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Review article

# Procedural learning is impaired in dyslexia: Evidence from a meta-analysis of serial reaction time studies☆

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ABSTRACT

A number of studies have investigated procedural learning in dyslexia using serial reaction time (SRT) tasks. Overall, the results have been mixed, with evidence of both impaired and intact learning reported. We undertook a systematic search of studies that examined procedural learning using SRT tasks, and synthesized the data using meta-analysis. A total of 14 studies were identified, representing data from 314 individuals with dyslexia and 317 typically developing control participants. The results indicate that, on average, individuals with dyslexia have worse procedural learning abilities than controls, as indexed by sequence learning on the SRT task. The average weighted standardized mean difference (the effect size) was found to be 0.449 ($CI_{95}$: .204, .693), and was significant ($p < .001$). However, moderate levels of heterogeneity were found between study-level effect sizes. Meta-regression analyses indicated that studies with older participants that used SRT tasks with second order conditional sequences, or with older participants that used sequences that were presented a large number of times, were associated with smaller effect sizes. These associations are discussed with respect to compensatory and delayed memory systems in dyslexia.



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## 1. Introduction

Individuals with developmental dyslexia have significant difficulties with reading despite appropriate educational opportunities and an absence of intellectual impairments or an identifiable disease or disorder that might otherwise account for the problem (American Psychiatric Association, 2000; World Health Organization, 1996). Dyslexia is one of the most common learning impairments, with prevalence estimates from data collected in the United States and other western countries varying from 3% to 7% (Barbiero et al., 2012; Shaywitz, Shaywitz, Fletcher, & Escobar, 1990).

Behavioral investigations have revealed a pattern of deficits in dyslexia beyond reading impairments. Evidence suggests that difficulties with phonological processing may constitute the core impairment in dyslexia, in particular problems with phonological awareness, that is, the ability to identify and manipulate the sound structure of words in a language (Snowling, 2000). Research has also revealed a range of impairments and problems in other domains. This includes impairments in visual processing (Stein & Walsh, 1997), auditory processing (Tallal, 2004), working memory (Gathercole, Alloway, Willis, & Adams, 2006), oral language (McArthur, Hogben, Edwards, Heath, & Mengler, 2000) and motor functioning (Ramus, Pidgeon, & Frith, 2003). However, the relationship between the reading and other co-occurring problems in dyslexia is still unclear. In particular, it remains a subject of ongoing debate which, if any, of the cognitive, language, and/or motor impairments may best account for the reading problems in the disorder (Bishop & Snowling, 2004; Rosen, 2003).

### 1.1. Dyslexia and procedural memory impairments

Similarly, there has been ongoing interest in whether one or more functions of the procedural memory system also contribute or underlie the reading impairments in dyslexia (Nicolson & Fawcett, 1990, 2007; Nicolson, Fawcett, Brookes, & Needle, 2010; Ullman, 2004). This memory system underlies the learning, knowledge, and execution of motor and cognitive skills and habits (Gabrieli, 1998; Packard & Knowlton, 2002; Ullman, 2004). The system underlies a range of types of knowledge, including context-dependent sequential or probabilistically structured information. Learning and knowledge in this system seems to be implicit (not available to conscious awareness), and the learned skills can be processed automatically and rapidly. Learning the skills is relatively slow, with a fair amount of repetition or practice required in order for them to be processed rapidly and automatically. The neural substrates of the procedural memory system are also reasonably well understood, with the basal ganglia, cerebellum, and motor-related areas all playing roles (Kandel, Schwartz, & Jessell, 2012; Packard & Knowlton, 2002; Parent & Hazrati, 1995; Ullman, 2004).

It has been hypothesized that the reading impairments in dyslexia may be at least partly explained by problems with the procedural memory system. Nicolson and Fawcett (2007, 2011) argue that the reading difficulties in dyslexia are, in part, related to parts of the procedural memory system that support language, in particular phonology. Specifically, it is claimed that the reading problems in dyslexia are linked to problems with learning and/or adapting phonological knowledge and automatizing skills necessary to support reading. Nicolson and Fawcett particularly implicate the cerebellum in dyslexia. Ullman (2004) also posits the presence of procedural memory impairments in dyslexia, but suggests that the underlying neural abnormalities may encompass various brain structures underlying procedural memory, including the basal ganglia. Consistent with these views, neural abnormalities have been reported in various structures underlying procedural memory, including the cerebellum (Brambati et al., 2004; Kronbichler et al., 2008), the basal ganglia (Eckert et al., 2005; Pernet, Poline, Demonet, & Rousselet, 2009), and motor areas (Silani et al., 2005). Finally, both Nicolson (Nicolson & Fawcett, 1990, 2007) and Ullman (Ullman, 2004; Ullman & Pullman, 2013) consider that the declarative memory system plays a compensatory role for at least some of the procedural memory deficits in dyslexia.

A key prediction of the proposal that procedural memory impairments are found in and may underlie dyslexia, is that individuals with dyslexia should in fact have worse procedural learning abilities than control individuals with typical reading skills. A number of studies have examined learning in procedural memory in dyslexia, using a variety of paradigms, including artificial grammar learning (Pavlidou, Louise Kelly, & Williams, 2010; Rüsseler, Gerth, & Münte, 2006), alternating serial reaction time task (Howard, Howard, Japikse, & Eden, 2006), as well as the classic serial reaction time (SRT) task first described by Nissen and Bullemer (1987). Indeed, many of these studies have reported procedural learning impairments in the disorder (e.g., Vicari et al., 2005; Vicari, Marotta, Menghini, Molinari, & Petrosini, 2003). However, this finding has not always been replicated (e.g., Bussy et al., 2011; Deroost et al., 2010; Menghini et al., 2010), leaving open the question as to whether procedural learning deficits are indeed found in dyslexia. Moreover, the heterogeneity of findings suggests the possibility that participant level variables (e.g., the age of tested individuals) or methodological factors (e.g., the amount of training in the learning tasks) might help explain the pattern of results.