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PREDICTIVE TIMING IN DEVELOPMENTAL DYSLEXIA: A NEW HYPOTHESIS

Anticipatory skills across language and motor domains

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Content

List of figures

Abstract

Developmental Dyslexia (DD) is a learning disorder characterized by specific difficulty in learning to read accurately and fluently. It has been argued that the source of the disorder in DD is phonological in nature (Snowling 2000; Ramus et al. 2003). However, this theory does not account for fine and gross motor problems frequently attested in DD (Lam et al., 2011; Nicolson & Fawcett, 1990). In addition, dyslexics often suffer from subtle deficits in the processing of morphosyntactic features and of complex syntactic structures (e.g., Cantiani et al. 2013; Robertson & Joanisse 2010). These facts could be accounted for in terms of comorbidity. But, the frequency of co-occurrence of these disorders can also hint at something deeper. In this thesis, I take up the following questions: which is the nature of the impairment in individuals with DD? What do language and motor activities have in common? To answer to these queries, I propose a framework according to which dyslexics struggle in exploiting temporal regularities to efficiently anticipate linguistic and motor events. I provide evidence for this hypothesis with 5 studies on Italian children and adults with DD.

Study 1 shows that handwriting (a motor activity) and reading (which is based on language) follow a similar pathway in pupils in the first years of school. **Study 2** shows that children with DD are less able to comply with the rhythmic principles of handwriting (RPH) as compared to controls. Moreover, the presence of correlations among handwriting and reading/language measures suggests that the language and the motor systems are potentially linked in the brain. **Study 3** shows that RHP are at work from the age of 6 and that all groups of children (age range: 6 - 10 years) comply with them in equal terms, thus disconfirming the possibility that the RHP emerge after some amounts of handwriting and reading experience. **Study 4** shows that adults with DD display a greater error and are more variable than controls in high predictable rhythmic stimuli. They also display a poorer performance in the test for reception of grammar and inserted fewer pegs in the fine motor skill task. **Study 5** is an extension of Study 4 to children with DD. It shows that children with DD over-anticipate the occurrence of the beat and are very variable in their response. They are also impaired in morphosyntax as compared to controls. In Study 4 and 5, participants with good predictive skills are also faster in reading and performe better in language tasks.

Overall, the results show that the language and the motor system are more linked than it has been previously suggested. Language and motor acts have a rhythmic structure that allows humans to generate timing predictions about an upcoming sensory input. The ability to predict efficiently future events reduces memory load through the pre-activation of the sensory system. In the light of the present results, it seems that dyslexics are unable to exploit temporal regularities to efficiently anticipate the next sensory event. Therefore, the predictive timing system of dyslexics appears impaired, thus affecting both the reading/language and the motor domain.

La Dislessia Evolutiva (DE) è un disturbo caratterizzato dalla difficoltà nel leggere accuratamente e fluentemente. Secondo una delle maggiori teorie, la principale causa della DE è di natura fonologica (Snowling 2000; Ramus et al. 2003). Tuttavia, questa teoria non spiega i problemi di motricità fine e grossa spesso rilevati nei dislessici (Lam et al., 2011; Nicolson & Fawcett, 1990), così come i deficit riscontrati nel processamento di tratti morfonsintattici e di strutture sintattiche complesse (e.g., Cantiani et al. 2013; Robertson & Joanisse 2010). Questi fatti possono essere spiegati in termini di comorbidità. Ciò nonostante, la frequenza di co-occorrenza di questi disturbi suggerisce un nesso più profondo. Nel corso della tesi, mi occupo delle seguenti domande: qual è la natura del disturbo nella DE? Cos'hanno in comune le attività linguistiche e motorie? In risposta a questi quesiti, propongo un framework secondo il quale i dislessici stentano ad utilizzare le regolarità temporali per anticipare in maniera efficiente eventi linguistici e motori. Questa ipotesi è corroborata da dati provenienti da 5 studi su bambini e adulti italiani con DE.

Lo **Studio 1** mostra che la scrittura (un'attività motoria) e la lettura (che è basata sul linguaggio) hanno una traiettoria di sviluppo simile nei primi anni di scuola. Lo **Studio 2** mostra che i bambini con DE sono meno capaci di rispettare i principi ritmici di scrittura (PRS) rispetto ai loro pari. La presenza di correlazioni tra le misure di scrittura e lettura/linguaggio suggerisce che il sistema linguistico e motorio sono potenzialmente collegati a livello celebrale. Lo **Studio 3** mostra che i PRS sono attivi a partire dai 6 anni e sono rispettati alla pari da tutti i bambini (range di età: 6-10 anni). Questo dato scredita l'ipotesi che la comparsa dei PRS avvenga in seguito ad un certo tempo di esposizione alla scrittura e alla lettura. Lo **Studio 4** mostra che gli adulti con DE commettono un errore maggiore e sono più variabili rispetto ai controlli nel predire stimoli ritmici altamente regolari. Inoltri, essi conseguono una scarsa prestazione nel test di grammatica ricettiva e inseriscono meno pioli nel compito di motricità fine. Lo **Studio 5** estende lo Studio 4 a bambini con DE. I bambini con DE anticipano oltremisura l'occorrenza del battito e sono molto variabili nelle loro risposte. Inoltre, essi mostrano una competenza morfosintattica compromessa. Nello Studio 4 e 5, i partecipanti con buone capacità anticipatorie sono più veloci nella lettura e ottengono un risultato migliore nei compiti linguistici.

