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# 36 Implicit learning in developmental dyslexia as demonstrated by the Serial Reaction Time (SRT) and the Artificial Grammar Learning (AGL) tasks

## 1 Introduction

Developmental Dyslexia (DD) is characterized by non-fluent word identification and poor spelling performance, which are not the result of sensory impairments, impairments in intelligence, or inadequate educational experience (American Psychiatric Association, 2013; Pennington, 2009). Despite extensive research, the underlying biological and cognitive causes of DD remain under debate, depending on the criteria used to assess the severity of reading difficulty (Fletcher, 2009).

Three major theoretical frameworks were identified in a recent review of more than 1500 references on DD (Démonet et al., 2004). The mainstream hypothesis, i.e. *The Phonological Deficit Hypothesis* (Snowling, 2000), implicates a deficit of direct access to, and manipulation of, phonemic language units retrieved from the long-term declarative memory. This account has been supported by numerous studies which indicate a phonological deficit in DD (Vellutino et al., 2004). However, individuals with DD exhibit difficulties which are not restricted to the language domain. For example, they may also suffer from motor procedural learning impairments (Folia et al., 2008) as well as sensory processing deficits (Stein and Talcott, 1999). The major limitation of the *Phonological Deficit Hypothesis* is its inability to account for these additional impairments. Supporters of this account acknowledge the co-occurrence of these additional impairments along with the phonological deficit but do not see them as playing a casual role in the etiology of DD (Ramus et al., 2003). Nevertheless, the wide range of DD difficulties has led researchers to search for other, more basic deficits than reading which may underlie DD (Nicolson and Fawcett, 1990; Stein and Walsh, 1997).

The *Magnocellular Theory* of DD is unique in its ability to account for all other manifestations of DD (Stein and Walsh, 1997). This account is based on the observation that there are two visual pathways leading information from the eyes to the visual cortex: the magnocellular/parvocellular systems. The magnocellular system is thought to transmit visual and auditory information quickly, whereas the parvocellular system is more important for details. According to the *Magnocellular Theory*, the magnocellular pathway is selectively disrupted in individuals with DD, leading

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to visual/auditory perceptual deficits as well as difficulties in visuospatial attention via the posterior parietal cortex (see also Vidyasagar, 1999). Support for this account comes from studies which demonstrated impaired performance of DD individuals on a variety of tasks which tap magnocellular functions (for reviews see Laycock and Crewther, 2008; Stein, 2001) as well as from studies which demonstrated a direct link between reading and magnocellular dorsal stream measures (Kevan and Pammer, 2009). Nevertheless, the validity of this account is still hotly debated, mainly due to nonspecific or irreducible findings (for example, Amitay, Ben-Yehudah, Banai, and Ahissar, 2002; Stuart, McAnally, and Castles, 2001). Furthermore, the proportion of individuals with DD that exhibit motor and sensory disorders is relatively low in relation to phonological deficits (Ramus et al., 2003).

Finally, according to *the Automaticity Deficit Hypothesis* (Nicolson and Fawcett, 1990) which was later modified to the *Cerebellum Deficit Hypothesis (R. I. Nicolson, Fawcett, and Dean, 2001)*, DD children will suffer from problems in fluency for any skill that should become automatic through extensive practice. This hypothesis accounts neatly for the problems in acquiring phonological skills, in reading, in spelling, and in writing. In terms of behavior, that means that a process can be characterized as automatic, if it is executed fluently, less influenced by cognitive demands, and more resistant to interference. According to this framework, for most skills, individuals with DD learn to mask their incomplete automatization by a process of '*conscious compensation*', thereby achieving apparently near-normal performance, at the expense of greater effort (*the Conscious Compensation Hypothesis*; R. I. Nicolson and Fawcett, 1994). The brain region candidate which has been proposed by Nicolson and Fawcett to underlie the cognitive automatization deficit was the cerebellum, leading to difficulties in the acquisition and automatizing of cognitive and motor skills. This framework was recently modified to its current form, *Specific Procedural Learning Difficulties (R. I. Nicolson and Fawcett, 2011)* according to which DD arises specifically from impaired performance of the procedural learning system for language. This defect stems from damage to one of the brain areas related to this system (such as the prefrontal cortex around Broca's area, the parietal cortex and sub-cortical structures including the basal ganglia and the cerebellum).

