'neural systems', specialized for different types of information processing, are the sensory, declarative, and procedural systems. It has been proposed (*Trends Neurosci.*, **30**(4), 135–141) that dyslexia may be attributable to impaired function in the procedural system together with intact declarative function. We provide a brief overview of the increasing evidence relating to the hypothesis, noting that the framework involves two main claims: first that 'neural systems' provides a productive level of description avoiding the underspecificity of cognitive descriptions and the overspecificity of brain structural accounts; and second that a distinctive feature of procedural learning is its extended time course, covering from minutes to months. In this article, we focus on the second claim. Three studies—speeded single word reading, long-term response learning, and overnight skill consolidation—are reviewed which together provide clear evidence of difficulties in procedural learning for individuals with dyslexia, even when the tasks are outside the literacy domain. The educational implications of the results are then discussed, and in particular the potential difficulties that impaired overnight procedural consolidation would entail. It is proposed that response to intervention could be better predicted if diagnostic tests on the different forms of learning were first undertaken. Copyright © 2010 John Wiley & Sons, Ltd.

Keywords: dyslexia; reading disability; cerebellum; consolidation; procedural

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INTRODUCTION

Dyslexia is classified as a (specific) learning disability and is defined in terms of unexpected difficulties in learning to read. The major framework for dyslexia is the phonological deficit theory (Stanovich, 1988; Vellutino, 1979). For subsequent reviews, see Shaywitz, Morris, & Shaywitz (2008) and Vellutino, Fletcher, Snowling, & Scanlon (2004). A major strength of the phonological deficit hypothesis is its direct link to the process of learning to read, a link that led to significant changes in the pedagogy of reading instruction (Shaywitz *et al*., 2008).

Unfortunately, after the age of about 8 years, support in phonological processing provides diminishing returns, to the extent that the effectiveness is substantially reduced (NICHD, 2000). Furthermore, there remains concern as to how best to improve reading fluency, which is not directly improved by phonological instruction. More recent approaches (Fletcher, Lyon, Fuchs, & Barnes, 2007; Kuhn & Stahl, 2003)—see also Hatcher, Hulme, & Ellis (1994)—advocate use of a variety of different techniques, from phonological support to fluency training, with 'response to intervention' (RTI) taking an influential role (Fuchs & Fuchs, 2006), such that different methods are tried for children who do not respond well to each type of instruction. Despite some promising results, a recent review (Shaywitz *et al*., 2007) concedes (p. 466) that 'we await evidence to guide the more fine-grained selection of specific interventions for struggling readers at all ages and at all levels of reading ability'.

We concur with the importance of this challenge. If we knew why children with dyslexia had difficulties learning phonology, we might be able to devise better ways of helping them to acquire a broad range of skills, including, but not limited to, phonology. This question can only be resolved by considering how phonological (and other) skills are normally learned. One might legitimately expect, therefore, that theories and analyses of learning would be a natural explanatory framework for dyslexia theory and practice.

Unfortunately, the role of learning in dyslexia as a potential explanatory construct was strongly questioned by the seminal analysis (Vellutino, 1979), ably summarized 25 years later by Vellutino *et al*. (2004) pp. 7–8 as 'dyslexia has also been attributed to deficiencies in general learning abilities that are involved in all learning enterprises and not just learning to read. …Such theories can be questioned on logical grounds alone …given that all of these cognitive abilities are entailed on virtually all tests of intelligence and are most certainly entailed in all academic learning.'

Since that time most theorists have shied away from considering learning as a fruitful area of exploration. Arguably, the only theoretical framework focusing explicitly on the learning process in dyslexia is the automatization deficit framework (Nicolson & Fawcett, 1990). This framework proposes that dyslexia is characterized by difficulty in making skills automatic, so that they can be undertaken fluently and with little conscious effort. Although this description captures the difficulties in literacy-related domains, the framework also proposed that automaticity deficits should occur in all areas of skill, even those outside the literacy domain. Consequently, even for fundamental skills such as balance, individuals with dyslexia would perform differently, and even in skills where their performance was apparently within the normal range, this performance was

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achieved by trying harder, by 'conscious compensation'. A full review of the automaticity deficit and subsequent developments in terms of cerebellar deficits is beyond the scope of this article. See Nicolson & Fawcett (2008) for a comprehensive account.

In this article, we focus on the learning processes in dyslexia and will show that the problem is not too few general methods of learning, as supposed by Vellutino, but rather the opposite!

Any psychology student will know the compelling tale of HM, an amnesic patient who, following unavoidable brain surgery, became incapable of explicitly remembering any new events or facts, but was nonetheless capable of learning over several days the skill of mirror drawing—even though he never had any memory of having tried it before (Milner, Corkin, & Teuber, 1968). These findings provided a strong basis for distinguishing between two types of memory (Squire, 1987): declarative memory (memory for facts and events) and procedural memory (skills and habits). The process(es) by which declarative and procedural memories are developed are declarative learning and procedural learning, respectively.

Automaticity is the end product of procedural learning, and so the automatization deficit hypothesis in effect proposed that many individuals with dyslexia show the opposite problem to HM—good declarative learning but impaired procedural learning. In this article, we consider in more detail the processes of procedural learning, starting with a discussion of the neural systems that underpin learning in the brain.