Nel complesso, i risultati mostrano che il sistema linguistico e motorio sono più collegati di quanto finora supposto. Le azioni linguistiche e motorie hanno una struttura ritmica che permette agli umani di generare predizioni a livello temporale rispetto l'occorrenza di un imminente input sensoriale. L'abilità di predire efficacemente eventi futuri riduce il carico di memoria per mezzo della pre-attivazione del sistema sensoriale. Alla luce dei presenti risultati, il sistema di predizione temporale nei dislessici appare compromesso, con effetti conseguenti nella sfera linguistica e motoria.

Chapter 1

Introduction

To raise new questions, new possibilities,
to regard old problems from a new angle
requires a creative imagination
and marks the real advances in science.
(Albert Einstein)

1.1 Aims and background

Developmental dyslexia (DD) is a learning disorder characterized by specific difficulty in learning to read accurately and fluently. Despite recent development in research and the proposal of several theories, its exact etiology is still a matter of debate. Classical theories of DD argue that the source of the disorder in DD is phonological in nature and stress deficits in phonological processing (Ramus, et al., 2003; Snowling, 2000). However, it now seems that the phonological deficit hypothesis is by no means an exhaustive explanation of the range of difficulties experienced by individuals with DD. It is well attested that at least some children (and adults) with DD show fine and gross motor problems (Capellini, Coppede, & Valle, 2010; Cheng-Lai, Li-Tsang, Chan, & Lo, 2013; Lam, Au, Leung, & Li-tsang, 2011; Nicolson & Fawcett, 1990) and subtle deficits in the processing of morpho-syntactic features (e.g., Cantiani, Lorusso, Perego, Molteni, & Guasti, 2013, 2015; Rispens, Been, & Zwarts, 2006) and of complex syntactic structures (e.g., Robertson & Joanisse, 2010). These facts could be accounted for in terms of comorbidity. But, another option is to ask whether the co-occurrence of these disorders is a hint that there is something deeper. In this dissertation, I take up the following questions: which is the nature of the impairment in individuals with DD? What do language and motor activities have in common? In order to answer to these questions, I propose the **Predictive Timing Framework** (PTF). According to such framework, individuals with DD have difficulties in exploiting temporal regularities to efficiently anticipate linguistic and motor events. I provide evidence for this hypothesis with five studies on children and adults affected with Developmental Dyslexia as well as on typical developing children.

1.2 Outline of the thesis

The present dissertation is structured as follows.

Chapter 2 provides the theoretical background. First, a brief overview of the major theories of dyslexia is given. We will then review some recent literature showing that the problems faced by many children with dyslexia are not narrowed to reading and spelling, but spread to the motor domain. We will posit that both language and motor abilities (in particular handwriting) have a rhythmic structure, which enhances the generation of prediction. We will discuss the key role of rhythm in language acquisition and we will see that humans are inborn with an implicitly sensitivity to specific rhythmic patterns which are used to chunk the language stream. Likewise, we will observe that handwriting (considered in its motor aspect) has a temporal structure and it is governed by principles of rhythmic organization, namely isochrony and homothety.

Chapter 3 presents **Study 1**. The aim of this explorative study is to investigate the developmental trajectory of reading and handwriting in pupils in their first years of school. One hundred and two Italian children, ranging from the first to the fourth grade of primary school, are tested. The quantitative kinematic measures of the handwriting gestures are collected by means of a digitizing graphic tablet. These results showed that pupils make a significant progress from grade 2 to grade 3, both in reading, phonological memory, and the fine motor ability required in handwriting, followed by stagnation between Grade 3 and 4. The fact that these different domains display similar developmental curves is discussed in relation to developmental disorders and the influence of handwriting in learning to read (and vice versa). A modified version of this Chapter has been submitted for publication as Pagliarini, E., Stucchi, N., Bouamama, S., Arosio, F., & Guasti, M. T. *The development of handwriting and language in the first years of school: a cross-sectional study.*

Study 2, reported in Chapter 4, compares the language and handwriting performance of children with DD with (21 participants) and without (17 participants) diagnosis of handwriting difficulties (dysgraphia), to that of age matched typically developing children (39 participants). All children were Italian monolingual speakers. Likewise Study 1, the quantitative kinematic variables of handwriting are collected by means of a digitizing graphic tablet. The results show that all children with DD write slower than their peers. The findings also reveal that children with DD are less able to comply with the rhythmic principles of handwriting (isochrony and homothety) as compared to control children. The presence of correlations among handwriting measures, reading/language measures and a measure sensitive to children's ability to comply with isochrony further suggests that the language and the motor systems are more linked than previously suggested. In the light of our results, we propose that the link between handwriting and reading/language deficits is mediated by rhythm, as both reading (which is grounded on language) and handwriting are ruled by principles of rhythmic organization. A slightly modified version of this Chapter has been published as Pagliarini, E., Guasti, M. T., Toneatto, C., Granocchio, E., Riva, F., Sarti, D., Molteni, B. & Stucchi, N. (2015). Dyslexic children fail to comply with the rhythmic constraints of handwriting. *Human movement science*, *42*, 161-182. Here, it is reprinted with the kind permission from Elsevier and from all the authors.

