ASSOCIATIVE IMPLICIT LEARNING IN ADULT DYSLEXIC READERS

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Abstract

This thesis examined associative implicit learning in dyslexic young adults. Dyslexic adults' associative implicit learning has been examined from three perspectives: what, when, and how. More specifically, it has been investigated if dyslexics have deficit in learning more complex knowledge, such as longer chunks or abstract knowledge (i.e., 'what'); if learning occurs at different stages in dyslexics compared to non-dyslexics (i.e., when); how dyslexics learn, and especially the role of both implicit and explicit processes (i.e., 'how'). The empirical findings from 9 experiments in 5 studies are: i) implicit learning deficits in dyslexic people are more manifest in second-order learning than first-order learning, with both motor and perceptual stimuli; ii) when only zero- and first-order information is required, dyslexic people developed abstract learning under implicit learning condition as well as, and as fast as non-dyslexics; iii) dyslexic participants had different sequence learning profiles compared to matched controls: dyslexic participants' expression, but not learning per se was impaired under resource-demanding condition compared to controls. Moreover, implicit learning was found to correlate with word reading score, phonological awareness, and working memory. This thesis is the first comprehensive study to consider a wide range of associative implicit learning with different learning content on a dyslexic population. The findings contribute to the current framework of explanatory theories of dyslexia, suggesting a new route through which cerebellar dysfunction can lead to phonological impairment, and eventually lead to reading difficulties.

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Chapter One: General Introduction

1.1. What is dyslexia

The origin of the word ‘dyslexia’ comes from two Greek words: *dys*, which means abnormal or impaired, and *lexis*, which refers to language or words. The word ‘dyslexia’ simply means difficulty with the written word, which is a descriptive, not a diagnostic term. According to British Psychological Society (BPS):

> *‘Dyslexia is evident when accurate and fluent reading and /or spelling develops very incompletely or with great difficulty. This focuses on literacy learning at the ‘word level’ and implies that the problem is severe and persistent despite appropriate learning opportunities.’ (BPS, 1999, p64)*

Reading problems in such a population are manifested in severe difficulties in acquiring basic reading skills such as word identification and phonological (letter-sound) decoding (Vellutino, Fletcher, Snowling, & Scanlon, 2004). Such difficulties have been estimated to occur in approximately 10% of the UK population and 4% are seriously affected (the British Dyslexia Association, 2004).

Although defined as a ‘specific reading disability’, dyslexia is not only a language specific disorder: the deficits of dyslexics can be observed in executive, motoric, and even sensory abilities (Ramus, Pidgeon, & Frith, 2003; Wimmer, 1993). As stated by the British Dyslexia Association (1995):

"Dyslexia is a complex neurological condition which is constitutional in origin. The symptoms may affect many areas of learning and function, and may be described as a specific difficulty in reading, spelling and written language. One or more of these areas may be affected. Numeracy, notational skills, motor function and organizational skills may also be involved. However, it is particularly related to mastering written language, although oral language may be affected to some degrees."

The above definition provides information about the specific problems associated with dyslexia in all possible areas, thus is of value to teachers, parents and other practitioners. However, some forms of reading difficulties may be explained in terms of a non-neurological deficiency in vision or hearing, or poor reading instruction (Stanovich, 1992) while others may reflect more general learning problems (Rutter & Yule, 1975). Therefore, it is also important to exclude reading difficulties which can be explained by poor schooling, physical difficulty (e.g., vision problems, impaired hearing, etc.), emotional and behavioural difficulties, or severe neurological impairment that goes significantly beyond literacy (Lyon, 1995).

A traditional view to define dyslexia also excluded the reading difficulties caused by poor intelligence, i.e., a child is deemed to be dyslexic only if their reading ability is significantly below that is predicted from their general intelligence on the basis of the correlation between reading and IQ (intelligence quotient) in children of the same age (Aaron, 1997). However, this IQ-independent view of dyslexia is questioned by more and more researchers (Goswami & Bryant, 1990; Singleton, 2009; Stanovich, 1994).

IQ is a score derived from one or several standardized tests designed to assess intelligence (Colman, 1990). IQ scores are volatile indices of global functional outcome, the final common path of an individual's genes, biology, cognition, education, and experiences (Gardner, 1987). The traditional view of dyslexia is that it should be regarded as reading-IQ discrepant; consequently, the individuals with reading difficulties with lower IQ are reading-IQ non-discrepant, i.e., their reading capability is not a specific problem, and in accordance with their lower cognitive capabilities. Therefore, following this view, these reading-IQ non-discrepant individuals would be regarded as generally 'backward' readers (Rutter & Yule, 1975), or poor readers (Stanovich, 1988).

However, IQ is a fuzzy concept itself. One problem with the reading-IQ discrepant definition is that there is still uncertainty over the exact definition of intelligence and what factors make a person intelligent. Therefore, it is problematic to attempt to measure a concept, which is not fully understood. From a psychometric view, there are different dimensions of cognitive abilities underlying intelligence, and two major forms of intelligence are involved in most intelligence assessments: Verbal Intelligence and Nonverbal Intelligence (Gardner, 2011). For example, with the Wechsler Adult Intelligence Scale (WAIS), each test has two batteries of subtests grouped into two general areas: 1) verbal scales, which measure vocabulary, verbal comprehension, and verbal reasoning; and 2) non-verbal (performance) scales, which measure spatial, visual perception, and problem-solving skills (WAIS-IV, 2008).

Some researchers (Colman, 1990; Goswami & Bryant, 1990) have claimed that overall IQ is highly correlated with reading capability, as reading capability is related to verbal IQ, and non-verbal IQ is highly correlated to verbal IQ. However, IQ tests are not reliable over age, and non-verbal IQ, “at least as measured by the 'pure' reasoning tests and subtests, is highest among 18-30 year olds and significantly lower in older groups” (Colman, 1990, p342). Therefore, such lack of stability of IQ scores and uncertainty of the selection of IQ tests make it even more difficult to decide the IQ-discrepant nature of dyslexia.

More importantly, the key reason of dyslexia’s reading-IQ discrepant nature is the assumption that dyslexia should be etiologically and neurologically distinct from ‘backward readers’ or ‘poor readers’. However, in a review of the literature, Stanovich (1994) stated there is no indication that the nature of processing within a ‘word recognition module’ differs between high and low IQ poor readers. Several other studies (e.g., Gustafson & Samuelsson, 1999; Siegel, 1989; Fletcher, 1992) have also found that poor readers with or without reading-IQ discrepancy show the same reading performance patterns, and suggest both groups might benefit from the same remedial activities.

Reading-IQ discrepancy is no longer the criteria for identification of dyslexia in the US or the UK (Singleton, 2009), however, there is still not an all agreed operational definition of dyslexia (BPS 2005, p17). In this thesis, dyslexia is defined following the working definition by the British Psychological Society, which identified dyslexia as “marked and persistent problems at the word level of the National Literacy Strategy[1] curricular framework” (BPS 2005, p20). This definition has 'no exclusionary criteria', and focuses on difficulties at the 'word level' and implies that the problem is severe and persistent.

Consequently, in the current thesis, one criteria for the participants being identified as dyslexic is they all have been formally diagnosed as dyslexic by a registered healthcare professional[2]; the other criteria is their standard score in word spelling and word reading tests being significantly worse than the standard average score in that age group.

1.2. Phonology, automaticity and naming deficit theories of dyslexia

‘The history of dyslexia research, the well-known heterogeneity of dyslexic children and the very complexity of the reading process argue against any single unifying explanation for reading breakdown.’ (Wolf & Bowers, 1999, p 432)

Researchers have been looking for the causes from the very beginning, and after 1930s, researchers already agreed, or defined that dyslexia is an actual impairment with biological and neurological origins (Guardiola, 2001).

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[1] National Literacy Strategy (NLS) is a framework produced by the Government to assist and guide teachers to raise standards of literacy teaching.

[2] More information regarding to the formal diagnosis procedure of dyslexia in the UK is available from NHS website: http://www.nhs.uk/Conditions/Dyslexia/Pages/Diagnosis.aspx.

Researchers have been examining dyslexia from different perspectives, and have proposed hypotheses with different emphases, trying to find the reasons for the dyslexic's difficulties. If we wish to compare these different models of dyslexia, we need to first connect the various factors within in this framework. Morton and Frith (1995) created their 'causal modeling' framework within which dyslexia can be defined as a neuro-developmental disorder with a biological origin and behavioural signs (symptoms) which extend far beyond problems with written language. The framework involves three levels of description: behavioural, cognitive and biological. At the cognitive level, the cause of the behavioural symptoms can be specified and targeted on the underlying information-processing mechanisms; while at the biological level, causal factors may include genetic contributions and neuro-anatomical factors, which provide neurological explanations.

A number of theories of dyslexia have been proposed to date, with different focuses and varying degrees of overlap, and may be describing the same impairment with a consistent etiology but at different sensory, cognitive, and neurological levels, and as discussed earlier, it is difficult to apply one theory to all dyslexic individuals. Following Morton & Frith's framework, the review of theories of dyslexia will focus on clarifying the behavioural deficits and the cognitive explanation models.

1.2.1. Phonological deficit of dyslexia

A very well established body of evidence from longitudinal, experimental, intervention and cross-cultural research suggests that a range of phonological skill deficits are involved in the failure to learn to read (Savage, 2004). The phonological deficit theory of dyslexia proposes that people with dyslexia have a specific impairment in mental word representation and speech sound manipulation, which affect dyslexics' ability to deconstruct written words into spoken speech sounds, thus preventing dyslexics' word identification (Bryant & Bradley, 1985; Stanovich, 1988) (Fig. 1).

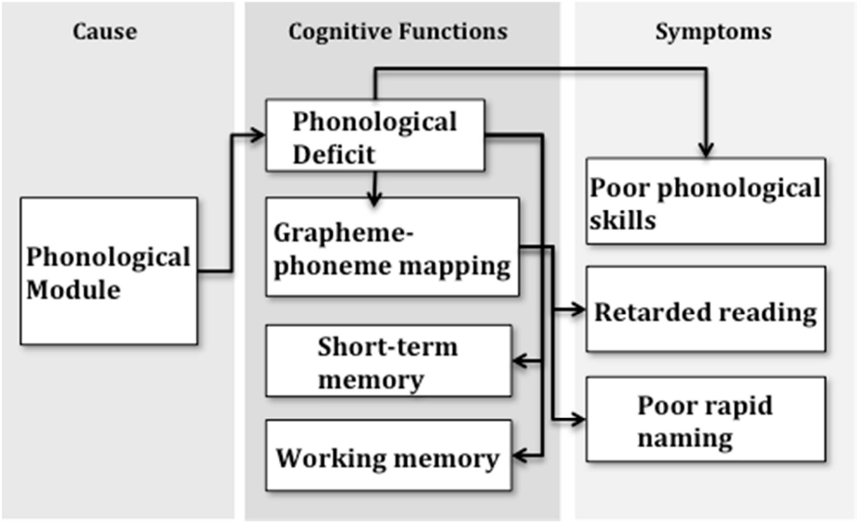


Figure 1 A causal analysis for phonological deficit theory

Although the difficulties of dyslexic people do not stop at single-word identification, phonological deficits have been recognized as a core deficit of dyslexic population. The phonological abilities of dyslexics have been investigated with a wide variety of tasks yielding abundant evidence that dyslexics have problems with phonological processing. More importantly, phonological-specific deficits have been found to be a good predictor of reading difficulties and consistent results have been found to suggest a causal relationship between a phonological-specific deficit and reading disability (Bradley & Bryant, 1978; Goswami & Bryant, 1990).

The relationship between phonological awareness and reading ability

In an alphabetic language, the learner has to find a way to decode the printed word into sounds they are familiar with as a spoken language, a skill that is referred to as alphabetic coding. The grapheme-speech connection requires the knowledge of the letter symbols and sensitivity to the organization of letters and written words awareness. However, someone who knows the letter 'p' but lacks the understanding that this letter both represents the first sound in 'pan' and the last sound in 'lip', will still not be able to establish a precise connection between the grapheme and speech sounds. The phonological skill for the beginning readers is thus crucial to gain knowledge of phonological structures of printed words about how to compose individual sounds and combine different sounds. Phonological awareness here has been defined as conscious access to the component sounds of speech within words and the ability to manipulate these sounds, which primarily involves the sound units of phonemes (Walton & Walton, 2002). The phoneme refers to the smallest segmental unit of sound (The International Phonetic Association), including onset (the opening consonant phoneme of a syllable), rime (or rhyme, from the first vowel to the end of a syllable), and sometimes the pitch of the syllable. However, a phoneme is generally regarded as an abstraction of a set of speech sounds, which is actually an idea in mind, which are perceived as mentally equivalent to each other in a specific language. For example, in English, the 'k' sounds in the word 'kit' and 'skill' are not identical acoustically, but they are mentally perceived as the same sound by English speakers, and are therefore both considered to represent a single phoneme 'k'. Typical measures of phonological awareness includes separating the syllables of a word, selecting words with the same rime or onset phoneme, counting the number of syllables or phonemes of a word, replacing part of a phoneme in a word with another phoneme, etc. For example, in a spoonerism test, two words 'kate' and 'lite' are orally presented to the participants, and they are required to swap the onset phonemes in two words, in this case the right answer should be 'late' and 'kite'.

In language systems, the letters in printed words present the sounds in spoken words in a regularly programmed manner (Treiman, 2000). For a successful reader, it is important for every printed word to be conceived as a sequence of phonemes, and phonological awareness is considered as a major cognitive prerequisite for the acquisition of the mappings between graphemes and phonemes, which provides the foundation of reading acquisition (Ramus & Szenkovits, 2008). Therefore the phonological decoding of single words is the earliest phase of reading.

What is behind the phonological processing deficit?

There are three main dimensions to the phonological deficit (Wagner & Torgesen, 1987): i) poor phonological awareness (as exemplified in phoneme deletion tasks); ii) poor verbal short-term memory (as exemplified in digit span repetition tasks); iii) low lexical retrieval (as exemplified in rapid automatic naming tasks). All three dimensions implicate phonological representations: the first dimension concerns conscious access to and explicit manipulation of the phonological representations; the second dimension refers to the short-term phonological storage, either briefly copied in phonological buffers, or actively recycling them between input and output sublexical representations; the third dimension involves the retrieval of lexical phonological representations from long-term memory (Ramus & Szenkovits, 2008).

Although the phonological deficit hypothesis could account for the above three main deficits observed with dyslexic people, it should be noted that it is a theory mainly at the cognitive level, and researchers have been looking for the underlying explanations for dyslexia's phonological impairment. However, the underlying biological origins of the phonological impairment are still conjectures, and researchers are still unable to map this cognitive phonological functioning in the brain (Slaughter, 2001). Within the phonological deficit hypothesis different models have been proposed with different emphases, but the basic assumption of all models is dyslexics' poor capability in constructing, maintaining, and retrieving phonological representations (Elbro, Nielsen, & Petersen, 1994; Goswami & Bryant, 1990; Ramus, 2001).

The two parts of phonological awareness, i.e., the ability to detect and process speech sound, depend upon the sensitivity of the phonemes and the ability to manipulate these phonemes (Mann, 1987). The sensitivity to different speech sounds relates to perceptual capability, which suggests an impairment in detection may lead to processing difficulties; the manipulation of phonemes is more on a cognitive level, which might be associated with a number of distinct processing subsystems or component skills, with potential candidates being general cognitive ability and verbal short-term memory (McBride-Chang, 1997).

Therefore, studies examining phonological deficit have typically focused on two areas: lower-level perceptual tasks involving the discrimination and categorization of speech sounds; and higher-level phonological processes, including both the phonological representation, and the short-term memory, speed retrieval and conscious manipulations involved in the phonological process.

Summary

The phonological core deficit hypothesis has been described as a 'near-complete' explanation of dyslexia (Fawcett & Nicolson, 1994), and has become a widely accepted theory in the last 20 years. The phonological deficit theory can account for dyslexics' impairments in short-term memory, long-term memory, item naming, verbal repetition and word recall, all of which are consistent with a deficiency in the use of phonological-based information, i.e., the problems with accurate and fluent recall of phonologically-coded items in memory (Rack, 1994). Studies have found rather consistent results for dyslexia's phonological deficit theory, and according to a study employing a large dyslexic sample (Ramus, Rosen, Dakin, Day, 2003), 100% of the dyslexic sample were found to show phonological impairments.

However, even if '100% of dyslexic individuals' can be found with their phonological ability affected, this would not constitute evidence of a causal relationship between a phonological deficit and dyslexia. Deficits do not definitely lead to dyslexia or permit dyslexics to be differentiated from other poor readers (Miles, Wheeler, & Haslum, 2003). In this case, the phonological deficit might indeed be the direct cause of the reading difficulties, but there might be another more 'fundamental' impairment of dyslexic individuals accounting for the phonological deficit and the consequent reading problems, and phonological deficit theory might be a description rather an explanation of dyslexia.

Moreover, this theory cannot account for all of the difficulties that dyslexic people have shown: it predicts dyslexia's impairments only with the phonological aspects of spelling, but makes no predictions about dyslexics' motor skill problems, like handwriting (Nicolson, 1996). Therefore, researchers have tried to identify other hypotheses to account for dyslexia, based on different brain regions, but for every hypothesis, the prior task is if it can explain the phonological deficit of dyslexia (Wimmer, 1993).

Another interesting point is whether phonological awareness can only account for the reading difficulties in alphabetic or more transparent languages?

Despite the different definitions of dyslexia in different language systems, knowledge of phonological structure plays a less important role in non-alphabetic languages (Wimmer, 1993) , instead, the grapheme-phoneme orthographic knowledge might be more essential for these logographic languages.

Does this mean that one type of reading disability is activated by non-alphabetic languages, and a second type of reading disability is activated by all languages? Genetic evidence provided supportive evidence that there are two independent sources of reading dysfunction, one related to phonological processing only and one related to lexical access, or naming speed only (Grigorenko et al., 2001): the 'double deficit' hypothesis (Wolf & Bowers, 1999; Wolf, Bowers, & Biddle, 2000), which might suggest an alternative to the phonological core deficit theory of dyslexia.

1.2.2. Rapid automatic naming and dyslexia

Phonological deficit theory focuses mainly on the reading accuracy at a word decoding level, however, research findings provide evidence that the measures of accuracy and fluency are independent from each other. Wolf and Bowers (1999) claimed that besides the core deficit in accuracy, there is a second core deficit in fluency, indexed in the linguistic domain by rapid automatic naming (RAN) speed, and they combined the deficits in reading accuracy (phonological deficit) and fluency (naming speed deficit), and proposed a double-deficit hypothesis of dyslexia, which represents an evolving, alternative conceptualization of reading disabilities (Fig. 2). In this account, three subtypes of impaired readers can be categorized under this hypothesis, characterized respectively by phonological deficits, naming speed deficits, and a combination of both. The people with double deficits may be more seriously impaired, compared to people with deficits solely in phonological processing (accuracy) or RAN (fluency) (Wolf & Bowers, 1999).

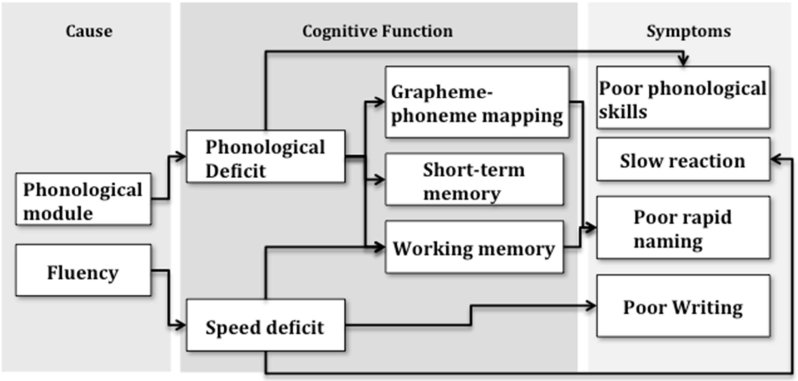
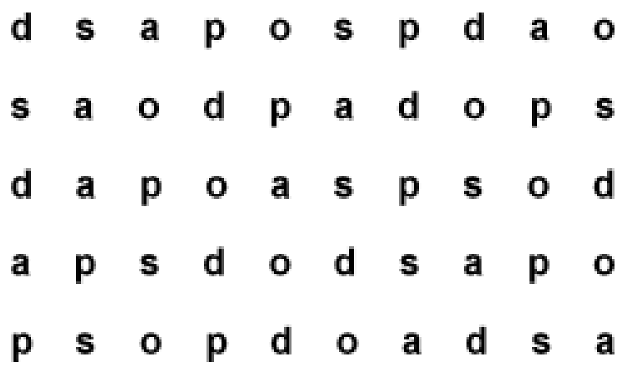


Figure 2 A causal analysis for double deficit hypothesis

Is RAN deficit distinct from phonological processing deficit

One critical premise for the double-deficit hypothesis is reading fluency (naming speed) being independent from reading accuracy (phonological processing), and not just a sub-process or the consequence of poor phonological decoding. Naming speed has been considered as an indicator of reading fluency (Wolf & Bowers, 1999), which is achieved when more efficient lower-level word recognition frees up memory capacity for higher-level reading comprehension (Fuchs, Fuchs, Hosp, & Jenkins, 2001).



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a	p	s	d	o	d	s	a	p	o
p	s	o	p	d	o	a	d	s	a

Figure 3 An example for the Rapid automatized naming (RAN) letters stimulus card

Impaired rapid naming of pictures, colors and numeric stimuli have been widely found impaired on people with reading difficulties (Badian, 1995; Bowers, Steffy, & Tate, 1988; Meyer, Wood, Hart, & Felton, 1998). The most popular measure of continuous rapid naming speed is the rapid automatized naming (RAN) test (Fig. 3), designed by Denckla (1972) and developed by Denckla and Rudel (1976). This test involves the rapid naming of a visual series of stimuli, consisting of different symbols in a given category (e.g., letters, numbers, colors, or objects) and the participants are asked to name these items one by one, as accurately and as fast as they can.

Researchers working within a phonological core deficit framework tend to subsume naming speed deficit as part of the phonological processing deficit found in dyslexia (Savage, 2004). For example, phonological processing deficits might require more resource for the retrieval of visual-phonological paired association, therefore more time is required to name a series of items (Neuhaus, Foorman, Francis, & Carlson, 2001; Wagner, Torgeson, Laughon, Simmons, &

Rashotte, 1993). The rapid naming does reflect an output phonological difficulty, however, such reason is not sufficient enough to categorize and subsume naming speed under phonology (Wolf, et al., 2000), and research evidence and theoretical accounts have been widely found to suggest that the naming speed deficits should be categorized separately from phonological deficits and considered as additional perceptual processing speed problems. This argument has been mainly supported by the evidence that the RAN and phonological awareness load are separate factors and make independent contribution to the variance in word identification, orthographic skill, fluent text reading, and comprehension (Blachman, 1984; Bowers & Swanson, 1991; Mann, 1984; Meyer, et al., 1998; Wimmer, 1993).

What causes the naming-speed deficit: the nature of rapid naming

The cognitive processing underlying the naming speed task is rather complex, it is thus important to clarify exactly which processing underlying RAN independently leads to reading difficulties aside from phonological deficits, since the phonological decoding apparently plays a role in RAN processing.

Wolf & Bowers (1999) argued that the rapid naming tasks approximate the repeated and speeded access to visual-phonological associations which require integration of:

"(a) attention to the letter stimulus; (b) bihemispheric, visual processes that are responsible for initial feature detection, visual discrimination, and letter and letter-pattern identification; (c) integration of visual feature and pattern

information with stored orthographic representations; (d) integration of visual information with stored phonological representations; (e) access and retrieval of phonological labels; (f) activation and integration of semantic and conceptual information; and (g) motoric activation leading to articulation." (p418)

Precise rapid timing is critical both for the efficiency of operations within each component and for integrating across them. Therefore, rapid naming speed has been characterized as a combination of a cluster of low- and high-level processing factors in appropriate temporal contiguity (Savage, 2004). In this sense, the rapid naming deficit might reflect a general problem with timing, processing speed, and the integration/coordination of cognitive and motoric sub-processes, which may be specific to reading.

Does the RAN deficit reflect a more general processing speed difficulty of dyslexia?

Farmer and Klein (1995) reviewed evidence suggesting that deficits may reflect underlying general impairment in ability to process sequences of rapidly presented brief information. This proposal was first made by Tallal (1984), who proposed a general temporal processing deficit of dyslexia. Dyslexics appear to have difficulty rapidly processing information unless it requires a name or a higher order judgment (Nicolson & Fawcett, 1994).

It is important to understand the influence of processing speed in the acquisition and performance of reading. Skilled reading requires word recognition that is rapid and fluent. For example, training studies that have demonstrated that practice in speeded recognition of orthographic patterns can lead to improved decoding ability (Frederiksen, Warren, & Rosebery, 1985; Gilbert, 2002).

As Wolf & Bowers argued, naming speed is both an index of dysfunction in lower level processes and also contributes to pervasive reading failure. In this scenario, deficits in naming speed can be conceptualized as one manifestation of a cascading system of more general processing speed deficits affecting visual, auditory, and possibly motoric domains, in addition to orthographic and phonological processing systems (Wolf & Bowers, 1999). This conjecture suggests a broader and more systematic timing deficit, which leads to a more generalized disruption in multiple processes with processing-speed requirements.

Another possible explanation of dyslexics' RAN deficits is that if the magnocellular system in the thalamic visual areas is aberrant, then the processing of lower spatial frequency components will be slowed, potentially leading to slower visual discriminations, slower letter-pattern identification, slower naming speed for serially presented visual stimuli, and delayed induction of orthographic patterns (Rice & Brooks, 2004). Slower naming speed in this scenario is viewed as an index of lower level problems that disrupt the smooth development of fluency in word identification and comprehension (Wolf & Bowers, 1999). This argument focuses on what occurs when the underlying rate of processing of orthographic representation is disrupted, and emphasizes the connections between processes underlying naming speed and automatic orthographic pattern recognition in word identification.

However, at a more general level, greater general processing speed is often associated with overall IQ (Cattell, 1963). The intelligence-independent reading difficulties of dyslexics may suggest it is not simply the general processing speed *per se* which is impaired in dyslexia, rather, fluently matching visual representations to phonological codes may require the integration of precisely-timed perceptual, attention and naming mechanisms. Therefore, theoretical reviews of naming speed automaticity have thus sought to bring together all the evidence on temporal processing, recognition and perceptual speed research and even research on phonological aspects of naming (Savage, 2004).

1.2.3. Motor proficiency and the automaticity of dyslexia

A universal feature of human behavior is that human cognition may comprise two different types of processing: controlled and automatic (James, 1890). A controlled process is “a temporary sequence of nodes activated under control of, and through attention by the subject” (Schneider & Shiffrin, 1977). In contrast, an automatic process is the activation of a sequence of nodes that “nearly always becomes active in response to a particular input configuration”, and that “is activated automatically without the necessity for active control or attention by the subject” (Schneider & Shiffrin, 1977).

Reading is a complex skill, and for fluent reading, it is necessary that both word-recognition and reading comprehension are automatic. Nicolson and Fawcett (1990) first proposed the automatization dysfunction hypothesis of dyslexia: the ‘Dyslexia Automatization Deficit’ (DAD) theory, which highlighted the impairment of general difficulties in motor control and skill automatization (Fig. 4). The DAD hypothesis proposes an explanation of dyslexics’ failure to automatize skills in word-recognition and other domains. Wolf & Katzir-Cohen (2001) defined automaticity in terms of processing speed (e.g. Wolf & Katzir-Cohen, 2001), however, automaticity seems to involve more processes than only speed, strategic or controlled processing, and Klein (2002) has suggested that independent evidence of automaticity might come from dual task studies.

The rationale for this was to impose the secondary task demands to remove any ‘conscious compensation’, which may mask subtle deficits in automatization skills by coping strategies and by active allocation of extra attentional resources. Nicolson and Fawcett demonstrate such an effect, as their dyslexic group was significantly impaired in the execution of motor skill tasks under dual-task but not single-task conditions. Research showed that no RT differences appear on single-task conditions at the most basic level of perceptual detection; rather, perceptual timing differences in dyslexic readers seem to occur when the integration of more than one set of sub-processes are required, thus cognitive sub-processes must be smoothly coordinated. The resulting threefold prediction that dyslexic performance breaks down primarily for resource-intensive tasks, is particularly susceptible to stress and can be maintained only for relatively short periods, is consistent with the available evidence (Nicolson & Fawcett, 1990).

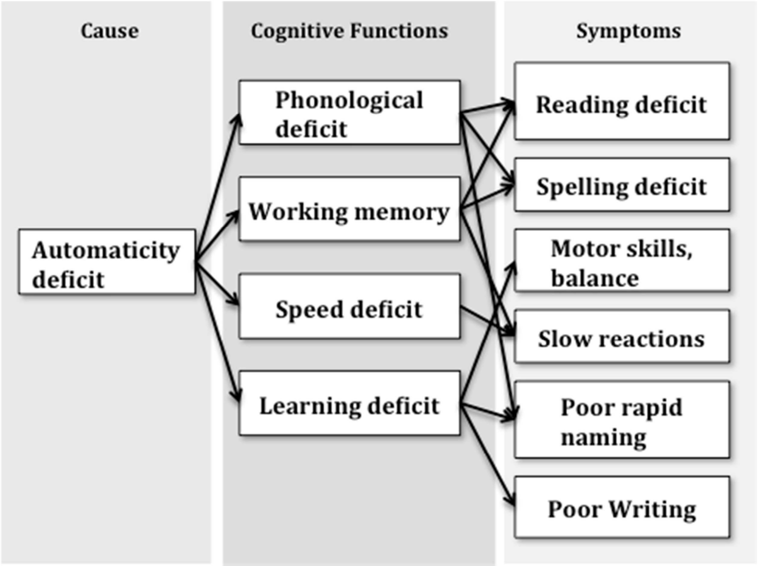

Figure 4 A causal analysis for automatization deficit

The DAD hypothesis can also explain dyslexics' observed deficits in writing, speaking and other motor language skills, because all these skills require precise timing and coordination of the muscles (Fawcett & Nicolson, 2001). Actually under the dual-task condition, dyslexics have been found to exhibit general motor deficits such as balancing on a beam with two feet or one foot, or beam walking (Nicolson & Fawcett, 1990). These motor tasks provide a good way to explore automaticity of dyslexics as these tasks are unlikely to share any processing elements with phonological processing which dyslexics are known to have difficulty (Savage, 2004).

The DAD hypothesis can be seen as the underlying mechanisms for the RAN deficit of dyslexics, and together with the phonological deficit hypothesis, is considered as the two components of the double hypothesis, which provide cognitive level explanations of the fluency and accuracy reading problem (Rice & Brooks, 2004). More interesting, the DAD hypothesis provides a cognitive explanation of dyslexics' difficulties in automatizing skills unrelated to reading thus explain the difficulties phonological or RAN hypothesis could not cover (Nicolson & Fawcett, 1990).

The cerebellar deficit hypothesis

Nicolson & Fawcett (2001) further proposed a cerebellar deficit hypothesis (CDH) for dyslexia, which provides an overall neurobiological explanation for dyslexics' observed behavioural symptoms in automatizing both cognitive and motor skills (Fig. 5).

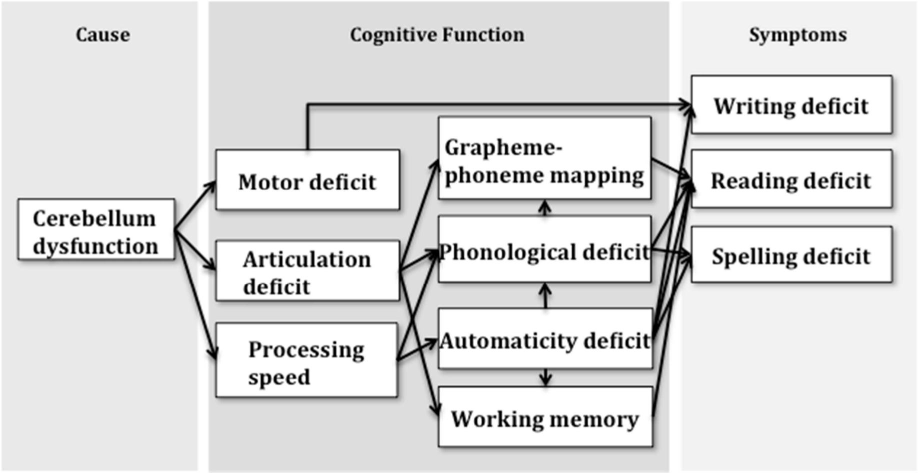

Figure 5 A causal analysis for cerebellar deficit hypothesis

The cerebellum, considered the "brain's autopilot" (Stein, 2001) is thought to be involved in linguistic as well as motor skill acquisition (Ito, 1993). Apart from motor control and coordination, cerebellar contributions to such diverse functions as language, emotions, abstract reasoning, sequence processing, and sequence learning have been proposed (Ivry & Keele, 1989). These abilities seem to play an important role in acquiring reading competency, especially in the automatization of letter recognition and elementary articulatory and auditory skills. The CDH has been supported by findings that dyslexic and non-dyslexic participants do not overlap on measures of cerebellar impairment (Beaton, 2002; Bishop, 2002; Rae et al., 2002), which could also predict dyslexics' difficulties in skill automatization, information process, and motor skills. More important, the cerebellar deficit hypothesis offers a potentially unifying framework for dyslexia, in that a cerebellar deficit can give rise to articulatory difficulties (leading to phonological problems), slowed central processing speed (leading to problems with reading rate), deficits in motor skills (leading to problems with handwriting) and reading skills deficits in consequence of impairments in learning new skills and automatizing those skills (Nicolson, et al., 2001).

Nicolson and Fawcett have proposed two mechanisms by which the cerebellum may play a role in dyslexia. One route is related to the motor theory of speech perception, which suggests recognition of the phonological units of words is based upon inferring the corresponding articulatory gestures (such as tongue, mouth movement, etc.). Cerebellar dysfunction leads to mild motor problems in the infant, which lead to articulation difficulties. Poor quality articulatory representations lead to impaired sensitivity to the phonemic structure of language and to reduced phonological awareness. In addition, decreased articulation speed can reduce verbal short-term/working memory functioning, as subvocal rehearsal is important in keeping memory traces in the store. Reduced verbal working memory functioning may cause difficulties with language acquisition. The other route is related to processing speed. Cerebellar dysfunction may lead to reduced processing speed, which would affect cognitive functioning on a more global scale than merely producing deficits in phonological processing. Based upon these two routes, the cerebellar deficit hypothesis attempts to explain the phonological deficit hypothesis and the double deficit hypothesis. The oral-motor difficulties lead to deficits in phonological awareness whereas the processing speed deficits lead to difficulties with rapid naming. The cerebellum in particular may be involved with rapid naming given its role in speech, inner speech, and speeded processing.

However, there is inconsistent support for Nicolson & Fawcett's cerebellar hypothesis (Ramus, et al., 2003; Wimmer, Mayringer, & Landerl, 1998). Wimmer et al. (Wimmer, et al., 1998) suggested that the reason for the motoric problems found in dyslexics might have to do with the presence of attention deficit hyperactivity disorder (ADHD) in some dyslexic children. There is evidence for motor problems in ADHD, and there is a high degree of co-morbidity between dyslexia and ADHD (Ramus, et al., 2003). Wimmer et al. (1998) hypothesized that automaticity impairments might be found only in such co-morbid individuals by showing balance problems only in dyslexic/ADHD comorbid children, not in pure dyslexics (Wimmer, Mayringer, & Raberger, 1999). However, it is likely that German speaking dyslexics, as used in Wimmer et al's study, are different from English dyslexics, because German dyslexics show only rate but not accuracy deficits (Fawcett & Nicolson, 2001).

On the other hand, assuming the findings of a cerebellar dysfunction in dyslexia are reliable, it is still unclear whether cerebellar abnormalities are causes or correlates of dyslexia (Ramus, 2003; Savage, 2004), and even if cerebellar abnormalities are found to cause reading difficulties for some dyslexic individuals, they might not explain every case of reading difficulty and reflect a sampling effect. In other words, the CDH has not yet been shown to be a unifying theory of dyslexia and may only apply to a subgroup of dyslexia.

1.3. Implicit learning deficit in dyslexia

The reason researchers started to use the implicit paradigm with the dyslexia population is because of a conceptual problem with Nicolson & Fawcett's DAD account. This is the lack of a clear definition or cognitive explanation for conscious compensation, specifically why conscious compensation does not extend to dyslexic people's literacy difficulties. Savage (2004) also notes that a specific methodological problem with dual-task studies is that the requirement for integration of responses may cause problems in central resource allocation rather than automaticity of learning, per se. Achieving an unbiased measure of automaticity is important, as "the DAD model is potentially falsifiable by any example of skill automaticity in dyslexic children" (Savage, 2004, p314). One possible alternative to the dual task approach, which offers a purer measure of automaticity, is to examine implicit acquisition of skilled action. It may also remove concerns over confounding effects of co-morbidity of attentional deficits (Wimmer, et al., 1999) as implicit sequence learning is thought to be an automatic associative process that does not rely on attentional resources (Jimenez & Mendez, 1999).

Kelly, Griffiths and Frith (2002) examined skill-learning ability with an implicit sequence learning task with the assumption that if no sequence contingencies were to be explicitly learned then individuals would be unable to use any conscious compensation strategy. No learning deficit for the dyslexic group was found suggesting that earlier dual-task studies may have introduced unintended confounds, questioning Nicolson and Fawcett's conclusion that automatization was impaired in dyslexia. However, subsequent studies on implicit learning in dyslexia have yielded inconsistent results (Sperling, Lu, & Manis, 2004; Stoodley, Harrison, & Stein, 2006; Stoodley, Ray, Jack, & Stein, 2008; Vicari et al., 2005; Vicari, Marotta, Menghini, Molinari, & Petrosini, 2003).

1.3.1. Some conceptual questions of implicit learning

Implicit learning conceptually refers to learning without consciousness, when we learn new information without intending to do so (Berry & Dienes, 1993; Cleeremans, Destrebecqz, & Boyer, 1998). Learning can be described as implicit in several different ways according to whether one focuses on the acquisition processes, on the knowledge resulting from these processes, or on the retrieval processes. Some researchers (Berry & Dienes, 1993; Cleeremans, 1993b) believe that implicit learning happens when people acquire new information without intending to do so, hence in such a way that the resulting knowledge is difficult to express, suggesting it is difficult for people to intentionally express their implicitly gained knowledge, and consequently making it difficult to measure the implicitly learnt knowledge.

By this definition, implicit learning thus contrasts strongly with explicit learning (e.g., as when learning how to solve a problem), which is typically hypothesis-driven and hence requires explicit efforts. However, it is still difficult to demonstrate the difference between implicit and explicit learning through either the learning process or the resulting knowledge. Researchers have mainly focused on attempting to establish functional dissociations between implicit and explicit learning by manipulating factors such as intention to learn or the availability of attentional resources during learning (e.g., by means of a secondary task). These functional approaches raise the issue of whether implicit learning should be characterized as a distinct process of learning that relies on separable memory and processing systems from explicit process.

However, this is not the focus for the current thesis which is concerned with the learning capability of those with dyslexia under implicit conditions, and examination of the potentially different cognitive processes under which learning occurs. More specifically, it examines dyslexics' learning performance under different learning conditions, if dyslexics show similar learning profile as control group, and how dyslexics' implicit learning performance is related to their reading skills, cognitive abilities, and attention problems.