Neural Systems

An influential analysis by Striedter (2005) argues that 'concerted evolution' has shaped brain development, such that evolutionary pressures act at the level of functional systems (that is the brain structures and also the neural pathways joining them) rather than on individual structures. Consequently, it may sometimes be more appropriate to analyse brain function at the level of the neural systems involved.

One of the most significant developments in recent years in cognitive neuroscience is the development of methods of identifying which brain systems work together, using a variety of converging theoretical and technical methods (Dehaene & Cohen, 2007; Ramnani, 2006; Seghier & Price, 2009; Striedter, 2005; Ullman, 2006). Interestingly, Parvizi (2009) highlights the 'corticocentric' nature of traditional cognitive neuroscience studies (that undue prominence has been given to the cerebral cortex) and stresses the rich interplay between cerebral cortical structures and subcortical systems. Furthermore, there is now extensive evidence that damage to subcortical structures can lead to impaired function in a range of neural systems. For example, Schmahmann & Pandya (2008) document motor, cognitive, and neuropsychiatric disorders in patients with lesions restricted to basal ganglia, thalamus, or cerebellum, and claim that these lesions mimic deficits resulting from cortical lesions.

Focusing on neural systems involving the cerebellum, there is an emerging consensus (Balsters *et al.*, 2010; Ramnani, 2006) that there are two major routes involving two way connections between the cerebral cortex and the cerebellum: a

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motor route (between primary motor cortex and cerebellum via cerebellar modules V,VI, VIIb, and VIIIa) and a cognitive route (between prefrontal cortex and cerebellum via cerebellar lobules Crus I and Crus II). The latter strongly supports the view that the cerebellum is centrally involved in cognitive processing related to language (e.g. Ackermann, Mathiak, & Riecker, 2007; Ito, 2008). Not least is the acknowledgment that the cerebellum is strongly activated in verbal working memory tasks (Desmond & Fiez, 1998; Hayter, Langdon, & Ramnani, 2007) and during reading (Fulbright *et al*., 1999; Vlachos, Papathanasiou, & Andreou, 2007).

In terms of reading and in reading disability, there has been great progress in identifying some of the brain circuits involved (McCandliss, Cohen, & Dehaene, 2003; Schlaggar & McCandliss, 2007; Turkeltaub, Gareau, Flowers, Zeffiro, & Eden, 2003). There is considerable evidence of 'migration' of functional modules over time and, especially, experience during the slow acquisition of reading fluency (Carreiras *et al*., 2009; Pugh *et al*., 2001; Schlaggar & Church, 2009; Schlaggar & McCandliss, 2007; Shaywitz *et al*., 2007; Turkeltaub *et al*., 2003). Overall, the process may be characterized as: in beginning readers, there is an increase in activity in the left temporal–parietal cortex (attributed to phonological processing) accompanied by decreasing activity in right inferotemporal cortical areas (attributed to decreasing reliance on 'visual engrams'); and then as fluency increases a gradual reduction in activity in the left temporal-parietal cortex and increasing activity in the left ventral occipital–temporal cortex (the so-called visual word form area) reflecting fast, direct access to lexical or semantic processing.

These clear and changing linkages between different brain regions when considering the development of reading fluency provide evidence of further within-brain developmental pressures leading essentially to competition between the different functional systems such that function is gradually taken over by more efficient systems following suitable learning; though in cases of atypical stimuli (for example unfamiliar words), it may be necessary to return to an earlier-developed system.

The Procedural Learning Difficulties Framework

The discovery of the involvement of the cerebellum in language skills (Desmond & Fiez, 1998; Ito, 1993; Leiner, Leiner, & Dow, 1993) provided the basis for the cerebellar deficit hypothesis (Nicolson, Fawcett, & Dean, 1995, 2001) that the problems in skill automatization are attributable to impaired cerebellar function as are the problems in reading, though via different cerebellar circuits. This hypothesis led to lively debate in the literature (Beaton, 2002; Nicolson & Fawcett, 2006; White *et al*., 2006; Zeffiro & Eden, 2001), a debate that has considerably enriched our understanding of the issues but has remained unresolved, with critics arguing that apparent cerebellar deficits reflect comorbidity with other disorders or alternatively impaired function in some other component of the cerebellar-language circuits.

The developments in the understanding and identification of neural systems provided strong motivation for considering dyslexia in terms of the functionality

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of the underlying neural systems, as a way of augmenting the established knowledge regarding abnormalities in specific structures such as the cerebellum.

The procedural learning difficulties hypothesis for dyslexia (Nicolson & Fawcett, 2007) adopted a neural systems approach and put together several sources of suggestive but incomplete information—the distinction between declarative and procedural neural systems; the cognitive neuroscience of the human cerebellum as a motor loop and a cognitive/language loop; and the evidence of cerebellar abnormality for function and structure in dyslexia. The authors proposed that the majority of developmental disorders—including dyslexia, specific language impairment, developmental coordination disorder and ADHD—could fruitfully be considered as impairments of the procedural system, with DCD resulting in a primary impairment of the motor loop of the system (with possible secondary impairments of the cognitive/language loop), with the reverse aetiology for dyslexia and SLI. The outline of the hypothesis is shown in Figure 1, taken from Nicolson & Fawcett (2007, p. 138).