The results of Study 2 left open the possibility that the principles of rhythmic organization (isochrony and homothety) are the outcome of a certain amount of handwriting (or even reading) experience, and that the subtle problems found in children with DD are mere consequences of the fact that these children have less experience in both reading and handwriting. The cross-sectional **Study 3** reported in Chapter 5 aims at investigating the development of isochrony and homothety. For this purpose, the ability to modulate the size and the tempo of handwriting was assessed in 298 Italian pupils (age range: 6 – 10 years), divided into five groups, ranging from the first to the fifth grade of primary school. The results of this study disconfirm the likelihood that the principles of rhythmic organization in handwriting emerge after some amounts of handwriting and reading experience. Both isochrony and homothety are at work from the age of 6 and all groups of children comply with them in equal terms. A modified version of this Chapter has been submitted for publication as Pagliarini, E., Scocchia, L., Vernice, M., Zoppello, M., Ballottin, U., Bouamama, S., Guasti, M. T., Stucchi, N. *The rhythm of handwriting.*

In the light of the results of Study 3, we can reconsider the findings of Study 2. Taken together, these results suggest that children with DD have difficulties in constructing a timing internal representation, which should enhance the anticipation of the occurrence of future sensory events (in the case of handwriting, events can be letters, words, phrases). However, in all the previous above-mentioned studies, we adopt handwriting task in which the temporal properties are implicit. In Study 4 and Study 5 we use a task in which the temporal properties are explicit.

Study 4, presented in Chapter 6, 18 well-compensated adults with DD (mean age 22;3) are tested along with 20 controls (mean age 23;4). Participants are Italian monolingual speakers. Participants are engaged in a task requiring entrainment to a given rhythm using a warning and imperative paradigm. Moreover, the language and the fine-motor abilities of these participants are assessed. The results show that adults with DD display a greater synchronization error and are more variable than controls. Moreover, a sub-set of adults with DD turn out to be slower in processing sentences of different syntactic complexity and inserted fewer pins in the fine motor skill task as compared to control participants. Finally, the correlation analysis shows that participants with good anticipatory skills inserted more pegs in the fine motor task, they are faster both in reading and in the receptive grammar task, and in this latter task they also turn out to be more accurate. A modified version of this Chapter will be submitted for publication as Pagliarini, E., Guasti, M. T., Maffioli, G. Scocchia, L., Stucchi, N. *Predictive timing in adults with developmental dyslexia*.

Chapter 7 reports **Study 5,** which is an extension to children with DD of Study 4. This study is still on going. The ability of 14 Italian children with DD (mean age 9;75) to make predictions upon the timing of occurrence of rhythmic regular stimuli is examined by means of the same paradigm used in Study 4 and it is compared to the performance of 7 age matched control children (mean age 9;40). The study is also set out to explore oral language abilities as well as fine motor skills in children with DD. Possible correlations among predictive timing abilities, reading skills, phonological awareness and fine motor abilities are also studied. The preliminary results show that children with DD over-anticipate the occurrence of a beat in high predictable rhythmic stimuli and are very variable in their response, though generally children data are less clear than adult data. As for oral language competence, a sub-set of children with DD displays subtle difficulties in the production of inflectional morphology as compared to age matched children. Contrary to adults with DD, dyslexic children did not differ from their peers in the number of pins inserted in the pegboard task. Similarly to Study 4, the children who showed a bigger synchronization error, were those who read fewer syllables/seconds, who recalled fewer digits, and who performed worse in the verbal morphology and phonological awareness task. A modified version of this Chapter will be submitted for publication as Pagliarini, E., Guasti, M. T., Stucchi, N. et al. *Predictive timing and developmental dyslexia: a new hypothesis*.

Finally, Chapter 8 summarizes the content of the dissertation and discusses the main findings. In the light of our results, a novel causal model for DD is proposed, namely the Predictive Timing Framework (PTF). Ultimately, possible directions for future research are suggested.

Chapter 2

Theoretical assumptions

2.1 Developmental dyslexia

Learning to read involves establishing connections between graphemes (printed words) and phonemes (sounds). Children are taught to read generally starting from 6 years of age (Italian mainstream), and the full mastery of reading requires some years of practice and instruction. Once completely automatized, reading becomes fluent and does not longer require conscious control. However, the 3–7 percentage of the school population children struggles in automatizing the reading process. Indeed, these children suffer from developmental dyslexia (henceforth DD). In Italian, the percentage ranges from 1.5% to 5% (Cornoldi & Tressoldi, 2007; Cornoldi, 1991; Stella, 1999; see also (Barbiero et al., 2012). Children with DD turn out to read slower and less accurate than children equal on age who received the same amount of teaching. Reading is assessed by asking children to read aloud lists of unrelated words (which are read from memory by retrieving memorized spelling patterns) and non-words (which is a test of decoding abilities, since direct orthographic representations cannot be accessed).

The *Diagnostic and Statistical Manual of Mental Disorders* (DSM-5) (American Psychiatric Association, 2013) included Developmental Dyslexia (DD) among the Specific learning disorders and described it as "a pattern of learning difficulties characterized by problems with accurate or fluent word recognition, poor decoding, and poor spelling abilities" (p. 67) in children with average intellectual abilities, without mental or neurological disorders, proficient in the language of academic instruction and provided with adequate educational instruction.