In this paper, we assume the third theory that claims that people with DD are impaired in implicit learning (Nicolson and Fawcett, 1990). Implicit learning refers to a learning process by which we acquire knowledge of the regularities of the learning environment in a passive way, and possibly without awareness (Pothos, 2007). We show that reading impairments in DD mainly reflect a deficient in general capacity for statistical learning. In other words, individuals with DD have difficulty picking up and assimilating the statistical properties and systematic patterns of a structured environment. The current paper demonstrates the deficient general capacity for statistical learning in individuals with DD using two implicit sequence learning paradigms: the Serial Reaction Time (SRT), and Artificial Grammar Learning (AGL). Our aim is to show that the pattern of findings that emerges from studies investigating dyslexic performance on implicit skill learning (as reflected in the SRT) and implicit sequence learning (as reflected in the AGL) helps us identify the nature of deficits that underlies DD.

## 2 Implicit learning

The term “implicit learning” refers to the unconscious acquisition of new information. It is defined as an unintentional and automatic process that results in knowledge that is difficult to verbalize completely (Reber, 1967). It is typically used to characterize situations where a person learns about the structure of a complex stimulus without necessarily intending to do so (Berry and Dienes, 1993; Reber, 1967). Studies examining implicit learning found that participants were able to abstract and recognize generalized regularities and patterns in presented stimuli without explicit knowledge about these regularities. It has been suggested that this ability may be a prerequisite for acquiring language (Brown, 1973; Pinker, 1994) and for learning linguistic skills such as reading and writing, since this ability is needed for building a system of linguistic categories and ‘rules’ or generalizations. Since these linguistic skills exhibit much regularity, it is conceivable that contact with such a system will induce implicit learning (Gombert, 2003).

It has already been shown that children are able to detect patterns in real or artificial languages at a very early age by using distributional information such as transitional probabilities. The detection of such distributional patterns may result in skills as diverse as phonetic categorization in infants aged 0:6 (Maye, Werker, and Gerken, 2002), syntactic category formation in children aged 6:1 (Gerken, Wilson, and Lewis, 2005), and sensitivity to lexical orthographic regularities that have not been explicitly taught (Gombert, 2003; Habib, 2000). This pattern sensitivity depends partly on a sequential analysis of distributional information, such as the number of occurrences of elements or the sequential co-occurrence relations among them. The importance of implicit learning to reading is bolstered by connectionist modeling simulations of reading. According to connectionist models (Harm and Seidenberg, 1999; Seidenberg and McClelland, 1989), some initial orthography- phonology connections may be ‘taught’ explicitly. However, the majority of such learning occurs through coincidence detection of probabilistic properties in the input, and is thus implicit (Sperling, Lu, and Manis, 2004).

Some researchers claim that a deficit in implicit learning may lead to difficulty in learning to read often displayed among individuals with DD (Bennett, et al., 2008; Folia, et al., 2008; Gabay et al., 2012; Pavlidou, Kelly, and Williams, 2010). According to this view, dyslexia is associated with a deficit in extracting statistical regularities from transient input, and affects language as well as other domains (Kerkhoff, De Bree, De Klerk, and Wijnen, 2013). Individuals with DD may have difficulties in acquiring a variety of language skills such as reading, writing, spelling, as well as reading sub-skills such as word identification and phonological decoding (Vellutino, Fletcher, Snowling, and Scanlon, 2004). Studies investigating implicit learning among individuals with DD suggested that this weakness in implicit learning may be narrowed down to paradigms that involve sequential processing (Bennett, et al., 2008; Folia, et al., 2008; Howard, Howard, Japikse, and Eden, 2006; Menghini, Hagberg, Caltagirone, Petrosini, and Vicari, 2006; Russeler, Gerth, and Monte, 2006; Stoodley, Harrison, and Stein, 2006).

## 3 The Serial Reaction Time (SRT)

A commonly-used task for studying skill learning is the Serial Reaction Time task – SRT (Nissen and Bullemer, 1987). In this task, participants are presented with a visual stimulus in one of several discrete locations and are requested to make a rapid key press corresponding to the stimulus location. Unknown to the participants, the stimuli appear in a repeated sequence and learning of the sequence is indicated by a decreased reaction time across blocks or as a difference between reaction time to sequence and random (or a different sequence) blocks (Seger, 1998). There is a clear evidence of learning irrespective of the participants' conscious awareness to the repeated sequence.