Another issue concerns the difference between automaticity and implicit learning. The development of automatic knowledge does not causally overlap with implicit learning. Automatic knowledge might arise from explicit procedures, by practicing over and over again, until the required performance could be applied without attention any more (e.g., learning to swim or cycle) (Pothos & Kirk., 2004). In other words, automaticity includes both learning and expression of the knowledge/skills. Therefore, automatization deficit will not definitely lead to implicit learning problem; in other words, a deficit in automatization may lead to either expression problem, or learning problem, or both.

1.3.2. Why implicit learning

As discussed earlier, the reason for researchers to investigate dyslexics' implicit learning capability is because the implicit paradigm could provide a rather pure automatic learning condition which is an alternative way for the dual-task paradigm to test the DAD hypothesis for dyslexia. Actually, implicit learning plays a more important role in people's language acquisition, and the role of implicit learning has been well studied in the domain of reading acquisition. In fact, many reading skills, including automatic grapheme-phoneme recognition, skilled grammatical processing, and the formation of basic meaning proposition units for reading comprehension would only emerge as an outcome of implicit learning (Grabe, 2010). Implicit learning involves learning processing skills and language knowledge without being aware of attending to the specific information, and implicit learning can only come about through extended periods of exposure and meaningful time on task (Ellis, 2005).

Reading is a learnt skill

Although the difficulty of providing an accurate and encompassing definition of dyslexia has been acknowledged earlier, the core concept of dyslexia reflects some problem in learning to read. There are two main types of learning: declarative, and procedural learning. Declarative learning is the acquisition of facts, which is language-based learning, and declarative knowledge could be learnt by taught and not necessarily physically present; in contrast, procedural learning is the acquisition of skills, or knowledge regarding how to perform tasks, like learning to walk, talk, swim, etc. (Seidler & Ashe, 2008). Anderson (1982) proposed a three-stage model for skill learning: declarative, procedural, and autonomous. In his opinion, human learning starts from a task with clear instructions, learning the procedural skills; eventually the skills could be conducted better over practice and independent from attention or working memory.

However, learning to read starts during infanthood and Goswami and Bryant (1990) proposed three key skills which are important for learning to read: preschool phonological skills provide children the initial word attack skills; learning of the alphabetic script provides the basis for analyzing the sounds of a word into phonemes, which also underlies the ability to spell words alphabetically; and reading and spelling skills which provide more specific orthographic rules.

Goswami and Bryant's argument focuses on the word reading level, while there may be other skills required for more skillful reading. For example, Rayner and Pollartsek (1989) using measures of eye-tracking, found that for fluent reading, the eye-span of the reading materials must be ahead of the phonemic translation of the printed words. Therefore, they claimed that skilled readers must be capable of using nonphonemic route for reading, and have highly developed skills to read without subarticulating. Nicolson an Fawcett (2008) further argued that children may start to read by articulating each letter independently (/c/-/a/-/t/, that's cat), and then their reading becomes more on a whole-syllable or whole-word, but still with overt articulation; next, the children find it is not necessary to use overt articulation for reading, and they can use 'inner speech', thereby gaining access to the phonological loop more directly and efficiently. Finally, a fluent reader could read by purely visual processing, and the procedure has become internalized with direct access from the graphemic code to the semantic lexical entry (p52).

Schneider and Shiffrin (1977) highlighted two different kinds of cognitive processing, one is controlled processing, which requires attentional control and working memory capacity; the other is automatic processing, which was learned in long-term memory, and could be operated independently from control or working memory resources. Thus for skilled readers, it is important to automatically process the reading materials, by practicing reading over time.

Implicit learning, phonological processing and fluent reading

The assumption that all native speakers of a language have an intuitive knowledge has been the touchstone of linguistic methodology for several decades. The implicit learning process may even be pre-natal, with infants attuning to the speech patterns of their native language (Hepper, Scott, & Shahidullah, 1993). It is argued that before children can become explicitly aware of the phonological segments and explicitly learn the phonological-orthography correspondences, they must implicitly develop the knowledge of global phonological characteristics corresponding to syllables, onsets and rimes (Goswami & Bryant, 1990). Therefore implicit learning allows the child to develop considerable language knowledge and implicit phonological representation about their language. Gombert (2003) suggests that dyslexia prevents implicit learning of linguistic regularities while Sperling, Lu and Manis (2004) argue that impaired implicit learning interferes with the construction of grapheme-phoneme representations, phonological processing and even the application of rules that are necessary to successfully implement these abilities.

Implicit learning is also central for reading comprehension and reading fluency and underlies the reutilization of common default strategies by skilled readers without realizing that they are using these strategies (Grabe, 2009). Because of its role in procedural learning and automatic processing, implicit learning most strongly supports and develops discourse-structure knowledge, main-idea recognition, and so on by the gradual routinizing of common strategy applications over time.

When we learn to read, we utilize implicit learning by the extensive repetitive inputs from reading, e.g., skipping a word, rereading a previous sentence, refreshing a main idea, forming inferences. Knowledge gained by implicit learning is gradually developed based on repetition of form and process over a long period of time. This is why reading fluency skills are connected to the pedagogical importance of extensive reading, reading rate practice, and text rereading and recycling as learning activities for reading development (Grabe, 2010).

1.3.3. Empirical paradigms and methodological issues of implicit learning

Empirical experimental paradigms

There are various paradigms for implicit learning, and two essential experimental paradigms of implicit learning will be discussed here: artificial grammar learning, and sequence learning (Cleeremans, et al., 1998; Russeler, Gerth, & Munte., 2006).

Artificial Grammar Learning Task

The first experimental paradigm of implicit learning was developed by Reber (1965). In his famous Artificial Grammar Learning task, a complex finite state language is created to specify a set of continuation relations among symbols (e.g., Fig. 6), including beginning and end states. Any symbol strings which follow the rules of the finite state language are grammatical (G) and the strings which are inconsistent to the language are ungrammatical (NG). In the training phase, participants are presented with a series of the G strings (such as VJTXXVT) without knowing the rule about how the strings were generated or about the test phase. In a following test phase, the participants are told that the training items were generated by a complex set of rules and that they would have to discriminate between novel G and NG items with no feedback. Research shows that participants can discriminate between G and NG sequences with above-chance accuracy without expressing the knowledge of the rule, which suggest they have gained the grammar knowledge (Reber, 1967).

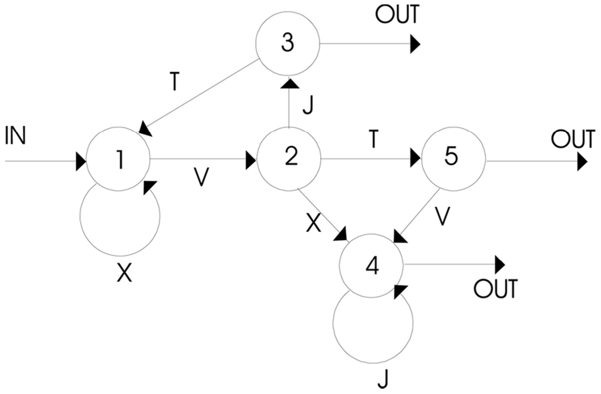

Figure 6 An example of an artificial finite grammar

From a statistical view, G strings are typically fewer than NG ones, as not all transitions between states of a finite state grammar are possible (Miller, 1958). Participants consistently favor the G items in test, so they are more sensitive to the regularity in the G items relative to the NG ones. Plus, the test G sequences are usually different from training ones, thus it is usually considered that it is the complex grammar participants have learnt. However, what has been learnt in the AGL task is a complicated topic as the above-chance judgment can related to not only the grammar rules, but also the repeated chunks between the training and testing strings (more details of the AGL paradigm will be discussed in Chapter Two).

Serial Reaction Time Task

Another well-researched implicit learning task is the Serial Response Time (SRT) task (Nissen & Bullemer, 1987). In a classic SRT task, participants were presented with a series of stimuli at four spatial locations (four digits 1, 2, 3, and 4 can be used to refer to the four different locations) on a computer screen and made reaction-timed key presses to stimulus locations (Fig. 7). The stimuli followed a repeating sequence of spatial locations, though participants were not informed of this (e.g., a sequence like 143241243123). After several training blocks, the stimuli was changed to be presented randomly and the reaction-time decrement to respond to the randomly presented stimuli was taken as an index of the amount of learning that had occurred, presumably outside of conscious awareness.

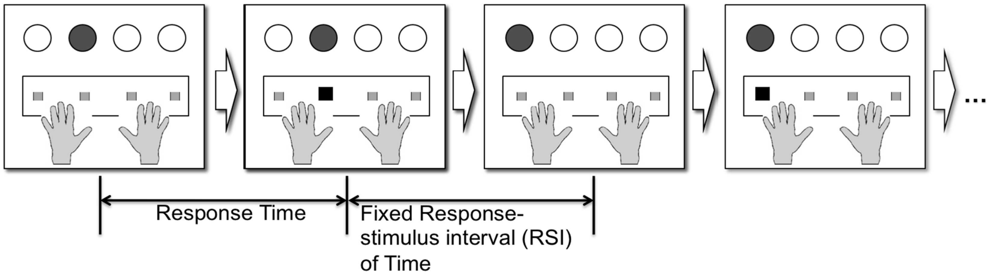

Figure 7 Schematic summary of the serial reaction time task (SRT) task

The sequence used in an SRT task can be either probabilistic or deterministic. Cleeremans & McClelland (1991) used sequences generated by a finite state language with an SRT paradigm, and found that the complex finite-state grammar information could also be learnt by unaware participants by improved RTs. In this task, participants were required to press one of the six keys corresponding to six different locations on the screen as quickly and as accurately as possible. Unknown to the participants, the stimuli were generated from a finite-state grammar, which is more complicated than normal deterministic sequence. The results showed that with 60,000 trials training, participants demonstrated significant sensitivity to the grammatical information. This result further suggests that complex information, such as the rule like finite-state grammar could also be learnt within an SRT paradigm.

Both of the AGL and SRT tasks test associative implicit learning, i.e., knowledge of the co-occurrence between individual stimuli. There are also several differences between the AGL and the SRT task, however. First, the different cognitive perceptual demands of the stimulus inputs: in an SRT task, sequential stimuli are presented one by one across time; while in an AGL task, participants see strings of letters and are expected to learn the rules underlying the letter strings. Secondly, the involvement of the motor system: SRT task is an automatic motoric procedural learning task, which requires the activation of memory for sequences and a motor response to each stimulus; while in an AGL task, only visual observation of the stimuli is required during the learning process.

A third difference between the two tasks is the measurements used: participants in the AGL task made subjective judgments, while in the SRT task, the learning is measured by objective RTs difference participants' responses to sequential and random stimuli.

Methodological issues

One key issue about these implicit learning paradigms is to what extent the learning is implicit or explicit. No task is purely implicit (Cleeremans, 1993b), and there are various methods to minimize participants' explicit contribution to the learning in the tasks and to test participants' explicit knowledge to their performance in the implicit learning test. Several methods will be discussed here. If no implicit learning task is purely implicit, is there any method to make the learning 'more implicit', or to examine to what extent the learning participants have showed could be accounted for by implicit learning? This issue is even more important for studies of the dyslexic population, who may be expected to be impaired under implicit but not explicit conditions, because the explicit compensation could probably cover any implicit impairment.

Recognition Test: direct test of the structural knowledge

An indirect test, such as the judgment test in the AGL paradigm, is assumed to have no reference to the explicit knowledge. In contrast, direct measures, such as recognition or recall test, involve tests in which the instructions make objective explicit instructions. For example, in a recognition test in the SRT paradigm, after finishing the task, participants are told the locations of the stimuli they saw earlier actually followed a repeated sequence, and they are asked to judge if the sequences they are going to see are the same as what they saw before or not. By assumption, direct tests should be dominated by conscious knowledge, thus the learning performance shown in the recognition test is usually considered as the explicit knowledge participants gained. However, because implicit knowledge can possibly affect participants' performance in the direct tests, and implicitly learnt knowledge can be possibly accessed explicitly, we cannot claim the learning performance shown is purely, or definitely conscious knowledge, this is the contamination problem (Cleeremans, 2002).

Confidence Rate: the Zero-correlation Criterion

Researchers also developed other methods to test to what extent the participants' judgment in the AGL test is unconscious. Dienes et al. (Dienes, Altmann, Gao, & Goode, 1995) proposed a zero-correlation criterion for the unconscious knowledge in the AGL task, which suggests taking a confidence rating after every. Dienes et al. argued that only when participants' judgments in the AGL task are above baseline but the person believes they are guessing or their confidence of their judgment does not relate to their accuracy is the evidence of unconscious knowledge.

In Dienes' zero-correlation paradigm, in an AGL task, after the training phase with some letter strings generated by a finite grammar, participants were then told about the rules underlying the letter strings, and were asked to discriminate novel letter strings that did or did not obey these rules, in addition, a confidence rating was made for every judgment. Dienes claimed that the zero-correlation between the confidence rate and the accuracy shows whether or not the participant is aware of knowing the content of the judgment, but unlike the direct awareness test, this correlation does not show whether the person is aware of what knowledge enabled the judgment. Thus, a distinction is made between judgment and structural knowledge, and it is shown how the conscious status of the latter can also be assessed.

Dienes' confidence rating test can be also used in the recognition test, to provide extra information about based on what knowledge participants make judgment about the discrimination results in the recognition tests.

Process-dissociation procedure (PDP): the difference between inclusion and exclusion

Destrebecqz and Cleeremans (2001) developed a test to control participants' use of their implicit/explicit knowledge. In their study, after participants completed an SRT test, they were asked to generate a sequence under two different conditions. In the inclusion condition, participants were asked to generate the same sequence they had been trained as far as they could; in the exclusion condition, the participants had to make sure they did not generate the sequence they had been trained. The assumption for this inclusion/exclusion generation task is that in the inclusion condition, both conscious and unconscious knowledge would affect participants' performance; while in the exclusion condition, only the explicit knowledge would be avoided. The different performance (usually measured as the proportion of legal bigrams and triplets) between the two conditions can be considered as the explicit knowledge. The interesting finding was that under the exclusion condition, when people were trying not to generate the sequence, the participants still generated the sequence at above baseline levels. Because the explicit knowledge of the sequence should lead to below-chance performance under the exclusion condition, Destrebecqz and Cleeremans concluded the above-chance exclusion performance is evidence for unconscious knowledge.

Further, they showed that above baseline exclusion was associated with rapid trials; when subjects could take their time, subjects excluded more effectively. With slow trials, there was a clear difference between the extent to which the sequence was generated in inclusion and exclusion. The latter results suggest that conscious knowledge takes time to apply.

The use of shorter inter stimulus interval (ISI)

Cleeremans at al. in 2003 used different RSI (response-to-stimulus interval) (0ms, 250ms, 1500ms) in an SRT task, and suggested that the time available for processing each stimulus in the SRT task is critical in determining to extent to which sequence knowledge is available, e.g., the longer RSI provided, the more explicit knowledge is gained, so the sequence learning in SRT shall be 'nearly purely implicit' when RSI is reduced to 0ms.

The use of more complex information

Because of the side-effect of the distraction task discussed, it might be worth thinking about using more complex information to learn to simply prevent the potential explicit learning. If more complex information can to some extent avoid explicit learning, the interference made by a secondary task shall be smaller than the task obtained with simpler sequence, and this hypothesis has been sustained by studies which showed that the effect of a dual task was indeed smaller when the sequences were probabilistic rather than deterministic (e.g., Cleeremans & Jimenez, 1998; Jimenez & Mendez, 1999; Schvaneveldt & Gomez, 1998).

1.3.4. Previous studies on dyslexics' implicit learning capability

Compared to the vast literature available on implicit learning in typical population, only a few studies have looked at the effects on dyslexia. Kelly, Griffiths and Frith (2002) examined dyslexics' implicit learning ability by using an adapted version of the SRT task, and found intact sequence learning of dyslexic participants. After Kelly et al.'s study (2002), with the same SRT paradigm, Vicari et al. (Vicari, et al., 2005; Vicari, et al., 2003), Howard et al. (Bennett, Romano, Howard, & Howard, 2008; Howard Jr., Howard, Japikse, & Eden., 2006), and Stoodley et al. (Stoodley, et al., 2006; Stoodley, et al., 2008) drew a contrasting conclusion to Kelly et al. (2002) and demonstrated the presence of a specific implicit learning deficit in dyslexic participants; while two other studies found no difference between a dyslexic population and control group (Russeler, et al., 2006; Waber et al., 2003). Two neurological studies also found supportive evidence that an implicit sequence learning deficit in dyslexia is associated with a level of activation in higher cerebellar and parietal regions (Menghini, Hagberg, Caltagirone, Petrosini, & Vicari, 2006; Menghini et al., 2008).

Examining learning in other implicit learning tasks, no deficit was found on an artificial grammar task (Pothos & Kirk., 2004; Russeler, et al., 2006), or cued reaction time task (Roodenrys & Dunn, 2007) but a deficit was shown in an implicit categorical task (Sperling, et al., 2004) and a mirror drawing task (Vicari, et al., 2005). However, also with the AGL tasks, Pavlidou et al. found dyslexic children were impaired in only implicit abstract learning with three studies (Pavlidou, Kelly, & Williams, 2010; Pavlidou & Williams, 2010; Pavlidou, Williams, & Kelly, 2009).

The above limited studies on dyslexia's implicit learning lead to controversial results, with several conceptual and methodological issues to be addressed, and thus in order to clarify if dyslexics may have an implicit learning deficit in general, or just certain tasks requiring specific cognitive processing, a careful discussion will be conducted regarding to the effects of different tasks requirements, the complexity of the stimuli, and contribution of explicit knowledge in these previous studies upon dyslexic people's implicit learning capacity.

Motor slowness

Several key points become apparent in dyslexics' varied perceptual and motoric speed impairments. As noted by Nicolson & Fawcett (1994), and Wolf & Bowers (1999), dyslexics have been found to be generally slower than normal people in motoric and perceptual (auditory and visual) task. Are studies investigating sequence learning among dyslexic population specifically related to impaired motoric sequence processes?

It is important to clarify the difference between motor performance and motor skill learning. Motor performance refers to people's ability to execute a motor task measured with accuracy and RTs performance. Motor skill learning refers to people's ability to improve the motor performance with practice to the specific information (Willingham, 1997). In the previous studies with the SRT tasks on dyslexics, dyslexic participants indeed showed slower RTs (Howard Jr., et al., 2006; Kelly, et al., 2002; Russeler, et al., 2006; Vicari, et al., 2005; Vicari, et al., 2003; Waber, et al., 2003), but dyslexic participants did not show impaired learning performance (measured by the improved RTs performance) in all of the above studies (Kelly, et al., 2002; Russeler, et al., 2006; Waber, et al., 2003).

On the other hand, with the non-motoric AGL paradigm, three studies found impairment with dyslexic children (Pavlidou, et al., 2010; Pavlidou & Williams, 2010; Pavlidou, et al., 2009). There is no motoric processing involved in these tasks, which may suggest although dyslexics' slower response may affect their general RTs performance in the SRT task, this is not the key reason underlying their potential implicit learning performance in the previous studies.

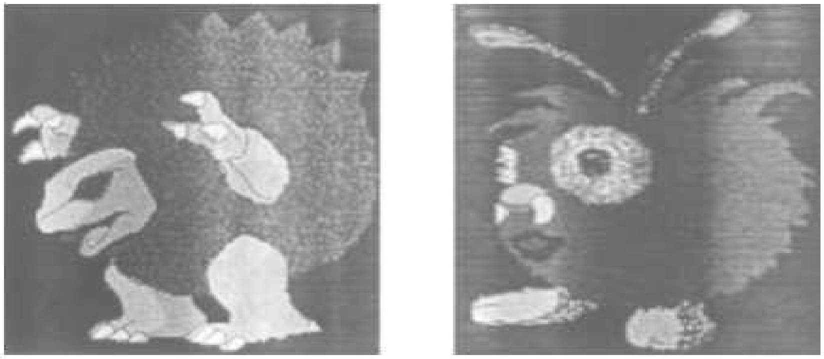

Figure 8 An example of the stimulus used in Kelly et al.'s study (2002)

However, another issue arises pertaining to the representational changes occurring during learning. Is the sequence learning of dyslexics related to the acquisition and retrieval of effector-specific or effector-independent representations of the sequence? In the study by Kelly, Griffiths and Frith

(2002), they further examined implicit motor sequence learning in a single SRT task by independently examining the contribution of stimulus-based and response-based learning. That task replicated Mayr's (Mayr, 1996) methodology in the SRT task by exposing participants to two structured displays, simultaneously. Participants in that task were required to press the corresponding key to a certain target in different visual shapes (two examples as shown in Fig. 8); at the same time, the targets were presented at the different four locations on the screen. Mayr's results showed that participants could learn both of the sequences of the different targets (the finger press, i.e., the motoric sequence), as well as the sequence of the locations (i.e., the spatial sequence). Using this task, motor/spatial and perceptual sequence information were uncorrelated and no deficit was found for either sequence with adult dyslexic participants. This suggested that both spatial and perceptual sequence learning is intact in dyslexia and that explicit, attentional processes, which would be under resource pressure to follow two concurrent sequences, do not play a role in sequence learning in either dyslexic or typically developing participants.

In another study (Bennett, et al., 2008), a triplet frequency learning task (TRIP) with the SRT paradigm was used which involved learning a sequential regularity in which the location of certain events followed a repeating pattern, but finger press responses did not follow the pattern but only made a response to a certain color of the target event. Although a positive correlation was found between individual sequence learning scores and reading ability, no between-group differences was found in pattern learning. The above two studies indicate that if reduced implicit sequence learning is found in dyslexics, that cannot be entirely accounted for by motor deficits.

Attentional deficit

Another reason which may also be relevant to dyslexics' implicit learning performance is difficulties with attention disengagement. Dyslexics have been found to have problems in shifting their attention in response to the presence of peripheral cues relative to controls and in maintaining their attention on a target, so that the target was presumably processed less adequately (Facoetti & Molteni, 2001). It is also suggested that dyslexic individuals have difficulty with the disengagement of attention once their attention is engaged (Hari & Renvall, 2001). In other words, dyslexics have problems in shifting their attention between different targets. Such attentional problems have been linked to poor reading attainment (Brannan & Williams, 1987; Morris & Rayner, 1991).

Many studies (Chun & Jiang, 1998; Hsiao & Reber, 1998; Jimenez & Mendez, 1999) provided evidence that selective attention to the relevant stimuli is required for implicit learning. The attentional problem of dyslexia has led researchers to consider dyslexics' implicit learning capacity associating to attentional deficits. Pothos and Kirk (2004) proposed that the inability to shift attention rapidly enough or to focus attention on the same target long enough may make it difficult for dyslexic people to attend to constituent element information and so they might develop processing biases against doing so generally. Furthermore, they proposed that dyslexic people may be impaired in processing the constituent elements of stimuli and thus affect their implicit learning performance in the tasks. To investigate their hypothesis, Pothos & Kirk (2004) examined if dyslexics' implicit artificial learning incapacity may actually reflect a perceptual problem, or in other words, reflect their different way to perceive the learning stimuli.

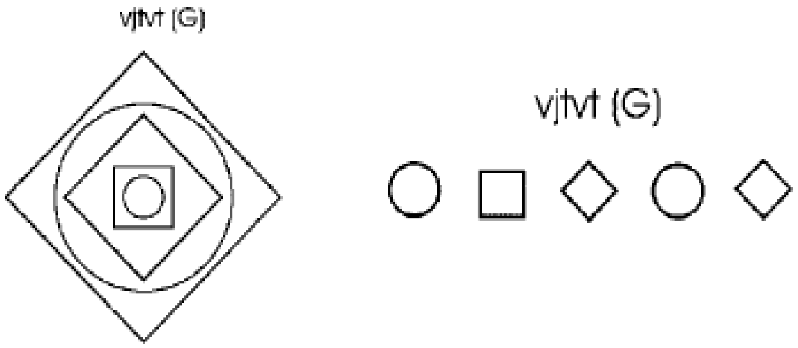

Figure 9 An Example of the stimuli used that are referred to as 'sequences of shapes' of 'embedded stimuli' (left) and the 'sequence stimuli' (right), with the corresponding letters referring to the grammatical strings 'vjtvt'.

Two AGL tasks were used in Pothos & Kirk's study. The first encouraged participants to perceive each stimulus as a whole, with less emphasis on the stimulus constituent elements (the 'embedded' stimuli), while in the second task the constituent elements of each stimulus were emphasized by presenting them serially (the 'sequences' stimuli) (see Fig. 9 above). Using a between-participants design, dyslexic participants performed equally well in the two versions of the learning task. By contrast, non-dyslexic participants performed as well as dyslexic ones only with the embedded stimuli but were impaired in the sequences stimuli. Pothos and Kirk offered an interesting interpretation of their findings, as the different stimulus format did not make a difference in dyslexics' AGL performance, but indeed affected non-dyslexic participants' performance. Their assumptions are that dyslexic participants' learning in both conditions would be primarily implicit. By contrast, non-dyslexic participants' learning with the embedded stimuli would be primarily explicit, however, with the sequences stimuli a mixture of implicit learning and explicit efforts were used to understand the stimuli, and the impaired learning in the sequence stimulus condition of non-dyslexic participants is due to the implicitly acquiring knowledge in the AGL can be impeded by explicit efforts.

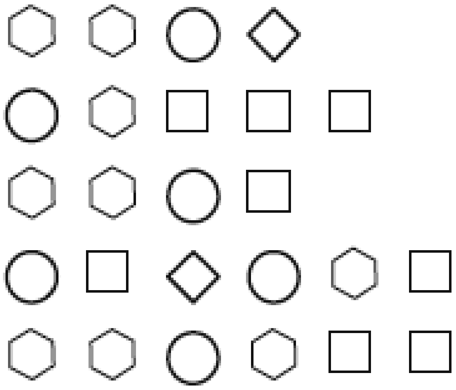

Figure 10 Some examples of the training strings used in Pavlidou et al.'s study (2009)

It was surprising that the non-dyslexic participants in Pothos & Kirk's study (2004) did not show learning for the sequence stimulus, as in a series of later studies, with very identical AGL tasks (see Fig. 10 above), Pavlidou and her colleagues (Pavlidou, et al., 2010; Pavlidou & Williams, 2010; Pavlidou, et al., 2009) also used the same shapes to replace the letters in the original AGL task and found intact implicit learning with their non-dyslexic children. However, Pothos & Kirk's interpretation may still make sense with Pavlidou's studies, as the children participants in Pavlidou's studies may fail to use explicit learning strategies to process the learning materials in a similar way to the adult participants in Pothos & Kirk's study.

Pothos & Kirk further claimed that the dyslexic participants are impaired in processing individual learning stimulus, and thus limit the development of knowledge that depends on these individual elements. Their dyslexic participants in both conditions and non-dyslexic participants in the embedded task condition perceived stimuli as wholes, with less emphasis on the constituent elements of the stimuli. By contrast, non-dyslexic participants in the sequences condition perceived stimuli primarily in terms of the individual elements of each stimulus, so that the explicit efforts to understand the structure of the stimuli inhibited learning.

Research Question One: Do dyslexics show impaired implicit learning when the attentional resource is limited?

Although Pothos & Kirk's study did not provide direct evidence of their proposal, their study provided an interesting perspective into the attentional problem of dyslexics when looking at their different performance in implicit learning tasks. Pothos & Kirk's study (2004) focused mainly on dyslexics' incapacity to shift attention between different individual elements at a visual perceptual level. However, attention plays a complicated role in implicit learning: different implicit learning tasks appear to require different amounts of attention and may involve different attentional subsystems (Goschke, 1997). It will therefore be important to go beyond unitary constructs such as 'attentional resource' or unspecific 'processing capacity' and to explicitly examine the mechanisms underlying dyslexics' implicit learning capacity on the basis of detailed task analyses. This research question will be discussed and investigated by Study V in Chapter Four.

Processing speed deficit

As discussed earlier, the RAN deficit observed in dyslexia might suggest a general processing speed deficit of dyslexia (Wolf & Bowers, 1999). From a more general perspective, slower cognitive processing speed may cause a variety of memory, problem-solving, reasoning, and learning problems (Willingham, 1997).

Given the broad nature of processing speed as a parameter, one might expect it to be related to individual differences in implicit learning, even in the absence of implicit learning's association with more complex cognitive mechanisms (Kaufman et al., 2010). There is a significant relation between processing speed and implicit learning (Kaufman, et al., 2010; Salthouse, McGuthry, & Hambrick, 1999). Processing speed could play an important role in implicit learning and memory through the acquisition of lexicalized procedural skills, as it does in other procedural skill learning domains (Ackerman, 1989; Underwood & Batt, 1996). For example, training studies that have demonstrated that using speeded practice as part of an intervention can lead to improved implicit decoding ability (Gilbert, 2002).

Salthouse (1996) has proposed the mechanism underlying slow cognitive processing speed: the limited time mechanism and the simultaneity mechanism. According to the limited time mechanism, the time to perform later operations is greatly restricted when a large proportion of the available time is occupied by the execution of early operations. The simultaneity mechanism states that the earlier processing products may be lost by the time that later processing is completed. The result of both of these mechanisms is a degradation of performance. The simultaneity mechanism is similar to working memory capacity (Baddeley, 1986), but more specific to the processing capacity limited to timing (Willingham, 1997). However, because processing speed involves encoding, retrieval, and other working memory functions, it is difficult to separate processing speed from working memory, and processing speed has an exceptionally strong relationship with working memory (Dehn, 2008). The potential slower processing speed deficit of dyslexia may lead to several other hypotheses.

Research Question Two: Do dyslexics show impaired performance when learning longer sequences?

The operation of the simultaneity mechanism also indicates that dyslexic participants may not be able to learn longer sequences compared to controls. This is because when the next element is registered and required to be active simultaneously in working memory, the information of the earlier element may be already lost. This hypothesis is linked to the relationship between processing speed and memory. Processing speed mediates articulation rate and rehearsal rate, which in turn determines the number of items that can be rehearsed before decay. Thus faster processing speed extends short-term memory span. In the case of curtailed phonological short-term capacity, processing speed can compensate somewhat by rapidly encoding information into working memory for higher level processing (Dehn, 2008). Dyslexics' impaired phonological short-term memory as well as their slower processing speed may make them more likely to show deficits in learning associations of more elements.

This hypothesis has been supported by two studies. Howard, Howard, Japikse & Eden (Howard Jr., et al., 2006) found impaired 'alternating SRT (ASRT)' performance of dyslexics. In their study, they used an alternating SRT (ASRT) task in which the stimuli follow a predictable four-element-long repeating sequence, and randomly determined stimuli alternate with these predictable stimuli. For example, if a person receives the pattern '4231', in which 1 stands for the leftmost position and 4 for the rightmost position, then the sequence encountered would be 4r2r3r1r4r2r3r1r. . ., where r stands for a randomly chosen position of the four. In this task, participants have to learn at least the lag 2 information thus bigram knowledge alone cannot lead to learning performance in this task.

In a second study by Benett et al. (2008), a similar SRT task was used, in which the location of every other stimulus follows a repeating pattern. Similar to the sequential regularity in the ASRT task, stimulus location on trial n predicts the location of trial n + 2. For example, in the triplet 1r2, where 1 and r refer to red events and 2 refers to the green event, the first red circle at location 1 predicts that the green circle will occur at location 2, with the location of the second red event being randomly determined. The participants were required to make response only to the green event. Triplets were presented at either higher or lower frequency, the results showed that although dyslexic participants were able to learn the higher-frequency triplets as well as controls, a correlation between the learning performance and two reading relevant scores (the pseudo-word reading and the RAN) was found, suggesting a relationship between reading and implicit triplet learning.

These two studies are consistent with the hypothesis that dyslexic people are more likely to show learning deficits when sequences contain more element associations. However, a more straightforward comparison between the learning of fewer elements (e.g., bigrams) and more elements (e.g., triplets) should be made (Deroost et al., 2010). This research question will be discussed and investigated in details by Study I and II in Chapter Two.

Research Question Three: Do dyslexics show impaired learning performance when effective explicit strategies are required?

Dyslexic participants are also expected to become less aware of an explicit strategy that could be applied to a learning task because of the slower processing speed. As discussed earlier, the participants might be able to adopt an explicit strategy that will greatly improve performance even if they are not told the learning nature of the task. For example, in the SRT task, participants are not told that the stimuli are sequenced, but the participants might spontaneously notice that they are and explicitly memorize the sequence and significantly improved their RTs. It is reasonable to assume that developing and testing the explicit hypotheses to respond in a learning task is demanding of working memory (Willingham, 1997). Because of the simultaneity mechanism, dyslexic participants may be less likely to spontaneously develop explicit strategy or abstract knowledge, both of which involve the hypothesis-testing phase and require extra processing. Their slower processing speed makes it more difficult to simultaneously perform the task and maintain in working memory processes that might generate new explicit knowledge.

According to this hypothesis, dyslexic participants may first, gain less explicit knowledge in the implicit learning tasks; and second, acquire less abstract knowledge in the implicit learning tasks. The first prediction emphasizes the importance of analyzing how much implicit or explicit learning happens when studying dyslexics' implicit learning performance. If dyslexic participants are impaired here, is it because they gained less explicit knowledge compared to controls? If so, it may not be because of poor explicit learning capacity, but incapacity to involve explicit learning process in implicit tasks because of the slower processing.

The second prediction of dyslexics' poor abstract learning emphasizes the importance to carefully examine the forms of knowledge when studying dyslexics' implicit learning performance. Three studies (Pavlidou, et al., 2010;

Pavlidou & Williams, 2010; Pavlidou, et al., 2009) with the AGL paradigm found dyslexics' impaired implicit learning on only abstract knowledge. However, the mechanism underlying abstract knowledge learning under implicit condition is rather complex, this research question will be discussed and investigated with more details with Study III and IV in Chapter Three.

Research Question Four: Do dyslexics show impaired performance for experiment-paced tasks rather than self-paced tasks?

The operation of the limited time mechanism indicates that tasks that are experiment-paced may be impaired in dyslexic people, whereas those that are participant-paced may not be (Wolf & Bowers, 1999) because the external time constraints force participants to make a response, and the response may therefore have to be made before processing is completed. Both the SRT and the AGL task are self-paced tasks, and there is no study so far using experiment-paced implicit learning task on dyslexic population. Dyslexic participants may be more likely to show deficits in experiment-paced implicit skill learning tasks. This research question will be discussed and investigated with more details by Study III in Chapter Three.

Research Question Five: Do dyslexics show impaired implicit learning performance when multiple processes are required?

As in other cognitive tasks, the operation of the simultaneity mechanism indicates that the implicit learning tasks that demand multiple processes, which are active simultaneously in working memory may more likely be impaired in dyslexic participants. This is because if multiple processes are required in the tasks, the slow processing speed makes it more likely that the critical information will be unavailable. For example, an SRT task that requires an extra corresponding stimulus-response mapping (e.g., the motoric sequence in Kelly et al.'s study in 2002 required participants to make response to different visual targets instead of the locations) is more demanding than an SRT task using a compatible stimulus-response mapping (e.g., other SRT tasks requiring participants to make response to compatible locations), and thus more likely to reveal dyslexics' impaired performance. In Kelly et al.'s study, dyslexic participants showed intact motoric sequence learning as well as the spatial sequence learning. However, in that study, the two sequences were learnt in a single SRT task, the requirement for integration of cognitive processing raises the possibility that problems in resource allocation and other more central processes may affect the results.

Summary

The current thesis aims to evaluate implicit learning performance in relation to reading skills, cognitive ability and attention problems of dyslexic people. The following outline explains how each chapter of this thesis has addressed the above research questions and investigated the hypotheses outlined earlier. The primary research question is whether dyslexic people have a deficit in implicit learning. The second research question examines what cognitive processes influence dyslexics' implicit learning performance.

Chapter Two (Study I and II)*: How much can dyslexics learn?* Previous studies have compared dyslexic participants on implicit sequence learning tasks yielding mixed findings. While some studies have found dyslexic participants showed impaired learning of sequence with more complex structure, in this chapter, we therefore examined whether the implicit learning of dyslexics is influenced by the structural complexity of the to-be-learnt sequence in two studies with three different experiments using both the SRT and AGL paradigms.

Chapter Three (Study III and IV): *What can dyslexics learn?* Two tasks were designed to examine dyslexics' abstract learning under implicit conditions. Following two studies in Chapter Two, the influence of different degrees of structural complexity was controlled in these two studies, and dyslexic participants' abstract learning was directly examined when only simple information (e.g., bigram association) was needed.

Chapter Four (Study V): *Attention, expression and implicit sequence learning of dyslexics.* Four experiments were conducted to explore how implicit and explicit learning interact, and the influence of a secondary tone-counting task was used to examine how dyslexics' implicit learning and expression of the knowledge would be affected with varied attentional resource. In this chapter, data is also combined and correlation analysis is used to evaluate task performance in relation to reading skill. Relevant cognitive ability and linguistic scores were included to evaluate to what extent any deficit in implicit learning were specific to reading and to what extent they might be correlated to general intellectual ability and other cognitive abilities.

Chapter Two: Does Structural Complexity Matter: Study I & Study II

Two studies in this chapter examine implicit sequence learning in adult dyslexics with a focus on the influence of structural complexity of the to-be-learned sequences.

There are a number of studies (Bennett, et al., 2008; Deroost, et al., 2010; Howard Jr., et al., 2006) which attempt to explore if statistical complexity of the to-be-learned sequential information will affect dyslexic people's implicit learning performance, but the results are inconsistent. Moreover, there is no study to date, which includes a manipulation of the statistical properties of the structural complexity of both the SRT and AGL tasks in a dyslexic population. In this chapter, it is proposed that differences in the statistical complexity of the sequences may affect implicit learning in dyslexia and therefore to some extent account for the controversial results found on dyslexic people's implicit learning capability. This chapter discusses the background to implicit learning of different sequential information, and with two studies directly manipulates the statistical properties so that learning of first-order and second-order transitions in dyslexics would be compared with both SRT and SGL paradigms.

2.1. How much can be learnt: implicit learning and sequence structural complexity

2.1.1. Memory limits and sequence structure

There are many limits to how much we can learn, and one is that the longer a sequence is, the more difficult it is to learn (Ebbinghans, 1885). This is true for explicit memory and explicit learning. However, earlier researchers used to believe that implicit learning, which is "reflected in the effects of experience on performance rather than in intentional remembering", might be free of such limits (Stadler & Neely, 1997).

The reason to believe that people may be capable of implicitly learning much longer sequences is implicit sequence learning may not be limited by working memory capacity. First, implicit sequence learning is unaffected by the working memory resources devoted to learning the sequence. Studies have shown that explicit learning of a sequence is accompanied by parallel implicit learning of the sequence, and the extent of implicit learning is equivalent to that when there is no explicit learning (Willingham, 1999; Willingham, Salidis, & Gabrieli, 2002). Second, sequence knowledge acquired through implicit learning cannot be used in a controlled and flexible manner, suggesting no involvement of working memory (Jiménez, Vaquero, & Lupiáñez, 2006).

However, there is also evidence showing that implicit sequence learning involves the operation of associative processes on sequence elements stored in a short-term memory system (Frensch, Lin, & Buchner, 1998; Frensch & Miner, 1994). Cleeremans and McClelland (1991) suggested that people could learn to use sequence elements up to three trials back to anticipate the next element in the sequence. Remillard (2008) found that people could only implicitly learn up to four-trial association information, and in a later study (Remillard, 2010), found evidence for participants showing learning for as long as six elements. Of course, it is possible that participants could eventually gain knowledge of even longer sequences with enough training trials, but in the published research to date, people show implicit learning performance of limited length sequences, which is probably linked to short-term memory, with a commonly cited capacity of 7 ± 2 elements (Frensch & Miner, 1994).