An exhausted definition of DD is also given by Lyon and colleagues (Lyon, Shaywitz, & Shaywitz, 2003): "Dyslexia is a specific learning disability that is **neurobiological** in origin. It is characterized by **difficulties**

with accurate and/or fluent word recognition and by poor spelling and decoding abilities. These difficulties typically result from a deficit in the **phonological component of language** that is often unexpected in relation to other cognitive abilities [...]" (p. 2). This definition is particularly satisfying because it raises the most important points which characterize DD. The first point is the neurobiological origin. Multiple genetics and environmental factors play a role in the development of dyslexia, but the exact etiology of dyslexia is still unclear. Recent evidence showed that dyslexia is heavily influenced by genetic risk factors. *KIAA0319* and *DCDC2* on the 6p21- p22 chromosomal region have been suggested to be possible candidate genes for DD (see Cope et al., 2005; Paracchini et al., 2008 for *KIAA0319* among others; see Schumacher et al., 2006 for *DCDC2* among others). *KIAA0319* and *DCDC2* control early brain development and are involved in neural migration (Meng et al., 2005; Silvia Paracchini et al., 2006). Therefore, these genetic mechanisms might influence the development of brain tissues at the basis of the neural systems for reading, as there is evidence in dyslexic individuals for both structural and functional differences in many left hemisphere brain regions engaged during spoken language and reading. However, despite considerable progress towards the identification of specific genes and causes that might be involved in the development of DD, we can acknowledge that genetics and neurobiological studies are quite complicated (and sometimes speculative), considering the complexity of the traits of the dyslexic phenotype and the limitations of the accessibility of cohort with sufficient sample size to conduct genome-wide screening. Along these lines, Pennington (2006) argued that the etiology of dyslexia, similarly to other developmental disorders, is multifactorial and involves the interplay of multiple risk and protective factors, which can be either genetic or environmental, and that, as a consequence, comorbidity among disorders is to be supposed given the shared etiologic and cognitive risk factors.

The second sentence of the definition points to the difficulties with accurate and/or fluent word recognition and to poor spelling and decoding abilities that affected individuals with DD, which are the result of a deficit in the phonological component of language. It also introduces one of the major theories of developmental dyslexia, the **phonological theory**, according to which the core problem across languages is a deficit specific to phonology. It is widely agreed that DD is a language disorder (Vellutino, 1979), specifically due to phonology related processes (e.g., Castles & Coltheart, 2004). Children who turn out to be dyslexic usually show a phonological deficit before they learn to read and the size of the severity of the phonological deficit is usually predictive of the variation in the size of the severity of the reading deficit. Thus, children with DD struggle in reading accurately and with fluency and experience particular difficulties in phonological awareness tasks (explicit phonology), phonological processing tasks and in tasks demanding rapid automatized naming (implicit phonology). Phonological awareness tasks measure the ability to explicitly judge the sound structure of a word. Children with DD have been found to perform more poorly than younger reading age matched children when asked to select the word out of a sequence of four words that did not rhyme (Bradley & Bryant, 1978), and on tasks of syllable segmentation and onset-rime similarity (Swan & Goswami, 1997). Phonological processing tasks tap on implicit phonology, thus it does not requires to overtly reflecting upon the sound structure of the spoken words. Children with DD have been found to have difficulties in repeating nonwords (Snowling, 1981) and to be slower in tasks of rapid automatized naming (RAN) than typically developing readers of the same age (Wolf & Bowers, 1999). Also verbal short-term memory appears to be an area of difficulty for children with DD, as they usually have shorter memory spans than typically developing children of the same age. Thus, the core cognitive problem of dyslexic individuals lies in phonological abilities (Snowling, 2000), as supported by the multiple case study conducted by Ramus and colleagues (Ramus, et al., 2003). Despite the heterogeneity among the profile of dyslexic individuals, they showed that 16 out of 16 adults with DD suffered from a phonological deficit. Other impairments, such as the auditory or motor deficits, were restricted to few individuals.

However, beside the undisputed core phonological deficit, the literature depicts a much more complex picture since children with dyslexia are affected by a variety of disorders, and this has led to the proposal of different theories of dyslexia, aside the major phonological theory.

In the following pages, I will provide a brief neutral overview of the main theories of dyslexia. A more detailed description is beyond the aim of the present dissertation. At this point, it is worthwhile pointing out that the studies collected in this dissertation were all administered to individuals who could not convert letter to sound and therefore had a phonological dyslexia.