The framework was strongly influenced by the seminal analysis of Ullman (2001, 2004), which highlighted the fact that the procedural/declarative distinction applies just as much to language circuits as it does to motor circuits. The framework can also be related to the Functional Co-ordination deficit model for reading (Lachmann, 2002; Lachmann & van Leeuwen, 2007). Furthermore, the framework also adopts the distinction (Doyon, Penhune, & Ungerleider, 2003) between the corticostriatal procedural system (primarily for

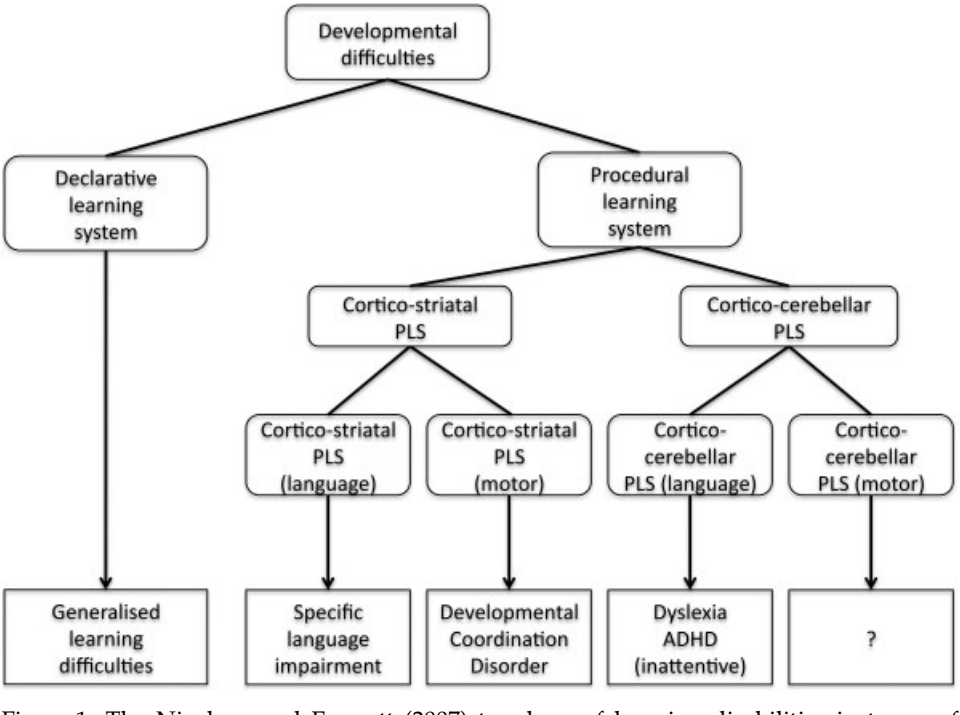

Figure 1. The Nicolson and Fawcett (2007) typology of learning disabilities in terms of neural systems. The figure is taken from Nicolson and Fawcett (2007), p. 138, and is reprinted with permission of Elsevier. See the text for details.

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motor sequence automaticity) and the corticocerebellar system (primarily for motor adjustment), suggesting that SLI may be attributable to a primary impairment in the corticostriatal language system (see also Ullman & Pierpont, 2005), whereas dyslexia may be attributable primarily to the corticocerebellar language system. However, as becomes clear below, the two systems overlap very significantly in how they affect learning, especially in the early stages (see Figure 2), and so for the purposes of this article we will mostly ignore the distinction between the striatal and cerebellar procedural learning routes.