The process of skill acquisition begins with the first exposure to the task, known as acquisition phase or fast learning phase. This phase requires a training interval involving repeated engagement with the procedure being learned (Rattoni and Escobar, 2000), and is accompanied by fast improvements in performance that can be seen within seconds to minutes. The improvements during initial task practice follow a curve and performance gradually reaches an asymptote (i.e., power function). At the brain level, this phase is presumably too fast for extensive structural change, which involve the synthesis of new proteins and the formation of new synapses. Instead, disinhibition or "unmasking" of already existing cortical connections may be the common mechanism underlying acquisition (Walker, 2005). This phase actually reflects the creation of a fragile and unstable mental representation for the task.

A slow learning phase is believed to evolve following successful completion of acquisition, in which slow improvements in performance may be seen within hours or days. This phase involves a consolidation process, a process whereby a newly formed memory becomes increasingly less susceptible to interference (Walker, 2005). Consolidation in the procedural domain relates to two behavioral stages: (1) *Consolidation-based stabilization (CBS)* and, (2) *Consolidation-based enhancement (CBE)*. *CBS* can be described as a reduction in the fragility of a memory trace after the acquisition of a novel skill (Robertson, Pascual-Leone, and Miall, 2004), which can be seen in the loss of an acquired skill, if an individual immediately attempts to acquire a skill in another task. However, if time elapses between the acquisition of the first skill and training in the second, the amount of interference decreases

(Goedert and Wilingham, 2002). This process, in which memory traces become more stable, takes place within six hours following the initial acquisition. At this stage, behavioral performance is maintained and is not improved. Nonetheless, different patterns of regional brain activation can be developed, indicating a change in the neural representation of the skill (Shadmehr and Holocomb, 1997). Further behavioral improvement can be seen in an additional stage named *CBE*. During this stage, additional learning takes place in the absence of any further rehearsal or experience. These additional improvements are named *offline learning* and are accompanied by synaptic and structural changes in the brain. Offline learning occurs after a period of night sleep, although additional offline enhancement may occur within several days. Furthermore, it appears that offline learning depends on the amount of practice being given during the entailment practice (Hauptman, Reinhart, Brandt, and Karni, 2005). Following consolidation, the learned skill reaches automaticity (Stickgold and Walker, 2005). In this context, automaticity refers to a shift from controlled performance to a more efficient performance (i.e., is faster, less variable, less vulnerable to interference and with fewer errors) with reduced demands on attention (Shiffrin and Schneider, 1977) and a corresponding shift in brain networks that support performance (Jueptner and Weiller, 1998).

One of the advantages of the SRT task is that several sequence-learning measures could be extracted from it. First is learning rate, which is reflected in reduction in reaction time (RT) across training blocks when the same sequence is presented repeatedly. In addition to the sequence-specific learning, this measure reflects a more generalized skill learning (e.g., mapping the specific response to the specific stimulus position) (Ferraro, Balota, and Connor, 1993; Knopman and Nissen, 1987). Second is indirect sequence learning measured as the increase in RT when a block with a random or different sequence is presented compared to the previous repeated sequence.

The SRT task has been studied extensively in DD in order to examine motor procedural learning. Several studies have revealed impairment in sequence learning among adults with DD as measured by the SRT task (Howard, Howard, Japikse, and Eden, 2006; Menghini, Hagberg, Caltagirone, Petrosini, and Vicari, 2006). These studies point to a deficit in the acquisition stage of sequence learning in DD individuals. This online deficit may be attributed to differences in the processes involved in sequence learning. These processes include the “reaction-time-task learning”, as defined by Knopman and Nissen (1987). This process is regarded as related to proficiency in execution of the SRT task (e.g., mapping the specific response to the specific stimulus position). It is argued that individuals with DD failed to show significant decrease in RT during the first session, since they were impaired in general learning ability. Therefore, the practice given to them is not sufficient to produce a reduction in reaction time during the initial stage of learning. This suggests that DD stems mainly from a deficit in the procedural learning system.

In a study that was designed to examine whether this impaired acquisition was attributed to a lack of automatization, Gabay, Schiff and Vakil (2012a) tested a skill learning task in DD and normal readers using a dual task paradigm. The impact of dual task costs on participants' performance was used as an indication of automaticity. Participants completed a sequence-learning task over a first session (acquisition) and a second session 24 hours later (consolidation,) when half of them are under a full attention condition and another half is under a divided attention condition. Results showed delayed acquisition of the motor skill in the DD group compared to normal readers. This study highlights that the differential effect of divided attention on acquisition and consolidation of procedural skill in DD and normal readers, supports the automaticity deficit hypothesis in DD.