The **rapid auditory processing theory** proposed by Tallal (Tallal, 1980; Tallal & Piercy, 1973) claims that a problem with basic auditory perception might cause the phonological difficulties found in children with DD. Notice that in origin, this theory was developed to account for the language-learning problems of children with Specific Language impairment (SLI). According to Tallal, individuals with DD (and SLI) suffer from an inability to integrate sensory information that converges in rapid succession in the central nervous system. Instead, when the input time for signal processing is sufficient, children with language impairment have enough time to discriminate sequence of sensory information normally. This claim is based on findings which showed that at slow presentation rate (ISI 428 ms), children with language impairment did not differ from control children in identifying, discriminating and sequencing basic acoustic information (tone of 75 ms) (Tallal, 1980). However, when the ISI was reduced at 150 ms or shorter, the performance of children with language impairments dropped to chance level, whereas typical developing children reached 75% correct responses with decreased ISIs. The failure to process acoustic information that enter the nervous system within the tens of milliseconds can cause difficulties when the acoustic events are indications of phonemic contrast, such as in the syllables /ba/ and /da/, since formants change very rapidly over time, and formants transitions (e.g., changes from consonant to vowel) are critical for syllable discrimination. In fact, the syllables /ba/ and /da/ differ only over the initital 40 ms, which is the time when syllables change very rapidly in time, whereas the vowels /a/ are steady-state throughout the remainder of 250-ms syllables. Tallal showed that children with language impairment were on par with typical developing children in detecting, associating and sequencing vowel stimuli /ɛ/ /æ/, but when the stimuli where stop consonant-vowel CV syllables with a 40-ms formant transition, 10 out of 12 children with language impairment failed the task. In further experiments the authors showed that children with LI were not impaired in process transitional auditory elements per se, but they were impaired in the ability to integrate brief acoustic elements occurring within tens of milliseconds in the ongoing speech stream, regardless the phonemic classification (Tallal & Stark, 1981). These results have been extended to speech production. By means of a spectrographic analysis of speech production, it has been found that children with language impairments were impaired in their ability to control the production of temporal components that characterize speech syllables in their motor output (Stark & Tallal, 1979; Tallal, Stark, & Curtiss, 1976). Tallal also reported correlation between the degree of temporal processing impairment and the degree of receptive language deficits (tested by means of standardized clinical receptive language tests) (Tallal, Stark, & Mellits, 1985). To conclude, Tallal claimed that children with language impairment suffered from a pansensory deficits, which affects both the processing of acoustic information that enter the nervous system presented within the tens of milliseconds range and the rapid sequential motor output.

Along these lines, Hornickel & Kraus, (2013) showed that poor readers displayed more variable auditory brainstem responses to formant transition (stimuli were 170 ms /ba/ and /ga/ syllables, having 50 ms formant transitions), whereas responses to the slower vowel region of the syllable did not differ between good and poor readers.

The **visual theory** claims that dyslexia affects the transient pathway of the visual system causing a deficit in low-level visual processing (Lovegrove, Garzia, & Nicholson, 1990; Lovegrove, Martin, & Slaghuis, 1986). When reading, these results in visual confusion, as letters might seem to move around. It has been found that children with DD have been shown to have poor binocular control than typically developing children (Cornelissen, Bradley, Fowler, & Stein, 1994) especially when fixing small letters, to have reduced luminance contrast sensitivity and to be less sensitive to motion (Cornelissen, Richardson, Mason, Fowler, & Stein, 1995). Moreover, a larger crowding effect has been found in adolescent dyslexic compared to normal readers, also when symbols were used instead of letters, thus showing the effect of crowding arises at a pre-linguistic level (Spinelli, De Luca, Judica, & Zoccolotti, 2002). Notice that, according to the visual theory, the origin of this deficit is cortical and not retinal.

According to the **attention theory** (Facoetti et al., 2003; Hari & Renvall, 2001) a cross-modal letter-to-speech sound integration deficit is one of the major causes of dyslexia. Children with DD are affected by spatial attentional deficits, which impair their ability to focus on each sequential letter before letter is converted to sound. In a similar approach, visual attention deficit is considered a core problem in DD, which limits the number of distinct visual elements that can be processed in parallel (Bosse, Tainturier, & Valdois, 2007). In other words, individuals with DD exhibit a reduced visual attention span.

The first version of **Automatization Deficit Hypothesis** was proposed by Nicolson and Fawcett in 1990. In the following years the theory has first been amended to the more comprehensive **Cerebellar Deficit Hypothesis** (Nicolson, Fawcett, & Dean, 2001) and later to the **Procedural Learning Deficit Hypothesis** (Nicolson & Fawcett, 2011) (see Chapter 3). The Automatization Deficit Hypothesis, as well as its later versions, holds that people with DD suffer from difficulties in skill automatization beyond the reading domain (e.g., motor balance). Difficulties in automatization point to the cerebellum, whose role is the regulation and fine-tuning of motor activity. This prediction was borne out by experimental results. In a PET study, adult dyslexic subjects showed less cerebellar activation in the right hemisphere while executing a previously overlearned task (Nicolson et al., 2001). The Cerebellar Deficit Hypothesis put forward a causal explanation of the development of the difficulties experienced by dyslexic children. Cerebellar abnormality provokes mild motor problems during the development. This can result in a lack of articulatory fluency which in turn might lead to an impoverished representation of the phonological features of sounds, thus providing a plausible explanation of the phonological core deficit (and also of the motor problems attested in dyslexic individuals).

The **magnocellular theory** proposed by Stein & Walsh (1997) can be considered a sort of unifying theory. It argues that individuals with DD suffer from an impairment of the development of the magnocellular system. The magnocellular neurons distributed principally in the visual and auditory systems play a key role in controlling visual and auditory attention when reading and are specialized to respond to temporal transients (Galaburda, & Livingstone, 1993). Therefore, this theory accounts for a defective temporal processing that spans across different domains (somaesthetic, auditory, visual, and motor domains).