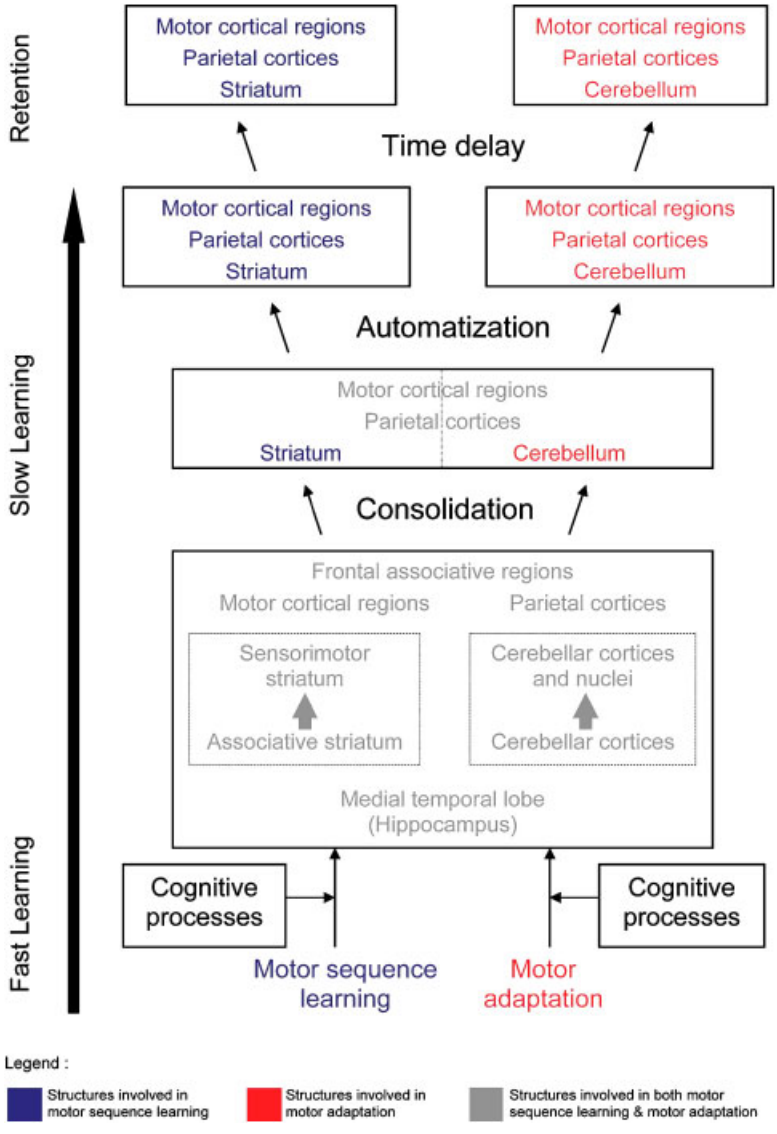

Figure 2. The Doyon and Ungerleider (2002) model of motor skill learning. The figure is taken from Doyon and Benali (2005), p. 4, and is reprinted with permission of Elsevier. See the text for details.

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The Time Course of Learning

The second key component of the procedural learning difficulties framework is its emphasis on learning, and in particular the different forms and stages of learning. The default view of learning of much early education was 'practice makes perfect'. It is interesting to note that this established creed is in fact reasonably appropriate for procedural learning though less so for declarative learning, which generally occurs more by building up increasingly organized, complex, and meaningful schemata (Kintsch, 2009; Mandler, 2002). Cognitive psychology managed to improve somewhat on brute practice by stressing that practice was necessary, but only when under conditions of consistent mapping of stimulus to response (Shiffrin & Schneider, 1977), and preferably through deliberate practice of a systematic nature (Ericsson, Krampe, & Heizmann, 1993).

Recent developments (Doyon & Benali, 2005; Robertson, Pascual-Leone, & Miall, 2004) on the cognitive neuroscience of learning have transformed our understanding of these processes. They distinguish five phases of acquisition—fast learning (min), slow learning (h), consolidation (overnight), automatization (hundreds of trials), and retention (weeks). Figure 2 illustrates an influential model (Doyon & Ungerleider, 2002; Orban *et al*., 2010) matching brain structures to the stages of learning. Cortex, basal ganglia, and cerebellum are all involved in the initial fast and slow learning phases, highlighting the difficulty in isolating specific contributions. When the skill has been well learned, however, its neural representation is thought to be distributed in a network of structures involving only one of these two circuits. This model is instantiated in Eickhoff, Heim, Zilles, & Amunts (2009) in dynamic casual modelling of the interplay between brain regions during speech, which indicates that the cerebellum is part of at least two loops, supporting the planning of articulation and the initiation of articulation respectively. These correspond to procedural and declarative processing, respectively.

We reproduce the figure because it portrays clearly the great range of brain structures and brain processes involved in motor skill automatization. Note also the involvement of the declarative learning system initially. Almost all brain structures are therefore involved at some point!

Interestingly, there is now strong evidence that there are changes in which circuits actually represent the skill over the course of automatization, for motor learning (Coynel *et al*., 2010), for internalization (Imamizu *et al*., 2000), and, of course, for the development of fluent reading, as discussed above.

THREE STUDIES OF PROCEDURAL LEARNING AND DYSLEXIA

These three studies probe the time course of learning, and the different forms of learning, and cover the range of attainments, from performance on reading to acquisition of entirely novel skills. They were undertaken at different times, with different groups of participants, but together they give an indication of the types of study that are suggested by the procedural learning framework. Furthermore, while they lack the systematicity needed for a comprehensive analysis, they do together lead to intriguing and novel suggestions for how the learning difficulties might arise.

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Study 1: Reading Single Words Under Time Constraints

This study (Brookes & Nicolson, submitted) probed the reading process itself, presenting a series of word-like stimuli to groups of dyslexic or control university students matched for age and IQ. All participants read at high levels of given unlimited time, but the key finding (which extends a study by Yap & van der Leij, 1993) is shown in Figure 3.

The stimuli were 100 words, including 5, 6, and 7 letter real words, nonsense words derived from published sources, and illegal non-words which did not match the structure of English. Examples are river, belong, problem, paible, lrinx. Note that, as expected, the students with dyslexia were good at reading single words (such as 'river'), being able to cope with presentation times as low as 150 ms. By contrast, although they were able to read pseudowords (such as 'paible') when given sufficient time, they needed more than 260 ms to read them reliably, whereas the control students coped easily with pseudowords given only 100 ms presentation times. Irregular 'words' (such as 'lrinx') needed extended time for both groups. However, the striking aspect of these results is that in all the three conditions the group with dyslexia needed at least 260 ms to perform at the same level as the controls given only 100 ms.