Stadler (1992) further clarified a confound between sequence length and sequence structure, and suggested it is the sequential structure instead of the sequence length to affect implicit sequence learning. As a sequence of events departs from complete randomness, it increases in redundancy; a completely random sequence has 0% redundancy; a completely predictable sequence has 100% redundancy. Moreover, the redundancy can be calculated separately for each level of the sequence, and the 'complexity' of sequence structure can thus be described as the different statistical computations carried out on the structural properties of the sequence at different levels: for example, a zero-order structure is at an event level, e.g., knowledge of which event occurs more frequently than others. A first-order structure is at the pair level, in which an event t can be predicted by t-1; and second-order structure exists when an event t can be predicted by the combination of the previous two events t-1 and t-2.

Table 1 structural complexity of sequence information

Order	Smallest Learning Unit	Example
Zero-order	**Probability of a single element t**	**2 2 4 2 3 2 1 2 3 2 2 1 2**
First-order	**Probability of a pair: t predicted by t-1**	**1 2 4 3 1 2 4 3 1 2 4 3**
Second-order	**Probability of a triplet: t predicated by (t-2, t-1)**	**1 2 1 3 4 2 3 1 4 3 2 4**

Broadly speaking, in an unknown environment, without any background information, the mathematical probability of any association between two events provides the chance for discrimination from other associations. Laming (1969) assumed that participants continuously update running average estimates of the probability of occurrence of each stimulus, on the basis of an arbitrarily limited memory of the sequence. Learning involves elementary association or recoding processes that are highly sensitive to the statistical features of the training (Cleeremans & Dienes, 2008). For example, in Nissen and Bullemer's study (1987), the repeating sequence used in the SRT task is 4231324321, where the number 1 to 4 indicate the four positions from left to right that stimuli appeared on the computer screen, respectively (Fig. 11). The single elements ‘2’ and ‘3’ are presented more often than the other two elements ‘1’ and ‘4’; also the pair ‘32’ is presented more often than other pairs, knowledge of which can significantly improve participants’ performance in the SRT task (Perruchet & Pacteau, 1990).

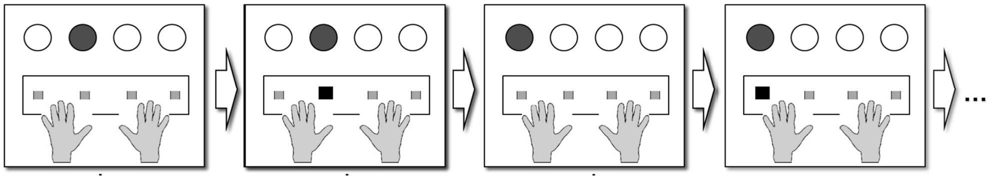

Figure 11 Schematic summary of the serial reaction time (SRT) task

Actually, two main families of associative implicit learning models both emphasize the importance of memory capability in implicit learning. Fragment-base models (Perruchet & Vinter, 1998; Servan-Schreiber & Anderson, 1990) assume that learning involves accumulating fragmentary knowledge of the training material, and that performance at test involves using this knowledge to decide on the grammaticality of each novel string, for instance, by comparing its overlap in terms of fragments. Neural network models (Cleeremans & McClelland, 1991) assume that over the course of training, information about the statistical structure of the stimulus material is stored in the connection weights between the processing units.

For fragment-based models, items are committed to short-term memory by organizing information so as to make it possible to exploit the redundancy of the materials. A short-term memory process is used to store at least part of the sequence. The stored sequential information and on-line comparison grow with an increasing sequence length, until a single chunk can be used to represent the entire knowledge. An essential demand on these models is the appropriate temporal indexing of the occurrence of every element so that the sequence can be stored and retrieved as a sequence (Pascual-Leone et al., 1993). Pascual-

Leone et al. (1993) suggested, in order to achieve sequence knowledge, "the serial reaction time task requires the "storage" of preceding asterisk positions in a "*working memory buffer" and "the comparison of each new asterisk position with the previous ones. (...) The demands on the memory buffer and on-line comparison grow with an increasing sequence length, thus increasing the difficulty of the task*" (p600).

Perruchet and Gallego (1997) further proposed that, under the framework of a fragment-based model, the input data is explicit perceptual units and not implicit representations; units emerge from the association of the primitive features that are jointly processed in the attentional focus; the implicit process focuses on shaping and generating these conscious learning materials. Because the explicit perceptual units facilitate participants' interaction with the learning environment, they are directly responsible for the improvement in learning performance observed in implicit learning tasks.

On the other hand, neural network models take the most influential Simple Recurrent Network (SRN) model as the example. In the original version (Cleeremans & McClelland, 1991), learning depends only on the predictive relations between an event and its immediate predecessor. In this SRN model, on each trial, element *t* of a sequence is presented to the network (by activating a single input unit), and the network has to predict element *t+1* of the sequence by activating the corresponding output unit. To make this prediction task possible, the network is equipped with 'recurrent context units', which, on each time step through the sequence, contain a copy of the network's pattern of activity over its hidden units. Over time, the network learns to use these representations of its own activity in such a way as to refine its ability to predict the successor of each sequence element (Cleeremans & Dienes, 2008). The size of the recurrent context units is specified by the number of time steps that are encoded.

Interestingly, Cleeremans (1993b) added an additional short-term memory buffer to the SRN model to explain the explicit contribution in the learning process. An SRN and a buffer network are both assigned the task of predicting the next element of a sequence presented one element at a time. The SRN may use information coming from its own mechanisms for maintaining the temporal context (direct pathway) to produce the next element, or it may base its performance on information produced by the buffer network (indirect pathway)(Cleeremans, 1993a). The central assumption upon which the dual simple recurrent network (DSRN) model is based is that participants who are aware of the sequence use their explicit memory of the sequence (Fig. 12). Thus, awareness of sequence structure changes the task from one of (implicitly) anticipating the next event based on temporal context to one of (explicitly) retrieving the next event from short-term memory.

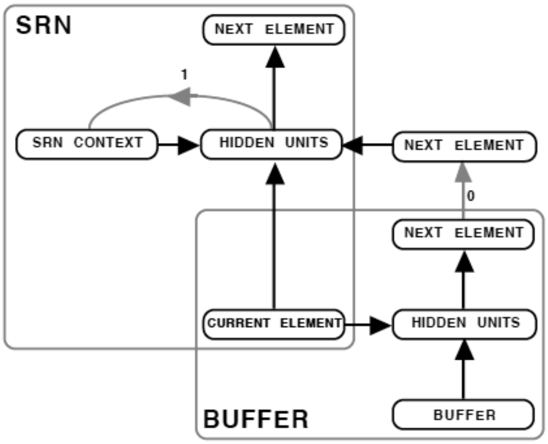

Figure 12 Architecture of the dual simple recurrent network (DSRN) Model

These models suggest an important role of short-term memory capacity in associative implicit learning, using short-term memory either to encode associations between events, to process short runs of events, or to store contextual information. Other researchers (Frensch & Miner, 1994; Howard & Howard, 1989; Keele & Jennings, 1992) also suggest different models in which short-term memory plays an important role in implicit sequence learning. It is generally considered that higher-order (e.g., second-order information compared to first-order information) transitions are more difficult to learn implicitly in the SRT task (Remillard & Clark, 2001; Soetens, Melis, & Notebaert, 2004; Stadler, 1992), and as Frensch & Miner (1994) proposed, the magnitude of implicit learning might be related to memory span and the rate of element presentation, thus limited short-term memory capability may lead to problems remembering longer chunks.

2.1.2. Attention and sequence structure

Another factor related to learning different sequence structural information is attention, as there is evidence which both the AGL and SRT paradigms show that learning of second-order information might require more attentional resource for full encoding. Cohen, Ivry, and Keele (1990) conducted a series of experiments and reported that sequence structure interacts with attentional requirements. In that study, participants undertook a SRT task with a secondary distraction task. The results revealed that the participants were only able to learn first-order sequential information with attention distracted. More complex sequences involving second-order information could only be learnt without secondary task interference.

Cohen et al. (1990) hypothesized that the differential effects of the secondary task on the different types of sequences might be due to the existence of two different learning mechanisms: one establishes direct bigram associations between an element of the sequence and its successor, and the other creates hierarchical representations of entire subsequences of events. Furthermore, the first mechanism requires fewer attentional resources than the latter mechanism and would thus not suffer as much from the distraction by the secondary task. This argument is consistent with Cleeremans' DSRN model, in which the short-term memory buffer functioned to account for explicit learning. Similar findings were reported by Keele and Jennings (1992) that under dual - task conditions, second-order conditional (SOC) sequences are learned to a lesser degree than SOC sequences with one inserted first-order condition (FOC) sequence.

Gomez (1997), using the AGL paradigm, tried to explore if learning in AGL task would be affected by different chunk sizes (e.g., bigrams, triplets, etc.). In that study, after training with 17 letter strings presented 6 times each, nongrammatical testing strings with nonpermissible bigrams (first-order information) or triplets (second-order information) were used to investigate learning of different complexities. The results showed that learning can only occur without explicit awareness in cases of lesser complexity (i.e., learning of first-order dependencies).

These findings suggest that learning of first-order information may require less attentional resource, whereas learning of second-order information may be more attention-dependent.

2.2. Study I: dyslexics' learning of different structures in the SRT[3]

2.2.1. Controversial results come from methodological issues

In earlier research on dyslexic children, Howard, Howard, Japikse & Eden (2006) found impaired 'alternating SRT (ASRT)' performance but intact learning with a Contextual Cuing task (Chun & Jiang, 1998) suggested that implicit learning impairment in dyslexia might be limited to paradigms involving sequential processing. Further, the authors suggested that previous discrepant results in SRT performance may be due to the different sequence complexity between the ASRT and previous SRT studies. In an ASRT task, unlike the simple repeating sequence used in previous studies with dyslexics, only higher-order prediction exists (Howard Jr. & Howard., 1997). An example of an 'alternating sequence' is 1r4r3r2r, where the digits '1 2 3 4' refers to different spatial positions (either stimuli on screen or key press locations) and 'r' refers to a randomly chosen one of these four positions with the RT difference between sequential stimuli and random stimuli across the entire experimental session indexing implicit knowledge. Howard et al. claimed that the ASRT contains no first-order information and studies with sequences affording first-order information learning (e.g., Kelly, et al., 2002; Waber, et al., 2003) might

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[3] This study has been written up as a separate paper and published as: Wenchong Du & Steve Kelly, 2012. Implicit Sequence Learning in Dyslexia: a within Sequence Comparison of First- and Higher-order information, Annals of Dyslexia, Sep, 1-17.

thus be expected to show learning if impairment is mainly at a higher-order level (Howard Jr., et al., 2006). In further support of this idea, Bennett, Romano, Howard & Howard (2008) used a similar ASRT paradigm with a non-motor sequence, and also found a correlation between pseudo-word reading and higher-order implicit sequence learning performance.

It is generally considered that higher order transitions are more difficult to learn implicitly in the SRT task (Remillard & Clark, 2001; Soetens, et al., 2004; Stadler, 1992), and as Frensch & Miner (1994) proposed, the magnitude of implicit learning might be related to memory span and the rate of element presentation, thus poor working memory capability may lead to problems remembering longer chunks. This gives broader theoretical support to the idea that differences in statistical complexity of the sequence information may account for previous conflicting findings since dyslexia is generally believed to include poor working memory capability (Jeffries & Everatt, 2004; Roodenrys, Koloski, & Grainger, 2001). However, empirical evidence may not yet be conclusive on this issue. Deroost et al. (2010) compared learning of both first-order conditional (FOC: 13234213414) and second-order conditional (SOC: 121342314324) sequences and found that dyslexic children had intact implicit sequence learning for both levels of complexity. An SOC sequence contains no predictive first-order information (all first-order transitions 12, 13, 14, 21, 23, etc., occur equally often), but each first-order transition is followed by a unique position in the sequence (e.g., after the transition 12 only position 1 can occur) thus the sequence is only predictive on a second-order level. In comparison, learning of FOC sequences can be based on first-order information about the immediate preceding position.

Although Deroost et al.'s study tried directly to manipulate dyslexics' implicit sequence learning on different levels of statistical complexity, the learning of different higher-order, i.e., lag 2 and second-order information is confounded between their task and an ASRT task. In Howard's alternating sequence, e.g., 1*r*4*r*3*r*2*r*, an event *t* can be predicted by the event *t-2,* while the event *t-1* occurs randomly, which means P[*t*|(*t-2*), *x*] (i.e., the probability of the occurrence *t* after *t-2* and a random event x) is the same for all sequential events. Therefore, the learning of an alternating sequence is specifically lag 2 learning. In an SOC sequence, an event *t* is predicted by the previous two events, in which P[*t*|(*t-2*), (t-1)] is the same for all sequential events. However, the lag 2 information may not be well controlled. For example, in the SOC sequence used in Deroost's study, 121342314324 , P(2|4, 1) and P(2|4, 3) are both .33 but P(2|4, x) is .67, so higher-order information contained in an alternating sequence and an SOC sequence is not exactly the same.

Furthermore, the measures for learning in these two studies are different. In Deroost's study, a classic SRT task was used in which the learning was indexed by the increase in RT to the randomly presented stimuli compared to the sequential stimuli. In Howard et al.'s ASRT task, the learning was indexed by comparing the RTs to sequential stimuli and random stimuli trial-by-trial across the entire experimental session. These two measures lead to several essential differences: (i) the probabilistic sequential structure used in an ASRT task minimizes the explicit knowledge compared to a deterministic sequence, thus less explicit learning might contribute to performance in an ASRT task; (ii) in the standard task, knowledge other than sequential regularities may contribute to faster RTs. For example, in the SOC sequence (121342314324) used in Deroost's study, the third element '1' appeared as a trill, and previous studies (Howard, et al., 2004; Soetens, et al., 2004) have noted pre-existing response tendencies to the relative frequencies of three consecutive events like trills (e.g., 121 or 434) lead to slower response time to the last element in the trills. Therefore, unless such effect of trills was reflected in the novel sequence block, the learning of this zero-order information may also contribute to the RT increase to the random trials; while in an ASRT task, for the remaining random trials, the positions from 1 to 4 were chosen randomly and uniformly for the random trials, thus, if participants reveal pattern sensitivity in the form of better performance on pattern than on random trials, this cannot reflect simple learning of the frequency of individual items (zero-order learning) because the four events occur equally often on both random and pattern trials. Nor can better performance on pattern than random trials be due to learning the relative frequencies of individual pairs of events (first-order learning); (iii) a within-participant design was used in Deroost et al.'s study; all participants carried out two SRT tasks with both FOC and SOC sequences and undertook awareness tests after finishing both learning sessions. Proactive interference could make the second awareness test less reliable. These differences between the two paradigms could contribute to results with a classic SRT task being less sensitive or reliable compared to an ASRT task when examining higher-order sequence learning.

Study I examined implicit sequence learning in dyslexics with a focus on comparing sequence transitions with different statistical complexities. A new measurement with the SRT paradigm was introduced to compare the RT of trials across levels of sequence complexity. In the sequence used in the current study (132342134142), the first-order, second-order and lag 2 transition probabilities for each trial are shown in Table 2. As mentioned earlier (p70 in this chapter), a first-order structure is at the pair level, in which an event t can be predicted by t-1; and second-order structure exists when an event t can be predicted by the combination of the previous two events t-1 and t-2. Complexity greater than second-order (e.g., third-order, fourth-order, etc.) requires significantly more training for learning to occur than will be given in the current study (e.g., training of 25200 trials to learn lag 3 information in Howard et al.'s (2004) study ; training of 19680 trials to learn third-order information in Remillard's (2008) study; but for the current study only 786 trials' training is presented). It is therefore unlikely that the current study contains sufficient trials to afford learning of greater complexity than first-order, second-order, and lag 2 information. By indexing the statistical probabilities of sequence transitions in this way, the contribution of different levels of sequence information to learn within one sequence can be compared.

Transitions occur with probabilities of either .33 (termed Low), or .67 (termed High). All 12 elements in the sequence can be sorted into 3 categories as shown in Table 2 according to their different first-order and second-order transition probabilities. Thus, for example, the learning of first-order information in the sequence can be obtained by comparing RTs for trials in Category II and Category III trial-by-trial over the entire experiment, as both probabilities of second-order and lag 2 transitions in these two categories are the same. Therefore, any RT difference between the two categories must be due to the different probabilities of first-order transitions. It should be noted that two trials (at place L and C to form another two sub-categories as shown in Table 3) in the sequence have a higher lag 2 transition probability thus responses to these two trials will be excluded in the final data analysis in order to remove the potential influence of lag 2 information.

Table 2 Transition probabilities of every element in the sequence 132342134142

Place	Element	First-order	Second-order	Lag 2
A	**1**	0.67	0.67	0.67
B	**3**	0.67	0.67	0.67
C	**2**	0.33	0.33	0.67
D	**3**	0.33	0.33	0.33
E	**4**	0.67	0.33	0.33
F	**2**	0.67	0.33	0.33
G	**1**	0.67	0.67	0.67
H	**3**	0.67	0.67	0.67
I	**4**	0.67	0.33	0.33
J	**1**	0.33	0.33	0.33
K	**4**	0.33	0.33	0.33
L	**2**	0.67	0.33	0.67

Table 3 Categorization of transition probabilities of the sequence 132342134142

Category	Place	Element	First-order	Second-order	Lag 2
I	**A**	**1**	High	High	High
	B	**3**	High	High	High
	G	**1**	High	High	High
	H	**3**	High	High	High
II	**E**	**4**	High	Low	Low
	F	**2**	High	Low	Low
	I	**4**	High	Low	Low
II'	**L**	**2**	High	Low	High
III	**D**	**3**	Low	Low	Low
	J	**1**	Low	Low	Low
	K	**4**	Low	Low	Low
III'	**C**	**2**	Low	Low	High

This novel method has several advantages. First, it can offer more subtle insights into the information learned by examining responses to categories of trial containing different probabilistic information throughout the entire learning process. In an SRT task, the decrease of RT during the entire procedure can be due to learning of the sequence itself but also more general response learning. In a standard SRT task many hundreds of trials are presented before a random block of trials occurs, therefore learning specific to the sequence acquired can only be measured after the training phase (Curran, 1997b). With this 'on-line' measure, it is possible to know whether the decrease of RT in performance is due to sequence learning or response learning even during early stages. In addition, a within-participants comparison makes it possible to examine more than one kind of information within a single sequence experiment without the risk of proactive interference effects, compromised awareness tests from using more than one sequence or sampling error across different groups of participants receiving different sequence structures.

Experiment 1 explores in detail the statistical information that facilitates performance in the SRT task and compares performance of a dyslexic group with a control group matched on age, or verbal and performance IQ. If sequence-learning deficits in dyslexia are related to sequential complexity, then the dyslexic group should show a deficit for higher-order information only.

2.2.2. Experiment 1: a within-sequence comparison of first- and higher-order information[4]

Method

Participants

12 students with documented diagnosis of dyslexia were recruited by emails sent by learning disability support centres at Strathclyde University and Glasgow Caledonian University. 12 control group members responded to recruitment posters placed on campuses of both universities and the Strathclyde University website. No control group member reported any learning

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[4] All studies in this thesis were approved by the School Ethics Committee (SEC) in Strathclyde University.

disability or relevant diagnosed history. All of the participants were native English speakers.

In addition, a series of behavioural tests were conducted to characterize participants' relevant abilities: the Wide Range Achievement Test- Revised-Tan (Wilkinson, 1993) was used to test spelling and reading ability, with which a standard score can be obtained; the Rapid Naming Speed Tests (Denckla & Rudel, 1976) showed the time every participant needed to name 50 digits and objects; the Spoonerism task (Perin, 1983) tested participants' ability to segment and manipulate phonemes, and a raw score can be obtained; digit forward and backward span tests were based on the Automated Working Memory Assessment (AWMA) (Alloway, 2007), with which a standard score can be obtained; the Wechsler Abbreviated Scale of Intelligence (WASI) provided a standard measures of participants' verbal and performance IQ (Wechsler, 1999). The difference between the two groups in terms of Object Naming, Digit Forward or Backward Span was non-significant, but the dyslexic group obtained lower scores on phonological awareness (Spoonerisms), literacy (WRAT-spelling and WRAT-Reading), and the other rapid naming test (Digit Naming) as expected.

Table 4 Participant characteristics

	Dyslexia		Control	
	Mean	SD	Mean	SD
Gender	4M8F	/	6M6F	/
Age	23Y4M	2Y11M	21Y5M	5Y0M
WRAT-Spelling (Tan) * **	88.83	10.78	104.58	3.87
WRAT-Reading (Tan) * **	90.83	7.31	118.08	3.45
Digit Naming(secs/50items)*	20.40	5.06	17.25	2.36
Object Naming(secs/50items)	34.61	6.43	30.73	3.18
Spoonerisms * (mean correct, max = 20)**	13.92	1.56	18.58	0.79
Digit Forward Span	28.25	6.84	32.67	8.70
Digit Backward Span	16.83	7.65	18.67	4.08
WASI-verbal	117.83	7.21	116.75	7.26
WASI-performance	106.67	11.15	101.33	8.87
WASI-overall	113.58	8.18	110.08	6.29

*$p \leq 0.05$ **$p \leq 0.01$ ***$p \leq 0.001$

Stimuli and Procedure

SRT

Testing was split across two consecutive days. On Day 1, all participants undertook the SRT task followed by three separate awareness tests. On Day 2 they were given the various behavioural tests as mentioned above.

The SRT tasks were run on an Intel Core Duo personal laptop with 15-inch screen. The programme was written in E-prime v2.0. The target stimulus was a white circle (1.5cm diameter) on a black background. The target circle appeared in one of four horizontally aligned black circles of 1.5cm diameter with a white border as location markers. The target was presented following a sequence which was 132342134142 where 1234 indicates the spatial locations on the screen from left (1) to right (4), with a response-stimulus interval (RSI) of 50ms. There were 10 blocks; each block began with 4 random trials followed by 96 sequential trials except block 9, in which the trials followed a pseudo-random order with all four stimulus alternatives occurring equally often without immediate repetition.

For the SRT task, the participants were instructed to use their index and middle fingers of both hands to make responses to the targets by pressing the corresponding key as the same horizontal positions on the response pad and both speed and accuracy were emphasized. Participants were able to take a break of up to 30s between blocks.

Explicit Awareness Tests

Participants first completed an awareness questionnaire comprising the following questions:

- *Did you use any strategy to try to improve your performance? If so, what was your strategy?*
- *Do you think your strategy worked? Why or why not?*
- *Did you notice any kind of pattern or regularity of the stimulus?*
- *Do you have anything to report regarding the task?*

Participants were then informed that a sequence was present, and completed a generation test based on the process-dissociation procedure developed for SRT (Destrebecqz & Cleeremans, 2001). The generation test contained two blocks: an inclusion and an exclusion condition, in which the participants were asked to generate a 96-element long sequence which either resembles or does not resemble the learned sequence, respectively. Finally, participants completed a recognition test in which they made judgments to 3-element sequences for whether this sequence had occurred previously or not. There were 24 trials (12 old and 12 new).

Results

For RT data, the standard deviation can be greatly increased by a relatively low number of slow RTs, therefore, median RTs have been used in the current and following studies in this thesis, because it is less susceptible to departures from normality (Whelan, 2008). Mean of median RTs and mean accuracy rates were determined separately for all trials in each block. The accuracy rate of both groups was consistent through sequential blocks, with no significant difference from each other: 97.76% for dyslexic group vs. 97.17% for control group, F(1, 22) <1. Both groups demonstrated more errors in the random block: 95.62% for dyslexic group and 95.51% for control group, with no significant difference from each other, F(1, 22) <1. The overall pattern indicates no evidence for a speed-accuracy trade-off in either group.

Overall Learning

As seen from Fig. 13, the response pattern for both groups was similar: both groups show a shallow learning slope and a dramatic increase in reaction time to the random block, with the control group appearing marginally slower.

A 2 × 9 ANOVA with Group (dyslexic vs. control) and Block (9 sequential blocks excluding the random Block 9) showed no significant difference for the between-participants' factor of Group, F (1, 22) = .59, p= .45, ŋ^2 = .03. A significant main effect for Block was found, F(1, 22) = 15.14, p =.001, ŋ^2 = .41, with no interaction for Block * Group, F(1, 22) = 1.31, p= .27, ŋ^2 = .06. A trend analysis on Block revealed a significant quadratic effect, F(1, 22) = 27.09, $p < .001$, ŋ^2 = .55; and a smaller but significant linear effect, t(22) = 4.78, p = .04, ŋ^2 = .18. These results indicated that both the dyslexic and control group showed significant performance improvement across the sequenced blocks, though this could be due to either learning of the sequence transitions and/or other non-specific practice benefits.

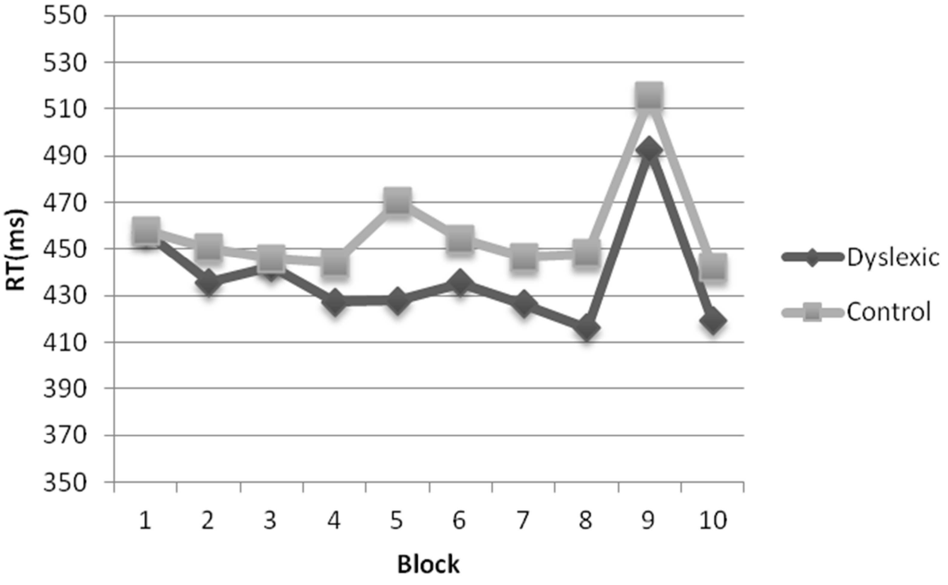

Figure 13 Mean of median RTs per block for both groups with all 10 blocks

In order to test for the effect of sequence specific knowledge, a 2 × 2 ANOVA with Group (dyslexic vs. control) and Block (the mean of Block 8 and 10 vs. random Block 9) was performed, showing a significant main effect of Block: F(1, 22) = 45.08, $p<.001$, $\eta^2 = .67$; no significant effect of Group, F(1, 22) = .82, $p= .37$, $\eta^2 = .04$, and no significant interaction of Group × Block, F(1, 22) = .05, $p= .83$, $\eta^2 =.002$. These results indicate that both dyslexic and control groups demonstrated significant and comparable learning.

Statistical Learning

Further between-category analysis examined whether information concerning different transition probabilities has any effect during the learning phase. Median RTs were determined separately for all trials in each category (seen in Table 3) in every block apart from Block 9 (the pseudo-random transfer condition) for every participant, and means of these values were calculated to obtain RT values per category.

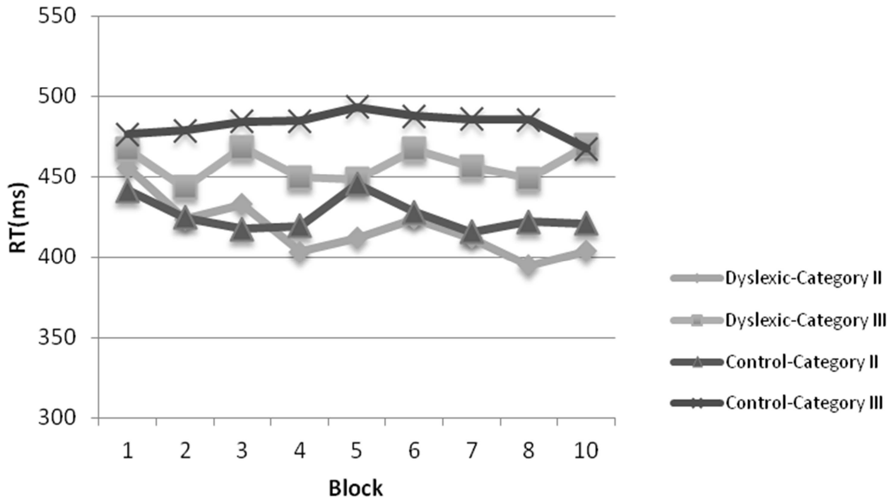

Figure 14 Mean of median RTs in Category II and III for both groups with all sequential blocks except random Block 9

To examine learning of first-order transitions, median RTs in Category II were compared to Category III, as probabilities of higher-order (i.e., second-order and lag 2) transitions in these two categories are equivalent. Hence, if there is any RT difference between these two categories, this must be due to learning of first-order transitions. Fig. 14 suggests learning occurs more slowly for trials in Category III than Category II for both groups and the difference between two categories appears to increase gradually over time. A mixed design ANOVA with Group (dyslexic vs. control) × Block (9 sequential blocks) × Category Type (II vs. III) shows a significant main effect of Category Type: F(1, 22)=63.27, p<.001, ŋ^2 = .74, with a faster RTs to Category II (422.10ms), than RTs to Category III (470.20ms). No other main or interaction effects reached significance.

Some previous studies (Howard, et al., 2004; Soetens, et al., 2004) have noted pre-existing response tendencies to the relative frequencies of three consecutive events such as trills (e.g., 121 or 434). There are two trills (the last elements in two trills are at place D and K as shown in Table 2) in the current sequence. Thus in order to eliminate the potential influence of these alternating patterns, mean of median RTs of trials in Category II and III were compared again excluding these two trials showing no difference in results from the ANOVA which included those trials.

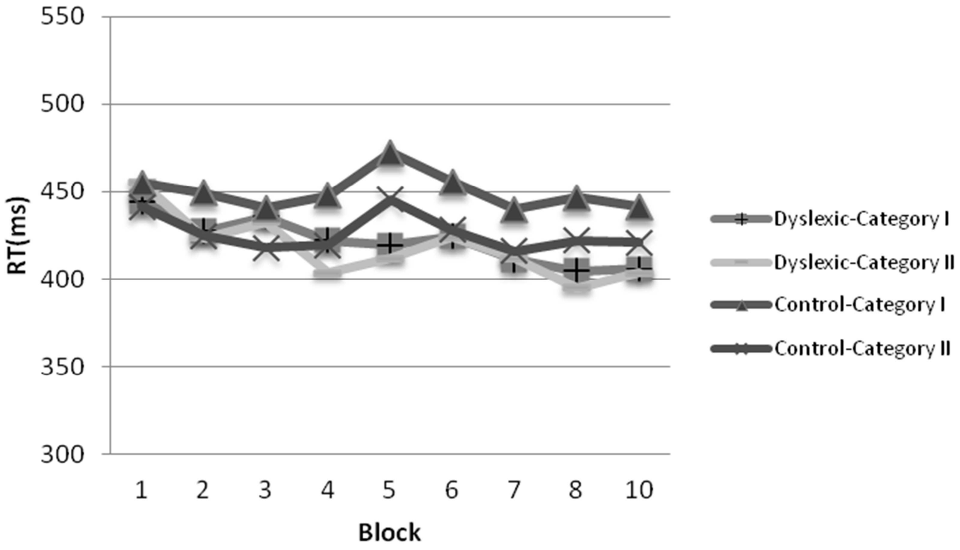

Figure 15 Mean of median RTs in Category I and II for both groups with all sequential blocks except random Block 9

Similar analyses were carried out between median RTs in Category I and Category II to examine learning of second-order information. As probabilities of first-order transitions in these two categories are equivalent, any RT difference must be due to learning of higher-order transitions. A 3-way ANOVA for Block x Group x Category shows a significant effect of Category (F(1,22) = 10.65, p=.004, ŋ^2 = .33), with a faster RTs to Category II (422.10ms) than RTs to Category I (435.80ms); a non-significant main effect was found for Group (F(1,22) = .65, p= .43, ŋ^2 = .02). The Category x Group interaction approached marginal significance, F(1, 22)= 3.63, p= .07, ŋ^2 = .14. The main effect of Block (F(1,22)= 2.28, p= .15, ŋ^2 = .09), and Block x Group (F(1, 22)= 1.55, p= .23, ŋ^2 = .06) were non-significant.

As a difference in higher-order learning is a specific prediction of this study, this marginally significant interaction was explored further with two separate ANOVA analyses for each group. No significant difference between levels of the Category variable was found for the dyslexic group (F(1,22) = 2.50, p = .14, ŋ^2 = .18) but a significant difference was found in the case of the control participants (F(1,22) = 8.21, p = .02, ŋ^2 = .43). These results suggest that in contrast to the control group, the dyslexic group failed to show learning of higher-order information although caution is required in view of the marginal level of significance of the original interaction. It should be noted that participants made slower RTs to trials in Category I than Category II. Interestingly, a correlational analysis shows a negative relationship between first-order transition learning and higher-order transition learning, r(24) = -.59, p = .002, which will be discussed with more details in the discussion.

Correlation between Implicit Learning and Memory

As mentioned earlier in the chapter, higher-order learning impairment in the SRT task may be due to poor memory capability, thus in addition to the group comparison analyses reported above, correlations examining the relationship between implicit higher-order sequence learning and short-term working memory as measured with two standardized tests of digit forward and backward span tests (AWMA) were further explored. Unlike the group comparisons, these correlation analyses aimed to investigate the relationship between individual memory ability and implicit sequence learning independent of diagnostic category (Bennett, et al., 2008; Howard Jr., et al., 2006; Stoodley, et al., 2008).

First, median RTs were determined separately for all trials in category I and II for each of the final two sequential blocks (Block 8 & 10), and means of median RTs of the two blocks were calculated to obtain the RT values for each category. A score for higher-order information learning was calculated for each participant by taking the percentage difference in the final two sequential blocks (Block 8 & 10), between Category I and Category II. However, no significant correlation was found between higher-order information learning and short-term memory (forward digit span), r= -0.04, p= .85; or working memory (backward digit span), r = -0.05, p = .84. It may be noted here that there is no significant group difference in forward/backward digit span, and the insignificant Pearson's correlation coefficient may be influenced by the distribution of these independent variables in the sample.

Explicit Awareness

Questionnaire

Two control and one dyslexic participants reported 'maybe there is some sequence' when asked if there was any pattern in the experiment, but no participant could verbalise even one triplet of the sequence. Hence, the questionnaire revealed no evidence of explicit knowledge for any of the 24 participants.

Recognition Test

Mean accuracy rates for the dyslexic and control group in recognition test were both .51 with chance being .50. Hence, this more sensitive recognition test demonstrated no explicit awareness of the sequence for either group.

Generation Test

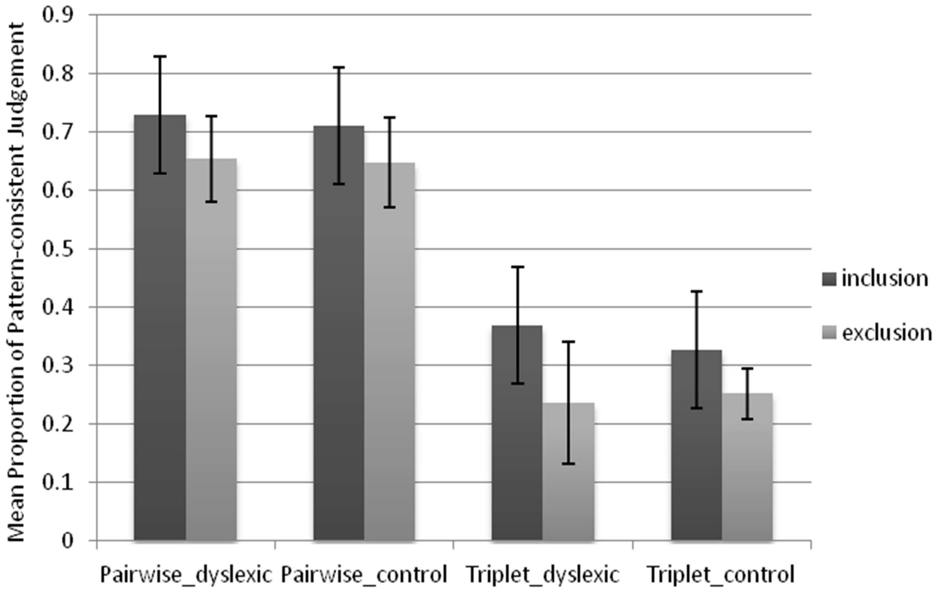

Figure 16 Mean production rate of pattern-consistent pairs and triplets under inclusion and exclusion instructions for both groups

Numbers of pattern-consistent pairs and triplets generated in the inclusion and exclusion conditions were calculated separately for each group. As can be seen in Fig. 16, more pairs were generated than triplets though it is statistically more probable that this should be the case so this comparison is uninteresting. Crucially, more pairs and triplets were generated under inclusion conditions where participants were asked to generate as many parts of the sequence as they could than under exclusion conditions where they were asked to try not to reproduce any parts of the sequence.

A 2 (Group: dyslexic vs. control) x 2 (Instruction: inclusion vs. exclusion) x 2 (Chunk: pair vs. triplet) carried out on the generation data shows significant main effects of Chunk (F(1,22) = 2078, $p < .001$, $\eta^2 = .99$) and of Instruction

($F(1,22) = 15.4$, $p < .001$, $\eta^2 = .41$). All other main effects and interactions were non-significant with F values less than 1. Hence, both groups of participants were able to generate more correct pairs and triplets under inclusion conditions than exclusion suggesting that they had some explicit awareness of these.

Two correlational analyses were further conducted: one between the higher-order information learning and triplet explicit awareness. The higher-order information learning score was calculated for each participant by taking the percentage difference in the final two sequential blocks (Block 8 & 10), between Category I and Category II. The triplet explicit awareness was calculated for each participant by taking the percentage difference for pattern - consistent triplets between inclusion and exclusion conditions. No significant correlation was found between higher-order information learning and triplet explicit awareness, $r(24) = .30$, $p = .16$. This result suggests that explicit knowledge of triplets in both groups did not affect their learning of higher-order information in the SRT task. A similar analysis was conducted for pairwise information learning and explicit knowledge of pairs and again, no significant correlation was found, $r(24) = .29$, $p = .17$ suggesting no effect of awareness on pairwise learning.

Discussion

As demonstrated previously (e.g., Kelly et al., 2002) both dyslexic and matched control participants showed learning of a novel sequence in an SRT task using a 12-item deterministic sequence. However, a novel measurement compared learning for different structural complexities within the sequence. With careful controlling of both second-order and lag 2 information in the sequence, the dyslexic group performed as well as the control group on first-order learning. However, the dyslexic group showed some degree of impairment in learning higher-order transitions compared to the control group. These results support Nicolson and Fawcett's automatization hypothesis of dyslexia, to the extent that the learning information may fail to be automatically learnt after a certain length of chunks threshold. These results in a standard SRT task also converge with those of Howard et al.'s (2006) ASRT task results in that these individuals with dyslexia were only impaired on sequence learning with non-predictive pair and predictive higher-order structure. This highlights the important contribution that structural complexity makes to successful learning in this task and raises the possibility that differences in complexity may partly account for differences in learning across previous studies.