The last theory I will outline is Goswami's **Amplitude Envelope Onsets Deficit Hypothesis** (Goswami et al., 2002). This hypothesis argues that deficit in amplitude and frequency-modulation detection in DD children might relate to deficits in the processing of acoustic structure at the level of the syllable. Amplitude envelope rise time sensitivity was assessed by means of a *beat detection task*, in which the AM was varied to affect the perception of distinct beats in the auditory stream (tones had a rise time which varied from 15 ms to 300 ms logarithmically spaced). Children with DD turned out to be less sensitivity to variations in the rise time of the beat across a continuum. The authors also found significant correlations among beat detection and RAN, phonological memory, phonological awareness, reading, spelling and non-word reading. The detection of beats in AM sequences coincides with the detection of "perceptual centers" (P-centers). P-center has been defined as the "moment of occurrence" of an acoustic event (Marcus, 1981; Morton, Marcus, & Frankish, 1976) occurs a short time after onset, before the sound reaches its maximum amplitude (Scott, 1998). Generally, in speech, it is the near onset of the syllable vowel. Thus, the basic idea is that the rhythmic periodicity in speech is related to the P-center (or amplitude envelope onset of the vowel (AEO)) and that individuals with dyslexia suffer from a deficit in the perceptual experience of rhythm detection, caused by a deficit in AEO rise time sensitivity (Goswami et al., 2002; Muneaux, Ziegler, Truc, Thomson, & Goswami, 2004; Richardson, Thomson, Scott, & Goswami, 2004). The latest version of this proposal is the **Temporal Sampling Framework (TSF)** (Goswami, 2011), which is an integrated theoretical framework based on neural oscillations. According to the TSF, individuals with DD suffer from a right-lateralized impairment in Theta and Delta oscillators, which are dedicated to a temporal integration of ~100-300 ms (syllable tracking). We will return to Goswami's proposal in Chapter 6 and 7.

2.2 Motor problems and developmental dyslexia.

"My little brother often mixes up his left and his right […] Is it because he mixes up left and right that he has trouble with maps? [...] You mustn't give him a long list of things to do. He only remembers the first or the last one. So I can't ask him to go shopping […] He is great at making models […] But he's a bit clumsy, knocking things over. Bumping into furniture. When he breaks things, we forget all the good things he can do. My little brother writes some letters the wrong way round. And numbers too! He often mishears words and names. So he says them wrong too. A Par Car means a Car Park. A Fieth is a Thief! But he can remember the number pi. When he is talking, he seems to know a lot. But his exam results are not great. It's not that he's lazy. Studying just takes him longer than his friends. He finds it hard to remember thing he has read in books. But he can always remember thing he has seen on TV […] My little brother doesn't like reading in front of his class. Letters on the page jumble up and move around. I helped my brother with his spelling. And he taught me how to play games… Is it my brother who is different? Or me? My aunt, my cousin and my dad are like him. But my mum is like me. My little brother is dyslexic. He isn't stupid." (Tateno & Brocklebank, 2007, pp. 2-22)

These passages are taken from an engaging book, *My little brother* (Tateno & Brocklebank, 2007), which narrates the story of a dyslexic boy told by his big sister. From this paragraph, the reader can deduce that beyond difficulties in reading accurately and with fluency, children with dyslexia are affected by impairments in other domains, such as short-term memory, attention, language, fine and gross motor abilities. Some of these difficulties will be discussed extensively throughout the various chapters of this dissertation.

The co-occurrence of two (or more) different disorders in the same individual is defined comorbidity. A high comorbidity among linguistic, developmental and motor disorders has been well-attested for decades (Kaplan, Wilson, Dewey, & Crawford, 1998; Robinson, 1987). Aside comorbidity, if we focus on developmental dyslexia, it is well established that at least some children with DD frequently suffer from subtle motor and language difficulties (see Chapter 6 and 7 for a detailed description of language problems in children and adults with DD). Nicolson and Fawcett (1990) compared the performance of 23 children with DD (mean age 13;00 years) to that of age matched children on a battery of tests of motor balance. The authors of the study found that children with DD experienced difficulties in motor balance under dual-task condition (counting backwards and auditory choice reactions). Further evidence of impairments in motor skills comes from Fawcett et al.'s study (Fawcett, Nicolson, & Dean, 1996). Children with DD aged 10, 14 and 18 years were tested along with age-matched controls on a battery testing muscle tone, coordination and fine motor abilities. The findings showed that children with DD were significantly impaired in different motor control tasks, more specifically: 25/29 children with DD had balance time problems; 28/29 had problem in postural stability; 23/29 had problem in the finger to thumb task[1]. These results have been replicated by Ramus and colleagues (Ramus, Pidgeon, & Frith, 2003) as they found that children with DD (aged between 8 and 10 years old) scored significantly poorer than control children in postural stability, bead threating[2] and finger to thumb. In this study, the incidence of motor problems in children with DD was of 59%, though part of these children had an additional disorder (ADHD or DCD). Nevertheless, 5 pure dyslexic children reported severe motor problems. In a more recent study, Capellini and colleagues (Capellini et al., 2010) assessed the fine motor, sensorial and perceptive functions of 20 students with DD (mean age 10;5 years) and found that these children performed poorly in finger opposition task and body imitation. Furthermore, it has been found that 33 of 88 young children at familial risk for DD were slower in both gross and fine motor development (Viholainen, Ahonen, Cantell, Lyytinen, & Lyytinen, 2002). Interestingly, it has been shown that children with DD suffer from handwriting difficulties, since studies on Chinese language showed that dyslexic children are affected by a specific motor deficit, namely dysgraphia (Capellini et al., 2010; Cheng-Lai et al., 2013; Lam et al., 2011) (see Chapter 4 for an exhaustive definition of dysgraphia). The presence of subtle handwriting difficulties in dyslexic individuals having a logographic language points to conjecture the presence of latent handwriting deficits also in Italian dyslexic individuals having an alphabetic lettering language, a hypothesis that will be addressed in Chapter 4. Along these lines, the recurring association between DD and dysgraphia led Nicolson and Fawcett (2011) to propose the