Individual analyses indicated that none of the 16 students with dyslexia was able to read pseudowords with a 150-ms presentation time, whereas all 16 of the controls could do so. These results clearly indicate the absence of fast automatic word reading even in these highly competent dyslexic university students, most of whom were reading at a high level given normal conditions. The results are particularly interesting in terms of the possibility of 'migration' of single word

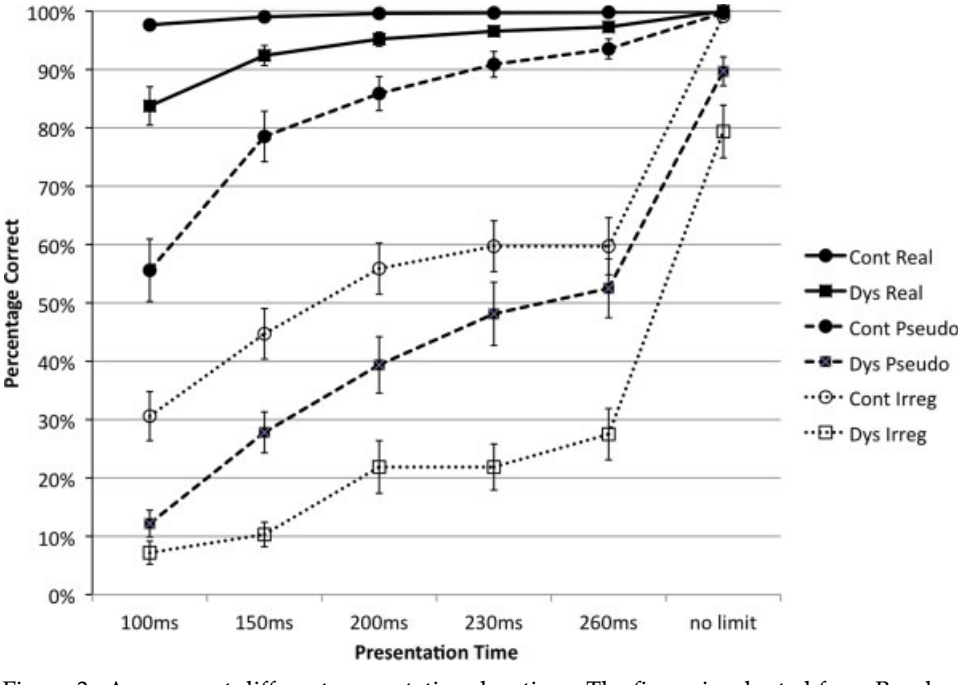

Figure 3. Accuracy at different presentation durations. The figure is adapted from Brookes (2007) and is reprinted with permission from the University of Sheffield. See text for details.

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representations to the visual word form area (see above). At best, such a process remains incomplete in the students with dyslexia, and more likely the processing still occurs via the less efficient earlier routes. But, the question arises, what part of the learning process is it that leads to the failure to establish this fast automatic reading method? To address this issue, we turn to two studies that looked at the learning processes for non-linguistic information over an extended period.

Study 2: Blending of Existing Skills

This study (Nicolson & Fawcett, 2000) investigated long-term procedural learning of the simplest possible kind. It started with the simplest possible tasks—pressing a button with one's foot on seeing a flash or pressing a button with one's finger on hearing a tone. These tasks were initially undertaken separately, so there was only one possible response—a simple reaction task. The focus of the study was then on the blending of these two simple reactions into a choice reaction in which both stimuli were presented equally frequently and therefore one had to decide which response to make. The adolescent participants returned twice weekly for up to 10 weeks, completing three sessions of 100 choice reactions per day, and the issue investigated was how the 'response blending' proceduralization proceeded in two groups of children matched for IQ and age. The group with dyslexia were significantly slower and significantly less accurate at all stages (see Figure 4 for the choice reaction times over the sessions).

It may be seen that, on average, the control group eventually reached a level of performance on the choice reaction that was faster even than the initial performance on the simple reaction, demonstrating the effect of automatizing the task. In order to investigate this issue further, we subsequently analysed the individual data, assessing whether, for each day the participants reached the criteria of 'acceptable choice reaction accuracy[1] and choice reaction speed at least as fast as simple reaction speed'. The data are shown in Figure 5. It may be seen that within 4 days' training over 50% of the control group had managed to meet

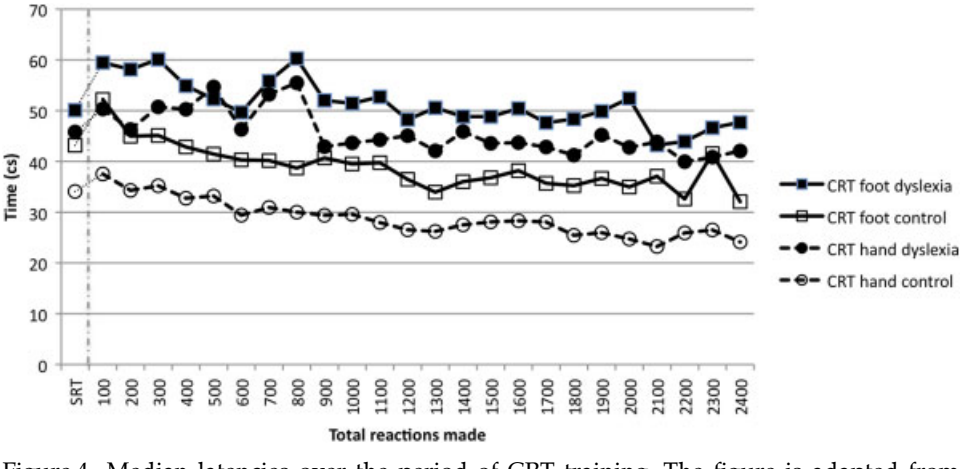

Figure 4. Median latencies over the period of CRT training. The figure is adapted from Nicolson & Fawcett (2000), figure 2, p. 370, and is reprinted with permission from Taylor and Francis journals. See text for details.