More specifically, the current study provides a potential explanation to mixed reports of implicit sequence learning studies on higher-order learning in dyslexia. According to Howard et al. (2006), dyslexia involves impairment in higher-order, rather than first-order implicit sequence learning. However, using an SRT task with a 12-element SOC sequence, neither Russeler et al. (2006) nor Deroost et al. (2009) found impairment in dyslexia. In the current study, when the between-category comparison was used to measure sequence learning, the dyslexic group showed impairment only on higher-order learning but not first-order learning (Fig. 15 & Fig. 14). This between-category comparison is more comparable with Howard's ASRT, which also used an on-line trial-by-trial comparison as the measure of higher-order sequence learning, implying that the different measures used in previous studies determined the outcome of higher-order comparisons.

As discussed earlier, the classic measure with a comparison to random trials and the trial-by-trial measure with a comparison between trials in a sequence that have had identical exposure may reflect different learning. The former might be influenced by the learning of zero-order transitions, i.e., if the frequencies of single trials were not completely counterbalanced across all sequences given. The trial-by-trial comparison across the entire process offers a much more precise index to show learning performance with balanced zero- and first-order information and hence may illuminate an impairment exclusive to higher-order learning. Also, this study used one SRT task and the same participant sample to explore learning of different degrees of statistical complexity information, which avoids potential proactive interference or explicit awareness that may be problematic for previous studies.

It is interesting to note that some studies have found that elderly participants showed impairments with the ASRT task (Howard, et al., 2004; Howard Jr. & Howard., 1997), but others failed to find such deficits with a classic SRT task with a deterministic SOC sequence (Curran, 1997a). It is possible that these two different measures might reflect different reliabilities and sensitivities in studies of this population as well. Therefore, the results of the current study suggest that when studying how different statistical complexities facilitate learning in the SRT task, the on-line trial-by-trial comparison is a better measure of the outcome of implicit learning compared to the classic measure, since with the trial-by-trial comparison measure, (i) learning is more likely to remain unconscious and non-strategic, as the classic measure presents a more obvious disparity comparing the original sequence with the random trials, while the trial-by-trial comparison offers a much less obvious discrepancy between trials in different categories and therefore can minimize the explicit learning; (ii) it can yield precise insights into what information participants are actually learning, because with the classic measure, the pattern sensitivity compared to random trials might reflect learning of other uncontrolled information.

In the current study, the second-order probability actually showed a negative effect, with participants showing shorter RTs to elements with higher second-order probability (i.e., RTs to trials in Category I with higher second-order probability is slower than RTs to trials in Category II with lower second-order probability), which might suggest a suppressive effect of higher-order information when performance can be successful using only first-order information. This finding is also supported by a negative correlation between first-order and higher-order learning, i.e., the higher-order learning indexed by the negative effect is consistent with the first-order learning. Most models of learning in the SRT task describe the underlying process as association-based connectionist learning, in which the co-occurrence of events has been gradually gained as knowledge (Cleeremans & Dienes, 2008). Cleeremans (1993a) fits his simple recurrent network (SRN) model with a memory buffer network, which not only receives the current event t as input, but also event t-1, t-2, and t-3, suggesting that the prediction of the next element is not a simple additive rule using event t and t-1, but a more complex combination of t and t-1, etc. Thus, prediction from an association of two events may be more complicated than prediction from a single event or a combination of two single events so learning of higher-order associations may have a negative effect in a sequence with concomitant first-order information as it is less certain and may interfere with the first-order facilitation. As no suppressive effect was found for the dyslexic group, only the control group, it suggests that the dyslexic group did not learn as much higher-order information as the control group.

A further aim of this study was to examine the contribution of explicit learning. A very short RSI (50ms) was used in the current study, which could also minimize the contribution of explicit knowledge (Cleeremans, 1993a). Measures of recognition memory showed neither dyslexic nor control group had above chance explicit knowledge of the sequence on first-order information. Also as the results reveal, although participants showed preferential use of first-order information, both groups showed awareness of both first- and higher-order information with the generation test. However, there was no significant difference between two groups in explicit knowledge of either pairs or triplets as shown from the generation tests. There was no significant correlation between either first-order learning and pair awareness, or higher-order learning and triplet awareness, which further supports the conclusion that explicit knowledge had no effect on the sequential learning performance. Therefore differential explicit knowledge cannot account for the RT difference between groups with between-category comparison.

There is a clear discrepancy between explicit knowledge on the generation task and the other two tests of awareness. Although some explicit awareness is evident, it is unclear whether this was formed after the indirect task, or during the latter stages, and whether development of such knowledge had any effect on performance in the task.

While the current study found no evidence for learning of higher-order information in the dyslexic group, the training period was relatively short using 768 trials across the 8 learning blocks. However, rather than a profound deficit in higher-order learning, it may be that associations are made much more weakly in dyslexia and substantially more training instances are necessary for such learning to approach levels quickly displayed by a control group. Howard et al. (2006) found impaired higher-order learning using 3200 trials though Bennett et al.'s (2008) study using an alternating sequence with much longer training (responding to one third of 18000 trials) showed no difference between the performance of the dyslexic group and control group on higher-order learning. An earlier study by Nicholson and Fawcett (2000) also found that a dyslexic group was initially worse in learning using four letter-key positions to move a target on the screen under a dual-task, however their performance matched that of controls after an extended period of training. Though mixed, the experimental evidence to date raises the possibility that rather than being unable to learn higher-order contingencies, either implicitly or explicitly, dyslexic individuals may simply be slower to learn (Orban, Lungu, & Doyon, 2008). As noted above, the current study used 768 trials across the 8 learning blocks but it is possible that the higher-order learning impairment may disappear even in the comparison between categories if more extensive training was given.

In summary, adult dyslexic participants were found to be impaired only on higher-order but not first-order sequence learning. In addition, no difference was found between the two groups on explicit awareness tasks. This suggests that statistical complexity of the sequence may account for intact and impaired learning performance in dyslexia. Further, studies reporting intact higher-order learning use less sensitive comparisons and/or may be more affected by explicit knowledge contribution suggesting that the higher-order learning deficit in dyslexia is subtle and requires specific tasks to demonstrate any impairment.

2.3. Study II: dyslexics' learning of different structural information in the AGL

2.3.1. Dyslexics' implicit artificial grammar learning

Implicit grammatical judgment has been given an important role in linguistic and language development theories. The paradigm of the AGL provides a direct measure of how people acquire language grammar information without awareness, and that the competence of children to make grammatical judgments develops considerably across ages has been well established by researchers (Gelder & Morais, 1995).

The results of study suggest that a difference in statistical complexity of sequential information may explain previous conflicting findings with dyslexia in the SRT task. However, the SRT task, as a visual-motor procedural learning task, requires the activation of memory for sequences and a motor response to each of the presented stimuli; and in an SRT task, sequential stimuli are presented one by one across time, thus sequential processing is required. This is important to consider because there is evidence that dyslexics have problems in executive motor movements and sequence perception.

Dyslexic individuals have been found to have deficits in response time tasks. For example, Nicolson and Fawcett (2000) found that even after extended practice, participants with dyslexia are slower and more prone to error on a keyboard spatial task and on a choice response task. Another study conducted by Wolff, Michel, Ovrut, and Drak (1990) also found dyslexics perform more poorly on finger-tapping tasks when they require alternating movements between hands. Dyslexic individuals are also found to be impaired in processing sequentially presented stimuli. For example, Gross-Glen and Rothenberg (1984) reported a significant deficit in detection of simple visual stimuli among dyslexics with dyslexic participants requiring a longer stimulus exposure than controls. Lovegrove and his colleagues (Badcock & Lovegrove, 1981; Lovegrove, Martin, & Slaghuis, 1986) have reported that dyslexic children required longer ISIs than do controls to detect blanks between two visual stimuli. These findings suggest dyslexic individuals may:

1) have a deficit in making quick motoric response in tasks; and

2) have impairment in detecting quickly presented visual stimuli.

Therefore it is important to exclude the possibility that the motoric response requirement or the sequencing deficits are not the sole source of impairment reported in Study One.

In Study Two, another very popularly used implicit learning task, the AGL task was introduced. AGL is a non-motor task which requires the classification of strings of stimuli. In the AGL task, participants see strings of letters and are expected to learn the rules underlying the letter strings. Although both being implicit learning tasks, the AGL task is different from the SRT task on their underlying cognitive process. Specifically, Boucher and Dienes (2003) speculated that the SRT task involves error correction mechanisms based on prediction, whereas AGL learning may involve an automatic chunking mechanism. More important, SRT task involves the acquisition of perceptual and motor implicit knowledge, whereas AGL involves acquiring implicit knowledge for the purpose of making judgments. If motor deficits were responsible for the impairment in study, then dyslexic participants should show intact implicit learning with the AGL task; but if the statistical complexity of the information affects dyslexics' learning performance, dyslexic participants may also show similar learning patterns in a non-motor AGL task.

The complexity of the AGL task requires more abstract and conceptual representations compared to the SRT task (Dienes, 1992) thus there is controversy over exactly what kind of knowledge is learnt in the AGL task and several different learning mechanisms have been proposed . A basic distinction is between learning of the exemplar information on the one hand, and the abstract grammar, on the other. The exemplar knowledge refers to specific training examples and the learning is based on the frequency of occurrence of chunks (i.e., the relations of different elements: bigrams, triplets, etc.). Abstract grammar knowledge presents the abstract rule information which goes beyond the perceptual element strings, which is a mental operation that allows characterization of a stimulus by examining only a part of the knowledge (Pothos, 2005). Two of the most common ways to measure AGL learning performance are grammaticality (to measure grammar learning) and chunk strength (to measure exemplar learning). Grammaticality refers to the grammaticality of strings relative to the rules of grammar employed to generate the training stimuli. Chunk strength reflects whether a test item is composed of parts which have been frequently encountered in the training phase and is generally thought to correspond to similarity, which is technically defined by the frequency of total amount of bigrams (letter pairs) and triplets (letter triplets) in every testing string appeared in the training strings. The chunk strength of a test item is the average of the associative chunk strength of all its chunks. In other words, chunk strength is a measure of whether a test item is composed of parts which are familiar from training (Knowlton & Squire, 1996).

Previous studies using the AGL paradigm lead to different results. Neither Pothos & Kirk (2004), nor Russeler et al. (2006) found any impaired learning of dyslexic participants in their study. Pavlidou and her colleagues (Pavlidou, et al., 2010; Pavlidou & Williams, 2010; Pavlidou, et al., 2009) was the first study to look at the abstract and exemplar learning of dyslexics. They used an AGL task on dyslexic children and found dyslexic children are impaired in only abstract knowledge learning, but not exemplar learning. In this study, two AGL experiments were conducted, with either implicit or explicit instructions. Results showed a group effect only with implicit instructions, with only the typically developing children showing evidence of learning. More importantly, the dyslexia group did not show learning of grammatical knowledge. This study suggested dyslexic individuals' impairment in implicit abstract learning when their explicit learning has been shown to be intact (for a more detailed introduction for these studies see Chapter Three). However, both Pothos and Russeler's studies only examined dyslexic people's general learning performance in the AGL task, without separating abstract learning and exemplar learning, and it is difficult to compare and interpret their different results.

Study II was developed from the AGL experiment used by Knowlton and Squire (1994) to investigate both grammaticality judgments and exemplar learning in dyslexia. In addition, the stimuli were presented in two different ways with two AGL tasks (Exp. 2a and Exp. 2b): in the first standard AGL task, stimuli in one string were presented horizontally at the same time; while in the second sequential AGL task, stimuli in one string was presented in a continuous one by one manner, which makes the presentation of the stimuli more like the way stimuli are presented in an SRT task. The reason to include a sequential condition is because there is no spatial relationship between different stimuli in a sequential AGL task, which could reduce the explicit chunking strategy or explicit awareness of the patterns contributing to the learning. Thus the current study explores if the perceptual difficulty of having sequentially presented stimuli involved in the implicit learning task hinders performance, rather than implicit learning ability *per se* being impaired in dyslexia.

Overall, the current study aims to explore the different degrees of information complexity and abstractness which is used to facilitate the learning performance in the AGL task to compare the learning performance of dyslexic and control participants, with the regards to the different terms of stimulus presented formats. Grammaticality and exemplar learning were measured with two experiments to address whether implicit learning of dyslexics is related to knowledge of first-order and second-order dependencies, ranging from holistically to sequentially presented stimuli. If dyslexics' learning deficits are related to structural complexities, dyslexics' learning deficits are expected to be more manifest in higher-order learning than first-order learning. If dyslexics' impairment in implicit learning is more related to perceptual processing, they may only show different performance in sequential AGL but not the holistic one. If dyslexics only have abstract learning problem as suggested by previous study, they should show poor abstract learning only.

2.3.2. Experiment 2a: Structure complexity in artificial grammar learning

Method

Participants

12 students with formal diagnosis of dyslexia were recruited by emails sent from the Learning Disability Support Centre at Strathclyde University. 12 control group members responded to a recruitment advertisement on the Strathclyde University website. No control group member reported any learning disability or relevant diagnostic history. All the participants were native English speakers.

In addition, a series of behavioural tests were conducted to characterize participants' relevant abilities: the Wide Range Achievement Test- Revised-Tan (Wilkinson, 1993) was used to test spelling and reading ability; the Rapid Naming Speed Tests (Denckla & Rudel, 1976) showed the time every participant needed to name 50 digits and objects; the Spoonerism task (Perin, 1983) tested participants' ability to segment and manipulate phonemes; digit forward and backward span tests were based on the Automated Working Memory Assessment (AWMA) (Alloway, 2007); the Wechsler Abbreviated Scale of Intelligence (WASI) provided measures of participants' verbal and performance IQ (Wechsler, 1999). As shown in Table 5 below, the dyslexic group obtained lower scores on tests of literacy (WRAT-spelling and WRAT-Reading), phonological awareness (Spoonerisms), both rapid naming tests, short-term and working memory (Digit Forward and Backward Span) as expected. The difference between the two groups in terms of both verbal and performance IQ scores was non-significant.

Table 5 Participant characteristics for Experiment 2a

	Dyslexia		Control	
	Mean	SD	Mean	SD
Gender	5M7F	/	5M7F	/
Age	22Y1M	2Y1M	22Y3M	2Y9M
WRAT-Spelling (Tan) * **	94.67	6.47	114.25	3.47
WRAT-Reading (Tan) * **	92.00	7.43	110.33	5.19
Digit Naming(secs/50items) *	20.74	4.26	17.13	2.42
Object Naming(secs/50items) **	37.22	6.90	28.82	2.51
Spooneris ms * (mean correct, max = 20)**	14.25	1.42	18.58	0.90
Digit Forward Span*	26.42	3.65	31.83	5.59
Digit Backward Span **	15.00	3.95	20.58	3.48
WASI-verbal	118.67	4.03	123.50	8.35
WASI-performance	109.58	8.28	108.58	9.34
WASI-overall	115.75	4.58	118.00	8.15

$^*p \leq 0.05$ $^{**}p \leq 0.01$ $^{***}p \leq 0.001$

Materials and procedure

The grammar structure was taken from Reber and Allen's (1978) study (see Fig. 17) and generated by StimSelect (Bailey & Pothos, 2008), a MATLAB based software specifically designed to generate appropriate AGL strings with controlled relevant psychological variables. In this study, three variables were controlled: Grammaticality, Chunk Strength, and Chunk Novelty. Grammaticality and Chunk Strength were used to measure the learning of abstract and exemplar knowledge (Knowlton & Squire, 1996). Chunk Novelty was used to decide how many new bigrams or new triplets[5] could be included in the testing strings. In this study, the nongrammatical testing strings were generated by inserting either new bigrams or new triplets. Therefore, the learning difference

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[5] A new bigram/triplet refer to the bigrams/triplets, which were never presented in the training strings. However, a new bigram/triplet can be grammatical or nongrammatical.

between nongrammatical testing strings with new bigrams and new triplets only can be considered as participants' different learning performance of bigrams and triplets.

As dyslexics have been shown to have difficulty in naming (Swan & Goswami, 1997; Ramus et al., 2002), 5 unpronounceable symbols '火为心风木', which are balanced by their strokes, were used as the elements as shown in Fig. 17. Previous studies showed that participants' learning performance with such abstract symbols in the AGL tasks is equivalent to performance with standard letters (e.g., Pothos & Kirk, 2004; Pavlidou & William, 2010). In addition, all participants were able to tell the difference of the appearance of those five symbols, and not able to name any of those symbols.

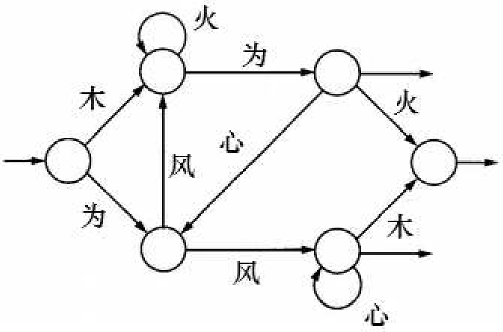

Figure 17 Structure and content of the grammar used in Exp. 2a & Exp. 2b

Training Materials: 20 symbol strings, ranging in length from 6 to 8.

Indirect Testing Materials: additional 60 symbol strings, ranging in length from 6 to 8, generated under four different conditions, with 15 strings each (Table 6):

i) GO: New grammatical letter strings without any new bigram/triplet;

ii) GN: New grammatical letter strings with new bigrams and triplets;

iii) NGNB: nongrammatical letter strings with new bigrams;

iv) NGNT: nongrammatical letter strings with no new bigrams but only new triplets.

Table 6 Four conditions of the testing strings

		Condition	No. of new bigrams	No. of new triplets
Grammatical (G)	Old	GO	0	0
	New	GN	1	1
Nongrammatical (NG)		NGNB	1	1
		NGNT	0	2

Awareness Testing Materials: additional 40 symbol chunks, with 20 grammatical and old chunks (10 bigrams and 10 triplets), and 20 nongrammatical and new chunks (10 bigrams and 10 triplets).

Training:

Participants were asked to learn the symbol strings and were told that they would receive a subsequent memory task. The 20 training strings were presented once and then repeated for another three rounds, so every training string was presented for four times and in every round the 20 training strings were presented randomly. Each training string was shown on the computer screen for 4000ms, with a 50ms interval between each two strings.

Indirect Test:

After training, participants were told that all the training items actually followed a same set of rules, which allowed only certain symbols to follow other symbols in a complex way. Participants were informed that they were about to see some new symbol strings and the task required them to judge whether these new strings conformed to this rule structure or violated it. Each test string was presented on the computer screen until the decision was made, and no feedback was given.

Awareness Test:

Finally, participants were asked to look at new symbol bigrams/triplets, to make judgments if they think they have seen these chunks in the training phase or not. All 40 chunks (20new/old bigrams; 20new/old triplets) were presented randomly for each participant, and still, each test string was presented on the computer screen until the decision was made, and no feedback was given.

Results

Total learning performance

Following other AGL studies (e.g., Knowlton & Squire, 1994, 1996; Pothos & Wood, 2006), mean endorsement[6] for each group in each testing condition was calculated as the proportion of strings that have been endorsed by participants. The percentage of the endorsed testing strings under every condition is shown in Table 7. As indicated from the table, the endorsement percentage of both groups under every condition was significantly different from chance (i.e., 50%), except the dyslexic group selected 47.2% strings from the NGNT strings, and the control groups selected 52.8% strings from the GN strings. The learning of both grammaticality and exemplar knowledge was calculated to indicate participants' learning performance: the index of grammaticality learning was calculated by comparing the endorsement for GN strings and for the NG strings (the mean of NGNB and NGNT strings), as the strings under these conditions only differed in the grammaticality variable but with the same chunk strength, so any difference of the endorsement percentage should be due to the learning of grammaticality; the index of exemplar learning was calculated by comparing the endorsement for GO strings and GN strings, as the strings only differed in the chunk strength variables but both are grammatical.

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[6] For each participant, endorsement rate under every condition was calculated by the percentage of strings selected as 'correct' under each condition.

Table 7 Means and SDs for percentage endorsement for the different conditions for the testing strings for Experiment 2a (%mean/%SD)

	Condition	Dyslexia	Controls
G	GO	61.7/9.0**	68.9/5.2***
	GN	42.8/6.0**	52.8/7.2
NG	NGNB	39.9/6.4***	44.4/7.2**
	NGNT	47.2/8.3	45.0/7.0*

*p≤ 0.05 **p≤ 0.01 ***p≤0.001

For grammaticality learning performance, as shown from Table 7, both groups endorsed GN strings more often than NG strings (i.e., the mean of NGNB and NGNT strings): 52.8% vs. 44.7% for controls and 42.8% vs. 43.6% for dyslexics. A mixed design ANOVA with Group (dyslexic vs. control) × Condition (GN vs. NG) shows a marginally significant main effect of Condition, F(1, 22)=3.23, p=.08, $\eta^2 = .13$. A significant effect of Group was also found: F(1, 22)=11.00, p=.003, $\eta^2 = .33$. Furthermore, a significant interaction was observed between Group and Condition: F(1, 22)= 4.82, p=.04, $\eta^2 = .18$. Separate t-test carried out for each group: for controls, a significant difference was found between GN and NG condition, t(11)= 3.12, p= .009; however, for dyslexic group there was no significant difference between GN and NG condition, t(11)= -.25, p= .81. These results suggested that the dyslexic group showed less grammaticality learning compared to controls.

Similarly, for exemplar learning, the endorsement for 15 grammatical strings without any novel bigram/triplet (GO) was compared with the endorsement for 15 grammatical strings with novel chunks (GN). A 2 × 2 ANOVA with Group (Dyslexic vs. Control) and Condition (GO vs. GN) showed a significant main effect for Group: F(1, 22)=21.53, p<.001, $\eta^2 = .50$; a significant effect for Condition: $F(1, 22)= 64.30$, $p<.001$, $\eta^2 = .75$; but no interaction of Group × Condition, $F(1, 22)= .41$, $p= .53$, $\eta^2 = .02$. These results indicated that although control group endorsed more strings under both GO and GN conditions than dyslexic group, both dyslexic and control groups demonstrated significant and comparable learning of exemplar information, and no significant difference was found between two groups' learning of exemplar knowledge.

Learning of bigrams and triplets

Further analysis examined whether information concerning different sizes of chunks had any effect on learning. Mean endorsement of NGNB and NGNT strings was compared for each group. A mixed design ANOVA was carried out with Group (Dyslexic vs. Control) as the between-participant factor and Condition (NGNB vs. NGNT strings) as the within-participant factor, to compare the endorsement by each group for testing strings with novel bigrams (NGNB) and the endorsement for testing strings with only novel triplets (NGNT). There was a significant main effect of Condition, $F(1,22)= 6.61$, $p= .02$, $\eta^2 = .23$, with a lower endorsement of 42.2% for NGNB strings, compared to 46.1% for NGNT strings; no significant effect was found for Group: $F(1,22)= .21$, $p= .65$, $\eta^2 = .01$; but a significant interaction was found between Group and Condition: $F(1,22)= 4.88$, $p= .04$, $\eta^2 = .18$. Paired-sample t-tests were carried out for each group between two conditions: for dyslexic group, $t(11)= 4.19$, $p=.002$; for control group, $t(11)= .22$, $p=.83$. Furthermore, as shown from Table 7, for both groups, the endorsement of NGNB strings was found to be significantly different from chance (.50): for dyslexic group, t(11)= -5.45, p= .001; for control group, t(11)= -2.69, p= .02; however, only for control group, the endorsement of NGNT strings was significantly different from chance: t(11)= .03; for dyslexic group, t(11)= -1.16. These results indicate that compared to controls, the dyslexic group displayed poorer judgment of strings with only novel triplets rather than strings with novel bigrams; only controls showed learning of both bigram and triplet information, dyslexic participants could only learn bigram but not triplet exemplar information in the task.

Awareness Test

Table 8 Accuracy rate for both bigram and triplet judgment in awareness test for Experiment 2a (%mean/%SD)

	Dyslexia	Control
Bigram	.67(.05)***	.64(.08)***
Triplet	. 54(.06)	.56(.04)***

*p≤ 0.05 **p≤ 0.01 ***p≤0.001

As shown from Table 8, both groups gained higher rate for judging bigrams than triplets. A mixed design ANOVA with Group (Dyslexic vs. Control) and Condition (Bigram vs. Triplet) showed a main effect of Condition: F(1, 22)=57.34, p< .001, η^2 = .72; no significant effect was found for Group, F(1, 22)<1; no significant interaction of Group × Condition, F(1,22)= 2.67, p= .12, η^2 = .11. Furthermore, mean accuracy rates for the bigram testing items were both significantly above chance (.50) for both groups: for dyslexic group, t(11)=11.73, p<.001; and for control group, t(11)= 5.79, p<.001. Only control group gained above chance accuracy rate for triplet judgment, t(11)= 5.63, p<.001. Dyslexic group only showed marginally above chance accuracy rate for triplet judgment, t(11)= 2.02, p=.07. These results showed that both groups gained explicit awareness for bigram, but only control group gained explicit triplet knowledge.

2.3.3. Experiment 2b: sequence-based grammar learning

Experiment 2b addressed the issue of whether dyslexics' learning in the AGL task would be affected by their perceptual processing of the stimuli if the stimuli presented sequentially one by one by using the same design and materials as Experiment 2a, but in the context of a temporally sequential-based grammar learning paradigm. In the sequence-based grammar learning, participants respond to stimuli presented in a continuous one-by-one manner. Experiment 2b required participants to view one stimulus element at a time instead of viewing the entire string per trial. The primary difference between a spatially presented grammar in Experiment 2a and a temporally presented grammar in this experiment is that the elements in the strings in the former experiment involve learning the spatial relationship between elements. In temporal sequence-based grammar learning, however, there is no spatial relationship between stimuli. Therefore, the temporally presented stimuli require participants to keep every event in the strings in short-term memory to establish the associations between different stimuli.

Additionally, when strings of stimuli are presented spatially at one time together, the explicit chunking strategy might be more activated compared with temporally sequential presentation (Gomez, 1997), because the way stimuli are processed is more passive under temporal sequential conditions.

Participants

12 students with formal diagnosis of dyslexia and 12 control group students were recruited in the same way as in Experiment 1. No control group member reported any learning disability or relevant diagnosed history before. All of the participants were native English speakers and reported no learning experience of Chinese or any other Asian language. Similar behavioural tests were conducted to characterize participants' relevant abilities as previous studies. As shown in Table 9, the difference between the two groups in terms of Digit Backward Span was non-significant, but the dyslexic group obtained lower scores on phonological awareness (Spoonerisms), literacy (WRAT-spelling and WRAT-Reading), and the two rapid naming test (Digit & Object Naming) as expected.

Table 9 Participant characteristics for Experiment 2b

	Dyslexia		Control	
	Mean	SD	Mean	SD
Gender	6M6F	/	4M8F	/
Age	22Y8M	3Y4M	22Y6M	1Y10M
WRAT-Spelling (Tan) ***	91.42	10.12	110.00	5.13
WRAT-Reading (Tan) ***	92.17	8.18	109.83	7.51
Digit Naming(secs/50items) **	20.25	4.14	16.16	1.93
Object Naming(secs/50items) ***	34.49	4.40	27.79	2.36
Spoonerisms * (mean correct, max = 20)**	14.08	1.78	18.00	1.35
Digit Forward Span*	26.50	7.56	34.75	9.79
Digit Backward Span	15.33	7.45	19.41	4.34
WASI-verbal	119.17	7.44	119.67	6.65
WASI-performance	110.00	11.52	106.50	12.18
WASI-overall	116.58	8.84	114.75	8.20

$^{*}p \leq 0.05$ $^{**}p \leq 0.01$ $^{***}p \leq 0.001$

Materials and procedure

The stimuli were identical to those used in Experiment 2a.

The procedure was identical to the training and testing phases in Experiment 2a, except that each symbol in one string was displayed in the center of the screen with an ‘x’ between two strings rather than concurrent presentation of all elements in a string. Each symbol, including the ‘x’, was presented in the centre of the screen for 250ms and there is a 50ms interval between two continuous symbols.

Results

Similar analyses as in Experiment 2a were used to Experiment 2b: mean endorsement for each group under every condition of the testing strings was calculated as the proportion of strings that have been endorsed by participants (Table 10).

Table 10 Mean endorsement for the different conditions for the testing strings for Experiment 2b (%mean/%SD)

	Condition	Dyslexia	Controls
G	GO	51.7/9.9	54.4/4.8**
	GN	46.1/15.7	45.0/7.6*
NG	NGNB	47.0/13.1	43.5/5.7**
	NGNT	51.1/5.9	48.3/5.8

$^*p \leq 0.05$ $^{**}p \leq 0.01$ $^{***}p \leq 0.001$

For grammaticality learning, a 2 × 2 ANOVA with Group (Dyslexic vs. Control) and Condition (GN vs. NG) showed no significant main effect of Condition: F(1, 22)=.48, p=.50, η^2 = .02; no significant effect was found for Group, F(1, 22)= .59, p= .45, η^2 = .03; or an interaction of Group × Condition, F(1,22)= .14, p= .72, η^2 = .01. These results suggested no group showed grammaticality learning.

For exemplar learning, a 2 × 2 ANOVA with Group (Dyslexic vs. Control) and Condition (GO vs. GN) showed a significant main effect of Condition: F(1, 22)=8.91, p=.007, η^2 = .29, but no significant effect was found for Group, F(1, 22)= .18, p= .68, η^2 = .01; nor an interaction of Group x Condition, F(1,22)= .86, p= .36, η^2 = .04. Separate t-test were conducted for each group and only the control group showed a significant learning effect with a significant difference between GO and GN condition: t(11)= 3.98, p= .002. There was no significant learning effect for the dyslexic group, t(11)=1.18, p= .26. These results suggested control revealed more exemplar learning compared to dyslexic group.

Learning of bigrams and triplets

Further analysis examined whether information concerning different sizes of chunks has any effect on learning. Mean endorsement for each group of NGNB and NGNT strings was compared. A 2 × 2 ANOVA with Group (Dyslexic vs. Control) and Condition (NGNB vs. NGNT) showed a marginally significant main effect of Condition: F(1, 22)=3.68, p=.07, η^2 = .14, with a higher endorsement rate for NGNT (49.7%), compared to NGNB (45.3%); no significant effect was found for Group, F(1, 22)= 1.72, p= .20, η^2 = .07; no significant interaction was found for the Group × Condition, F(1,22)= .03, p= .87, η^2 = .001. Furthermore, as shown from Table 10, for control group, only the endorsement of NGNB strings was found to be significantly different from chance (.50): t(11)= -4.00, p= .002; for NGNT strings, t(11)= -1.00, p= .34. For dyslexic group, their endorsement of neither NGNB nor NGNT was significantly different from chance (.50): for NGNB and NGNT respectively, t(11)= -.79; t(11)= .65. These results indicate that dyslexic participants could not learn either bigram or triplet exemplar information; controls could only learn bigram but not triplet exemplar information in this task.

Awareness Test

Table 11 Accuracy rate for both bigram and triplet judgment in awareness test for Experiment 2a (%mean/%SD)

	Dyslexia	Control
Bigram	.56(.08)*	.59(.07)***
Triplet	.50(.07)	.50(.05)

*$p \leq 0.05$ **$p \leq 0.01$ ***$p \leq 0.001$

As shown from Table 11, both groups gained higher rate for judging bigrams than triplets. A mixed design ANOVA with Group (Dyslexic vs. Control) and Condition (Bigram vs. Triplet) showed a main effect of Condition: $F(1, 22)=27.67$, $p< .001$, $\eta^2 = .56$; no significant effect was found for Group, $F(1, 22)<1$; no significant interaction of Group × Condition, $F(1,22)= 1.83$, $p= .19$, $\eta^2 = .08$. Furthermore, mean accuracy rates for the bigram testing items were significantly above chance (.50) for both groups: for dyslexic group, $t(11)=2.65$, $p=.02$; and for control group, $t(11)= 4.47$, $p=.001$. Neither group gained above chance accuracy rate for triplet judgment, $t(11) <.1$. These results suggested that both groups gained explicit awareness of bigram but not triplet information.

Discussion: Exp. 2a & Exp. 2b

The aim of Study II was to investigate implicit artificial grammar learning of adult dyslexics. The results clearly show a different learning performance for dyslexic participants compared to controls. Dyslexic participants performed as well as the control group on exemplar learning in the standard AGL task, but not in grammaticality learning. Furthermore, the results supported the hypothesis that implicit learning by dyslexic participants is affected by statistical complexity and sequential processing. Compared to controls, dyslexic participants were less capable of identifying test strings with novel triplets than test strings with novel bigrams compared to controls.

In Exp. 2a, grammaticality and exemplar learning showed equivalent contribution to control participants' learning performance; in contrast, although dyslexic participants showed learning of both grammaticality and exemplar information, their grammaticality learning performance is significantly poorer than controls, and their overall performance was reflected more by the exemplar learning. Specifically, although dyslexics' learning performance seemed to be dominated by exemplar learning, such learning was mainly influenced by knowledge of bigrams, but not triplets. These results confirmed the hypothesis that dyslexics' learning performance would be affected by more complex learning information, such as triplets in this study, but their learning of simpler bigram information was equivalent to controls.

Some learning mechanisms suggest that simple associative learning can support the acquisition of the entire knowledge base, i.e., that abstract grammar information can be explained by associative knowledge traces in long-term memory (Ackerman, 1989; Cleeremans & McClelland, 1991; Servan-Schreiber & Anderson, 1990). Noting that dyslexics were only able to learn the simple association between two elements (bigrams), therefore, it is possible that the lack of higher-order information is the reason to block any further possibility for dyslexic participants to learn abstract knowledge. The abstract learning capability of dyslexics will be investigated further in Chapter Three.

When learning strings were presented sequentially in Experiment 2b, dyslexic participants failed to show learning of grammaticality and exemplar knowledge. This result seems to support the proposal that dyslexics are impaired in tasks involving sequential process (Tallal, 1984), and extends this evidence to a task requiring acquisition of conceptual knowledge with no motoric learning involved. It should be noticed that the control group also only showed exemplar learning in Exp. 2b, which suggests a general negative influence to learning of the sequentially presented stimuli. This might be simply due to sequentially presented stimuli making it more difficult to associate more elements to form larger chunks. Also, the control group failed to reveal abstract learning without triplet knowledge in Exp. 2b, which is consistent to the findings of Gomez's study in 1997, which suggests that knowledge of triplets is necessary to establish abstract knowledge.

In summary, adult dyslexic participants were found to have impaired artificial grammar learning compared to controls. Bigram information seems to dominate dyslexics' learning performance while grammaticality and bigram/trigram information influence learning in the control group. Dyslexics failed to show learning when stimuli were presented sequentially suggesting that dyslexics' learning performance is indeed affected by the sequentially presented learning stimuli. These results suggest that dyslexics might have an implicit learning impairment and their performance is affected by statistical complexity, abstractness of the information, and perception of the stimuli.

2.4. General Discussion

Two studies in this chapter examined dyslexic participants' implicit learning capability with the SRT and the AGL task. The results indicated that dyslexic individuals have intact implicit learning on first-order information but impaired implicit learning on second-order information. As shown in Table 12, in Exp. 1, the dyslexic participants showed overall implicit learning as well as controls; however, with further analyses, unlike controls, dyslexic participants failed to learn second-order information. Exp. 2a showed similar results that dyslexic participants' learning is impaired when the triplet knowledge is necessary to make the judgment; while dyslexic participants showed intact learning when only bigram knowledge is needed.

Table 12 Comparison of the results for Study I and II

Performance			Dyslexia	Control
Exp1 SRT	Overall learning		√	√
	Implicit learning	First-order	√	√
		Second-order	×	√
	Awareness	First-order	√	√
		Second-order	√	√
Exp 2a AGL	Grammaticality		×	√
	Exemplar		√	√
	Indirect	Bigram	√	√
		Triplet	×	√
	Direct	Bigram	√	√
		Triplet	×	√
Exp 2b Sequential AGL	Grammaticality		×	×
	Exemplar		×	√
	Indirect	Bigram	×	√
		Triplet	×	×
	Direct	Bigram	√	√
		Triplet	×	×

First, the present findings indicate that the impaired associative implicit learning observed in the current and some previous researches (Bennett, et al., 2008; Howard Jr., et al., 2006) does not reflect a general implicit learning deficit, and that the dyslexic participants' implicit learning performance in the tasks could be affected by statistical complexities. In all studies reported in the current chapter, dyslexic participants showed impaired second-order learning performance with both the SRT and AGL task suggesting that impairment of second-order learning can be generalized beyond that in motoric sequence learning in dyslexics.

We need to further consider the reason why these findings differ from those reporting intact implicit learning in dyslexia (Deroost, et al., 2010; Kelly, et al., 2002; Pothos, 2005; Russeler, et al., 2006). Deficits have been found on second-order implicit learning with three independent samples in three implicit learning tasks. Deroost et al.'s study was the only published study examining the sequence learning of different statistical complexities of dyslexics, but as discussed earlier, they used a within-participant design, which could lead to proactive interference. For the other three studies, the most likely explanation for the discrepancy should be based on the implicit learning tasks themselves. Specifically, by demonstrating a deficit in only second-order implicit learning, i.e., learning which requires integrating across at least three elements, the present studies indicates the potential importance of sequence complexities in studies of implicit learning in dyslexia. To date, sequence structure has not been varied systematically in studies in dyslexia, and previous studies have not distinguished the complexity of the learning materials, which may lead to the different findings of dyslexia population. These results are consistent with our earlier hypothesis that dyslexic participants are more likely to have deficits in learning longer chunks because of their slower processing compared to non-dyslexics.

Turning to the learning of longer chunks, such implicit sequence learning impairment has also been shown in older participants who are generally believed to have intact implicit learning capability (Curran, 1997a; Howard Jr. & Howard., 1997). These higher-order sequential transitions are more difficult to learn implicitly (Remillard & Clark, 2001; Soetens, et al., 2004; Stadler, 1992), which raises the possibility that dyslexia may influence the learning of simple and complex sequence information differently.

There are two factors related to the learning of different complexities as discussed earlier. First, the magnitude of implicit learning might be related to memory span and the rate of element encoding and processing. Dyslexics' poor short-term memory may only provide limited information and when the third event is activated, the first event has already been lost. Dyslexics' slower processing speed mediates articulation rate and rehearsal rate, which in turn decrease the number of items that can be rehearsed before decay. The poor short-term memory and slower processing speed would both make it difficult for dyslexic participants to associate more than two continuous presented events. This explanation assumes implicit learning shares the same memory system with explicit learning and the impaired learning of higher-order information might be due to the poor short-term memory storage.

The heterogeneity of samples in three experiments should also be noted. Although in all three samples, the dyslexic group achieved significantly poorer scores on RAN, phonological awareness, and Reading & Spelling, in Exp. 1, the two groups did not differ on either short-term memory (measured by the Digit Forward Span) or working memory (measured by the Digit Backward Span); in Exp. 2a, the two groups were significantly different on both short-term and working memory score; and in Exp. 2b, the dyslexic group showed only poor short-term memory but not working memory. Such heterogeneity among samples should be noticed because this might be related to participants' learning performance. The specific relationship between memory capacity and implicit learning will be further explored with a larger sample in Chapter Four.

