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Impaired implicit sequence learning in children with developmental dyslexia

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ABSTRACT

It has been proposed that an impairment of procedural memory underlies a range of linguistic, cognitive and motor impairments observed in developmental dyslexia (DD). However, studies designed to test this hypothesis using the implicit sequence learning paradigm have yielded inconsistent results. A fundamental aspect of procedural learning is that it takes place over an extended time-period that may be divided into distinct stages based on both behavioural characteristics and neural correlates of performance. Yet, no study of implicit sequence learning in children with DD has included learning stages beyond a single practice session. The present study was designed to fill this important gap by extending the investigation to include the effects of overnight consolidation as well as those of further practice on a subsequent day. The results suggest that the most pronounced procedural learning impairment in DD may emerge only after extended practice, in learning stages beyond a single practice session.

1. Introduction

Developmental dyslexia (DD) is characterized by unexpected difficulties with reading, in the context of typical educational opportunities and intact intellectual and sensory abilities (Lyon, Shaywitz, & Shaywitz, 2003). The disorder, which has a strong genetic component (Hensler, Schatschneider, Taylor, & Wagner, 2010), has been estimated to affect about 5–12% of children (Shaywitz, Shaywitz, Fletcher, & Escobar, 1990). Children with DD have difficulties with written word recognition and phonological decoding (using letter-sound mapping knowledge to decode novel words), which is widely believed to result from underlying phonological impairments (Snowling, 2000; Stanovich, 1988; Vellutino, Fletcher, Snowling, & Scanlon, 2004).

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However, while phonological impairments are indeed found in an overwhelming majority of studies of DD (Ramus & Ahissar, 2012), other impairments, which are not easily explained by a specific phonological deficit, are also commonly reported. These include impairments of motor functions (Nicolson, Fawcett, & Dean, 2001), working memory (Smith-Spark & Fisk, 2007; Swanson, Xinhua, & Jerman, 2009), executive functions (Brosnan et al., 2002), oculomotor and visuoperceptual functions (Quercia, Feiss, & Michel, 2013), implicit sequence learning (Howard, Howard, Japikse, & Eden, 2006; Jimenez-Fernandez, Vaquero, Jimenez, & Defior, 2011; Vicari, Marotta, Menghiai, Molinari, & Petrosini, 2003), artificial grammar learning (Pavlidou, Williams, & Kelly, 2009) as well as problems with other aspects of language that appear to be primary in nature (i.e. not only a consequence of impaired reading; Lyytinen et al., 2004; Snowling, Gallagher, & Frith, 2003; Wimmer & Schurz, 2010).

This pattern of wide-ranging impairments has encouraged attempts to provide a unitary explanation for DD that may account for both the phonological and non-phonological deficits in the form of a more general underlying deficit. Such theoretical accounts include the proposals that DD is the result of impaired temporal perception (Tallal, 1980), of an abnormal development of the brain's magnocellular systems (Stein, 2001), of a deficit in attentional mechanisms (Hari & Renvall, 2001), or in general processing speed (Wolf & Bowers, 1999). One influential theoretical view, which is the focus of the present study, posits that the underlying deficit in DD is caused by a dysfunction in the procedural memory system, specifically to the cortico-cerebellar (Nicolson, Fawcett, Brookes, & Needle, 2010; Nicolson et al., 2001) and/or to the cortical–striatal (Ullman, 2004) circuits in the brain.

The procedural memory system underlies the non-declarative/implicit acquisition, consolidation and processing of skills and habits (Gabrieli, 1998; Henke, 2010; Squire & Zola, 1996; Willingham, Salidis, & Gabrieli, 2002). The system relies on a network of brain structures in which the cortico-striatal and cortical–cerebellar circuits play crucial, and largely overlapping, roles (for a review, see Doyon and colleagues, 2009).