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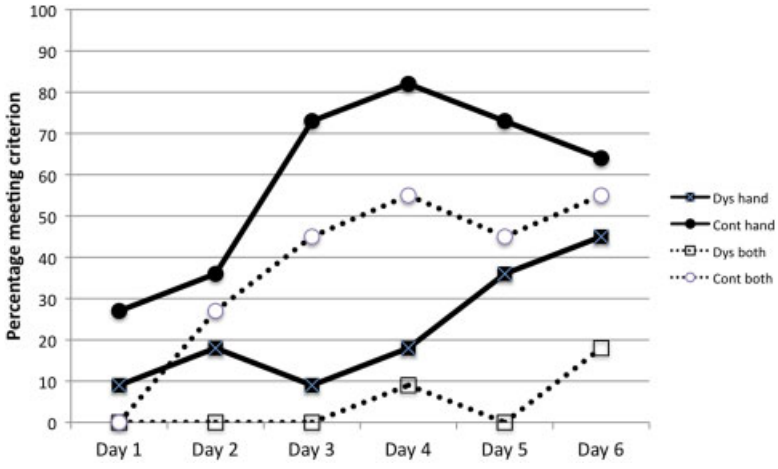

Figure 5. Percentage of participants reaching criterion on each day's sessions. The figure is based on an original reanalysis of the study presented in Nicolson & Fawcett (2000). See text for details.

all four learning criteria, whereas less than 10% of the dyslexic group had achieved this.

These data show clearly that individuals with dyslexia do struggle to learn the simplest possible choice response, even when it does not require language ability or sensory discrimination. The question we addressed in the following study is why this might be.

Study 3: Consolidation of Motor Sequence Learning

This study (Needle, Nicolson, & Fawcett, 2010) investigated the time course of procedural learning of a motor sequence skill over a 24-h period, replicating the methods of Karni and her associates (Karni *et al.*, 1998; Korman, Raz, Flash, & Karni, 2003). The task involves a sequence of 5 finger/thumb oppositions in which participants have to tap each of their fingers with their thumb in a pre-specified sequence, with the dependant variables being the speed and accuracy of operation. It is established in the above literature that under normal conditions, given sleep in between the initial learning and the re-test, most participants perform better on the re-test than immediately after training. This is attributed to the overnight consolidation of the motor sequence schemas into a more efficient format. Following familiarization, 13 dyslexic adults and 12 control adults matched for age and intelligence were asked to repeat a sequence of finger movements as many times as possible in 30 s to form a baseline. They were then trained on the sequence for 160 slow trials paced by a tone every 2.5 s, and then re-tested for maximum speed. A third testing session was carried out 24 h after the initial tests (without any further practice) in which participants were asked to reproduce the trained sequence as fast as possible.

The data for speed of execution at the three time points are shown in Figure 6. A multivariate analysis of variance indicated that the group with dyslexia were significantly slower than the controls overall, with significant differences initially

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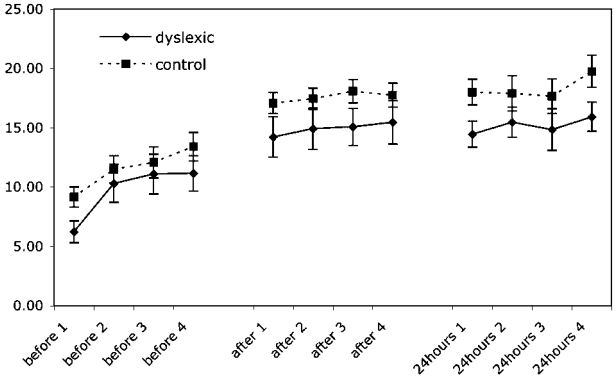

Figure 6. Mean correct sequences for each group over the 30-s periods. Error bars are standard errors. The figure is based on Needle *et al.* (2010) figure 1. See text for details.

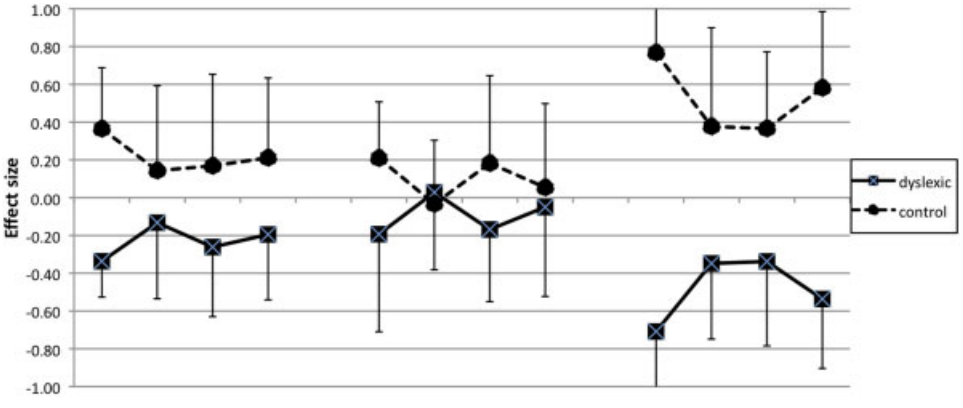

Figure 7. *Z*-score data for composite speed and accuracy. *Z*-scores have been adjusted such that a positive sign indicates better performance. Error bars are standard errors. The figure is based on Needle *et al.* (2010) Figure 1. See text for details.