A second possibility, as discussed earlier in the introduction in Chapter Two is that explicit knowledge plays an increasingly important role for more complex sequence learning, and dyslexic participants failed to involve such explicit learning in the tasks. This explanation indicates that implicit learning would lead to only limited, or no, higher-order learning. Those with dyslexia may be expected to become less aware of an explicit strategy that could be applied to a learning task because of the slower processing speed. It is reasonable to assume that developing and testing the explicit hypotheses to respond in a learning task is demanding of working memory (Willingham, 1997). As Salthouse (1996) suggested, dyslexic participants may have a deficit in a simultaneity mechanism, which leads to their general problems in processing speed, which is also highly related to working memory capability (Willingham, 1997). A deficit in a simultaneity mechanism may mean that the earlier processing products could be lost by the time that later processing is completed. Because of the deficit in a simultaneity mechanism, dyslexic participants may be less likely to spontaneously develop explicit strategy or abstract knowledge, which both involve the hypothesis-testing phrase and require extra processing. Their slower processing speed may make it more difficult to simultaneously perform the task and maintain in working memory processes that might generate new explicit knowledge. This explanation could also account for dyslexic participants' poor abstract learning in Exp. 2a, and the question of dyslexics' abstract learning capacity will be further discussed in Chapter Three.

Interestingly, in all experiments (Exp. 1, Exp. 2a & Exp. 2b,) we found that the dyslexic groups actually showed explicit knowledge with the direct awareness test when they actually failed to show the knowledge implicitly (see the Table 10). In Exp. 1, dyslexic participants showed above chance correct judgment to triplets although they failed to show any implicit learning of the second-order information; in Exp. 2b, dyslexic participants showed explicit knowledge of the bigrams in the direct test. These results suggest another possibility: that if dyslexics' impairment is decided by conditions at expression, because the direct testing data in these experiments indicate that when more attentional resource is available, dyslexic participants could express the knowledge even though they failed to express as much knowledge as controls under the implicit condition. If this is the case, dyslexics' implicit learning performance should be investigated under different attentional requirement conditions, and it is also necessary to clarify if the impairment observed by dyslexics is a learning or an expression problem. These questions will be further examined in Chapter Four.

In summary, the present findings reveal that dyslexics are impaired in second-order implicit learning, but spared in first-order learning. This indicates that dyslexics have difficulty integrating information across non-adjacent elements. The results in Study I and Study II also suggested dyslexic people may have problems in abstract learning and automatic expression, which will be further examined in the following chapters.

Chapter Three: Dyslexia and Abstract Learning: Study III & Study IV

In Chapter Two, three experiments were conducted and dyslexic participants were found to have intact learning of bigram information, but deficits in learning triplet information. Dyslexic participants also showed a deficit in learning abstract knowledge with two AGL experiments; however, it is possible that such a deficit in abstract learning is due to a failure to learn second-order information, which consequently might prevent any further possibility for dyslexic participants to learn abstract knowledge. Therefore, in this chapter, two studies were conducted to explore if dyslexics could learn abstract knowledge when second-order information is not involved. It is proposed that dyslexic people's abstract learning *per se* is intact, and their observed impaired abstract learning may reflect a deficit in learning higher-order information, as suggested by Study I and Study II. To investigate this proposal, two experiments with stimuli which only contain zero- and first-order information were designed, and dyslexic participants' abstract learning was examined when only this lower-order information was involved.

3.1. What can dyslexics learn implicitly?

The form of knowledge which can be learnt implicitly is a key issue in implicit learning. A number of studies have provided evidence for two distinct modes of implicit learning, which can be broadly considered as 'abstract rules' and 'similarity'. Early theories of implicit learning have tended to assume that it involves independent abstract rule-based unconscious learning mechanisms. For example, Reber (1967) claimed that implicit learning is a process in which "information is abstracted out of the environment ... without recourse to explicit strategies for responding or systems for recoding the stimuli" (p. 863). However, many computational models argue that knowledge of exemplars or fragments is sufficient enough to lead to rule-like learning performance, and the learning effect observed can be explained by simple mechanisms that are sensitive to the similarity between training and test exemplars (Timmermans & Cleeremans, 2001).

More recently, accounts that assume two separate learning systems for developing abstract and exemplar knowledge in artificial grammar learning tasks have been proposed based on evidence that significant sensitivity to grammaticality remains even when exemplar overlap is carefully controlled for (Knowlton & Squire, 1996). However, the complex methodological challenges associated with the assessment of awareness of implicit learning tasks (Shanks & St. John, 1994) mean that it is difficult to completely rule out methodological inadequacies in these studies.

3.1.1. Abstract rules vs. similarity

Reber (1989) claimed that implicit learning is characterized by the acquisition of abstract knowledge of the underlying structure of the surrounding environment, which suggests that there is a cognitive mechanism capable of unconscious automatic operation, based on statistical regularities, such as the co-occurrence of features, or the repeated occurrence of features in particular locations, across successive stimuli (Whittlesea & Wright, 1997).

The principle of abstract knowledge is “the notion that the mental content consists not of the representation of physical forms, but of abstract representations of those forms” (Manza & Reber, 1997). Lewicki et al. (1987) propose that implicit learning leads to abstract representations that retain a domain’s underlying structural characteristics while abstracting from specific surface information, and the assumed abstractive nature of implicit learning is hypothesized to be grounded in the unconscious acquisition of rules that capture covariation patterns of physical stimuli, rather than recording details of a single episode (Wallach & Lebiere, 2003). This learning of abstract knowledge was further substantiated by evidence that artificial grammar learning knowledge can transfer to strings based on the same artificial grammar but instantiated with a different letter set (Reber, 1989). It is claimed that under the transfer condition, only the surface properties are different (e.g., ‘MXQRT’ to ‘WNZSP’), but the underlying abstract grammar is identical, thus Reber (1989) argued that this transfer effect is the evidence that participants acquire knowledge of the underlying rules of the grammar. Further evidence for abstraction comes from the findings of knowledge transfer across modalities (Altmann, Dienes, & Goode, 1995; Manza & Reber, 1997), interpreted as demonstrating learning and utilization of the deep structure of the grammar when the surface structure undergoes as extreme a transformation as letter strings to auditory tones.

However, abstraction of underlying rules may not be the only explanation for transfer effects. Researchers subscribing to the ‘episodic chunking hypothesis’ define implicit learning as encoding and retrieval of representations of literal instances of stimuli and their successive order without assuming an underlying inductive abstraction process (Shanks & St. John, 1994). For example, Perruchet and Pacteau (1990) suggested a fragment learning hypothesis, and argued that in processing the training items, participants gradually recognize that certain symbols co-occur with others. Eventually, participants develop knowledge of the common bigrams or trigrams that make up the training set, and recognize whether the new strings are made up of familiar fragments and, accordingly, classify it as G or NG.

According to this exemplar learning perspective, the transfer effects do not necessarily indicate abstract knowledge, but are rather the result of comparing memorized surface fragments with surface level representations of the test strings (Redington & Chater, 1996). For example, given the sequences XVXV and VXVX, the participant might encode the bigrams XV and VX. Test sequences can be endorsed or rejected according to whether they are composed of familiar or unfamiliar chunks. Then the transfer sequence WZWZ would be considered grammatical because of the potential mappings between W/X and Z/V. However, if the test sequence WZZW was presented it would be judged as nongrammatical because the bigram ZZ cannot be mapped onto a bigram from the training set (Tunney & Altmann, 2001). Redington and Chater (1996) demonstrated that participants' knowledge of surface fragments of two or three letters together with explicit strategies were sufficient to perform abstraction at test in the transfer literature.

Moreover, many authors have suggested that computational mechanisms can perform in a rule-like manner without necessarily having acquired rule-based knowledge (Redington & Chater, 1996; Timmermans & Cleeremans, 2001). For example, the learning effects using a finite-state grammar could be influenced by the perceived familiarity of the various sub-sequences within each test string (Knowlton & Squire, 1994; Perruchet & Pacteau, 1990), in other words, participants might learn the co-occurrences which were presented more often before rather than underlying abstract rules. Perruchet and Pacteau (1990) found that in the AGL tasks, participants who went through a standard training phase performed at a comparable level with participants who were only shown the bigrams that made up the training sequences. Therefore Perruchet and Pacteau argued that the stored exemplars could supply sufficient knowledge with which the items proposed during the test phase are compared. This conception has been extended by the similarity assumption (Brooks & Vokey, 1991), which argued that the grammatical judgments are based on the degree of similarity between the stored training chunks and the testing chunks.

Gomez (1997) explained transfer from a different perspective, and argued that although participants are able to transfer knowledge to a novel letter set, the transfer is more associated with explicit knowledge, and found that only participants with higher awareness of the knowledge were able to show transfer effects. This result leads to a further issue as to whether the expressed abstract knowledge depends on explicit or implicit learning. This issue has been addressed by testing amnesic patients, due to amnesic patients being selectively impaired in explicit learning and memory (Squire & McKee, 1992). Results showed that amnesic patients do exhibit normal classification performance in the AGL tasks (Knowlton, Ramus, & Squire, 1992; Knowlton & Squire, 1994, 1996), suggesting that explicit learning does not play a material role in making classification judgments. Moreover, in these studies, Knowlton and Squire developed a new measure with the AGL tasks, in which both Grammaticality and Chunk Strength were tested. Grammaticality refers to compliance with the abstract finite state grammar employed to generate the training stimuli, and Chunk Strength reflects whether a test item is composed of parts which have been frequently encountered in the training phase and is generally thought to correspond to exemplar knowledge. The associative chunk strength of bigrams (symbol pairs) and trigrams (symbol triplets) in the test part is their frequency of occurrence in training (Knowlton & Squire, 1994, 1996). The chunk strength of a test item is the average of the associative chunk strength of all its chunks. In other words, chunk strength is whether a test item is composed of parts which are familiar from training (Pothos & Wood, 2009). The intact learning of both abstract grammar and similarity in amnesic participants suggests that both of these can be learned in the AGL task, and neither depends on an explicit learning system.

Knowlton and Squire (1996) further identified three distinct learning mechanisms underlying the AGL tasks : (a) the learning of abstract rules; (b) exemplar-specific learning, which permits individuals to judge the similarity between whole test items and specific training items, in which classification depends on the number of training items retrieved from memory that are similar to each test item; and (c) exemplar-specific learning that summarizes across the training exemplars such that individuals use acquired information about which letter bigrams and trigrams (chunks) are permissible or which appear frequently in the training set. In a sense, information about chunk frequency could be considered abstract in that it is abstracted/summarized across the training items. However, chunk-strength information is not abstract in that it is specific to the training items presented. Cleeremans and Dienes (2008) concluded that it is possible that a combination of both abstraction and exemplar-based processing is taking place, and successful models for implicit learning should be neither purely abstract nor exemplar-based.

Another model, the Self-Organizing Consciousness (SOC) model (Perruchet & Vinter, 2002), gave a more explicit role to attention in the learning process dealing with abstract knowledge. According to this view, participants automatically engage attentional processes guided by higher statistical properties (some bigrams or triplets presented more often than others) or salient perceptual features (e.g., repeated triplets like XXX, or XMXM) of the knowledge. The more salient a feature is, the more this feature can attract attention and consequently create a cognitive unit. Similarly, the more frequently this feature occurs, the more strongly the cognitive unit will be consolidated. Also, bigrams or triplets are chunked together to form larger fragments. Perruchet et al. (Perruchet, Vinter, Pacteau, & Gallego, 2002) asked participants to divide AGL sequences into parts before or after the training session, and found that participants formed the same number of cognitive units before and after the training phase, thus indicating that they did not tend to form increasingly large units. However, the number of different units reliably decreased. This result indicates that familiarization resulted in fragments more representative of the structure of the AGL stimuli (not larger ones), and more representative fragments are basically more frequent ones.

However, although models like SOC could explain some experimental data, it still remains uncertain if there is any difference in the mechanism between abstract knowledge and statistical exemplar knowledge learning. In assessing this, it is important to examine the conceptual difference between exemplar and abstract knowledge in the AGL. One perspective is to look at the learning process: abstract knowledge is top-down developed, through a hypothesis-testing phase; while exemplar knowledge is developed via bottom-up mechanisms (Sun, Merrill, & Peterson, 2001). Pothos (2005) proposed a frequency-independent nature of abstract knowledge. Exemplar knowledge develops by associative learning, with classification made by participants retrieving specific training examples from memory with learning being based on the frequency of occurrence of fragments (i.e., the relations of different elements, bigrams, lag information, etc.). Here any co-occurrence of two or more elements can be an association, which could be tracked by the cognitive system; and such association strength is weighted by the frequency of co-occurrence. According to Pothos' frequency-independent proposal, abstract knowledge is developed as a function of experience with exemplar knowledge, however, when the abstract model is established, the knowledge is applied in the same way but regardless of the frequency with which it has been experienced. The frequency-independent view of AGL rules may be compatible with the scope of Knowlton and Squire's (1996) three learning mechanisms (a, b, and c, p136 in this chapter): the exemplar knowledge (b) is gradually accumulated across the training, and the rule knowledge (c) is summarized but still dependent on the frequency, while the abstract rule knowledge (a) is eventually established and independent on the frequency.

Pothos' proposal does not identify whether the abstract and exemplar learning systems are separate or not. This may be because both Knowlton & Squire, and Pothos' hypotheses are more concerned with the outcome, learnt knowledge, instead of the actual learning process. It should also be noted that although the training materials are generated from a specific rule, it is possible that the set of exemplars could be generated from a different rule system. Therefore abstract knowledge continues to be tested and optimized by new stimuli until a frequency-independent model is established. The last phase involves top-down active hypothesis testing, however, implicit cognition typically involves processes that are automatic, passive and unintentional, therefore, from a conceptual view, the establishment of abstract knowledge must involve explicit hypothesis-testing process, which leads to a question of how exactly abstract knowledge can be acquired in an implicit learning task.

One hypothesis to explain this question is in fact during the exposure of the training strings, participants develop explicit hypotheses to describe the regularities in the training items. For example, Dulany et al. (1984) proposed a microrules hypothesis of AGL, which suggested that participants develop insights about which elements (bigrams, trigrams, etc.) are characteristics of the training items. For example, they might notice that training items start only with an X or a V. At test, when they are told that there are legal and illegal items, they may use these insights to determine which items are grammatical. Compared to the fragment learning hypothesis of learning in the AGL (Perruchet & Pacteau, 1990), the microrules hypothesis proposed by Dulany et al. could be considered more as a mechanism which leads to the development of frequency-dependent knowledge, and consistent with the (c) summarized exemplar knowledge in Knowlton & Squire's hypothesis (p136 in this chapter).

While Dulany's microrules are proposed to develop during the training phase, the other hypotheses (Pothos & Wood, 2009) suggest that the training phase only involves passive observation, while any hypothesis testing in AGL might take place at test. In Pothos & Wood's study, they adopt the COVIS (COmpetition between Verbal and Implicit Systems) model, which highlights two distinct learning systems in implicit learning, a hypothesis-testing system and an information integration/procedural-based system. Based on neuroscientific data (Ashby, Alfonso-Reese, Turken, & Waldron, 1998), the key neural structures for the procedural learning system in the COVIS model are the inferotemporal cortex and the tail of the caudate nucleus, and it is suggested that this system depends on a dopaminergic reward signal from the ventral tegmental area. The procedural learning system learns to associate a category response with a region of perceptual space without deriving any explicit rule, while the hypothesis-testing system involves the prefrontal cortex, the anterior cingulate cortex, and the head of the caudate nucleus. The role of the hypothesis-testing system is to identify explicit verbal rules, and has been widely implicated in planning, differentiating amongst conflicting goals, and identifying expectations based on actions (Pothos & Wood, 2009). Pothos and Wood applied this COVIS model to implicit learning in AGL, and argued that the procedural learning system possibly learns exemplar/chunk strength information about the training stimuli, since chunk strength knowledge is developed in a passive way, based on perceptual similarity and familiarity and it is not informed by any particular hypotheses of the training stimuli. When grammaticality and exemplar knowledge are balanced, then grammaticality plausibly involves knowledge, which is more rule-like and less frequency-dependent. The hypothesis-testing system can be hypothesized to be associated with grammaticality learning, which takes place at test. Therefore, according to this hypothesis, prefrontal cortex damage should be associated with impaired grammaticality but intact chunk strength performance. Their prediction was confirmed by finding that the traumatic brain injury (TBI) patients, who had diffuse prefrontal cortex damage as evidenced by the history of their injury and CT scans, performed impaired grammatical learning but intact similarity learning in the AGL task.

Pothos & Wood's argument with the COVIS model is interesting as, in addition to providing a neuropsychological explanation of the different learning systems underlying implicit learning, it has also provided an explanation to how the abstract knowledge has been acquired in the AGL tasks: the hypothesis-testing phase for acquiring abstract knowledge does not happen during the training phase, but at the testing phase. This argument is consistent with the opinion that the transfer effect may also reflect an explicit matching strategy between two different vocabularies (Redington & Chater, 1996). This argument suggests only accidental and unintentional process are involved in the learning phase in the AGL, while the abstract grammar learning performance requires the involvement of explicit process. Therefore the learning effect in implicit learning tasks could reflect both abstract and exemplar knowledge. As Barsalou noted:

> *"It is therefore impossible to conclude from behavioral research on category learning that people represent categories with exemplars or abstractions. Instead we can only conclude that particular models (i.e., representation-process pairs) are either supported or rejected." (Barsalou, 1990)*

If by definition, the hypothesis-testing phase is not able to be included into the implicit learning phase, the learnt classified exemplar knowledge can gradually develop into Fragment/Chunk Knowledge (Knowlton & Squire, 1996; Perruchet & Pacteau, 1990), which is still implicit and frequency-dependent. Frequency-independent microrules (Dulany, et al., 1984) could be established by the next-step hypothesis testing phase, which are the basic unit of the eventual abstract knowledge. However, the hypothesis testing may only be able to happen explicitly.

3.1.2. Implicit abstract learning in dyslexia

As discussed above, the ability to learn abstract rules is a cognitive one involving pattern recognition and hypothesis-testing (Sternberg & Pretz, 2004), while an impaired ability to abstract rules would be particularly apparent during language acquisition because linguistic systems are highly rule governed.

There is now considerable evidence that dyslexics appear to have particular difficulties spelling and reading those words where a rule needs to be applied (Dodd & Gillon, 1997). This suggests one deficit underlying dyslexia might be an impaired ability to abstract rules, and some evidence has been found that dyslexic participants have problems related to the production and comprehension of certain abstract grammatical constructions (Morrison, 1984; Rice, Wexler, & Redmond, 1999; Waltzman & Cairns, 2000; Wilsenach, 2006).

Morrison (1984) conducted a series of experiments that investigated the characteristics of abstract rules that may pose problems for poor readers. Those studies mainly assessed the rules on word pronunciation by normal and dyslexic participants of rule consistency ('ee' in 'keep' and 'queen' vs. 'o' in 'both' and 'moth'; word consistency ('meal' can inform the spelling of unknown words such as 'deal' or 'seal'), and rule conditionality (conditional grapheme-phoneme correspondences were defined as completely transparent). The findings indicated that rule consistency and conditionality had a greater influence on dyslexic participants compared to normal participants. Morrison concluded that one source of dyslexic people's problem lies in the complex, irregular system of rules governing grapheme-phoneme correspondences. However, the stimuli used in Morrison's study were real words, thus the results may have been influenced by the use of visual recognition strategies. More important, the tasks were all about the rules of grapheme-phoneme correspondences (i.e., the phonological rules), in order to correctly apply the regularities required by the tasks, participants must have fairly good representations of the phonological features, in which dyslexics may not be able to represent these phonological features correctly.

In another study by Dodd & Gillon (1997), the authors used both non-linguistic and phoneme-grapheme rules, and found that children with dyslexia had difficulties in dealing with rule flexibility, and abstraction difficulties were not restricted to linguistic tasks. For the non-linguistic task, the participants were required to transfer one abstract rule from color to size. Their findings suggest that the nature of some dyslexics' rule abstraction impairment may be a lack of flexibility in the application of rules, which are either irregular or complex.

Wilsenach (2006) reports the results of a battery of tests to assess the ability of a group of Dutch dyslexic children to perceive and produce abstract morpho-syntactic dependencies. Her study focused more on dyslexic children's capability on a more general language-specific grammar rules, and she found that dyslexic children are less able to discriminate between grammatical and ungrammatical combinations (e.g., 'kan geslapen' means 'can slept' in English as an ungrammatical example). In particular, dyslexic children are more inclined to accept ungrammatical combinations of a modal verb with a past participle.

A problem in the previous studies is that tasks typically require explicit instructions, attention to stimuli, and introspection, which may blur the interpretation of the effects observed, particularly so when the population tested has problems with phonological awareness (Ramus & Szenkovits, 2008). It is also important to clarify if the proposed abstraction problem of dyslexia is specific to relevant linguistic representation or not. One solution to this problem is to observe indirect effects of experimental manipulations of which participants are unaware of abstract rules, with visual and non-linguistic stimuli.

Pavlidou and colleagues conducted a series of studies on dyslexic children's abstract knowledge learning with the AGL task (Pavlidou, et al., 2010; Pavlidou & Williams, 2010; Pavlidou, et al., 2009), which all found dyslexic children's impaired in only abstract knowledge learning, but not exemplar learning. In the first study (Pavlidou, et al., 2009), two AGL experiments were conducted, with either implicit or explicit instructions. Results showed a group effect only with implicit instructions, with only the typically developing children showing evidence of learning. More importantly, the dyslexia group did not show learning of grammatical knowledge. This study suggested first dyslexic individuals' impairment in implicit abstract learning when their explicit learning has been shown to be intact.

In a later study (Pavlidou, et al., 2010), two measures of performance were used with the AGL tasks in both dyslexic children and controls: a perfect free recall (PFR) score and a grammaticality judgment score. Results showed that both groups of children required the same amount of exposure to learn complete information about all the items (i.e., PFR performance). However, typically developing children showed above chance performance in terms of both grammaticality and chunk strength of the stimuli, while children with developmental dyslexia on the other hand, failed to show implicit learning irrespective of the substring characteristics (i.e., grammaticality or chunk strength). Pavlidou et al. concluded that the dyslexic children may be only impaired in their implicit rule abstraction mechanism.

To further explore dyslexic children's impaired abstract learning, a third study was conducted by involving a transfer condition (Pavlidou & Williams, 2010). Two experiments were conducted in the study with both transfer and non-transfer conditions, and they found that typical children showed intact implicit exemplar and grammar learning under both transfer and non-transfer conditions. However, dyslexic children were less able to classify NG accurately compared to typically developing children under the non-transfer condition; under the transfer condition, children with developmental dyslexia had difficulties identifying grammatical items. These results further supported dyslexics' impairment in abstract learning.

Two other studies using the AGL paradigm did not find any impairment of dyslexics' AGL (Pothos & Kirk., 2004; Russeler, et al., 2006). However, both Pothos and Russeler's study only examined dyslexic people's general learning performance in the AGL task, without separating abstract learning and exemplar learning. Taking all the above five studies into account, it might be suggested that impairment in abstract learning exists within the dyslexic population. The results of the Exp. 2a in Study II in the current thesis also suggested an abstract learning problem in dyslexic participants; however, there are several issues, which require further exploration.

One issue concerns whether higher-order information is necessary to develop abstract knowledge. In all three of Pavlidou's studies, with Knowlton & Squire's classic measurement to look at both Grammaticality (G/NG) and Chunk Strength (High-CS/Low-CS) learning in the AGL tasks, the learning of Grammaticality is indexed by the interaction between G and NG strings. Typically, participants are only able to recognize a novel, grammatical bigram, by using 'deductive reasoning'. For example, they learn the fragments of 'V x X' ('x' refers to any random element) and 'MX', so 'VM' might be grammatical at a higher chance, and consequently 'VM' may be judged as 'grammatical' when tested. In this case, knowledge of longer chunks (like the lag 2 information V x X) is necessary for people to speculate on the grammatical knowledge, when only bigram knowledge is not enough to underpin this type of speculation. Some empirical evidence for this could be taken to be Gomez's (1997) finding that knowledge of triplets is important for the transfer effects in the AGL tasks, suggesting a link between triplet learning and transfer performance. This issue leads to a possibility that the deficit in learning longer chunks may influence dyslexics' performance in abstraction learning in tasks containing second-order information. This possibility suggests a measurement problem because the variable of abstract learning and second-order learning are not independent to each other when simply examining participants' learning of exemplar and abstract knowledge. Therefore, it is important to further clarify when only simpler lower-order (zero- and first-order) information is required in the task, if dyslexic participants still show impaired abstract learning.

A second issue concerns the underlying explanation if dyslexics have any different performance compared to non-dyslexic people in abstract knowledge learning. If dyslexics have abstract learning deficit even when only lower-order information (e.g., zero-order, bigram association) is involved, that may suggest impairment only in an abstract learning mechanism. Therefore, dyslexic participants should show intact fragment learning of zero- and first-order information, but only have problems in learning abstract knowledge.

The third issue concerns the length of training program. Some researchers investigating effects of phonological skills training have argued that participants benefit from an extended training period (Nicolson & Fawcett, 2000). The question is if dyslexic participants develop abstract knowledge at the same time as controls, or they will show abstract learning later than controls.

As discussed earlier in this chapter, pure implicit learning may not lead to any abstract knowledge (Pothos, 2007), as the hypothesis-testing phase may to some extent involve explicit effort. However, it is the process rather than the resulting knowledge which is the focus of the current studies, i.e., under incidental conditions, how much abstract knowledge dyslexic participants are able to gain and if there is any difference from the controls. It should also be noticed that also we focus on the implicit learning process instead of the learning nature (implicit/explicit) here, it is still important to avoid the explicit awareness as much as possible, especially when only simple information is involved, or the explicit compensation effect may mask any impairment.

3.2. Study III: the digit invariance task

3.2.1. What can be learnt in the digit invariance task?

McGeorge and Burton (1990) developed a 'digit invariance task'. The digit invariance (DI) task presents participants with 30 four-digit numbers one by one. The participants were asked to compare the total of the pair of digits on the left of the strings with the pair on the right and make a fast decision which digit pair adds to the higher total. Without any direct instruction, digit '3' appeared in all of the strings. Following this *arithmetic* task, participants were given a false-recognition task consisting of 10 pairs of four digit strings, and participants were told that they had seen one of the two strings in the arithmetic task and were asked to choose the string in each pair that they believed they had seen previously as quickly as they could. In fact, neither four-digit string in each pair is old (i.e., what they were presented in training phase) but one string contained the digit '3'(termed the "positive"). It is important for participants to make the judgment very quickly (e.g., in two seconds), so participants have no time to develop any explicit strategy for selection (Kelly & Wilkin, 2006). If participants were unsure they were asked to guess. McGeorge and Burton found that participants chose the 'positive string' with a digit '3' significantly more often than chance.

As with the similar argument with the AGL paradigm of learning of both abstract and exemplar knowledge (Knowlton & Squire, 1996), Cock, Berry, & Gaffan (1994) presented an explanation of learning in the digit invariance task in which whole string similarity between specific test strings and learning strings causes the above chance learning effect. Specifically, Cock et al. (1994) suggested that rather than relying on an implicit rule (i.e., the invariant digit ‘3’ in McGeorge and Burton’s study), participants may simply choose the test string that is more similar to one seen in the presentation phase. Cock et al. argued that during the testing phase participants are made to believe that they are doing a memory test so it is quite likely that they made the judgment between the two testing strings based on their feelings of familiarity. By this rationale, testing strings that are more similar to the learning strings will be chosen by the participants more often than the dissimilar strings. Cock et al.’s study carried out a series of alternative digit invariance tasks, in which the presence of the invariant digit ‘3’ and the specific similarity of testing strings to individual learning strings were independently manipulated in six different conditions of a between-participants design. The degree of similarity between learning and testing strings was determined by the overlap of digits and their position in the string. This led to the condition of positive (those with a digit ‘3’) similar (i.e., PS) and positive dissimilar (i.e., PD) strings, and negative similar (i.e., NS) and negative dissimilar (i.e., ND) strings. For example, if participants had seen the string 4376 during learning with an invariant digit ‘3’, then 1376 would be a PS string; in contrast having seen 3287 in the learning phase, 4287 would be a NS string; an example of a ND might be 2761 in comparison to 5327 and a PD might be 6923 compared with 2385. Cock et al. (1994) found across conditions participants were significantly more likely to select the similar strings; however, the selection of the positive strings was only at chance level. These findings suggest that a general similarity model could account for the learning performance in the digit invariance task.

However, Wright and Burton (1995) argued that in Cock et al.'s study, the repetitions in testing strings was not controlled (a string contains more than one same digit, e.g., 7274), and the participants may score at above chance levels is because it is easy to reject the very distinctive strings from very similar strings, as repetitions occur less frequently in the positive testing items, there will be fewer occasions when it is easy to reject positives on this basis, and hence subjects will score at above-chance levels. Wright and Burton then concluded the participants' performance in Cock et al.'s study should be considered as rejecting repetitions than accepting positives.

Kelly and Wilkin (2006) conducted a series of digit invariance tasks to explore the interaction between exemplar and abstract learning. Only the PD/NS comparison was included in the tasks, to either make participants select the strings with the invariant digit (the abstract rule), or the strings in higher similarity (the exemplar knowledge). In the second experiment, participants were put into three different conditions with either 10, 30, or 50 four-digit strings presented in the arithmetic training task, and the results showed that with only 10 strings during the training phase, participants showed a preference to select the NS string, suggesting learning of exemplar knowledge. However, with more training strings (30 and 50), participants developed abstract knowledge of the invariant digit by more selecting the PD strings. These results suggest a process for the development of abstract knowledge development, and are consistent with our earlier proposal: at the early stage of learning, the rule-like knowledge is based on the statistical learning of feature frequency before frequency-independent abstract knowledge is established.

The digit invariance task is much simpler than the AGL task regarding the knowledge involved: the abstract rule in the digit invariance task is considered to be knowledge of the 'invariant digit', which repeatedly appears in every training string (which can be considered as statistical zero-order information). Although Perruchet and Pacteau's (1990) suggestion about fragment learning in the AGL task involved the symbols' co-occurrence, in the digit invariance task, participants develop knowledge of the common single element across stimuli, and eventually may develop a frequency-independent rule about the 'invariant digit'. As the four-digit strings in the digit invariance task are arranged as two pairs of bigrams (see the earlier example strings and more examples in the following experimental method), no higher than first-order information is included in the digit invariance task, which is ideal for the purpose of ruling out any higher-order information of the current study.

The aim of this experiment was therefore to explore two main questions: first, whether dyslexic participants are capable of learning the invariant digit, whether as frequency-dependent exemplar knowledge, or as frequency-independent abstract knowledge. This question was investigated by asking the participants to select between PS/NS strings, as these two strings have identical specific similarity, but only differ in presence or absence of the 'invariant digit'. Therefore, if participants show any preferable selection of the PS strings, that means the participants have gained knowledge of the ‘invariant digit’, which may be considered as either exemplar or abstract knowledge. Second, if participants are able to learn the invariant digit, should this be considered as the exemplar knowledge or abstract knowledge? As discussed earlier in this chapter, with Knowlton & Squire’s framework (Knowlton & Squire, 1996) and the argument proposed by Pothos (Pothos, 2007), the key difference between exemplar knowledge and abstract knowledge is if such knowledge is frequency-dependent. This question was investigated by letting participants select between PD/NS strings, to determine if only one kind of knowledge could be applied to make the selection, what selection dyslexic participants will make. If participants have gained abstract knowledge of the invariant digit, they should select more PD strings, because the abstract knowledge is frequency-independent and participants’ selection should be dominated by the abstract knowledge. If participants’ knowledge of the invariant digit is not frequency-independent abstract knowledge, they may show similar preferable selection between the PD and NS strings, because these two kinds of strings contain either single element (zero-order information) or bigram (first-order information), which were both presented in the training phase, and participants may choose either of them by their familiarity of this information.

3.2.2. Experiment 3

Method

Participants

24 university students (12 dyslexic and 12 non-dyslexic) volunteered to participate in the study. Dyslexic participants were recruited by responding to emails sent by learning disability support centers in both Strathclyde University and Glasgow Caledonia University. All dyslexic participants offered their formal diagnostic documentation. The control group responded to recruitment posters placed on campus or the Strathclyde University website. All controls were required to report if they had any learning disability or relevant diagnosed history before, none of these controls reported such history. All of the participants are native English Speakers. None of these participants had participated in similar studies before.

A series of behavioral tests identical to previous experiments were conducted to characterize participants' relevant abilities: the Wide Range Achievement Test- Revised-Tan (Wilkinson, 1993) was used to test spelling and reading ability; the Rapid Naming Speed Tests (Denckla & Rudel, 1976) showed the time every participant needed to name 50 digits and objects; the Spoonerism task (Perin, 1983) tested participants' ability to segment and manipulate phonemes; digit forward and backward span tests were based on the Automated Working Memory Assessment (AWMA) (Alloway, 2007); the Wechsler Abbreviated Scale of Intelligence(WASI) provided measures of participants' verbal and performance IQ (Wechsler, 1999).

As shown in Table 13, the difference between the two groups in terms of Rapid Naming (Digit and Object), short-term memory (digit forward span), working memory (digit backward span), phonological awareness

(Spoonerisms) and literacy (WRAT-spelling and WRAT-Reading) are significant as expected. There was no significant difference between two groups' age or IQ (performance or overall IQ), but the dyslexic group showed a significantly lower verbal IQ than control group.

Table 13 Participants characteristics in Exp. 3

	Dyslexia		**Control**	
	Mean	SD	Mean	SD
Gender	6M6F	/	10M2F	/
Age	23Y10M	5Y6M	22Y2M	4Y3M
WRAT-Spelling (Tan) ***	98.75	6.65	112.08	6.32
WRAT-Reading (Tan) ***	102.92	6.23	116.58	4.81
Digit Naming(secs/50items)***	17.73	2.64	13.82	2.22
Object Naming(secs/50items)**	33.05	4.73	27.08	4.25
Spoonerisms * (mean correct, max = 20)**	14.83	2.73	18.42	2.07
Digit Forward Span***	27.25	2.38	40.67	3.06
Digit Backward Span **	15.75	4.88	22.83	7.02
WASI-verbal*	123.92	6.69	129.17	4.76
WASI-performance	115.92	7.17	109.33	11.25
WASI-overall	122.67	5.63	121.00	7.58

*$p \leq 0.05$ **$p \leq 0.01$ ***$p \leq 0.001$

Digit Invariance (DI) Task

Stimuli

30 four-digit strings were randomly generated but with the digit '5' in every string. Testing strings were generated in three different conditions: Positive and dissimilar (PD), positive and similar (PS), negative and similar (NS). These testing strings were generated in the same way as described by Cock et al. (1994) but without any repetition in each string. For a PD string, the

two digit pairs switched sides, and the digit pair that did not contain the invariant digit was replaced by another digit pair, which had not occurred in the training strings. For example, if the training string is 7523, a PD testing string can be 8475. To construct a NS string, the invariant digit was replaced by another digit but the other three digits stayed the same. For example, if the training string is 7523, a NS string can be 7623. For a PS string, the invariant digit '5' was always retained while another digit was changed. For example, if the participants had seen 7523 in the training phase, a PS testing string can be 7526.

The Digit Invariance tasks were run on an Intel Core Duo personal computer with 15-inch screen. The four digits in each of the strings were presented centrally on the computer screen in while against a white background in Arial font, Size 28. The program was written using E-prime Version 2.0.

Design

Each participant undertook two testing conditions: in one condition, they were asked to select one string from PD/NS pairs; under the other condition, they were asked to select one string from PS/NS pairs. There were 10 pairs of four-digit strings for every condition. All 20 strings were assigned in intermixed random order.

Procedure

Thirty four-digit strings appeared one at a time on the computer screen, and participants were required to add the digit pairs on both (left/right) sides and press a corresponding key on a response pad to indicate which pair came to the higher total. This task was self-paced, and the instructions emphasized accuracy rather than speed (Kelly & Wilkin, 2006).

Participants were then told they were going to be given a memory test for the four-digit strings that they had just seen. They were presented with 20 pairs of four-digit strings, under either PD/NS or PS/NS condition, and were required to choose which string had appeared in the earlier arithmetic task with corresponding keys. They were also told that they would only receive two seconds in which to make a response, and they were told to make a quick guess if they were not sure which one they had seen before. Prior to the testing, participants were given four simple arithmetic questions on the screen to make quick judgments, such as '1+5=7, true or false'. Participants were asked to make a true or false judgment using the response pad within two seconds. This practice task was to demonstrate to participants the required speed of response during the test phase.

After participants completed the practice questions, they started the testing with 20 selection testing pairs. Each pair of the four-digit strings appeared on the screen for two seconds, and any response after this duration was not recorded. There was a 2 second response stimulus interval after the response made till the next pair appeared. To ensure that the task is two-alternative forced choice rather than selection of rejection of a single test item, participants were also asked to look at both four-digit strings on each side of the screen rather than only look at one string before making the decision.

After participants had responded to all 20 testing pairs, they were asked the following questions:

- *Did you notice anything unusual about the digit-strings in the arithmetic task?*
- *Did you notice any similarity between the digit-strings in the arithmetic task?*
- *There was actually one digit that appeared in all of the digit-strings in the arithmetic task. Did you notice this?*
- *Even if you did not notice the repeating digit, if I asked you to guess at what that digit might have been, which digit would you pick?*

Results

Any participant who was not able to respond to any of the 20 pair-selection within the 2 seconds time limit was discarded. One dyslexic and one control participants' data was discarded, which left a total of 11 dyslexic and 11 control participants in each group.

Table 14 Mean number of positive strings chosen for both conditions (Mean/SD)

Condition	Dyslexic Group	Control Group
PS/NS	5.81/.87*	5.91/1.22*
PD/NS	6.00/1.34*	6.09/1.22*

*p≤ 0.05

Table 14 shows above chance (i.e., 50) performance for choosing positive exemplars in each pair and this was confirmed by one sample t-tests: with PS/NS condition, for dyslexic group, t(10)= 3.11, p=.01; for control group, t(10)= 2.47, p=.03; with PD/NS condition, for dyslexic group, t(10)= 2.47, p=.03; for control group, t(10)= 2.96, p=.01.

No significant difference was found between groups for PS/NS pairs: F(1, 20)= 2.26, p > .10; or between PD/NS: F(1, 20)< 1.

No participant reported noticing anything unusual or similarity between the digit-strings in the arithmetic task; and no participant reported noticing there was a digit appeared in all of the digit-strings in the arithmetic task. When participants were made to guess the repeating digit, one dyslexic participant made a correct guess of the invariant digit, however, she did not show a preferable use of the invariant digit: 6 for PS/NS selection and 4 for the PD/NS selection. Two participants even guessed the digit ‘0’ (digit ’0’ never appeared in the strings) which suggested participants had no explicit awareness of the invariant digit.

Discussion: Exp. 3

The aim of Exp. 3 was to examine whether dyslexic participants were able to learn the abstract knowledge under an implicit condition, by first testing if they were able to gain the knowledge of the invariant digit, and then checking if such knowledge is exemplar or abstract knowledge. In the task, dyslexic participants showed they have gained knowledge of the invariant digit '5' by a preferable selection of the PS strings from the NS strings. Moreover, they showed as much as abstract knowledge as controls, by showing a preferable use of the invariant digit between the PD/NS selection.

Therefore, in this study dyslexic participants demonstrated that they had intact abstract learning as measured by knowledge of the invariant digit. Furthermore, their knowledge of the invariant digit could be confirmed as abstract knowledge by their preferable selection of PD strings between PD/NS strings.