Investigating implicit learning among individuals with dyslexia, who are characterized by language learning difficulties, raises the question whether the nature of the stimuli in the learning process might be an influential factor in the process of sequence learning. The study by Simoës-Perlant and Largy (2011) is the first to examine the effect of the nature of the SRT stimuli on performance of dyslexic children by manipulating the items being tracked, rendering them linguistic or non-linguistic. Their results revealed sensitivity to the nature of the target in sequence learning among children with dyslexia, pointing to differences in the evolution of the response times according to the item being tracked. Their findings suggest that sequence learning among individuals with DD is related to the nature of stimuli rather than an indication of a more general deficit in procedural learning.

Another interesting study exploring the nature of the stimuli by Gabay, Schiff and Vakil (2012b) focused on letter names and motor sequence learning in participants with DD and control participants. Both groups completed the SRT task which enabled the assessment of learning of letter names and motor sequences independently of each other. Results showed that control participants learned both the letter names as well as the motor sequence. In contrast, individuals with DD were impaired in learning the letter names sequence and showed a reliable transfer of the motor sequence. While previous studies established that motor sequence learning is impaired in DD, finding of the abovementioned study indicate dissociation between letter names and motor sequence learning in individuals with DD. Specifically, it was found that both groups showed transfer when spatial locations and manual responses followed a repeated sequence. In contrast, only controls showed a reliable transfer when the letter names sequences followed a repeated pattern, while the DD group failed to show this expected increase. These results indicate that individuals with DD have greater difficulty in the procedural learning of letter names sequences. This impairment may be largely a direct consequence of an underlying dysfunction of the procedural learning system of language.

Data as to implicit learning efficiency or inefficiency among dyslexic children and adults is not yet complete. More studies using different age groups, modalities, and tasks are required for a substantiation of the specific procedural learning difficulties as the core deficit of DD. Another often used implicit learning task is AGL. Important differences of the two tasks concern the motor requirements and the postulated role of the cerebellum for learning.

## 4 Artificial Grammar Learning (AGL)

AGL examines the learning of symbol sequences generated by a finite state language (Pothos, 2007; Reber, 1967, 1993). A finite state language is a set of rules that indicate which symbol sequences are legal, or grammatical (G), as opposed to illegal, or non-grammatical (NG). In a typical AGL experiment, participants are first presented with a subset of the G sequences as letter strings in a training part, and are asked to observe them, but no other information is provided about the nature of the strings or about what would be required of them. They are then told that the strings they see are all complied to form a set of rules and are asked to identify the novel legal ones, in a set that contains both legal and illegal strings. The extensively replicated finding is that participants can identify the new G sequences with above chance accuracy, while they are largely unable to fully articulate the knowledge on which they based their decisions (Pothos and Kirk, 1994).

Research using the AGL paradigm among children with DD reveals a significantly lower performance among dyslexic than among typically developing readers (Pavlidou et al., 2009; Pavlidou and Williams, 2010; Pavlidou, Kelly, and Williams, 2010; Pavlidou and Williams, 2014). Children with DD are consistently found impaired in their implicit learning abilities, when the complexity of the learning situation is increased and irrespective of the implicit task in use and the stimulus characteristics. For example, Pavlidou et al. (2010) explored implicit learning in a group of TD and DD primary school children nine to twelve years of age using an AGL task. Performance was calculated using two measures of performance: a perfect free recall (PFR) score and a grammaticality judgment score. Findings showed that children with DD, compared to TD children, failed to show implicit learning irrespective of the substring characteristics. This poor performance of reading impaired children on the AGL task raise the hypothesis that implicit learning deficits may not be limited to sequence learning but could also extend to learning mechanisms that abstract rules and could account for some of the reading problems encountered in DD.

Indeed, Pavlidou and Williams (2014) addressed this hypothesis of rule abstraction by testing TD and children with DD on a transfer task, in which the testing items were composed of a different shape set than the one used to create the training set, but the grammar rules remained the same. Their assumption was that if children are deeply learning a grammar, then they should be able to transfer this learning to a novel setting, and this would strengthen the claim that AGL learning requires the abstraction of rules alongside the acquisition of item specific knowledge. Their experiments show that implicit learning is impaired in children with DD regardless of the type of task and/or the stimulus characteristics, as they have difficulties in abstracting higher-order information across complex stimuli.