and on the first trial of the second day. Interestingly, however, in terms of accuracy, the dyslexic participants made more errors initially and after 24 h but less errors immediately after training. When a speed accuracy trade-off analysis was undertaken (see Figure 7), the pattern of findings was confirmed, with a significant difference again after 24 h, despite no clear difference at all immediately after training. This strongly suggests an impairment in consolidation of learning (a prerequisite for normal automatization), together with normal ability to learn during explicit practice. These findings applied strongly to five dyslexic participants (40%), whereas others performed normally, reflecting the considerable heterogeneity of this disorder.

The results therefore provide a novel explanation of why dyslexic children have difficulty learning to read, and may have considerable applied and theoretical implications.

The findings are particularly interesting in the light of a recent review (Stickgold, 2005) of the effects of sleep on consolidation, which concludes that consolidation occurs primarily for procedural (rather than declarative) memories

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and that in the motor sequence learning task, improvements in speed and accuracy are much less marked following sleep deprivation the night after training. A study (Walker, Stickgold, Alsop, Gaab, & Schlaug, 2005) of brain activation changes following overnight sleep compared with wakefulness concluded that 'regions of increased activation were expressed in the right primary motor cortex, medial prefrontal lobe, hippocampus and left cerebellum; changes that can support faster motor output and more precise mapping of key-press movements' (p. 911). Activity decreases were identified in parietal cortices, the left insular cortex, the temporal pole, and the frontopolar region, reflecting a reduced need for conscious spatial monitoring.

INTERPRETATION OF THE THREE STUDIES IN TERMS OF PROCEDURAL LEARNING SYSTEMS

In summary, the studies illuminate three stages of the learning process: the end product of extensive learning over many years, the outcomes of systematic learning over several weeks, and the outcomes of overnight consolidation. The studies show, first, that even high achieving dyslexic adults do not learn a method of fast, automatic word recognition; second that even in the simplest procedural learning circumstances, around half of the children with dyslexia participating showed marked impairments in skill proceduralization for rapid responses; and third, that around half of a different sample with dyslexia showed failures of overnight memory consolidation of a simple motor skill. The procedural learning deficit predicts that not all dyslexic children would show a similar pattern of difficulties, in line with recent studies suggesting the existence of subtypes of dyslexia (Heim *et al*., 2008; Menghini *et al*., 2010; Valdois, Bosse, & Tainturier, 2004).

Despite the dominance of the phonological deficit framework in dyslexia research, it has absolutely nothing to contribute to the explanation of these difficulties. It is also extremely difficult to account for the results in terms of any theoretical framework, which does not have learning at its heart.

In general terms, the results are well accounted for by the automatization deficit hypothesis (Nicolson & Fawcett, 1990) and the cerebellar deficit framework (Nicolson *et al*., 2001). However, it might be objected that the automatization deficit is too vague to provide a detailed explanation of the underlying cause(s), whereas the cerebellar deficit hypothesis may be over-specific. After all, although the cerebellum is involved in most forms of procedural learning, it always acts in conjunction with other brain regions—see Orban *et al*. (2010) for an interesting analysis of the many contributory systems.

The specific interpretation we made for the set of data was in terms of neural systems because we consider that this represents a level of explanation intermediate between the cognitive level of description (as in phonological deficit) and the brain level of explanation (as in cerebellar deficit) that is sufficiently close to underlying brain structures to benefit from current progress in cognitive neuroscience while being sufficiently close to the cognitive levels of explanation to make predictions as to behavioural outcomes, and to be explicable in an educational setting.

It should be stressed that the above analyses by no means exhaust the different neural systems, nor do they exhaust the possible methods of learning. One

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important neural system that we have not addressed here is of course the sensory system. Much research has been devoted to the possibility of impairment of magnocellular visual system (Stein, 2001) together with auditory temporal integration difficulties (Tallal, Merzenich, Miller, & Jenkins, 1998). Discussion of these issues is beyond the scope of this article.

Of particular interest in this special issue, however, is the question of how many different types of learning there might be. While we distinguish between several forms of learning in, for example Figure 2, with declarative vs procedural, and procedural divided in motor and language, and then into corticostriatal and corticocerebellar, and then (though not shown) into visual, auditory, and mixed modality. What is not shown, however, is the existence of several other established learning systems (Thompson & Krupa, 1994), including habituation, conditioning, implicit learning, and statistical learning.

There is suggestive and increasing evidence that individuals with dyslexia may have difficulties in several of these non-declarative learning activities, with evidence of abnormal eye blink conditioning (Coffin, Baroody, Schneider, & O'Neill, 2005; Nicolson, Daum, Schugens, Fawcett, & Schulz, 2002); intriguing evidence of abnormal prism adaptation (Brookes, Nicolson, & Fawcett, 2007); and extensive evidence of implicit learning abnormalities (Howard, Howard, Japikse, & Eden, 2006; Menghini, Hagberg, Caltagirone, Petrosini, & Vicari, 2006; Stoodley, Harrison, & Stein, 2006; Vicari *et al.*, 2005; Vicari, Marotta, Menghini, Molinari, & Petrosini, 2003).