However, it is important to examine the differences between the digit invariance task and a classic AGL task. The instructions for the testing phase in the digit invariance task are deceptive as it is claimed that one of the two four-digit strings had been seen in the training phase, and participants were required to make a decision in just two seconds. Thus instead of 'judging if the strings follow the rule or not' as in the AGL task, in a digit invariance task, participants would believe they were doing a memory test and they may make the judgment based on their familiarity of the strings. Therefore, it is possible that judgments are typically based on perceptual recognition where there is an advantage for items that bear the same perceptual characteristics between the learning and test strings (Newell & Bright, 2002). In this case, it is difficult to determine the strategy that participants use to make their selection; it is possible that participants actually gained the knowledge of the invariant digit, but simply made their selection because of the familiarity of a bigram instead of a single invariant digit.

Even with the above concerns of the digit invariance paradigm, the results of Exp. 3 may still suggest dyslexics have intact implicit abstract learning capability. This result is different to the result of Exp. 2a, in which dyslexic participants showed impaired abstract learning when more than zero- and first-order information is required in the task. The results of Exp. 3 confirmed dyslexics have no problem in learning zero- and first-order information, and suggested the abstract problem they showed in Exp. 2a may be due to their impaired learning of second-order information.

3.3. Study IV: learning with an alternative SRT task

3.3.1. Howard's alternating SRT task: rules or similarity learning?

The ASRT (alternating SRT) task (Howard Jr. & Howard., 1997) has been discussed in Chapter Two. In the original version of the ASRT task, alternate stimuli follow a predetermined pattern, whereas the remaining stimuli are selected randomly, with each of the four events sampled uniformly (referring to four different locations on the screen). For example, if a given participant had been assigned the pattern 1432 (where 1 stands for the left-most position, and 4 for the right-most position), then that participant would encounter the following series, where ‘r’ stands for a random selection of one of the four possible positions: lr4r3r2rlr4r3r2rlr4, and so on.

Howard et al. claimed that there are several advantages for the ASRT paradigm. First, the probabilistic sequence makes participants much less likely to become consciously aware of any regularity and so the pattern learning is more clearly implicit. Second, alternating pattern with random trials makes it easier to examine the course of pattern learning in individual participants, because accuracy and response time can be calculated separately for pattern versus random trials for each testing unit (i.e., block or session), thus it is possible to determine precisely when pattern and random trials diverge for each individual.

A third advantage concerns the structure knowledge participants learn in the task, which is the focus of the current study. There is no first-order information in Howard’s ASRT task, because the sequence pattern is unstructured at the first-order level. If performance is better for the sequenced pattern than for random trials, then the simplest regularity that people could have learned would be that some triplets (chunks of three or second-order learning) are more probable than others because this is the lowest level at which random and pattern trials differ.

If we consider the pattern 1r4r3r2r as the example, chunks such as lr4, 4r3, 3r2, and 2r1 (where r refers to a random position) are frequent triplets because they are the only triplets that can occur when the third item is from the pattern as well as when it is random. In contrast, sequences such as 4r1 or 4r4 will be less frequent because they can only occur when the third item in the triplet is random. Furthermore, if participants show learning of the sequence pattern (in the form of better performance on pattern than random trials), two possibilities of what is learned can be actually distinguished as Howard et al. claimed (1997): first, it is possible that participants simply learn which triplets of events are relatively likely to occur, which is the learning of highly-frequent triplets; second, it is possible that individuals learn more than the relative frequency of event triplets. Howard et al. further argued that one possibility is that the participants learn something about the higher-order alternating structure of the sequence. In other words, they may learn that the sequence is structured on only alternate trials. Another possibility is that people learn the pattern structure that runs of four or greater are more or less likely to occur, and Howard termed both of the latter two possibilities as 'Higher-order Learning'.

To distinguish between the learning of highly-frequent triplets and higher-order learning, Howard et al. categorized each participant's performance on random items into two classes: those random items that occurred as the last item in a low-frequency triplets versus those random items that happened to occur as the last item in a highly-frequent triplet, thus the highly-frequent random triplets could be examined separately. If only knowledge about higher-frequency triplets has been acquired, the performance should be as good on these highly-frequent random triplet items as it is on pattern items, and only the low-frequency random items would lead to poorer performance. In contrast, if the Higher-order knowledge in addition to (or instead of) triplets has been gained, then performance to pattern events should be better than that to random events that are the third items of highly-frequent triplets.

In a series of studies (Howard, et al., 2004; Howard Jr., Howard, Dennis, & Kelly., 2008; Howard Jr., et al., 2006; Howard Jr. & Howard., 1997), Howard et al. found supporting evidence that instead of highly-frequent triplets, it is actually the higher-order knowledge participants have acquired in the ASRT tasks, by finding a significantly lower performance for the random events that are the third items of highly-frequent triplets compared to pattern events. The current study examines if the higher-order knowledge in the ASRT could be abstract rule knowledge and whether this is impaired in dyslexia.

Only above-first-order information is contained in the ASRT task sequence. However, there are several reasons to argue that the pattern sensitivity participants show in the ASRT tasks reflect knowledge of abstract rules. First, as Howard et al. claimed, if it is only the highly-frequent triplets that have been learnt, then performance for random events that happen to be the third items of highly-frequent triplets should be equal to the pattern events. However, performance is better for highly-frequent triplets ending on pattern trials than for those ending on random trials. Such a difference cannot be explained by triplet learning alone, and there must be some ‘other relevant information’ learnt. Second, as discussed by Howard et al., the ‘other relevant information’ may be the structure pattern, which is where the item *t* predicts the item *t*+2, and more important, the pattern is structured on only alternate trials. As discussed earlier, one important character for ‘abstract knowledge’ is it is frequency-independent (Pothos, 2005), and this is the reason why even with the same lag 2 prediction structure, the random events that are the third items of highly-frequent triplets still lead to lower performance compared to pattern events. This is because the abstract knowledge participants learnt here is the lag 2 prediction structure, not just highly-frequent triplets. Otherwise, performance should be the same for highly-frequent triplets ending on pattern trials than for those ending on random trials.

Following a similar paradigm to the ASRT, Howard et al. (2004) made the regularity in the SRT task even more complex by using lag 3 structure in which the lowest level of regularity spans four consecutive trials (e.g., sequence 1rr4rr3rr2rr, r refers to a random location). Interestingly, although a significant performance difference was found between the pattern and random events, no significant difference was found between the last events in the highly-frequent quadruplets ending on pattern trials and those ending on random trials, which suggest participants only gained the knowledge of the highly-frequent quadruplets rather than the abstract learning of specific sequence structure.

What made participants show different forms of knowledge learning in lag 2 and lag 3 ASRT, i.e., participants showed the 'abstract learning of specific sequence structure' in the lag 2 ASRT, but only the learning of highly-frequent quadruplets in the lag 3 ASRT? As has been argued, if the 'specific sequence structure' is considered as abstract knowledge, and the knowledge of the chunks (triplets in lag 2 or quadruplets in lag 3 ASRT task) can be considered as exemplar knowledge, there are two possible reasons to explain that although participants showed learning of the lag 2 abstract knowledge, they failed to gain lag 3 abstract knowledge but only lag 3 exemplar knowledge. First, previous studies suggested people could learn to use sequence elements up to three trials back to anticipate the next element in the sequence (Cleeremans & McClelland, 1991; Curran, 1997a; Remillard & Clark, 2001), and it is possible that the lag 4 information is necessary to establish the lag 3 abstract knowledge, which makes it difficult for participants to develop lag 3 abstract knowledge as participants can only learn to use up to four trials; second, it may take longer training to establish lag 3 abstract knowledge compared to lag 2 abstract knowledge. In the study (2004), Howard et al. conducted both lag 2 and lag 3 ASRT, with the same amount of training trials (2,100 pattern repetitions, i.e., 16,800 trials for lag 2 condition, and 25,200 trials for lag 3 condition). It is possible that only with much longer training trials, participants would be able to develop lag 3 abstract knowledge.

Besides, as discussed earlier in this chapter, the COVIS model predicts two independent learning systems for abstract learning and exemplar learning, therefore, it is also worth exploring if dyslexics have a profound deficit in abstract learning, i.e., it may be that dyslexics' abstract learning is impaired and cannot learn abstract knowledge at all, or just need more training instances. Earlier research showed that longer training can improve dyslexic individuals' learning performance. For example, Nicholson and Fawcett (2000) found that a dyslexic group were initially poorer in learning using four letter-key positions to move a target on the screen under a dual-task, however their performance matched controls after an extended period of training. Therefore, in the current study, we examine not only if dyslexics can implicitly learn abstract knowledge as well as controls, but also if they can learn abstract knowledge implicitly as quickly as controls.

In Exp. 4, using the similar paradigm of alternating SRT task but which only contains first-order information (i.e., bigram) and balanced second-order information (i.e., triplet), three questions were addressed: first, dyslexic participants showed implicit learning difficulties on only second-order learning but intact first-order learning in Study I and Study II, and can this be confirmed by dyslexic participants being able to show equal learning as controls when only first-order information is involved in the task? If so, their performance on pattern versus random trials should diverge. Second, Howard et al.'s study (2006) showed dyslexic individuals could not learn the abstract sequence structure knowledge with a lag 2 ASRT task, however, the results of Study III showed dyslexic participants have intact abstract learning when only first-order information is required. In this case, if only first-order information is required, do dyslexic participants learn only highly-frequent chunks (the exemplar knowledge), or do they learn the structure pattern information (the abstract knowledge)? Third, the results of Study I suggest a possibility that dyslexic individual might take longer training to show equal learning performance to controls. Therefore, can dyslexic participants gain this abstract knowledge as quickly as controls? If so, such knowledge should be revealed with similar amounts of training trials for both groups.

Compared to the AGL task and the digit invariance task, the SRT task demands are low because it is not necessary for participants to encode relevant information (either the letters or symbols in Exp. 2a or Exp. 2b, or the digits in Exp. 3) to perform according to task instructions. Besides, the structure embedded in the material is of very low salience, since most of the information relevant to optimizing performance on the task is present in the context rather than in the manifest stimulus, and both factors would tend to lower participants' attempts at using explicit learning strategies in typical implicit learning situations (Cleeremans, 1993b). Also the SRT paradigm is fast-paced so participants have little time to develop explicit strategies or to ponder about the regularities present in the materials.

There are further two advantages to use the ASRT instead of a normal SRT task with deterministic sequences to further assess dyslexic participants' abstract learning. First, it is necessary to control the explicit contribution to the learning in the task, as for examining the abstract learning of simple information (e.g., bigrams), it is actually easier for participants to gain explicit knowledge, and an ASRT paradigm provides a probabilistic sequence which could avoid explicit awareness; second, a RT paradigm allows both passive responses (i.e., the RTs response) and deliberate judgments (post testing after the ASRT) to test the learning.

3.3.2. Experiment 4

Method

Participants

12 students with documented diagnosis of dyslexia were recruited by emails sent by learning disability support centres at Strathclyde University and Glasgow Caledonian University. 12 control group members responded to recruitment posters placed on campuses of both universities and the Strathclyde University website. No control group member reported any learning disability or relevant diagnosed history. All of the participants were native English speakers.

In addition, a series of behavioural tests were conducted to characterize participants' relevant abilities as in previous studies: the Wide Range Achievement Test- Revised-Tan (Wilkinson, 1993) was used to test spelling and reading ability; the Rapid Naming Speed Tests (Denckla & Rudel, 1976) showed the time every participant needed to name 50 digits and objects; the Spoonerism task (Perin, 1983) tested participants' ability to segment and manipulate phonemes; digit forward and backward span tests were based on the Automated Working Memory Assessment (AWMA) (Alloway, 2007); the Wechsler Abbreviated Scale of Intelligence(WASI) provided measures of participants' verbal and performance IQ (Wechsler, 1999).

As shown in Table 15, the difference between the two groups in terms of Rapid Naming (Digit and Object), short-term memory (digit forward span), working memory (digit backward span), phonological awareness (Spoonerisms) and literacy (WRAT-spelling and WRAT-Reading) are significant as expected. There is no significant difference between two groups' age or IQ (verbal, performance, or overall IQ).

Table 15 Participants characteristics in Exp. 4

	Dyslexia		Control	
	Mean	SD	Mean	SD
Gender	8M4F	/	6M6F	/
Age	21Y1M	2Y5M	21Y10M	2Y2M
WRAT-Spelling (Tan) *	97.33	5.50	114.58	3.32
WRAT-Reading (Tan) *	94.08	9.27	111.17	5.12
Digit Naming(secs/50items)	21.30	3.56	17.10	2.29
Object Naming(secs/50items)*	36.80	5.75	28.29	2.47
Spoonerisms ** (mean correct, max = 20)	14.25	1.66	18.58	0.79
Digit Forward Span*	23.67	4.08	33.25	5.48
Digit Backward Span *	13.08	3.55	20.00	2.83
WASI-verbal	119.17	4.80	123.42	7.88
WASI-performance	111.92	7.27	108.75	9.46
WASI-overall	117.50	4.54	117.92	7.63

*p≤ 0.05 **p≤ 0.01 ***p≤0.001

Stimuli and Procedure

An alternative SRT task

Stimuli for the ASRT task in Exp. 4 were identical to those used in Exp. 1, except for the sequence. The sequence pattern only contains first-order information, with six higher-frequency bigrams. There are twelve possible bigrams in total for four different elements, P(4, 2) =12. In this task, '12' and '21' refer to two different bigrams, therefore, 13, 31, 12, 21, 42, 24 were used as higher-frequent bigrams. Training materials were generated by intermixed randomly presented six high-frequent bigrams. For example, a training sequence could be '12 31 42 24 13 21 21 13…'. Therefore, all first events in the bigrams are somehow unpredictable; all the second events in the bigrams are predictable, while the second unpredictable and the first predictable event together form other lower-frequent bigrams (i.e., 23, 32, 14, 41, 34, 43). Thus, for the Exp. 4, there is no second-order association; the only information participants could possibly learn was first-order prediction.

For the Alternative SRT task, there were 6 blocks in total; each block contains 120 trials generated by the lag 1 rules. In all blocks the trials followed a pseudo-random order with all four stimuli alternatives occurring equally often. The design was a 2×2×6 (Group × Trial Type × Block) mixed factorial, with Group (dyslexic versus control) as a between-participants variable and Trial Type (predictable versus unpredictable) and Block (1–6) as within-participants variables.

The experiment was run on an Intel Core Duo personal computer with 15-inch screen. The procedure was similar as Exp. 1 only the target followed the different sequence. The program was written using E-prime Version 2.0.

Rule Judgment Test

After completing the questionnaire, participants were told that all the training items followed the same complex rule structure and were asked to undertake the discrimination test. In this rule judgment test, 30 blocks with 20 trials each were presented and participants were asked to make the same response as they did in the SRT task they just finished. After they finished all 20 trials in every block, they were asked if the sequence they pressed followed the same rule as they did before or not. This rule judgment test is very similar to the testing in the AGL task, in which participants are asked whether the new sequence followed the rules or not, instead of the usual recognition test after the SRT task in which participants are asked if the new sequence chunks are the same as what they did in the task or not. In these 30 blocks, in ‘old condition’, trials in 10 blocks were generated by the same rule and the same bigrams used in the experiment; in ‘transfer condition’, trials in 10 blocks were generated by the same rule but different bigrams (the bigram 23, 32, 14, 41, 34, 43 were used to generate the testing sequences); in ‘random condition’, trials in another 10 blocks were randomly presented.

Explicit Awareness Test

Participants first completed an awareness questionnaire comprising the following questions:

- *Did you use any strategy to try to improve your performance? If so, what was your strategy?*
- *Do you think your strategy worked? Why or why not?*
- *Did you notice any kind of pattern or regularity of the stimulus?*
- *Do you have anything to report regarding the task?*

Results

First, pre-existing response tendencies exist for some trials. Following a similar method to Howard et al. (Howard, et al., 2004; Howard Jr., et al., 2008; Howard Jr., et al., 2006; Howard Jr. & Howard., 1997), the RTs for the trials which happened to be in specific patterns were ruled out. Trials incorporating repetitions (e.g., the second A in 'AA') and in trills (e.g., the second A in 'ACA') were ruled out in this case, as perceptual and motor priming participants tend to respond very quickly to repetitions and slowly to trills.

The median RT for correct trials was calculated separately for unpredictable and predictable trials for each block. The accuracy rate of both groups was consistent through 6 blocks, with no significant difference from each other: 97.03% for dyslexic group vs. 96.62% for control group, $F(1, 22) <1$. Both groups demonstrated more errors for unpredictable trials: for the dyslexic group, there is no significant difference between their accuracy rate for unpredictable and predictable trials: 96.50% for unpredictable trials vs. 97.55% for predictable, $F(1, 11)= 3.12$; for control group, 96.06% for unpredictable trials vs. 97.18% for predictable, and a significant difference was found, $F(1, 11)= 5.23$, $p= .04$, $ŋ^2 = .32$, suggesting a higher accuracy rate for predictable trials than unpredictable trials. The overall pattern indicates no speed-accuracy trade-off for neither group.

Learning of the regularity

Fig. 18 shows the mean of the median RTs for correct responses for unpredictable and predictable trials for dyslexic and control groups. A mixed design ANOVA with Group (Dyslexic vs. Control) × Block (6 sequential blocks) × Trial Type (unpredictable vs. predictable) shows a significant effect with Trial Type, $F(1, 22)= 60.43$, $p<.001$, $\eta^2 = .73$; a marginal significant effect was found for Block, $F(1, 22)= 3.48$, $p= .07$, $\eta^2 = .14$; no significant effect was found for Group, $F(1, 22)< 1$. A significant interaction was found of Block × Trial Type, $F(1, 22)= 6.10$, $p= .02$, $\eta^2 = .22$; no significant interaction was found for Block × Group, or Trial Type × Group, or Block × Trial Type × Group. A post-hoc trend analysis on Block revealed a significant quadratic effect, $F(1, 22) = 9.75$, $p = .005$, $\eta^2 = .31$. These results indicate that responses on unpredictable trials are slower than those on predictable trials, this difference slightly increases across blocks for both groups, and there is no significant difference between the groups. It should also be noticed that RTs to unpredictable trials being overall significantly slower over blocks (422.39 ms for Block 1 vs. 449.13.79ms for Block 6), while RTs to predictable trials stays rather similar over training (421.81 ms for Block 1 vs. 427.19ms for Block 6).

To get a better idea of the time course of learning, both groups' data was examined for each block. As early as in Block 2, both groups were responding significantly faster on predictable trials than unpredictable trials: the median RT for correct trials was calculated separately for unpredictable and predictable trials for Block 2, a mixed design ANOVA with Group × Trial Type (unpredictable vs. predictable) shows a significant effect with Trial Type, $F(1, 22)=35.81$, $p< .001$, $\eta^2 = .62$. There is no significant difference for Group, $F(1, 22) <1$; or Trial Type × Group, $F(1, 22)= .26$. These results showed that both groups gained some pattern sensitivity as early as the second block, and there is no group difference.

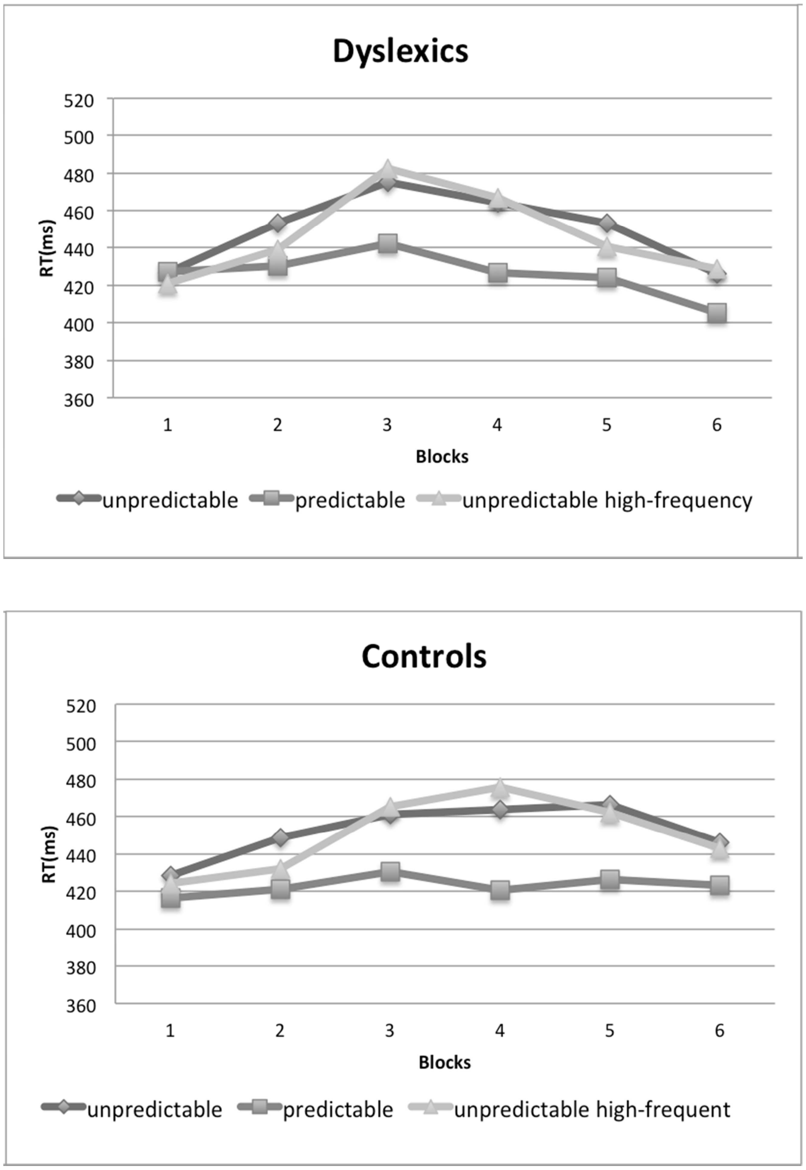

Figure 18 Mean of median RTs for unpredictable, predictable, and unpredictable trials but in the second place of highly-frequent bigrams per block for both groups with all 6 blocks

What did the groups learn?

To determine whether participants were engaging in learning of highly-frequent bigrams or abstract structure rules, the median RTs for unpredictable trials that were at the end of higher-frequency bigrams in each block for every participant were calculated, because the unpredictable trials still possibly followed the previous trials to by chance make up a highly-frequent bigram. For example, for the higher-frequent bigram '12', the '1' is in the unpredictable position, and '2' is in the predictable position; this highly-frequent bigram '12' could potentially be presented after another highly-frequent bigram '42', which makes the '1' happen to follow the '2' in '42'; while '21' is also a highly-frequent bigram, so the '1' here is an unpredictable event but happens to be at the first place of a higher-frequent bigram. As outlined in the introduction, if participants are only learning highly-frequent bigrams, then highly-frequent unpredictable trials should be identical to predictable trials, because the frequencies of the bigrams are identical to each other. In contrast, if participants are engaging in learning structural rules, then predictable trials should become faster than highly-frequent unpredictable trials over blocks.

As shown in the Fig. 18, the RTs for unpredictable highly-frequent trials seem different from predictable trials, but more similar to unpredictable trials. A mixed design three-way ANOVA with Group × Block (6 sequential blocks) × Trial Type (unpredictable vs. unpredictable highly-frequent vs. predictable) shows a significant effect for Trial Type, $F(1, 22)= 25.50$, $p<.001$, $\eta^2 = .54$; a marginally significant effect was found for Block, $F(1, 22)= 3.74$, $p=.07$, $\eta^2 = .15$; also a marginally significant interaction was found for Block × Trial Type, $F(1, 22)= 3.94$, $p= .06$, $\eta^2 = .15$. No significant effect was found for either Block ×

Trial Type × Group, or Block × Group, or Trial Type × Group, or Group, F(1, 22)<1. A Bonferroni post-hoc test (p < .05) showed that the RTs to the predictable trials produces significantly different result from the unpredictable and unpredictable highly-frequent trials, p<.001; the RTs to unpredictable and unpredictable highly-frequent trials were not significantly different from each other. These results suggested both groups showed learning of the structure rules but not the highly-frequent bigrams.

To examine the time course of learning, both groups' data was examined for each block. As seen from Fig. 19, at the first two blocks, the RTs to the unpredictable highly-frequent trials were still more similar to the predictable trials, and since Block 3, the RTs to the unpredictable highly-frequent trials were more similar to the unpredictable trials. This is confirmed for Block 3, a mixed ANOVA with Group × Trial Type (unpredictable highly-frequent vs. predictable) shows there is a significant effect of Trial Type, F(1, 22)= 27.00, p< .001, $\eta^2 = .55$. No significant effect was found for either Group, F(1, 22)= .13; or Group × Trial Type, F(1, 22)= .17. For Block 2, the difference between the RTs to the unpredictable highly-frequent trials and predictable trials is still non-significant, F(1, 22)= 1.55, p=.23, $\eta^2 = .07$. These results suggested both groups developed abstract structure knowledge to the rules with a similar amount of training.

Deliberate rule judgment

For the rule judgment test, sequences in Blocks in 'Old bigrams' condition are generated by the same rule and the same bigrams as presented in the task (i.e., bigram 13, 31, 24, 42, 12, 21); while sequences in Blocks in 'New bigrams' condition are generated by the same rule but different bigrams (i.e., bigram 23, 32, 34, 43, 14, 41); sequences in Blocks in random condition were generated randomly. It was considered a correct judgment if participants judged either the old or new bigrams as 'Yes'; or judged the random sequences as 'No'. Both groups showed above chance judgment performance (Table 16). It should be noted both groups showed above chance discrimination for judging trials with new bigrams, which confirmed that both groups gained not only knowledge of the bigram but a structural lag 1 prediction rule. For either condition, no significant difference was found between two groups. The results suggest that dyslexic individuals have intact implicit abstract learning capability.

Table 16 Accuracy rate under every condition for discrimination test for each group Means and SDs of percentages correct

Condition	Dyslexia	Controls
Old bigrams	60.83/9.00**	62.50/14.22*
New bigrams	59.17/11.65*	57.50/8.66*
Random	70.83/7.90***	73.33/8.88***

*P≤ 0.05 **P≤ 0.01 ***P ≤0.001

Explicit Awareness

The responses to the questionnaires after participants finished the SRT task showed that most participants (7 in 12 dyslexic participants, and 5 in 12 controls) noticed a pattern but had been unable to find one they could describe. Many participants said they felt there was some repeated pattern, and some of the participants (4 in 12 dyslexic participants, and 5 in 12 controls) reported repeated triplets but none of the participants reported repeated bigrams. None of the participants could describe exactly the structure of the lag 1 rules.

Discussion: Exp. 4

Exp. 4, using a SRT learning paradigm, which only contained randomly assigned bigram associations, leads to several conclusions. First, participants performed better on predictable trials than on unpredictable trials, despite no one being able to describe any regularity accurately. Therefore, it could be concluded that the learning of the regularity was mainly implicit for each group. This confirms the earlier findings that dyslexic participants have intact first-order sequence learning.

Second, regarding what is learnt, participants in both groups acquire at least first-order statistical information about the sequence. This follows from the fact that four different events occurred equally often overall for predictable and unpredictable trials, hence the sequence contains no zero-order information in a statistical sense. So the better performance for predictable compared to unpredictable trials confirmed the earlier findings in Exp. 1 that dyslexic participants have intact learning of first-order information. Furthermore, analysis of the unpredictable trials which happened to be on the second element of a highly-frequent bigram indicated that participants also acquired knowledge of abstract structure in the sequence. This follows from the finding that predictable trials diverged from highly-frequent unpredictable ones. Both groups showed equal knowledge of the abstract structure. More important, the learning of the structure rule by both groups was further confirmed by participants' above chance judgment accuracy to the sequence generated with new bigrams. These results are inconsistent with Study. 2, which found a problem with dyslexic participants' implicit abstract learning when higher than first-order information was involved, but consistent with Study 3, which found an intact implicit abstract learning of dyslexics when only zero- and first-order information was involved: this result supports the earlier hypothesis that when only first-order information is required, dyslexic participants are able to learn the abstract knowledge implicitly as well as controls.

Third, regarding the time course, both groups started to develop the abstract structure knowledge with the same training trials, suggesting for implicit abstract learning, dyslexic participants do not only learn as well as controls, they learn as fast as controls.

The task used in Exp. 4 is a first-order learning version of Howard's ASRT task. The probabilistic sequence can minimize the explicit awareness for first-order information learning. Dyslexic participants also showed above chance judgment accuracy to the sequence generated with new bigrams, which further confirmed dyslexic participants gained abstract structure knowledge, and this knowledge was not influenced by explicit processes.

3.4. General Discussion

Both Exp. 3 and Exp. 4 contained only lower-order (zero- and first-order) statistical information, therefore dyslexic participants' problem in second-order learning as suggested by Exp. 1 and Exp. 2 should not affect their performance in the current two experiments, and so learning of abstract knowledge could be explored independently. Both Exp. 3 and Exp. 4 found intact learning in dyslexic participants, and analyses suggest that participants learned abstract knowledge in addition to exemplar knowledge. This result is different to those reported in previous studies (Pavlidou, et al., 2010; Pavlidou & Williams, 2010; Pavlidou, et al., 2009) where impairment in dyslexia was found. This possible impairment in abstraction raises two questions, are dyslexics impaired in general abstract learning, and what caused the different performance between these two experiments and other studies?

The COVIS model indicates two distinct learning systems in implicit learning, a hypothesis-testing system and an information integration/procedural learning system. We argue that dyslexics suffer from a deficit affecting the procedural learning system, but not the hypothesis-testing system by finding intact implicit abstract learning performance but impaired second-order exemplar learning performance. Although dyslexic participants showed impaired abstract learning in Exp. 2a and Exp. 2b, however, we argue that may be due to the second-order information is required in those two tasks, and dyslexics' impaired second-order learning is the reason for them to fail to show any abstract learning.

As discussed earlier, although evidence has been found that people with dyslexia have problems related to the processing of phonological representations and to the production and comprehension of certain abstract grammatical constructions, the grammatical difficulties are in most cases associated with more complex grammar rules, and linked to linguistic capability. However, dyslexics' problem in phonological processing, including phonological short-term memory and phonological representation, as well as phonological naming may affect their performance in the tasks. This is because most studies used linguistic stimuli (Morrison, 1984; Rice, et al., 1999; Waltzman & Cairns, 2000; Wilsenach, 2006), or involved non-linguistic but grapheme-phoneme correspondences as the stimuli (Dodd & Gillon, 1997) which required naming process. Also, most of the studies used dyslexic children as the participants, which brings more uncertainty due to the dyslexic children participants' problems in understanding instructions, or attention to the stimuli.

More important, our results also suggest dyslexics' difficulties are directly correlated to the degree of complexity of the tasks. Compared to learning materials, which only require simpler knowledge of shorter chunks, learning materials involving longer chunk knowledge is more likely to prevent dyslexic participants from learning. Similarly, a word with a complex phonological representation is more likely to trouble dyslexic participants than a word with a simpler phonological representation. The results are consistent with previous studies which also found dyslexics' performance is related to the task complexity. For example, Moore, Kagan, Sahl & Grant (1982) investigated the differences between average and dyslexic readers on an extensive array of cognitive, perceptual, and motor tasks. They concluded that when the task is very simple, decision times for dyslexic and control participants tend to be very similar, but the differences between the two groups increase when the task is made more complex.

Therefore it is important to consider the complexity level of the to-be-learnt abstract knowledge when examining dyslexic people's learning in these tasks. The underlying reasons for impaired abstract knowledge learning in previous studies including Exp. 2a, may be due to memory and attention problems because higher than first-order knowledge is required in Exp. 2a, but results of Exp. 3 and Exp. 4 suggest dyslexics' abstract learning capability *per se* is intact under implicit conditions. In both Study III and Study IV, the dyslexic participants achieved similar performance IQ scores as the controls, in subtests such as Similarities and Matrix Reasoning which entail abstraction and flexible problem solving. However, in the implicit condition, when attentional resource is limited, dyslexic people tend to show problems in abstration when more complex information is needed.

Study I and Study II in Chapter Two suggest statistical complexity may affect dyslexic people's implicit learning performance. In this chapter, Study III & Study IV further examined the influence of statistical complexity on dyslexic people, suggesting they may have intact abstract learning when only zero- and first-order information is involved. These results suggest in an implicit learning condition, dyslexic participants have an intact abstract learning system, and their procedural learning system may be affected depending on different complexities of learning materials. However, what exactly causes dyslexic people’s poor learning performance is still unclear, and this question will be further explored in next chapter.

Chapter Four: Attention, Expression and Sequence Learning: Study V

The results of Study I & Study II suggest the statistical complexity may affect dyslexic people's implicit learning performance, and Study III & Study IV further examined the influence of statistical complexity to different learning forms of dyslexic people, suggesting they may have intact abstract learning when only zero- and first-order information is involved. These studies mainly focus on the learning results, i.e., what kind of information dyslexic people can learn. However, the process of the learning is still unclear, especially the way in which different participants approached the learning task. For example, it is unclear if dyslexic participants' different performance reflects their impaired learning in implicit process, or explicit process, or both. It is also unclear if dyslexic people are impaired in acquiring the information, or just fail to perform (express) the information. These are the questions to be discussed in this chapter.

4.1. Two previous explanations for dyslexics' implicit sequence learning impairment

It is not easy to claim any implicit learning task is pure in nature (Cleeremans, 1993a), and some researchers argued that the possible different involvement of explicit learning in the tasks may underlie the controversial findings of dyslexic people's implicit learning capacity.

With the finding that dyslexic children performed intact implicit sequence learning, Deroost et al. (2010) suggested that previous studies which found an implicit learning deficit in dyslexia actually reflect an explicit learning deficit, whereas dyslexic people's implicit learning is unaffected. Their argument is based on the complex nature of the implicit learning task, and it is probably the impairment in explicit sequence learning, which causes dyslexic people's poor performance in some implicit learning tasks. Deroost et al. further argued that this is because explicit sequence learning has been specifically associated with prefrontal functioning, which is the key structure for executive control and working memory, indispensable for literacy skill (Deroost, et al., 2010). The dual-task performance, which has been found largely impaired in dyslexia population, also heavily relies on the prefrontal functioning (Fawcett & Nicolson, 2001). However, compared to tasks used in other studies (e.g., Howard et al., 2006; Bennett et al., 2008) using probabilistic sequences, the two tasks in Deroost et al.'s study used deterministic sequences, which have been approved to encourage more explicit learning (Song, Howard Jr., & Howard, 2007). If Deroost's argument is correct, it should be predicted that dyslexics showed intact learning performance in tasks using probabilistic sequences. However, the results are opposite.

Howard et al. (2006) offered an alternative argument emphasizing the importance of using more complex sequence information and probabilistic sequences, which are known to afford less explicit awareness, and suggested that intact learning by dyslexic participants observed in some studies may be due to the explicit knowledge, caused by minimal complexity sequences.

In Exp. 1 and Exp. 2a, dyslexic participants showed poor learning performance on second-order learning in both experiments, and the analyses of awareness revealed that, although almost all participants detected the sequenced nature of the task (the SRT in Exp. 1 and the AGL in Exp. 2a), none of them were able to give a complete description of the sequence/artificial rule used in the learning task. Also, for the SRT task in Exp. 1, a very short RSI of 50ms was used, which is known to hamper the development of explicit awareness (Cleeremans & Jiménez, 1998). Hence, these suggest that learning performance in all participants was mainly governed by implicit processes in our experiments, and it is unlikely that dyslexic participants' different performance in the tasks was caused by the explicit learning impairment.

It is also interesting to note that although dyslexic participants showed impaired learning in second-order information in Exp. 1 and Exp. 2a, they showed explicit knowledge in both of the recognition and PDP test afterwards, which suggest they actually gained some triplet knowledge; similarly, in Exp. 2b, dyslexics failed to show any learning in the AGL task, however, the direct test showed that dyslexic participants gained some explicit bigram knowledge. Hence, these results may suggest that dyslexic people may not be able to incidentally express their knowledge in the SRT task, but are capable of doing so when asked intentionally to recall the knowledge.

As in most previous studies, explicit sequence learning was only assessed in a post hoc manner after the indirect task. Therefore, in order to determine whether dyslexics' performance differences relative to controls are due to explicit learning impairment, one possibility is to compare the performance of intentional, explicit learning in the SRT task. To further clarify the role of prefrontal functioning and dual tasking in sequence learning in dyslexics, implicit and explicit sequence learning under standard single- and dual-task conditions should be compared. A factorial design crossing implicit/explicit and single/dual-task factors allows determination of the respective contribution of each of these aspects to dyslexics' sequence learning performance.

In the SRT task, the secondary tone-counting task does not only occupy central processing resource like working memory, but also distracts attentional resource and thus could minimize the explicit involvement in the process. Kelly, Burton, Riedel, and Lynch (2003) found under the dual-task condition, participants did not explicitly learn a SOC sequence with intentional learning instructions. Thus the secondary tone-counting task will also hamper explicit learning and participants' performance should more reflect their implicit learning. In this case, if Howard et al.'s argument is correct, dyslexic people may reveal more deficits under the dual-task condition.

The role of the secondary tone-counting task in the SRT task is complicated, and in the next part, the studies are going to be reviewed which proposed different interpretations of the role of the secondary tone-counting task may play in sequence learning.

4.2. Attention, the secondary task and sequence learning

The most common secondary task is a tone-counting task in which, following each target stimulus, either a high- or low-pitched tone sounds, and participants are required to keep a running count of one of them. With this paradigm, Nissen and Bullemer (1987) first found participants' learning performance impaired under the dual-task condition, which suggests learning in the SRT task may require attention. However, the secondary tone-counting task may also be affected by other factors.

4.2.1.The role of the secondary task in sequence learning

Learning in the SRT task is sensitive to the secondary task (Dienes & Berry, 1997). Since Nissen and Bullemer's original study in 1987, there is no doubt that performing the secondary tone-counting task is disruptive because it invariably slows down participants' RTs to the primary SRT task. But more importantly, the secondary task also interferes with participants' ability to learn, as reflected in various performance measures (Hsiao & Reber, 1998).

The impaired effect of the secondary tone-counting task was at first interpreted as reducing the amount of attention available to encode sequence information. Cohen et al. (1990) reported that the participants were only able to learn bigram information under dual-task condition in the SRT task but were unable to do so with triplet information. They hypothesized that there are two mechanisms: one undemanding of attention to learn simple bigram associations, and the other requiring attention to learn the more complex successive events.

Curran and Keele (1993) further explored this dual-mechanism theory in a series of SRT tasks. They found that when the sequence knowledge was trained under distraction-free (ST) conditions, performance differences under the ST condition depended on participants' awareness of the sequence, and when distraction (i.e., DT condition) was added, participants continued to exhibit sequential knowledge to the same degree regardless of different degrees of awareness. Moreover, the degree of sequential knowledge expressed under DT conditions was the same regardless of whether participants originally learned with or without distraction. If the initial learning was conducted under the DT condition and then removed, there was no evident improvement in the expression of sequential knowledge. Curran and Keele therefore hypothesized that the sequence learning in the SRT task involves at least two different processes, which are differentially affected by the availability of attentional resources, and there are three types of sequence learning happening in the sequence learning task: unattentional, attentional without awareness, and attentional with awareness, and the concurrent tone-counting task reduces the part of sequence learning which requires the attentional resources.