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[1] Balance time was measured as the total time during which participants could stand,
[2] In the bead threading task, participants are given a string and 15 wooden beads and are asked to thread the beads as fast as possible, holding the string in the dominant hand. Ramus and colleagues measured the time taken to thread the 15 beads.

Procedural Learning Deficit Hypothesis (Nicolson & Fawcett, 2011) (see Chapter 3).

There is also substantial comorbidity between SLI and motor disorders. Hill, (2001) in a review of the literature reported that the majority of children with SLI experiences significant both fine and gross motor difficulties. Moreover, it has been showed that the imitation of complex movement predicts expressive vocabulary both in SLI children and in typically developed children (Vukovic, Vukovic, & Stojanovik, 2010) and that children with SLI scored significantly lower than language-matched and typically language comparison groups on all of the motor measures of the Movement Assessment Battery for Children (MABC-2) (Finlay & McPhillips, 2013).

The frequent co-occurrence of developmental disorders suggests that different disorders may derive from shared environmental and genetic risk factors, which in turn might influence brain development. It also leads us to suggest that reading, language and motor abilities share an underlying mechanism based on common principles (see also Paragraph 2.3). We also need to consider that brain regions that serve different cognitive functions can be anatomically proximal and part of the shared neural network (see Chapter 3). Finally, motor and cognitive developments have been traditionally considered separately, but several of the results reported throughout the course of this dissertation reveal that motor development and cognitive development are more interconnected than it has been previously suggested.

2.3 Rhythm is shared between language and motor activities

It is widely recognized that DD is a language disorder (Vellutino, 1979) but, as discussed in Paragraph 2.2, children with DD are also affected by motor problems. So the question is: what do the language and motor domain have in common? I would like to put forward the hypothesis that motor gestures and language performance are both governed by principles of temporal organization, in other words they have a rhythmic structure. Indeed, the word "rhythm" occurs in very different contexts besides music. It is usually applied to characterize different phenomena, such as speech, motor actions (such as dancing, clapping the hands, etc.), brain oscillations, and the circadian rhythm, among many others. In most of the above-mentioned circumstances, rhythm designates periodicity, that is to say a repeating pattern occurring regularly in space or time. Indeed, in the sensory environment, most significant stimuli exhibit strong regularities. Although periodicity is one of the main features of rhythm, a crucial (often neglected) distinction between the two concepts needs to be sketched. Inspired by Lashley's groundbreaking work (Lashley, 1951), Wolff (2002) gives a clear definition of rhythm, which stresses the difference between rhythm and periodicity (the latter referred to as cadence): "[…] *rhythm as any temporal pattern, other than a simple cadence, that can be recognized when it occurs again. The term **cadence** is here reserved for the linear repetition of events at isochronic interval that can be interchanged freely without affecting either the other individual events or the overall structure of the sequence. **Rhythm**, by contrast, will refer to any collection of units or elements that are similar in most respects but differ in at least one, and usually more than one, distinctive feature. The distinctive features may be variation in the duration of the units themselves (e.g., half and quarter notes), the intervals between units (pauses), and variation of stress, pitch or amplitude, or any combination of these features. The fundamental property that distinguishes rhythms from other temporal sequences is the contextual interdependence of all its elements within a hierarchic structure. Thus, changing either the location or feature of any one unit can reciprocally alter either the sequence or the qualitative attributes of the units that give any rhythmic pattern its unique characteristics. (Lashley 1951).*" (Wolff, 2002, p. 185). As remarkably argued by Lashley (1951), the fundamental concept of this definition, which will be further considered throughout this dissertation as being the fulcrum of the discussion, is that human complex actions are not just a succession of isolated acts, but they are organized processes in which each element is contextually interdependent to all the other elements within a larger unit having a hierarchic structure.

When considering rhythm, another important distinction is between grouping and meter (London, 2012). They are two distinct aspects of rhythm, which nevertheless interact with each other. Importantly, they both are *cognitive construct*, as defined by Fitch (2013), since they are not present in the external phenomenon (can be an acoustic signal or a motor sequence), but they are inferred by the listener.

Grouping implies the segmentation and organization of boundaries in which discrete elements (either visual, motor, or auditory) form a temporal unit. Importantly, these groups have a hierarchical structure, which means that they are "[…] related in such a way that one element or region subsumes or contains other elements or regions" (Lerdahl & Jackendoff, 1983, p. 13).