Studies with adult participants yield contradictory findings. While some studies found no deficit in AGL tasks (Photos and Kirk, 2004; Rüsseler, Gerth and Munte, 2006), Kahta and Schiff (2016) found a lower performance among dyslexic readers than among typically developing TD adults. The performance of adults with DD and TD readers was compared for endorsement rates and for classification rates. Findings showed that while the TD group exceeded chance level in both the transfer and the non-transfer conditions, the DD group exceeded chance level under the non-transfer condition, but failed to do so under the transfer condition, endorsing a borderline classification rate of 56% of the strings. This finding strengthens the conclusion that individuals with DD rely more heavily on surface characteristics of the stimuli, with no evidence of undergoing abstractive processing (Kahta and Schiff, 2016).

Methodological differences might account for the discrepancy between the findings as AGL experiments vary in the level of the grammar system complexity used. In an extensive meta-analysis study, Schiff and Katan (2014) demonstrated the effect of grammar complexity on performance, so that much of the discrepancy in the results of the different AGL studies can be explained by taking into consideration the complexity of the grammar used. By computerizing Bollt and Jones's (2000) technique of calculating topological entropy (TE), a quantitative measure of AGL charts' complexity, Schiff and Katan (2014) examined the association between grammar systems' TE and learners' AGL task performance. Using the automated matrix-lift-action method (Bollt and Jones, 2000), they assigned a TE value for each of these 10 previously used AGL systems and examined its correlation with learners' task performance. The meta-regression analysis showed a significant correlation, demonstrating that the complexity effect transcended the different settings and conditions in which the categorization task was performed. The results reinforced the importance of using this new automated tool to uniformly measure grammar systems' complexity when experimenting with and evaluating the findings of AGL studies.

For example, a study by Katan, Kahta, Sasson and Schiff (2016) investigated performance on two AGL tasks of different complexity levels among dyslexic readers, age matched and reading level matched controls. Results indicate that individuals with dyslexia have a deficiency in AGL tasks especially at the highest complexity grammar system. These findings clearly point to the importance of taking the complexity of the grammar system into account when experimenting with the AGL task, as it can have an impact on the results, particularly in special populations.

It should also be noted that thus far the studies exploring implicit learning processes among adults with DD have focused on the visual modality, while disregarding the auditory modality. Research indicates that individuals with DD exhibit poor access, memorization and manipulation of phonological information (Blachman, 2000; Bradley and Bryant, 1983; Snowling, 2000; Vellutino et al. 2004), and that they have a deficit in their sensitivity to the sequence of auditory stimuli (Tallal, 1980). In a study by Kahta and Schiff (2016), the researchers investigated implicit sequential learning processes among adults with DD using the AGL task. Findings show that individuals with DD failed to reach above chance level in the auditory tasks, whereas when processing visual stimuli they exceeded chance level although to a lesser extent than typically developing readers. This deficit exists for visual as well as auditory stimuli and appears to be more salient in learning auditory sequences. This discrepancy may be related to the specific characteristics of auditory input that might hinder the performance of individuals with DD. Hence, it is difficult to draw a conclusion regarding implicit learning processes among individuals with DD based on the available information. More studies into the auditory modality would complement the evidence available and provide greater insight about the important implicit processes in individuals with DD.

# 5 Conclusion

To summarize, the present paper observed deficient implicit learning of dyslexic individuals in two widely used implicit learning paradigms. The studies reviewed in it lend support to the notion that DD is associated with an implicit learning dysfunction. Furthermore, reading impairments in DD mainly reflect a deficient in general capacity for statistical learning, hence individuals with DD have difficulty picking up and assimilating the statistical properties and systematic patterns of a structured environment. This poor performance of reading impaired children on the SRT and AGL tasks supports the hypothesis that implicit learning deficits may not be limited to implicit skill learning but could also extend to statistical learning mechanisms that could account for some of the reading problems encountered in DD. The studies included in this paper measured implicit learning using the SRT and AGL tasks. More research is needed to assess the performance of individuals with DD on implicit learning tasks using the abovementioned and other paradigms. We wish to emphasize the importance of studying not only initial learning, but also memory consolidation and transfer abilities in implicit learning of individuals with DD in order to obtain a deeper understanding of learning and memory functions in affected children. Such knowledge would potentially be of great importance to the development of effective clinical strategies.

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