However, as Savage (2004) pointed out, there may be other explanations in addition to the extra attention demanded by the secondary task. This is because the two (primary and secondary) tasks chosen are not completely independent of each other in terms of the processing resources required, and more specifically, in research involving dyslexic participants, the tasks chosen may tap skills or processes involved in known and more circumscribed specific dyslexic deficits such as naming or phonological processing, or working memory. Therefore, there are several other alternative explanations for the impaired effect of the secondary task in the SRT task.

One possibility is the secondary tone counting task specially interferes with the mental formation of a sequence representation and disrupts grouping in sequence learning. Instead of arguing that the secondary task competes with the primary SRT task for a limited attentional capacity, Stadler (1995) suggested that the secondary task impairs sequence learning because it disrupts the organization of successive events during encoding. To test this prediction, Stadler used a memory-load secondary task which required participants to retain in memory a set of letters while performing the SRT task, and no significant difference was found between the learning under single and dual-task condition; a longer RSI was also used, which was five times as long on the same proportion of trails as that the tone counting group would hear a target tone. This longer RSI was presented randomly either at the end of each repeating sequence or between two trials of each sequence. Although this longer RSI didn't require any attentional resource, the disruptive effect of the randomly occurring longer RSI negatively affected the learning performance in SRT as well as tone-counting. Stadler argued that although memory load engages one's attention, it does not disrupt sequence grouping. In contrast, the randomly occurring long pauses place little extra demand on attentional expenditure, but they do impede consistent grouping. The functional similarity in participants' performance in the tone-counting condition and the long-pause condition invites the inference that similar processes were disrupted during learning.

There is a critical methodological problem with the memory-load task in that, unlike tone counting task, the memory-load task does not necessarily impose a task requirement on every single trial. Therefore Jimenez and Mendez (1999) used 'within stimulus' dual-task, in which participants were required to count the targets with particular features which were the same modality used in the primary SRT task. This secondary distraction task had no detectable effect on sequence learning, and visual stimuli were used in both tasks, instead of using auditory task to interfere with visual tasks as there may be separate attentional resources for visual and auditory processing. No evidence of a difference between single task and dual-task performance was found. This result is interesting, because this within stimulus secondary task is indeed attention demanding and produces disruption in every trial, but the secondary task was presented concurrently with the primary task instead of being produced during the RSI, and no interference in learning under this dual-task condition was found. This result suggests it may simply be because of the scheduling pause between trials, which makes it difficult for participants to link the series of stimulus, instead of the interruption in every trial.

Fresch and Miner (1994) provided supportive evidence for the conjunction of the negative effect of the scheduling pause between trials, although they attributed the detrimental effect of the secondary task to a reduction in the capacity of short-term memory. This memory-based theory presumes two assumptions, first, that working memory has a limited capacity, which varies among individuals; and secondly, that contents in this working memory decay rapidly. The disruptive effect of the secondary task could derive from simply lowering the probability that pieces of information about the target sequence are active in memory at any one time, therefore compromising the detection of covariation among elements. In the study by Frensch & Miner, participants performed the SRT task with RSIs of either 500ms or 1500ms. Under the single-task condition, all participants equally learned with either 500 or 1500ms RSI, suggesting a delay by itself may not necessarily prevent learning because maintenance rehearsal can be used to bridge it. Under the dual-task condition, participants under both the 500ms and the 1500ms RSI showed less learning, but the 500ms RSI participants were significantly better than the 1500ms RSI participants. In addition, participants' digit span, a measure of short-term memory capacity, correlates with sequence learning only in the 500ms RSI condition. Frensch and Miner (1994) thus argued that their results support a short-term memory hypothesis. In this study, the sequence learning was not determined by the availability or shortage of time, because a longer RSI impaired rather than facilitated learning. Frensch and Miner further explained their results by suggesting that as performing a secondary task tends to slow down RTs by about 200ms-300ms, and when the RT to each trial is added to an extra 500ms RSI, the interval is approaching the duration limits of short-term memory, the probability of participants detecting the covariations between events of the sequence begins to diminish. In addition the demand of the secondary task means there will be little chance for maintenance rehearsal. This explains why sequence learning is worse under the dual-task condition. Furthermore, the observation that short-term capacity correlates with sequence learning only when RSI is short (500ms) and in the presence of a distractor suggests an interaction between timing and a capacity limit.

Apart from the above explanations that the secondary task impairs the sequence learning by disrupting the sequence organization or occupying a capacity-limited working memory, Frensch, Lin, and Buchner (1998) proposed an alternative explanation from a different perspective. They argued that the dual-task condition does not impair sequence learning *per se*, but suppresses the expression of knowledge (Frensch, Wenke, & Riinger, 1999). They presented a series of SRT tasks with the same amount of practice but differing in the amount of practice under single- and dual-task condition. The learning was tested first under dual-task condition and secondly under single-task condition. The participants were found to demonstrate more learning under the single-task condition than the dual-task condition. Frensch et al. concluded that implicit sequence learning may be mediated by a single learning mechanism that is not affected by the availability of attention, although such learning may not be expressed under conditions of severe distraction that interferes with retrieval.

In summary, previous studies have shown that the secondary tone-counting task can affect participants' performance in the SRT task mainly in three ways: i) by impairing the sequence learning via additional attention requirement (Cohen, et al., 1990; Curran & Keele, 1993; Nissen & Bullemer, 1987); ii) by interfering with the sequence learning by occupying a capacity-limited working memory (Frensch & Miner, 1994), or by disrupting the organization of the sequence (Jimenez & Mendez, 1999; Stadler, 1995); or iii) by suppressing the expression of learning rather than disrupting learning itself (Frensch, et al., 1998). The first explanation accepts the possibility that there may be attention-required learning in the SRT learning process; and the first and second explanation both suggest the secondary task impairs learning in the SRT task. However, it is important to understand that there is likely no single impact of the secondary task on learning, and each of the above explanations could be correct to some extent without too much conflict (Hsiao & Reber, 1998), as the SRT task is a complex task and there are many ways in which performance on it could be compromised and many different processes that could be disrupted by the secondary task. It is possible that under some experiment conditions, some effects can't be observed, but that may be due to one strongest effect suppresses other effects, since not all potential contributors can be controlled.

It is not possible to simply consider only one explanation and exclude others under a dual task condition. More important, the results of the previous studies relied on comparing participants' performance under different experiment settings. However, the purpose for the current study is not to examine the role of the secondary task, but rather to compare dyslexic individuals' performance with controls under the same experiment setting, to test if dyslexic individuals will perform differently compared to controls. Therefore, all of the above possible influence of a secondary task will be considered when interpreting the task results in the current study.

4.2.2. The cognitive and neural architecture of sequence learning

It is also important to look at the underlying architecture of sequence learning before we further examine the features of dyslexic people's sequence learning mechanism. Several models have been proposed regarding the cognitive and neural bases of motor sequence learning, taking into account both explicit and implicit processes. One influential model of the neural bases of skill learning is Willingham's (1998) control-based learning theory (COBALT). This proposes that learning can occur via tuning of the processes directly involved in the control of movement, or through the use of conscious, strategic processes. This theory is based on the idea that learning grows directly out of motor control processes, and three motor control processes may be tuned to specific tasks and improve people's performance: selecting spatial targets for movement, sequencing these targets, and transforming them into muscle commands. These processes operate implicitly. A fourth, conscious process can improve performance in either of two ways: by selecting more effective goals of what should be changed in the environment or by selecting and sequencing spatial targets.

Another recent model of sequence learning (Ashe, Lungu, Basford, & Lu, 2006) suggests that instead of separable systems for explicit and implicit sequence learning, there are overlapping neural networks that contribute to both processes. For instance, when the intention to learn the sequence is explicit, either as a consequence of awareness or as an instructional set, explicit processes will originate in prefrontal cortex and will propagate to premotor areas. In this case learning will be based on mechanisms such as rehearsal and chunking. When learning is implicit, as a result of simply performing sequential movements without intention to learn or awareness about the sequence, implicit processes originate in motor cortex and propagate to the premotor areas. In such instances learning might be based on element-to-element associations or temporal coding. They further suggest that in most cases, implicit and explicit processes will interact with each other, and will change in importance depending on the stage of the learning process.

COBALT proposes that the dorsolateral prefrontal cortex only contributes to sequence learning under explicit condition; Ashe et al.'s (2006) models suggest that dorsolateral prefrontal cortex can play a role in pure implicit sequence learning. Moreover, a further remaining issue is whether the cerebellum participates in such learning. Although the cerebellum has traditionally been considered a motor area, and studies have found an association cerebellum and response time and movement initiation (Grill, Hallett, Marcus, & McShane, 1994; Ivry & Keele, 1989), its role in learning motor skills remains controversial. Boyd and Winstein (2004) reported that cerebellar-impaired patients had intact learning of the spatial features of a tracking task, but not its temporal features. Thus, sequence learning tasks may elicit cerebellar activation due to the role that this structure plays in motor timing.

One study that dissociated performance effects from the learning process found prominent activation in the cerebellum during the expression of learning but not during the learning process *per se* (Seidler et al., 2002). An SRT task was conducted in the study, and participants were not informed the sequence nature of the task. During the learning phase, participants performed a secondary visual distraction task. Upon removal of the distraction task, participants showed evidence of learning. No cerebellar activation was associated with the learning phase as shown by the fMRI image, despite extensive involvements of other cortical and subcortical regions. There was, however, significant cerebellar activation during the expression of learning. Thus, the authors argued that the cerebellum does not contribute to learning of the motor skill itself but is actually engaged primarily in the modification of performance.

Seidler et al. (2002) further discussed the possible explanations of how the cerebellum contributes to improvement in performance, including improved coordination of movement timing and enhanced motor planning. These results suggest that the cerebellum plays a critical role in motor response facilitation, which is manifested in the present experiment by the improvement in performance seen during the expression phase. This is consistent with predictions of the COBALT model, which only suggest a coordination role of cerebellum in motor sequence learning.

These above neuropsychological models of motor sequencing provide insights into the mechanisms underlying the SRT task under both single- and dual-task condition. More importantly, they provide separate neural mechanisms underlying explicit/implicit learning, as well as dual-task functioning in the SRT task. As the cerebellar hypothesis predicts (Nicolson, et al., 2001), an impairment in cerebellar function may lead to a poor dual-task performance. Moreover, in a motor learning task, this poor performance may more on a performance level, i.e., dyslexics may only not be able to express the sequence motorically. To further clarify if dyslexic individuals' impaired performance in an implicit learning tasks were more due to a learning problem or an expression problem, implicit and explicit sequence learning under standard single- and dual- task condition have been compared. A mixed-design with implicit/explicit and single/dual-task factors will provide more information in the respective contribution of each of these aspects to dyslexics' sequence learning performance.

4.3. Study V

To date, four SRT experiments have been reported in this thesis. In Exp. 5a and 5b, participants practiced the SRT task under Single Task (ST) condition and were tested under both ST and Dual Task (DT) conditions. In Exp. 5a, participants were given incidental instructions (i.e., they were not made informed of the sequential information in the tasks, but simply were told it was a reaction-timed task). In Exp. 5b, participants were given intentional instructions (i.e., they were informed of the sequential nature of the stimulus presentation prior to undertaking the task). In Experiments 6a and 6b, participants practiced the SRT task under the DT condition but again were tested under both DT and ST conditions with either incidental or intentional instructions.

It was hypothesized that if dyslexics' impaired performance more reflects their problems in nonattentional implicit learning, but which might be masked by the explicit knowledge involved, their poor performance should be revealed when the secondary task is added at the test phase; at the same time when they learn the sequence under the DT condition, they should show deficits tested under both DT and ST conditions. Moreover, if dyslexics' deficit in sequence learning more reflects an explicit learning problem under resource-demanding conditions, they may not be able to show learning under the DT learning condition even when they are told to learn to the sequence explicitly. On the other hand, if dyslexics more likely have an expression problem, they may be unable to express the knowledge under the DT condition, and be able to express the knowledge under the ST condition, regardless of the learning condition (ST/DT).

Methods

24 university students with documented diagnosis of dyslexia were recruited by emails sent by learning disability support centers at Strathclyde University and Glasgow School of Arts. 24 control group members responded to

recruitment posters placed on campuses and websites of both universities. No control group member reported any learning disability or relevant diagnosed history. All of the participants were native English speakers.

In addition, a series of behavioural tests were conducted to characterize participants' relevant abilities: the Wide Range Achievement Test- Revised-Tan (Wilkinson, 1993) was used to test spelling and reading ability; the Rapid Naming Speed Tests (Denckla & Rudel, 1976) showed the time every participant needed to name 50 digits and objects; the Spoonerism task (Perin, 1983) tested participants' ability to segment and manipulate phonemes; digit forward and backward span tests were based on the Automated Working Memory Assessment (AWMA) (Alloway, 2007); the Wechsler Abbreviated Scale of Intelligence(WASI) provided measures of participants' verbal and performance IQ (Wechsler, 1999).

Each participant completed one implicit task (either Exp. 5a or Exp. 6a) and then completed one explicit task (either Exp. 5b or Exp. 6b), sequentially. Each participant was randomly assigned to one of the four conditions (Exp.5a/Exp. 5b; Exp. 5a/Exp. 6b; Exp. 6a/Exp. 5b; Exp. 6a/Exp. 6b) and there were equal amount of participants in every condition. All participants undertook one implicit SRT task and the awareness tests, followed by one explicit SRT task. After finishing both SRT tasks, they were given the various behavioural tests. This design is to balance the possible proactive interference effects or the practice effect of the different implicit SRT tasks on the subsequent explicit tasks.

4.3.1. Experiment 5a

The assumption is that during the initial distraction-free learning, implicit learning may occur in parallel with explicit learning, and when distraction is added later, the expression of explicit learning might be suppressed, and the learning performance would reflect only the implicit learning (Curran & Keele, 1993).

Participants

As shown from Table 17, the dyslexic group obtained significantly lower scores on phonological awareness (Spoonerisms), literacy (WRAT-spelling and WRAT-Reading), rapid naming test (Digit and Object Naming), and short-term and working memory (Digit Forward and Backward Span) as expected. There is no difference between two groups' age, or verbal and performance IQ scores.

Table 17 Participants Characteristics in Exp. 5a

	Dyslexia		Control	
	Mean	SD	Mean	SD
Gender	4M8F	/	8M4F	/
Age (years)	24.09	4.55	21.84	5.10
WRAT-Spelling (Tan) **	95.58	8.70	107.50	7.55
WRAT-Reading (Tan) ***	99.67	6.62	114.50	5.20
Digit Naming(secs/50items)**	16.56	2.40	13.63	2.25
Object Naming(secs/50items)*	30.40	4.57	26.35	3.52
Spoonerisms* (mean correct, max = 20)**	13.83	3.41	18.17	2.04
Digit Forward Span*	31.08	6.65	37.83	7.69
Digit Backward Span*	17.83	4.17	23.33	6.68
WASI-verbal	124.00	9.07	128.50	5.99
WASI-performance	112.50	10.41	112.08	12.12
WASI-overall	120.50	9.52	122.58	8.68

*p≤0.05 **p≤ 0.01 ***p ≤0.001

Stimuli and Procedure

All the SRT tasks were run on an Intel Core Duo personal laptop with 15-inch screen. The program was written using E-prime v2.0. The target stimulus was a white circle (1.5cm diameter) on a black background. The target circle appeared in one of four horizontally aligned black circles of 1.5cm diameter with a white border as location markers. The target was presented following the second-order sequence (all possible pairs presented with equal frequency meaning first-order knowledge is not predictive): 241321423431 where 1234 indicates the spatial locations on the screen from left (1) to right (4). A short response-stimulus interval (RSI) of 50ms was used.

There were 16 blocks in total, each starting with 4 random trials followed by 120 sequential trials. Blocks 1 to 9 displayed the repeating SOC sequence under ST conditions. Blocks 10 to 12 comprised the ST test phase with the sequence becoming pseudorandom (constrained so that each element occurred with equal frequency and no immediate repetition). Block 13 to Block 16 was the DT testing phase. Prior to Block 13, participants were informed that they now would also hear high and low tones and were to count the number of high tones and report the total after each block. Block 13, 14 and 16 were random blocks, in which the trials followed the pseudorandom sequence. Block 15 displayed the repeating SOC sequence. The reason for including two DT random blocks before the DT sequential Block 15 in the DT testing phase was to allow participants to practice under DT conditions, avoiding additional training of the sequential trials.

For Exp. 5a, participants were not told about the sequential nature of the stimulus presentation. Instead, they were told that it was a complex visual stimuli response time experiment. The participants were instructed to use their index and middle fingers of both hands to make responses to the targets by pressing four keys corresponding to the same horizontal positions on the response pad as quickly and as accurately as they could. Participants were able to take a break of up to 30s between blocks. For the DT condition, the participants were required to count the number of high-pitched tones, ignoring the low-pitched ones, and report the number after every block. Before the first block in the DT condition started, every participant heard tones at either higher- or lower- pitch, and every participant could distinguish two kinds of tones.

Explicit Awareness Tests

Participants first completed an awareness questionnaire comprising the following questions:

- *Did you use any strategy to try to improve your performance? If so, what was your strategy?*
- *Do you think your strategy worked? Why or why not?*
- *Did you notice any kind of pattern or regularity of the stimulus?*
- *Do you have anything to report regarding the task?*

Participants were then informed that a sequence was present, and completed a recognition test in which they made judgments to 3-element sequences for whether this sequence had occurred previously or not. There were 24 trials (12 old and 12 new).

Results

Mean of median RTs for correct responses and mean accuracy rates were determined for each of the 16 blocks. Participants with an average tone count error of more than 10 per block on dual-task condition blocks were removed from the analysis (Curran & Keele, 1993), as poor performance on the tone counting task could indicate that participants assigned disproportionate attention to the main SRT task. No participant in Exp. 5a was removed due to tone counting errors.

As seen from Fig. 19, the response pattern for each group is remarkably similar during the training phase (Block 1 to Block 9): both groups show a shallow learning slope and a gradual improvement in reaction time over training. For the ST testing phase (Block 10 to Block 12), both groups showed a similar increase in reaction time to the pseudorandom Block 11; while for the DT testing phase (Block 13 to Block 16), both groups showed decreased reaction time to the DT sequential Block 15, with the dyslexia group's decrement appearing marginally smaller.

Accuracy rates were analyzed for each experiment. Overall, there was no significant difference between two groups' total accuracy rates, 94.22% for dyslexic group vs. 95.52% for control group, $t(22)<1$. Both groups demonstrated more errors in random blocks: 93.88% for dyslexic group vs. 93.21% for control group, with no significant difference from each other, $t(22)<1$. The overall pattern reveals no evidence of a speed-accuracy trade-off in either group.

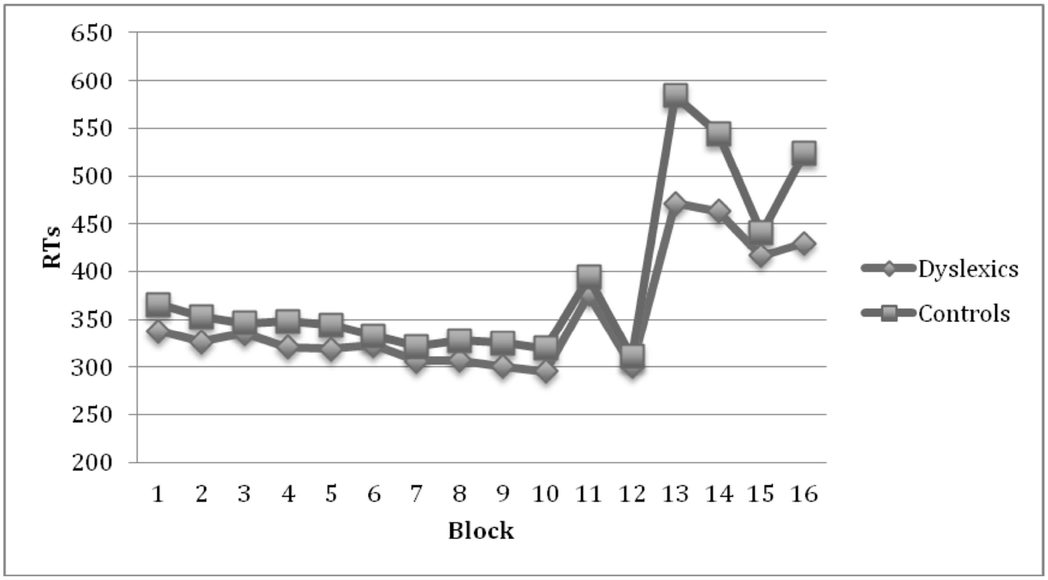

Figure 19 Mean of median RTs per block for both groups in Exp. 5a

A 2 × 9 ANOVA with Group (dyslexic vs. control) and Block (9 training blocks from Block 1 to Block 9) showed a significant main effect of Block, F(1, 22)=5.98, p= 0.02, $\eta^2 = .21$; no significant difference for Group, F(1, 22) = 1.39, p > .10, $\eta^2 = .06$; and no interaction, F(1, 22) = .42, p=.52, $\eta^2 = .02$. A post-hoc trend analysis on Block revealed a significant linear effect, F(1, 22) = 18.24, p < .001, $\eta^2 = .45$. These results indicated that both the dyslexic and control group showed significant performance improvement across the training blocks, though this could be due to either learning of the sequence transitions and/or other non-specific practice benefits.

In order to compare the performance under two different expression conditions of two groups, a 2 × 2 × 2 ANOVA was performed with Group (dyslexic vs. control) as the between-participant factor, Condition (ST vs. DT condition) and Content (Random vs. Sequence) as the within-participant factor. A main effect was found with Content: F(1, 22)= 105.67, p< .001, ŋ^2 = .83; and Condition, F(1, 22)= 17.53, p< .001, ŋ^2 = .44; no significant main effect was found with Group, F(1, 22) = 1.20, p= .28, ŋ^2 = .05. A significant interaction was found with Content × Group, F(1, 22)= 5.61, p=.03, ŋ^2 = .20; and Content × Condition × Group, F(1, 22)= 6.53, p= .02, ŋ^2 = .23. No significant interaction was found with Content × Condition, F(1, 22)= 1.73, p= .20, ŋ^2 = .07; or Condition × Group, F(1, 22)< 1. These results indicate both group reveal significant learning under both conditions, however, there is a significant difference between two groups' learning; more important, two groups' learning difference is significant between the ST condition and the DT condition.

In order to further test the learning effect under ST condition, a 2 × 2 ANOVA with Group (dyslexic vs. control) and Block (the mean of Block 10 and 12 vs. random Block 11) was performed, showing a significant main effect of Block, F(1, 22) = 113.73, p<.001, ŋ^2 = .84, with Block 10 and 12 showing faster RTs (306.79ms) compared to Block 11 (385.29ms); no significant effect of Group, F(1, 22) = 1.33, p= .26, ŋ^2 = .06, and no significant interaction of Group × Block, F(1, 22) < 1. These results indicate that under the ST condition, both dyslexic and control groups were able to express significant and comparable learning of the sequence transitions.

Similarly, to test the learning effect under the DT condition, a 2 × 2 ANOVA with Group (dyslexic vs. control) and Block (the mean of Block 14 and 16 vs. sequence Block 15) was performed, showing a significant main effect of Block, F(1, 22) = 32.48, p<.001, η^2 = .60, with a faster RTs for Block 15 (428.54ms) than Block 14 and 16 (490.50ms); no significant effect of Group, F(1, 22) = .90, p= .35, η^2 = .04; but a significant interaction was found with Group × Block, F(1, 22) = 8.80, p=.007, η^2 = .29. Further analyses were carried out separately for each group: separate t-tests were carried out for each group between the mean of Block 14 and 16 and sequence Block 15, the results showed that both groups demonstrated significant learning: for the dyslexic group, t(11)= 3.03, p = .01; for the control group, t(11)= 4.86, p = .001. These results indicate that although both groups showed equal learning under the ST condition, under the DT condition, the dyslexic group showed less learning compared to the control group.

None of the participants reported noticing a sequence during the task. Analysis of the recognition test showed both groups made above chance (i.e., 0.5) judgments: for dyslexic group, means of their accuracy rate for the recognition test is 0.54, SD= .06, t(11)= 2.45, p= .03; for control group, their recognition test result is 0.59, SD= .08, t(11)= 3.65, p= .004; no significant difference was found between two groups: t(22)= -1.55, p=.14.

Discussion

It has been suggested that when a secondary tone counting task is added, it immediately retards the expression of attentionally learnt knowledge (Curran & Keele, 1993), thus what was expressed under the DT condition in this study could be considered as implicit knowledge. Therefore, the first explanation for the results of Exp. 5a is dyslexic participants' poor performance only under the DT condition but not under the ST condition in Exp. 5a may be due to the nonattentionally learnt implicit knowledge gained by the dyslexic group being less than that in the control Group.

The other explanation is that the dyslexic and control groups might gain the same amount of implicit knowledge, but dyslexic participants' expression of such implicit knowledge would be affected more by the secondary tone-counting task, i.e., dyslexic participants have problems in expressing the sequence knowledge under the DT condition in the SRT task.

Overall, in Exp. 5a, dyslexic group showed similar learning pattern under implicit ST learning condition as control group, and dyslexic group were able to show equally well knowledge under the ST condition equally well as controls; however, when under DT condition, dyslexic participants were less able to perform as well as the control group. The two explanations discussed above have been further explored by following experiments.

4.3.2. Experiment 5b

An exception for the two potential explanations of Exp. 5a is if the secondary task was not sufficient to block the deliberate use of the attention and participants were still able to apply their attentionally learnt knowledge under the DT condition (Curran & Keele); in this case the two groups' different capabilities to express the explicit knowledge may affect their performance under the DT condition. Therefore, the Exp. 5b aimed to investigate dyslexic group's capability to express explicit knowledge under the DT condition.

Participants

As expected, the dyslexic group obtained significantly lower scores on phonological awareness (Spoonerisms), literacy (WRAT-spelling and WRAT-Reading), rapid naming test (Digit and Object Naming), and short-term and working memory (Digit Forward and Backward Span) compared to control group. There is no difference between two groups' age, or verbal and performance IQ scores (Table 18).

Table 18 Participants Characteristics in Exp. 5b

	Dyslexia		**Control**	
	Mean	SD	Mean	SD
Gender	6M6F	/	6M6F	/
Age	25.52	7.47	22.08	4.96
WRAT-Spelling (Tan) ***	96.33	5.73	107.33	4.98
WRAT-Reading (Tan) ***	100.17	5.81	111.67	5.21
Digit Naming(secs/50items)**	18.01	3.20	14.50	2.67
Object Naming(secs/50items)**	32.76	4.63	27.41	3.37
Spoonerisms* (mean correct, max = 20)**	13.83	3.38	18.08	2.06
Digit Forward Span*	29.42	6.56	36.50	9.12
Digit Backward Span*	15.67	3.92	20.33	6.14
WASI-verbal	124.83	9.16	127.58	4.87
WASI-performance	114.83	11.78	107.25	14.07
WASI-overall	121.67	10.99	119.00	9.59

$^{*}p \leq 0.05$ $^{**}p \leq 0.01$ $^{***}p \leq 0.001$

Stimuli and Procedure

The procedure of Exp. 5b followed that of Exp. 5a with one exception: all participants were informed that the locations of the stimuli would follow a repeated sequence. Participants were told that they would find it helpful if they discovered the underlying sequence, but that they should not slow down in order to do so. The sequence used in the Exp. 5b is also an SOC sequence: 324134231214.

Results

All participants described perfectly the sequence after the training phase (Block 9) in the SRT task. No participants were excluded for making more than 10 errors on the secondary tone counting task.

As seen from Fig. 20, the response patterns for the groups are remarkably similar through the training phase (Block 1 to Block 9). For the ST testing phase (Block 10 to Block 12), and the DT testing phase (Block 13 to Block 16), both groups showed more pronounced improvements in reaction time over training compared to the participants' performance in Exp. 5a. This might reflect the intentional learning effect. Both groups showed a similar large increase in reaction time to the random ST Block 11; and both groups showed similar decrease in reaction time to the sequential DT Block 15. However, the dyslexic group seemed to show an overall slower response time throughout the whole task.

Accuracy rates were analyzed for Exp. 5b. Overall, there was no significant difference between the two groups' total accuracy rates (93.32% for dyslexic group vs. 94.72% for control group, t(22) <1). Both groups produced more errors in random blocks: 91.81% for dyslexic group vs. 93.57% for control group, with no significant difference from each other, t(22) <1. The overall pattern revealed no evidence of a speed-accuracy trade-off in either both group.

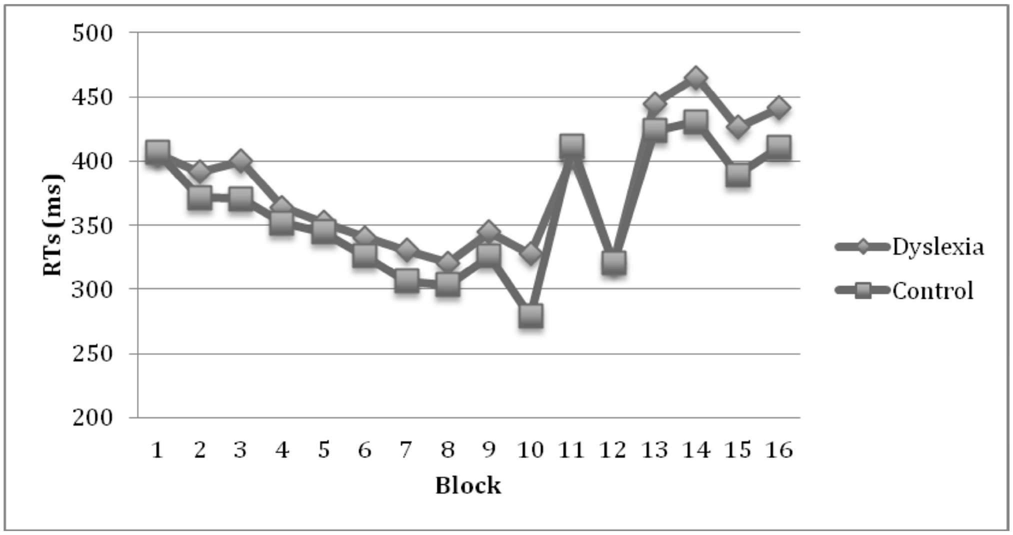

Figure 20 Mean of median RTs per block for both groups in Exp. 5b

A 2 × 9 ANOVA with Group (dyslexic vs. control) and Block (9 training sequential blocks from Block 1 to Block 9) showed a significant main effect of Block, F(1, 22)=8.17, p= 0.01, η^2 = .27; no significant difference was found for the interaction between Block and Group, F(1, 22) <1, or between-Group, F(1, 22) <1. A trend analysis on Block showed a significant a significant linear effect, F(1, 22) = 15.4, p = .001, η^2 = .41 These results indicated that the dyslexic and control groups showed significant response time improvements across the explicit ST training blocks, though still, this could be due to either learning of the sequence transitions and/or other non-specific practice benefits.

In order to compare the performance under two different expression conditions of two groups, a 2 × 2 × 2 ANOVA was performed with Group (dyslexic vs. control) as the between-participant factor, Condition (ST vs. DT condition) and Content (Random vs. Sequence) as the within-participant factor.

A main effect was found with Content: $F(1, 22)= 42.73$, $p< .001$, $\eta^2 = .66$; and Condition, $F(1, 22)= 21.78$, $p< .001$, $\eta^2 = .50$; no significant main effect was found with Group, $F(1, 22) <1$. A significant interaction was found with Content × Condition, $F(1, 22)= 12.61$, $p=.002$, $\eta^2 = .36$. No significant interaction was found with Condition × Group, $F(1, 22)= 1.53$, $p= .23$, $\eta^2 = .07$; or Content × Group, or Content × Condition × Group, $F(1, 22)< 1$. These results indicate both group reveal significant learning under both conditions, and there is a significant difference in both groups' learning performance between two conditions, but there is no significant difference between two groups' learning under the ST condition and the DT condition.

In order to test the learning effect under ST condition in Exp. 5b, a 2 × 2 ANOVA with Group (dyslexic vs. control) and Block (the mean of Block 10 and 12 vs. random Block 11) was performed, showing a significant main effect of Block, $F(1, 22) = 30.66$, $p<.001$, $\eta^2 = .58$; no significant effect of Group, $F(1, 22) <1$, and no significant interaction of Group × Block, $F(1, 22) <1$. These results indicate that under the explicit ST condition, both dyslexic and control groups were able to show significant and comparable learning.

To test the learning effect under the DT condition, a 2 × 2 ANOVA with Group (dyslexic vs. control) and Block (the mean of Block 14 and 16 vs. sequence Block 15) was performed. A significant effect was found only of Block, $F(1, 22)= 13.92$, $p= .001$, $\eta^2 = .39$; no significant effect of Group, $F(1, 22) <1$; or Group × Block, $F(1, 22) <1$. These results indicate that under the explicit DT condition, both dyslexic and control groups were able to show significant and equivalent levels of learning.

Discussion

Overall, two groups showed similar learning and expression patterns in Exp. 5b. All participants in the two groups reported complete knowledge of the sequence, which suggests in turn that all acquired explicit knowledge of the sequence, and participants in both groups were able to express explicit knowledge under DT conditions. Both groups' explicit expression of the knowledge was equally affected by the secondary task.

The results of Exp. 5b suggest that dyslexic people have no impairment in expressing explicit knowledge under the DT condition. Thus, even if in Exp. 5a the secondary task was not sufficient to block all deliberate knowledge, that could not be due to the dyslexic participants' incapacity to express the explicit knowledge.

4.3.3. Experiment 6a

Experiment 5a demonstrated that with training under ST conditions, dyslexic participants were able to perform as well as controls under the ST condition, however when the participants were required to transfer to a DT condition, the dyslexic group showed less learning compared to controls. Experiment 5b confirmed that dyslexic participants were able to express explicit knowledge in the DT condition as well as controls. We argued that the poor performance in only the DT condition might reflect either a learning or an expression problem of implicit knowledge of dyslexics. We examined this question with Experiment 6a, in which participants had initial training under incidental, DT condition and then tested under both the DT and the ST condition. A DT condition should make it very difficult for participants to develop explicit knowledge (Kelly, et al., 2003); and when the secondary task is removed, although the RTs should speed up, performance should still only reflect their implicit knowledge gained under the DT condition (Curran & Keele, 1993). If dyslexics have problems in implicit learning, or if their implicit learning is more interfered by the secondary task compared to controls, they should perform worse than controls under both the DT and ST condition; if the tone-counting task only affects dyslexics expression but not learning the sequence knowledge, dyslexic participants should perform better under the ST condition than the DT condition compared to the controls.

Participants

The dyslexic group obtained significantly lower scores on phonological awareness (Spoonerisms), literacy (WRAT-spelling and WRAT-Reading), rapid naming test (Digit and Object Naming), and short-term and working memory (Digit Forward and Backward Span) as expected. The dyslexia group's verbal IQ was lower than that of the control group, but there was no difference between the two groups' performance IQ or overall IQ scores (Table 19).

Table 19 Participants Characteristics in Exp. 6a

	Dyslexia		Control	
	Mean	SD	Mean	SD
Gender	4M8F	/	8M4F	/
Age	24.58	8.46	22.98	3.56
WRAT-Spelling (Tan) * **	97.42	4.80	112.17	3.24
WRAT-Reading (Tan) * **	101.17	7.28	114.33	6.31
Digit Naming(secs/50items) **	18.70	2.97	15.00	2.43
Object Naming(secs/50items) **	33.93	4.32	28.27	4.18
Spoonerisms* (mean correct, max = 20)**	14.75	1.82	18.67	1.23
Digit Forward Span **	29.58	4.19	38.08	7.48
Digit Backward Span **	15.17	3.69	21.75	6.73
WASI-verbal*	121.33	8.07	127.25	4.75
WASI-performance	114.50	8.51	106.92	11.27
WASI-overall	119.92	9.19	118.75	8.27

*p≤0.05 **p≤ 0.01 ***p ≤0.001

Stimuli and Procedure

An SOC sequence 121342314324 was used in Exp. 6a. The procedure of Exp. 6a was similar to Exp. 5a, with the following exceptions: 1) in Exp. 6a, the training blocks (Block 1 to Block 9) were performed in the DT condition (i.e., participants were required to do the secondary tone-counting task at the same time as the primary SRT task; 2) in Exp. 6a, Blocks 10 to 12 were DT testing phase, with Block 10 and Block 12 comprised of the training sequence, and Block 11 having pseudorandom presentation of stimuli; 3) in Exp. 6a, Blocks 13 to 16 was the ST testing phase, with pseudorandom presentation in Blocks 13, 14 and 16, and the training sequence in Block 15.

Results

No participants were excluded for making more than 10 errors on the secondary tone counting task. As seen from Fig. 21, during the training phase, although the dyslexic group seemed slower than the control group, both groups showed an overall decrease in RTs across the training phase; both groups showed increased RTs to the pseudorandom DT Block 11; both groups showed decreased RTs to the sequential ST Block 15.

Overall, there is no significant difference between the groups' total accuracy rates, 96.05% for dyslexic group vs. 96.32% for control group, t(22) <1. Both groups demonstrated more errors in random blocks: 95.80% for the dyslexic group vs. 95.83% for the control group, with no significant difference between each other, t(22)<1. The overall pattern indicates there was no speed-accuracy trade-off in either group.

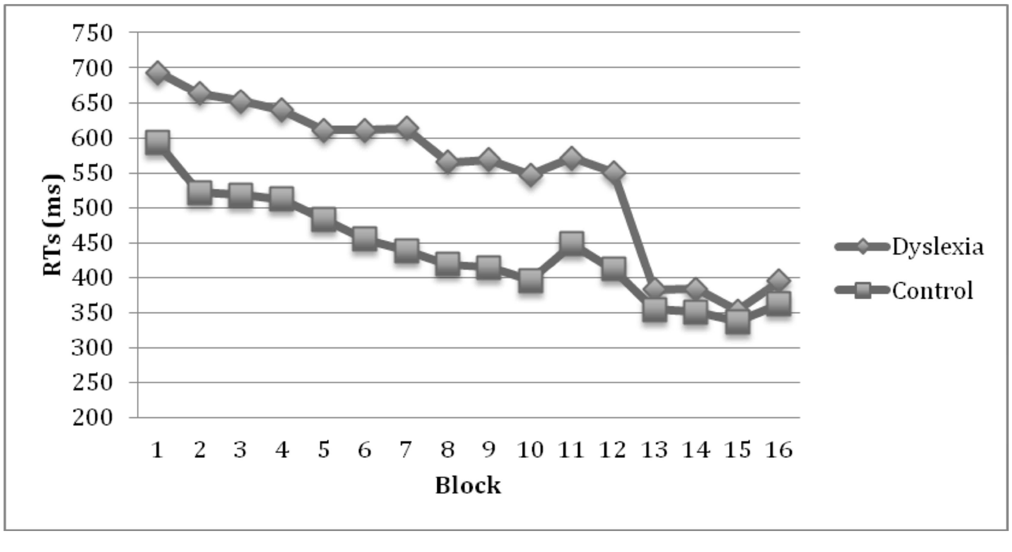

Figure 21 Mean of median RTs per block for both groups in Exp. 6a

A 2 × 9 ANOVA with Group (dyslexic vs. control) and Block (9 training sequential blocks from Block 1 to Block 9) showed significant main effects of Block, F(1, 22)=12.79, p= 0.002, η^2 = .37 and Group, F(1, 22)= 4.80, p= .04, η^2 = .18; but there was no significant effect found for the interaction, F(1, 22) <1. A trend analysis on Block showed a significant a significant linear effect, F(1, 22) = 22.85, p < .001, η^2 = .51. These results indicated that both the dyslexic and control groups showed significant response time improvement across the implicit DT training blocks, with the dyslexic group showing significantly slower overall RTs.