It should also be noted that even the above complex description of motor skill learning may underestimate the complexity of language-based procedural learning. An integrative recent review (Gervain & Mehler, 2010) of infants' language acquisition argues that statistical learning and perceptual learning mechanisms are interleaved with innate rule-based mechanisms all subject to a range of perceptual and memory constraints.

Perhaps of most direct interest in the development of phonological skills is the recent suggestion that there may well be considerable overlaps between statistical and implicit learning for language (Conway, Bauernschmidt, Huang, & Pisoni, 2009), and that children with SLI show impaired statistical learning (Evans, Saffran, & Robe-Torres, 2009).

In summary, as we indicated initially, the problem is not that there are too few forms of learning, as claimed by Vellutino *et al.*, but in fact there are too many! Difficulties in non-declarative learning are not directly tapped by traditional intelligence tests, which test memory rather learning, and are strongly biased towards tests of reasoning and declarative memory. With regard to the likely effects outside of literacy acquisition, there are so many interdependencies between the different modes and timescales of learning that it is not surprising that there is considerable heterogeneity within dyslexia, and considerable comorbidity between developmental disabilities.

EDUCATIONAL IMPLICATIONS

We are now in a position to address briefly the challenge posed by Shaywitz *et al.* (2007)—how can we develop a principled method of determining appropriate

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interventions for children who appear not to be benefiting from standard educational support?

Several scholars (Ramus, Rosen *et al.*, 2003; Shaywitz *et al.*, 2007; Vellutino *et al.*, 2004) have claimed that the near-complete incidence of phonological deficit in dyslexia (compared with the considerably lower incidence of other types of problem) is strong evidence for the primacy of phonology as a causal explanation.

We take the opposite view. Phonological deficits can arise from a range of factors, including 'surface' factors—such as the need to acquire an additional language, hearing difficulties, otitis media or expressive language difficulties—or 'deeper' factors such as difficulties in statistical learning, procedural learning, or declarative learning. The ubiquity of the phonological deficit, when taken in conjunction of the variability of the effectiveness of RTI, indicates that the existence of phonological deficit alone does not have sufficient power to indicate the underlying cause or the appropriate methods of intervention.

The above theoretical analyses make it clear that the brain can employ a variety of learning methods, using a variety of inter-dependent neural systems. The heterogeneity of incidence of difficulties in the three above studies (and in general for most studies in dyslexia) indicates that, unsurprisingly, different children with dyslexia may suffer from different underlying impairments, all of which lead to phonological problems and reading problems. The variability of outcome obtained in studies of RTI indicates that one ignores such heterogeneity at one's peril.

At the very least, the discovery that a significant proportion of children (including normally achieving children) appear to show abnormal consolidation has very clear implications for the teaching of procedural skills, and would appear to support the classic educational maxims of 'little and often'[2] (James, 1899), an approach that is strongly advocated in classic approaches to dyslexia support (Hickey, 1992; Miles, 1989; Orton, 1966).

Taking a broader perspective, there is a strong view in the dyslexia community (e.g. West, 1991) that individuals with dyslexia may have a learning style that is based more on creative, spatial thinking. One might hope therefore that analyses based on learning styles would be of value. Unfortunately, the learning style literature remains chaotic and unconvincing (Coffield, Moseley, Hall, & Ecclestone, 2004), perhaps because it is not grounded in terms of the underlying brain mechanisms.

A pragmatic approach to this critical issue of developing optimal support would be to develop a screening battery designed to probe the different forms of learning, thereby for each child creating a profile of learning abilities and disabilities. One might then hope to design an intervention approach based on either alleviating the specific learning disabilities, or by crafting an intervention to be based around existing strengths rather than existing weaknesses. The cognitive neuroscience of learning provides the necessary theoretical and practical tools to implement such a system.

There is of course very much to be carried out, both in terms of developing an accepted leaning abilities profiler, identifying common types of profile, adapting good practice in intervention to the different profiles, and then collecting the necessary evidence to inform educational developments. Several authors have suggested that it should be possible to blend the techniques of education and the

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insights of cognitive neuroscience to create a new discipline of 'pedagogical neuroscience' (Fawcett & Nicolson, 2007; Goswami, 2006). The cognitive neuroscience of learning provides the means to this end.

CONCLUSIONS

In conclusion, the procedural learning deficit framework has two key assumptions. First, that explanations at the neural systems level have the specificity needed to relate theory to hypotheses testable via neuroscientific and cognitive means while avoiding the danger of overspecificity entailed by explanations at the brain structural level. Second, that the interaction between neural systems and the different stages of learning provides the key to understanding where learning fails for each individual child.

For the majority of children with dyslexia, we believe that the primary neural system affected is the corticocerebellar, language-based procedural learning system. However, many children with dyslexia may have additional or different difficulties. Cognitive neuroscience has given us the tools to identify each child's profile of learning abilities. It is time to develop and use them.

NOTE

1. Defined operationally as percent correct $\geqslant 95\%$ for the hand responses and $\geqslant 90\%$ for the foot responses, which were less accurate in general.
2. 'Paths frequently and recently ploughed are those that lie most open, those which may be expected most easily to lead to results' (p. 59).

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