Although previously considered to be important mainly for motor functions (such as learning how to ride a bicycle), it is becoming increasingly clear that this system also underlies a range of perceptual, cognitive, and linguistic skills. A large literature suggests that the procedural memory system plays a crucial role in the learning and computation of sequences (Aldridge & Berridge, 1998; Knowlton, Mangels, & Squire, 1996; Poldrack, Prabhakaran, Seger, & Gabrieli, 1999; Saint-Cyr, Taylor, & Lang, 1988; Willingham et al., 2002). This system also appears to be important for other functions, including statistical learning (McNealy, Mazziotta, & Dapretto, 2010; Reeder, Newport, & Aslin, 2013; Saffran, Aslin, & Newport, 1996), probabilistic classification learning (Poldrack et al., 2001; Poldrack & Rodriguez, 2004), and tasks tapping complex learned motor skills (Ullman & Pierpont, 2005). Accumulating evidence indicates that procedural memory also underlies the learning and use of rule-governed aspects of grammar, across syntax, morphology and phonology (Conway, Bauernschmidt, Huang, & Pisoni, 2010; Conway & Pisoni, 2008; Dominey, Hoen, Blanc, & Lelekov-Boissard, 2003; Karuza et al., 2013; Teichmann, Dupoux, Kouider, & Bachoud-Levi, 2006; Ullman, 2001, 2004; Ullman et al., 1997; Ullman & Pierpont, 2005).

An extensively used task for the study of non-language procedural memory, specifically implicit sequence learning, is the serial reaction time (SRT) task (Nissen & Bullemer, 1987). In this task, participants are typically shown four boxes or circles arranged horizontally across a computer screen. Whenever a stimulus appears in one of the four positions, subjects are to press one of four corresponding response keys as quickly and accurately as possible. In the implicit version of this task, participants are not told that the stimuli are presented according to a fixed sequence (as opposed to the explicit version, in which the sequential pattern is verbalized and memorized prior to practice). Sequence learning is operationalized as improvements in the accuracy and/or reaction times of responses to the sequence, as compared to randomly ordered items introduced as a control condition at the end of practice. When administered as an implicit task, learning in the SRT task appears to be largely, though not completely, incidental and non-conscious (Howard & Howard, 1992; Willingham, Nissen, & Bullemer, 1989).

A fundamental aspect of sequence learning in the SRT task, and of procedural learning more generally, is that it takes place over an extended time-period. This period may be divided into distinct stages on the basis of both behavioural characteristics and neural correlates of performance (Debas et al., 2010; Hauptmann, Reinhart, Brandt, & Karni, 2005; Korman, Raz, Flash, & Karni, 2003; Orban et al., 2010; Robertson, Pascual-Leone, & Miall, 2004).

Typically, an initial fast acquisition stage, characterized by a rapid improvement in performance (as evidenced by a decrease in both response speed and errors), is followed by a gradual decrease in the learning rate and a trend towards an asymptote (Hauptmann et al., 2005; Korman et al., 2003). This asymptotic shape of the learning curve has been suggested to reflect a saturation of learning that appears to be necessary for consolidation processes to occur normally (Hauptmann & Karni, 2002; Hauptmann et al., 2005; Karni et al., 1998). Consolidation refers to the process by which an initially labile memory trace becomes more robust and resistant to interference (Doyon et al., 2009; Robertson et al., 2004). Sometimes consolidation involves an actual increase in performance, without further practice, a phenomenon referred to as off-line learning (Hauptmann et al., 2005; Nemeth et al., 2010; Song, 2009; Song, Howard, & Howard, 2007). The end point of procedural learning is automaticity of the learned behaviour. When a skill is automatized it can be performed effortlessly even when attention is directed elsewhere (as in dual task situations; Seger & Spiering, 2011).

Brain imaging studies suggest that implicit sequence learning in the SRT task depends largely on procedural memory brain structures, in particular the striatum, cerebellum, associated motor cortical regions, as well as portions of prefrontal and parietal cortex (Grafton, Hazeltine, & Ivry, 1995; Peigneux et al., 2000; Rauch et al., 1997; for a review, see Doyon and colleagues, 2009). In addition, recent studies have highlighted a role for the medial temporal lobe in sequence learning