To compare the performance under two different expression conditions of two groups, a further 2 × 2 × 2 ANOVA was performed with Group (dyslexic vs. control) as the between-participant factor, Condition (ST vs. DT condition) and Content (Random vs. Sequence, Random refers to the RTs to Block 11 and Block 14 & 16; Sequence refers to the RTs to Block 10 & 12 and Block 15) as the within-participant factor. A main effect was found with Content: F(1, 22)= 29.51, p< .001, η^2 = .57; and Group, F(1, 22)= 4.92, p= .04, η^2 = .18; no significant main effect was found with Condition, F(1, 22) < 1. A significant interaction was found with Condition × Group, F(1, 22)= 9.50, p=.005, η^2 = .30; and Content × Condition, F(1, 22)= 47.89, p< .001, η^2 = .69; and Content × Condition × Group, F(1, 22)= 8.09, p= .009, η^2 = .27. No significant effect was found with Content × Group: F(1, 22) < 1. These results indicate Content × Group, or Content × Condition × Group, F(1, 22)< 1. These results indicate both group reveal significant learning under both conditions, there is a significant difference in both groups' learning performance between two conditions, and there is a significant difference between two groups' learning under the ST condition and the DT condition.

In order to test the learning effect under implicit DT conditions in Exp. 6a, a 2 × 2 ANOVA with Group (dyslexic vs. control) and Block (the mean of Block 10 and 12 vs. random Block 11) was performed, showing a significant main effect of Block, F(1, 22) = 19.87, p<.001, ŋ^2 = .48, and Group, F(1, 22) = 6.64, p= .02, ŋ^2 = .23, and a marginally significant interaction of Group × Block, F(1, 22) =2.18, p=.15, ŋ^2 = .09. Further t-test analyses was carried out separately for each group between the mean of Block 10 and 12 and random Block 11. A larger effect in the case of the control group, t(11)= 3.55, p = .005, than in the dyslexic group, t (11)= 2.72, p = .02. These results indicate that under the implicit DT expression condition, the dyslexic group made slower responses and expressed less learning compared to controls, although both groups were able to express significant learning overall.

To test the learning effect under the ST condition, a 2 × 2 ANOVA with Group (dyslexic vs. control) and Block (the mean of Block 14 and 16 vs. sequence Block 15) was performed. Only a significant main effect was found for Block, F(1, 22)= 28.30, p< .001, ŋ^2 = .56, no significant effect of Group, F(1, 22) < 1, but a marginally significant interaction was found between Group and Block, F(1, 22) = 2.63, p = .12, ŋ^2 = .11. A further t-test analyses was carried out separately for each group between the mean of Block 14 and 16 and sequence

Block 15. A larger effect was found in the case of the dyslexic group, t(11)= 5.16, p < .001, than in the control group, t (11)= 2.50, p = .03. These results indicate that under the implicit ST expression conditions, the dyslexic group revealed more learning compared to the control group.

In the case of the awareness tests, none of the participants reported they had been aware of the sequence to the questions after they finished the task. A further analysis to the recognition test showed none of the two groups made above chance accurate judgments: for the dyslexic group, the mean accuracy rate for the recognition test was 46, t(11)= -1.34, p>.10, and for control group, the mean recognition test result was .48, t(11)= -1.09, p>.10. There was no significant difference between the groups' accuracy rates, t(22) <1.

Discussion

The results of Exp. 6a suggest that the dyslexic participants are less able to express knowledge under the DT condition than the ST condition compared to the control group. The DT learning condition interferes with attentional learning, and none of the participants showed any awareness in the awareness tests. Hence, this suggests that learning performance in all participants was primarily governed by implicit processes.

Both groups showed learning under both of the DT and ST conditions although at different levels. It is interesting to notice that dyslexic participants actually performed slightly better than controls under the ST condition when the secondary task was removed. This may be due to a rebound effect after the inhibition caused by the secondary task (Allport & Wylie, 2000), i.e., a better expression of learning follows a suppression of them. Because dyslexic participants' expression was suppressed by the secondary task more than controls, the rebound effect may have been greater for the dyslexic participants than the controls.

The results of Exp. 6a support our earlier hypothesis that the tone-counting task only interferes dyslexics' expression but not learning the sequence knowledge, as dyslexic participants performed better under the ST condition than the DT condition compared to the controls.

4.3.4. Experiment 6b

A further issue concerns whether dyslexic participants' explicit learning is intact under the resource-demanding condition, i.e., if the secondary task would affect dyslexic participants' explicit sequence learning. Thus Exp. 6b aimed to explore to what extent dyslexic participants' explicit learning would be affected by the DT condition.

Participants

The dyslexic group obtained significantly lower scores on phonological awareness (Spoonerisms), literacy (WRAT-spelling and WRAT-Reading), rapid naming test (Digit and Object Naming), and short-term and working memory (Digit Forward and Backward Span) as expected. The dyslexic group's verbal IQ is lower than the control group’s, but there is no difference between the two groups’ performance IQ or overall IQ scores (Table 20).

Table 20 Participants Characteristics in Exp. 6b

	Dyslexia		Control	
	Mean	SD	Mean	SD
Gender	2M10F	/	10M2F	/
Age	24.94	4.44	21.88	3.69
WRAT-Spelling (Tan) ***	96.67	8.23	112.33	6.40
WRAT-Reading (Tan) ***	100.67	8.02	117.17	4.82
Digit Naming(secs/50items)**	17.25	2.57	14.14	2.18
Object Naming(secs/50items)**	31.57	4.91	27.21	4.52
Spoonerisms* (mean correct, max = 20)**	14.75	1.86	18.75	1.14
Digit Forward Span***	31.25	4.27	39.42	5.21
Digit Backward Span**	17.33	4.25	23.50	7.27
WASI-verbal*	120.50	7.56	128.17	5.95
WASI-performance	112.17	6.37	111.75	8.92
WASI-overall	118.75	7.06	122.33	7.33

*p≤0.05 **p≤ 0.01 ***p ≤0.001

Stimuli and Procedure

The sequence used in the SRT task in Exp. 6b is a SOC sequence 124314213234. The procedure of Exp. 6b was identical to Exp. 6a with the exception that all participants were informed that the locations of the stimuli would follow a repeating sequence.

Results

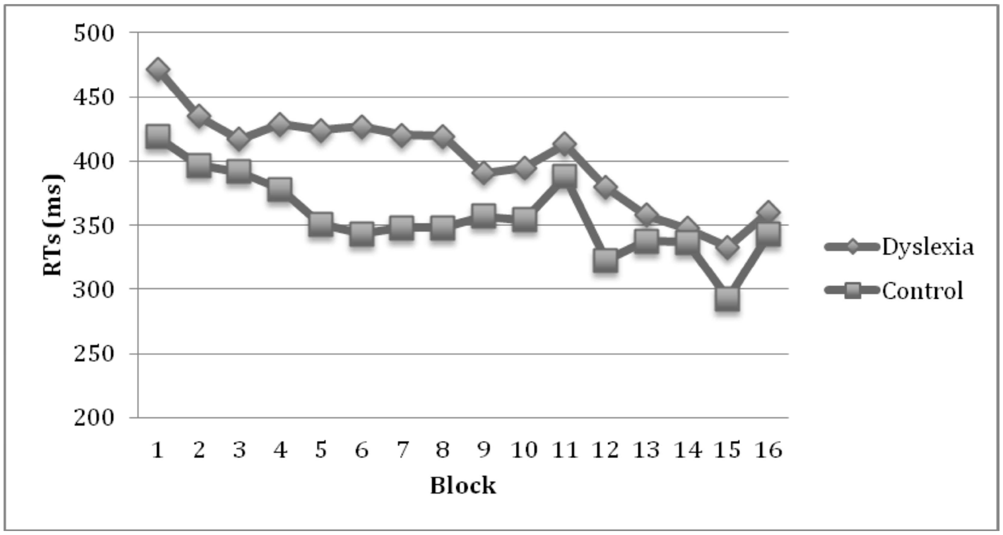

Figure 22 Mean of median RTs per block for both groups in Exp. 6b

No participants were excluded for making more than 10 errors on the secondary tone counting task. However, even with the intentional instructions, at the end of the training phase (Block 9), none of the 24 participants could report the sequence completely, but only some parts of the sequence. There are 12 different triplets in the 12-element sequence, thus we score each participant's explicit knowledge with the amount of the correct triplets they reported, with a full score of 12. The average number of triplets each group could report is 3.17 for the dyslexic group, and 3.58 for the control group; there was no significant difference between the explicit knowledge two groups gained, t(22) <1. The results indicated that dyslexic participants gained as much explicit knowledge of the sequence compared to controls.

As seen from Fig. 22 above, the dyslexic group seemed slower than the control group; both groups showed improved response time over the explicit

DT training phase; both groups showed increased RTs to the random DT Block 11, and decreased RTs to the sequential ST Block 15, although the dyslexic group seemed to show less changes to both the random Block 11 and sequential Block 15.

Accuracy rates were analyzed for each group. Overall, there was no significant difference between the groups' total accuracy rates, 95.10% for dyslexic group vs. 94.19% for control group, $t(22) < 1$. Both groups demonstrated more errors in random blocks: 93.93% for dyslexic group vs. 91.85% for control group, with no significant difference between the groups, $t(22) < 1$. The overall pattern indicates that there was no speed-accuracy trade-off in either group.

A 2 × 9 ANOVA with Group (dyslexic vs. control) and Block (9 training sequential blocks from Block 1 to Block 9) showed a significant main effect of Block, $F(1, 22)=5.87$, $p=.02$, $\eta^2 = .21$, but no significant difference for the interaction between Block and Group, $F(1, 22) = 1.26$, $p = .28$, $\eta^2 = .05$. However, the main effect of Group approached conventional levels of significance, $F(1, 22) = 4.15$, $p= .054$, $\eta^2 = .16$. A trend analysis on Block showed a significant a significant linear effect, $F(1, 22) = 14.35$, $p = .001$, $\eta^2 = .40$; and a smaller but significant quadratic effect, $F(1, 22) = 4.89$, $p = .04$, $\eta^2 = .18$. These results indicate that although dyslexic group responded slower than control group, both the dyslexic and control groups together showed significant response time improvement across the explicit DT training blocks, though this could be due to either learning of the sequence transitions and/or other non-specific practice benefits.

In order to compare the performance under two different expression conditions of two groups, a further 2 × 2 × 2 ANOVA was performed with Group (dyslexic vs. control) as the between-participant factor, Condition (ST vs. DT condition) and Content (Random vs. Sequence) as the within-participant factor. A main effect was found with Content: F(1, 22)= 18.88, p< .001, ŋ^2 = .46; and Condition, F(1, 22)= 20.33, p< .001, ŋ^2 = .48; no significant main effect was found with Group, F(1, 22) =2.49, p= .13, ŋ^2 = .10. No significant interaction was found with Content × Group, F(1, 22)= 2.32, p=.14, ŋ^2 = .10; no significant interaction was found with Condition × Group, or Content × Condition, or Content × Condition × Group, F(1, 22) < 1. These results indicate both groups showed significant learning under both conditions, and there is no significant difference between two groups' performance under different conditions.

In order to test the learning effect under explicit DT condition in Exp. 6b, a 2 × 2 ANOVA with Group (dyslexic vs. control) and Block (the mean of Block 10 and 12 vs. random Block 11) was performed. This revealed a significant main effect of Block, F(1, 22) = 7.79, p= .01, ŋ^2 = .26, but no significant main effect of Group, F(1, 22) = 1.89, p =.18, ŋ^2 = .08, and no significant interaction, F(1, 22) <1. These results indicate that under the explicit DT condition, both groups were able to express significant learning.

To test the learning effect under the explicit ST condition, a 2 × 2 ANOVA with Group (dyslexic vs. control) and Block (the mean of Block 14 and 16 vs.

random Block 15) was performed. Only a significant main effect was found for Block, $F(1, 22) = 19.10$, $p < .001$, $\eta^2 = .47$, with no significant effects of Group, $F(1, 22) = 2.04$, $p = .17$, $\eta^2 = .9$, or for the interaction, $F(1, 22) = 2.99$, $p = .10$, $\eta^2 = .12$. These results indicate that under the explicit ST condition, both dyslexic and control groups were able to express comparable levels of learning.

Discussion

Overall, in Exp. 6b, the dyslexic group seemed to be slower than the controls under DT learning with explicit instructions. None of the participants was able to give a complete description of the sequence used. However, a further analyses of explicit knowledge revealed that all participants detected more or less explicit knowledge of the sequence, and the amount of explicit knowledge did not differ between two groups, which suggests that the dyslexic participants' explicit learning capability is intact even under the DT learning condition.

The role of the secondary task to distract attentional resource in Exp. 4 and Exp. 3 was slightly different: the secondary task provided a more 'purely implicit' condition to avoid any explicit learning in Exp. 3; for Exp. 4, participants had to use limited resources to explicitly learn the sequence information at the same time when doing the tone-counting task. This may explain why both groups generally made the slowest response under the DT condition in Exp. 4 compared to other experiments: the explicit report suggested none of the participants was able to report the complete knowledge of the sequence at the end of the Block 9, therefore, they must continue looking for the sequence from Block 10 to Block 13.

4.3.5. Implicit learning and reading

Findings have already been reported that word reading performance but not spelling performance is highly related to SRT RT performance (Bennett, et al., 2008), and SRT RT performance has been found to be highly related to short-term memory measures (Frensch & Miner, 1994) and working memory (Bo, Jennett, & Seidler, 2011; Yurovsky, 2002), however, previous studies failed to find any correlation between SRT RT performance and phonological measures or RAN (Bennett, et al., 2008; Howard Jr., et al., 2006; Waber, et al., 2003). The results of these studies generally indicated that dyslexics did less well on implicit learning compared to good readers, but without a clear explanation of how implicit sequence learning deficit is related to reading performance. Therefore, it is important to conduct correlations between individual measures of reading ability and implicit learning because these analyses may better capture relationships with reading skill, especially when there is a broad range of reading ability within both groups, and an overlap between the groups (Bennett, Romano, Howard, & Howard, 2008). Learning scores from 48 participants in two implicit experiments (Exp. 5a and Exp. 6a) were included in this analysis. Correlation analyses were used to evaluate task performance in relation to reading skill, relevant cognitive skills, and IQ.

First, median RTs were determined separately for all trials in each block in Exp. 5a and Exp. 6a for every participant. A learning score under every condition was calculated by taking the percentage difference between the mean of Block 10 & 12 and Block 11, or the mean of Block 14 & 16 and Block 15. In this case, each participant had two implicit learning scores, namely implicit learning scores tested under ST and DT condition.

The reason to use data from Exp. 5a and Exp. 6a is because although the learning conditions are different in Exp. 5a and Exp. 6a, there is no significant difference between participants' learning performance under the two different learning conditions: for the learning score in the ST condition, t= 1.83, p= .08; for learning score in the DT condition, t= -1.58, p= .12. More important, results suggest dyslexics' expression but not learning per se was affected by different conditions. Therefore, these results suggest different learning conditions did not affect participants' performance in general.

To explore the detailed concurrent relationship among different measures of SRT learning performance, rapid naming speed, phonological awareness, short-term and working memory, reading and spelling, and IQ, correlations were calculated. The correlations among all of the variables for the full sample are shown in Table 21.

As shown from Table 21, RAN, phonological awareness, short-term and working memory all significantly correlated to both word reading and spelling. As shown from the Table 21, it is apparent that implicit learning in the ST and DT conditions are strongly correlated to each other, although this could reflect the factor of reaction time underlying these two scores. Both ST and DT implicit learning is significantly correlated to phonological awareness, working memory, and word reading. However, only DT implicit learning is significantly correlated to RAN and short-term memory. It is also interesting to notice that although word spelling is correlated with nearly all of the cognitive measures (RAN, phonological awareness, short-term and working memory), there is no correlation between word spelling and either implicit learning score.

In addition, there was no correlation between implicit learning score with IQ. Although verbal IQ and performance IQ correlated to each other, only verbal IQ showed a strong correlation with nearly all other cognitive measures (RAN, phonological awareness, short-term and working memory), and word reading and spelling. There is no significant correlation found between performance IQ and RAN, phonological awareness, short-term or working memory.

Table 21 Correlations between the implicit learning and experimental variables (one-tailed)

	1	2	3	4	5	6	7	8	9	10	11
1. IL (ST)	-	.35**	.24	.32*	-.20	.33*	.21	.39**	.17	-.13	-.02
2. IL (DT)		-	.23	.27*	-.37**	.27*	.26*	.36**	.01	-.21	-.14
3.Spelling			-	.79**	-.38**	.68**	.37**	.34*	.30*	.01	.14
4.Reading				-	-.53**	.84**	.51**	.49**	.43**	.10	.29*
5.RAN					-	-.43**	-.41**	-.58**	-.26*	.02	-.10
6.Spoonerisms						-	.43**	.47**	.26*	.19	.25*
7.Digit Forward Span							-	.66**	.31*	-.11	.09
8.Digit Backward Span								-	.37**	-.00	.18
9. WASI-verbal									-	.27*	.70**
10. WASI-performance										-	.86**
11. WASI-overall											-

*p≤0.05 **p≤ 0.01 ***p ≤0.001

Discussion

In the current study, two measures of implicit learning were administered to the dyslexic participants and their controls. These two measures were highly correlated. The results of this correlational analysis revealed that implicit learning under both ST and DT conditions was strongly correlated with reading, phonological awareness and working memory. However, interestingly, neither ST nor DT implicit learning performance was correlated with spelling; only DT implicit learning performance showed a significant correlation with RAN and short-term memory. Moreover, neither ST nor DT implicit learning was correlated to either IQ score (verbal, performance or overall).

This result is different from the results of Exp. 1. With the same analyses method, in Exp. 1, no correlation was found between the general implicit learning (measured as the RTs difference between random and sequence trials) and reading score. The difference between Exp. 1 and the current study may be because firstly, more participants were included in the current study; second and also more importantly, the sequence used in the Exp. 1 is a FOC sequence, but in the current study, SOC sequences were used in all experiments. It is possible that only sequence learning involving longer chunk information is correlated to working memory. Therefore, the results are consistent with our earlier argument that only the second-order learning may be associated with reading, and a deficit in second-order learning may cause any deficit in reading.

A correlation was also found between implicit learning scores and phonological awareness. Implicit learning has been found to play an essential role in the acquisition of phonological awareness (Gombert, 2003; Grabe, 2009;

Hepper , et al., 1993). The SRT task is a paradigm which does not involve lexical processing, therefore, a significant correlation between SRT performance and phonological awareness provides a strong support that implicit learning capability may be important in developing phonological awareness, which may be one of the routes by which an implicit learning impairment leads to reading problems.

Correlational analyses confirmed that both implicit learning measures were strongly related to working memory and phonological awareness, but only the DT score was correlated with short-term memory and RAN. This may suggest that both RAN and short-term memory may play roles only in the dual-task condition, but not sequence implicit learning *per se*.

Unlike previous researchers who claimed implicit learning is not limited by memory capacity (Berry & Broadbent, 1988; Hayes & Broadbent, 1988), our results support Frensch et al.'s (1994) argument that implicit sequence learning is correlated to memory capacity. Previous studies suggest that implicit performance improvements on the SRT task rely on the number of items that individuals can hold and operate upon in working memory, as opposed to the ability for chunking or rehearsal (Bo, et al., 2011; Bo, Jennett, & Seidler, 2012). More important, together with the earlier findings that dyslexics only showed poor performance in second-order but not first-order learning, the results suggest impaired working memory may be the reason to explain dyslexic participants' implicit learning deficit.

The findings that RAN and short-term memory were both correlated only with the implicit learning DT performance are consistent with Frensch et al.'s memory-based explanation for the secondary tone-counting task in the SRT, and also support the attention distraction explanation (Curran & Keele, 1993). RAN is considered to be an automatic task, and its correlation with the dual-task performance suggests an automatic central cooperation skill is required for both of the dual-task performance and RAN task. Short-term memory is essential to complete the secondary task: this is because participants need to remember the total count of the tones, which is stored in short-term memory.

Correlation analysis revealed that neither implicit learning score was significantly correlated with IQ. This is consistent with earlier claim that implicit learning is independent of intelligence (Reber, Walkenfeld, & Hernstadt, 1991). As expected, verbal IQ was significantly correlated with word reading and spelling, phonological awareness, RAN, short-term and working memory. However, unexpectedly, performance IQ did not show any correlation with any of the above variables.

4.4. General Discussion

The aim of the proposed study was to explore dyslexics' implicit and explicit learning and expression in the SRT task under the single- and dual-task conditions. The first conclusion is dyslexic participants have intact implicit sequence learning capability and could learn as well as controls even under dual-task conditions (Exp. 5a and Exp. 6a). The second conclusion is dyslexic participants' explicit sequence learning is intact even under very resource-demanding condition (Exp. 5b & Exp. 6b); the third conclusion is dyslexic participants' expression of the sequence knowledge is intact under the ST condition, but their expression is interfered by the secondary task more than controls (Exp. 5a and Exp. 6a).

A significant positive correlation between reading and implicit learning was found in the current study. A similar correlation between the SRT performance and pseudo-word reading score was also observed by Howard and colleagues (2006) and Bennett et al. (2008). The implicit sequence learning effect appeared to be very strongly related to reading and spelling across all participants, however, the way in which different participants approached the SRT task bears discussion.

Working memory, as well as phonological awareness as measured by digit backward span was consistently related to implicit learning performance tested under both conditions. These results may first suggest the important role implicit learning plays in phonological awareness; also poor working memory may be the reason to cause dyslexics' impaired second-order learning. However, the assumption of this causal relationship between these factors needs to be explored with larger sample and further analyses in the future.

As discussed in Chapter Two, there are arguments on the memory limits of implicit learning. Berry and Broadbent (1988) argue that only the selective learning mode is limited by working memory capability, whereas the unselective learning mode does not reflect the operation of a cognitive subsystem such as working memory. However, the current results clearly show a correlation between implicit learning and working memory, which does not accord with a memory-independent theory of implicit learning, but is consistent with other studies that have found a correlation between implicit learning performance and memory capacity (Fletcher et al., 2004; Frensch & Miner, 1994).

There are two theories to help interpret the correlation between implicit sequence learning and working memory capacity. One theory has posited that these implicit and explicit sequence learning systems both compete for a common capacity-limited system (Poldrack et al., 2001) such as working memory. The second (Keele, Ivry, Mayr, Hazeltine, & Heuer, 2003) suggests that the memory limitation may affect performance at the time of expression when undertaking the secondary task rather than during learning. However, in our study, both implicit learning measures tested under ST and DT conditions showed a correlation with working memory, which suggest a relationship between working memory and implicit sequence learning. These results suggested a general requirement of working memory in performing implicit learning. More specifically, implicit learning may also require a central executive processing to some extent because working memory depends heavily on central executive processing capability (Conway & Engle, 1996; Demetriou, 2002). However, it marks an important future direction for studies examining the relationship between working memory and implicit learning.

Between-group comparison indicates dyslexic participants differed from non-dyslexic participants in phonological awareness, RAN, short-term memory, working memory, and implicit learning tested under the DT condition. This is interesting as only the implicit learning (DT) performance could distinguish dyslexic and non-dyslexic participants but not the implicit learning (ST) performance. Furthermore, the RAN was found to have a strong correlation only with the implicit learning (DT) measure not the implicit (ST) measure.

Dyslexic participants showed identical learning under the ST condition in Exp. 6a, suggesting the secondary task did not affect dyslexic participants' learning more than controls, only the expression. Why were dyslexic participants impaired more by the secondary tone counting task compared to controls? The secondary task could not affect dyslexic participants' learning *per se* (Exp. 6a), which indicates that dyslexic participants could not be disrupted by the potential interfering factors brought by the tone counting task, such as a longer interval time between two stimuli (Schmidtke & Heuer, 1997; Stadler, 1995), or the change of the sequence structure (Schmidtke & Heuer, 1997; Stadler, 1995). It should not be due to the extra requirement to the capacity-limited working memory by the tone-counting task either (Frensch, Lin, & Buchner, 1998; Frensch & Miner, 1994), because if that is the case, the activation level of sequence elements in memory should be lowered, and dyslexics' learning *per se* should be affected. Furthermore, dyslexic participants also showed intact explicit learning performance even under DT condition, however, their performance of the explicit knowledge is still impaired under the DT condition (Exp. 6b). The suppression effect of the secondary on dyslexic participants' expression only but not learning suggests it should only be a performance impairment rather than acquisition deficit in the SRT task under the DT condition.

As discussed earlier, Seidler et al. (2002) performed a fMRI investigation showing that the cerebellum does not contribute to sequence learning *per se* during the acquisition of a motor skill but rather to its expression under DT condition. As the COBALT model (Willingham, 1998) suggests, the cerebellum plays a critical role in motor response facilitation and manifested in the motor learning tasks like the SRT task by improving the coordination of movement timing and enhanced motor planning. Our results suggest that dyslexic people may only have an expression problem under the dual-task condition, which implicates cerebellum function in the disorder.

Fawcett and Nicolson (2001) described two mechanisms by which the cerebellum may play a role in dyslexia. One route is related to the motor theory of speech perception, therefore the cerebellar dysfunction of dyslexia leads to mild motor problems, which lead to articulation difficulties, and decreased articulation speed can reduce verbal short-term and working memory functioning. The other route is related to processing speed, therefore the cerebellar dysfunction may lead to reduced processing speed, which would further cause impaired performance under dual-task condition. The results of the current study could be predicted by the two routes proposed by Nicolson and Fawcett: although dyslexic participants did not show overall slower RTs in Exp. 5a or Exp. 5b, however, when under the dual-task condition (Exp. 6a and

Exp. 6b), dyslexic showed significantly slower overall RTs. Furthermore, the implicit learning deficit of dyslexia could also contribute to the first route caused by the cerebellar deficit, i.e., the reduced verbal working memory functioning may cause difficulties in implicit learning, and hamper the development of the implicit grapheme-phoneme representation or implicitly learning to read fluently.

In conclusion, in the present study, the relationship between implicit and explicit sequence learning in dyslexic participants, and the role of the secondary tone-counting task on dyslexic people's learning and expression was examined. Dyslexic participants have been found to show intact implicit and explicit sequence learning as well as non-dyslexic participants, however, they showed impaired performance when the secondary tone-counting task was introduced, which suggested a dysfunction in cerebellum underlying the expression problem caused by the secondary task. Moreover, participants' implicit sequence learning under single- and dual-task conditions were both highly correlated to word reading scores, phonological awareness, and working memory. These findings offer additional evidence for a link between implicit sequence learning and reading, and other reading relevant cognitive abilities.

Chapter Five: Summary

This thesis began by outlining two critical questions in the relationship between dyslexia and associative implicit learning: 1) Are dyslexic people impaired in associative implicit learning? 2) What is the reason for any deficit of dyslexics' implicit learning performance? What follows are the findings of five studies in three chapters:

Chapter Two (Study I and Study II): Implicit learning deficits in dyslexic people are more manifest in second-order learning than first-order learning, with both motoric and perceptual stimuli.

Chapter Three (Study III and Study IV): When only zero- and first-order information is required, dyslexic people developed abstract learning under implicit learning condition as well as, and as fast as non-dyslexic participants.

Chapter Four (Study V): Dyslexic participants showed different sequence learning profiles compared to matched controls: dyslexic participants' expression, but not learning *per se* was more impaired under resource-demanding conditions compared to controls. However, dyslexic participants learned as well as controls under both explicit and implicit learning conditions. In addition, correlation analysis showed a strong relationship between implicit learning and word reading, phonological awareness, and working memory.

5.1. Re-examination of earlier hypotheses

Five hypotheses were proposed in the first chapter, based on earlier theories of dyslexics' impairments in different cognitive processing, and requirements of different implicit learning tasks. Three perspectives of dyslexics' implicit learning have been discussed: what, when, and how. More specifically, it has been proposed that dyslexics may have a deficit in learning more complex knowledge, such as longer chunks or abstract knowledge (i.e., 'what'); learning may occur at different stages between dyslexics and normal people (i.e., when); dyslexics may be less able to apply explicit strategy in learning, or not be able to learn as well as controls when multiple processes are required (i.e., 'how'). These three questions will be discussed in detail below.

5.1.1. What dyslexics could learn implicitly

We have examined how different knowledge forms affect dyslexic participants' learning performance with four studies (I, II, III, and IV). There are three main conclusions we have drawn: first, dyslexics seem to have intact implicit learning of first-order information, but not second-order information; second, dyslexics' abstract learning *per se* seems to be intact, however, they may show impaired abstract learning deficit when learning requires second-order information; third, the dyslexics' implicit learning deficit seems not to be limited to motoric or perceptual representations in nature, as they perform similarly with both motoric (SRT) and perceptual (AGL or DI) paradigms.

These results are consistent with most of our earlier hypotheses, except for the proposal that dyslexics may have deficits in learning abstract knowledge. We expected impairment in abstract learning because of dyslexics' proposed impairment in processing speed; therefore dyslexic participants shall be less likely to spontaneously develop an explicit strategy or abstract knowledge, which both involve a hypothesis-testing phase and require extra processing. This may explain the apparent paradox that some dyslexic individuals who have problems with elementary skills such as reading and writing can be highly gifted in problem solving and abstract thinking (Adult Dyslexia Report, 2004). It is possible that dyslexics' difference in cognition encourages them to develop different ways at processing information, which eventually turn at be effective in themselves.

Also, the possible influence of first- and second-order information in learning abstract knowledge was not predicted, and the results suggest the importance of the statistical complexity of learning materials in examining implicit learning, no matter with motoric or perceptual stimulus, or exemplar or abstract knowledge.

5.1.2. Timing issues in learning

There are two key questions concerning the timing of dyslexics' implicit learning: first, can dyslexics learn as fast as typically developing people, i.e., do dyslexics require the same number of training trials for equivalent learning performance? Second, would a self-paced or experiment-paced setting affect dyslexics' learning performance? The main conclusions are: first, when only zero- and first-order information is required, dyslexic people developed abstract learning under implicit learning conditions as well as, and as fast as non-dyslexic participants; second, dyslexic individual can learn as well as controls in both experiment-paced and self-paced tasks.

Knowledge develops across practice. The dyslexic participants showed intact first-order learning with Study I and Study II, more importantly, dyslexic participants gained first-order knowledge as fast as controls. The results of Study IV further suggested that dyslexic participants not only learn first-order knowledge as well as and as fast as controls, but they also develop exemplar knowledge into abstract knowledge as well as, and as fast as controls.

We also proposed that dyslexic individuals may show different performance for an experiment-paced task because of slower processing speed, and the time constraints may force participants to make a response before the processing is completed. Both the SRT and the AGL task are self-paced tasks, and there is no study so far using an experiment-paced implicit learning task on a dyslexic population. For the DI task, the external time constraints forced participants to make a response within 2 seconds. Dyslexic participants showed learning performance as well as controls under such experiment-paced condition.

5.1.3. Cognitive processes underlying learning

We proposed that dyslexic participants might be less able to develop explicit strategies and show impaired performance under multi-task conditions. There are three questions concerning three different task conditions, implicit, explicit, and dual-task conditions: first, under implicit conditions, could dyslexic participants develop explicit learning strategies as well as controls? Second, under explicit learning conditions, could dyslexic participants learn and express the knowledge as well as controls? Third, would the dual-task condition affect dyslexics' performance in both learning and expression?

These three questions can be answered together from a different perspective. i.e., do dyslexics have a general attentional or coordination deficit? The task condition *per se* (implicit/explicit) did not affect dyslexic participants' learning performance, however, results of Exp. 1 and Exp. 2a suggested although dyslexic participants failed to demonstrate second-order learning, they expressed knowledge as well as controls explicitly. This may suggest first, dyslexics could develop explicit knowledge (as well as abstract knowledge as discussed earlier) as well as controls, even though this means extra processing may be required; second, it is important to separate learning and expression. It is possible that the implicit condition may not affect dyslexics' learning *per se*, but only their expression of the knowledge. It is difficult to test the performance of intentional, explicit learners who memorize the sequence before carrying out the same learning task incidentally. A dual-task condition was therefore added in Study V to further examine this possibility.

The difference between an implicit condition and a dual-task condition is the dual-task paradigm does not only limit or prevent conscious compensation, but also introduces multiple-task processing because two tasks must be performed simultaneously. Therefore, a dual-task condition is more complex and requires extra working memory load compared to an implicit condition.

This is supported by the results in Study V that only implicit learning tested under the DT condition, not the ST condition was correlated with the RAN score.

The results of Study V suggest that the secondary task did not affect dyslexics' learning *per se*, instead, their expression of the knowledge was affected under the dual-task condition. Study (Seidler, et al., 2002) showed that with an SRT task, cerebellar activity was not observed during the sequence learning process in the absence of performance changes; rather, cerebellar activation was correlated with the response time savings observed at expression of learning. Therefore, the results may suggest a cerebellar deficit in dyslexics, which leads to their expression deficit in the SRT task.

Implicit learning was found to correlate with phonological awareness, working memory, and word reading. A regression analysis with regard to the casual relationship among these factors might be of interest in the future research with a larger sample size. However, with the data found in this thesis, it can be suggested that first, there is a positive link between implicit learning and reading and phonological awareness; second, working memory may be linked to implicit learning of longer chunks, and impaired working memory may lead to poor implicit learning of second-order information.

5.1.4. Summary

The results in the thesis may be well predicted by the cerebellar hypothesis of dyslexia, although the cerebellar deficit hypothesis can not explain all data reported in this thesis. There was no evidence suggesting dyslexics' show an impairment in processing speed, or motor processing; however, dyslexic participants showed impaired working memory, slower RT when a secondary task was introduced, and a sequencing deficit by being less able to process sequentially presented stimulus, which are all predicted by the cerebellar deficit hypothesis. Most importantly, dyslexics' expression in the SRT in the dual-task condition was impaired, which is linked to cerebellar function.

The cerebellar hypothesis of dyslexia and the phonological deficit hypothesis of dyslexia are not necessarily mutually exclusive; the argument regarding these two hypotheses is whether the phonological deficit directly causes the reading impairment in dyslexia and cerebellar dysfunction only relates to other symptomatology, or whether the phonological deficit itself arises from a more general cerebellar impairment (Ramus, et al., 2003). Actually whether cerebellum dysfunction plays any causal role in phonological impairment in dyslexia is the key question yet answered by the cerebellar hypothesis. As stated earlier, Nicolson et al. (2001) offered an explicit causal model by which the cerebellum may play a role in dyslexia, and three distinct causal pathways are hypothesized between the cerebellum and the various manifestations of dyslexia: 1) a general motor skill impairment would directly affect writing; 2) its manifestation in speech articulation would affect phonological skills, hence reading; 3) an automaticity impairment would make the acquisition of visual word forms more difficult, which would have consequences both for reading and spelling. Regarding the causal relationship between cerebellum dysfunction and phonological impairment, Nicolson et al. interpreted the phonological impairment with the motor theory of speech perception, and proposed that recognition of the phonological units of words is based upon inferring the corresponding articulatory gestures (such as tongue, mouth movement, etc.), therefore cerebellar dysfunction may lead to mild motor problems in the infant, which consequently lead to articulation difficulties. Poor quality articulatory representations lead to impaired sensitivity to the phonemic structure of language and to reduced phonological awareness.

The findings in the current thesis introduce a new route by which cerebellum dysfunction leads to phonological impairment: cerebellum dysfunction may lead to a reduced implicit learning capability, which prevent the early implicit acquisition of linguistic regularities, such as the construction of grapheme-phoneme representations, phonological processing and the application of rules that are necessary to successfully implement these abilities (Fig. 23). Therefore, children with an implicit learning problem may not be able to develop distributional knowledge and implicit phonological representation about their language as well as their peers.

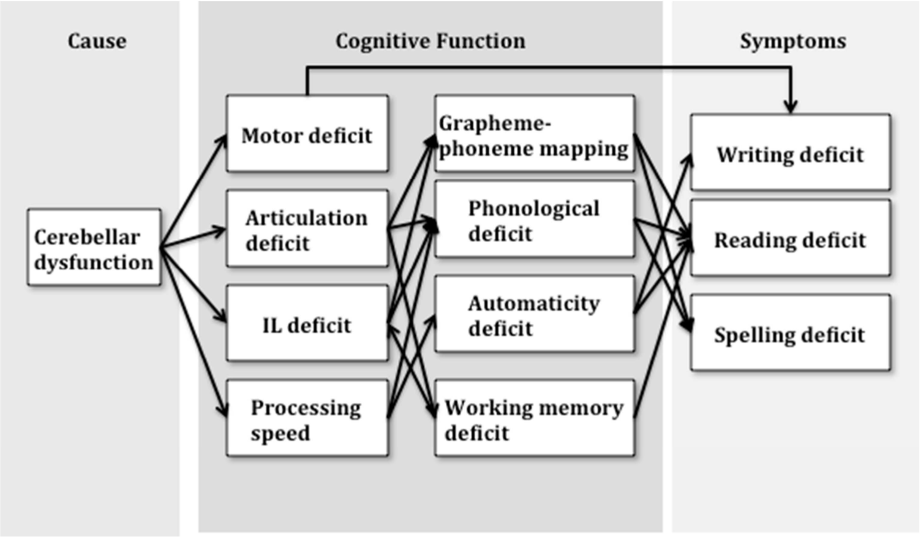

Figure 23 A revised casual analysis for cerebellar deficit hypothesis

However, one limitation of this research is this thesis focused on adult dyslexics, a group which may have reduced variability in reading capabilities due to age–related differences, and limits the extent to which conclusions can be made specifically to the developmental process of implicit learning of reading skills. Karmiloff-Smith (1998) argued that any causal theory of disorders must be studied in early infancy and longitudinally, to explore how alternative developmental pathways might lead to different symptoms. Studying adults may ignore the dynamics of development. Accordingly, any claims regarding impaired cognitive functions must be restricted to the developmental period under investigation or be investigated using a longitudinal approach. Therefore, with the methodology used in this thesis, it is difficult to address any causal relationship between implicit learning and reading skills. A longitudinal approach was not within the scope of this thesis, but it marks an important future direction for studies examining the status of associative implicit learning in reading development.

Besides, this thesis raises the important consideration of statistical information of the learning materials when examining both exemplar and abstract implicit learning, with both SRT and AGL paradigms. Studies of implicit learning must distinguish learning of different statistical information, especially if the target population is featured to have poor memory capability, otherwise, any deficit in implicit learning may be concealed.

5.3. Conclusion

In this thesis, with five studies, dyslexics' associative implicit learning capability has been carefully examined. Although with a suggestion of dyslexics' cerebellar deficit hypothesis, the cerebellar deficit can not explain all data reported in this thesis. Dyslexic participants have been found to have deficits in both implicit exemplar and abstract learning only when higher-order information was required, although this deficit may reflect more a performance problem instead of learning problem *per se*.

Moreover, participants' implicit learning performance was significantly correlated with word reading, working memory, and phonological awareness, which may suggest how implicit learning affects reading acquisition although further exploration is required to address a causal relationship among these factors.

Overall, with the results of five studies, dyslexic participants showed a different profile in implicit learning compared to non-dyslexics. As reported in this thesis, implicit learning is neither uniformly impaired nor uniformly spared in dyslexic people. This pattern of data is considered, along with several potential accounts that have been offered by previous researchers. There is reason to think that dyslexic people might be qualitatively different from typically developing people for implicit learning tasks.

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