The **meter** is a notion which is mostly associated to auditory signals. **Meter** is perceived by the listener as an instinctive regular alternation of strong and weak beats, occurring periodically {**strong**, weak, **strong,** weak, . . .} (Lerhdal & Jackendoff, 1983; London, 2012; (Fitch, 2013). Listeners usually assign a metrical structure even to a sequence of identical beats from a metronome, and this is a crucial point when considering entrainment and synchronization (see Paragraph 2.4.2). The perception of a metric structure has a physiological representation since the entrainment to a beat elicits a neuronal response tuned to the frequency of the perceived meter (Nozaradan, Peretz, Missal, & Mouraux, 2011).

According to Fitch (2013), the extraction of meter implies the choice of a particular time in the sequence, functioning as the dominant or "head" node around which a hierarchical structure is built. Therefore, according to the definitions outlined above, the main difference is that grouping structure consists of units whereas metrical structure consists of beats, where both structures are hierarchically organized.

The preference for certain rhythmic grouping is explained by two perceptual universals (Bolton, 1894; Woodrow, 1909). According to these universals, there is a natural tendency to perceive series of elements which alternate in duration as iambic {short, long, short, long, . . .} and series of elements that alternate in intensity as trochaic {strong, weak, strong, weak, . . .}. These two general perceptive universals have been adapted to language by (Hayes, 1995) and they are referred to as the Iambic/Trochaic Law:

(1) Iambic/Trochaic Law

a. a louder sound tends to mark the beginning of a group (trochee feet);

b. a lengthened sound tend to mark the end of a group (iamb feet).

Since the Iambic/Trochaic law's proposal, many studies have been conducted to investigate whether rhythmic grouping follows these two universal principles or it is rather influenced by language-specific factors (such as the phrasal structure of the native language). Bion and colleagues (Bion, Benavides-Varela, & Nespor, 2011) showed that Italian adults remembered better pairs of syllables that had short syllables preceding long syllables when familiarized with syllable alternating in duration. They also showed that participants were better at remembering high-pitched syllables preceding low-pitched syllables[3] when familiarized with syllables alternating in intensity, in line with the Iambic/Trochaic law. The same paradigm was adapted to testing infants, by using a head-turn preference paradigm. When familiarized with syllables alternating in pitch, infants preferred listening to pairs of syllables that had high pitch in the first syllable, whereas no preference was found in the duration condition. In another experiment, Hay & Diehl (2007) showed that the law applies to both speech (alternating /ga/ syllables) and non-speech stimuli (square wave segments) varying in either intensity or duration. In accordance with the Iambic/Trochaic law, they found

[3] The Iambic/Trochaic law does not make any predictions on the effects of pitch on rhythmic grouping, but there are evidence showing that pitch may also play a role in perceiving trochees at the phrasal level, as suggested by Bion et al., 2011 (see also Nespor et al., 2008).

that elements contrasting in duration are grouped in iambics while elements contrasting in intensity are grouped as trochees, and notably they found no significant differences between rhythmic grouping preferences of French and English participants. The authors concluded that the perception of linguistics rhythm relies on general auditory mechanism, which are not language specific. Peña, Bion, & Nespor (2011) demonstrated the Iambic/Trochaic law is not specific to auditory modality, but accounts also for grouping preferences in the vision modality. However, contrary to Bion et al. (2011) and Hay & Diehl (2007), Iversen, Patel, & Ohgushi (2008) found significant differences when confronting English and Japanese participants. English listeners grouped alternating tones varying in duration into short-long chunks (iamb feet) whereas Japanese's preferences were significantly biases toward long-short grouping (though the preference was not statistically significant). When the intensity was modulated, both English and Japanese listeners grouped alternating tones into strong-weak chunks (trochee feet). These results challenge the universality of grouping. The authors suggested that the syntactic parameter of head-direction which determines the functor/content words ordering of a language, shapes the rhythm of the phrase in English and Japanese, and ultimately influences grouping preference. Languages can be divided into two categories, according to their head-direction parameter. In head-complement (or head initial) languages such as English, the head (can be a N (noun), a V (verb), a D (determiner)) precedes the complement. In these languages, functional words precede content words as in [the book] = [determiner noun][4], as the determiner is taken to be the head of the phrase (Abney, 1987). In complement-head (or head final) languages, such as Japanese, the head follows the complement. Therefore, in these languages, functional words follow content words as in [hon ga] = [book subject marker]. Capitalizing on this syntactic proposal, the results of Hay & Diehl (2007)

[4] I assume Abney's (1987) structure of the determiner phrase (DP). On the DP-hypothesis, the determiner is taken to be the head of the phrase and the NP is taken to be the complement of the determiner.

follow, since both French and English are head-complement languages. It is worth underlying the syntactic ground of this proposal: English and French belongs to two different rhythmic classes when considering syllable structure, as they are respectively a stress-time language and a syllable-time language (Grabe & Low, 2002; Pike, 1945; Ramus, Nespor, & Mehler, 1999), yet English and French listeners showed the same preference for short-long groups, when duration was modulated. The crucial point is that both languages are head-complement language, and therefore they are similar at the phrase level (English: *the book*; French: *le livre*). Despite challenging the universality of the iamb feet, the results by Iversen et al. (2008) also suggested the existence of a universal trochaic bias (as also proposed by Patel, 2008). The results discussed above raised interesting questions regarding the development of these grouping preferences. Yoshida and colleagues (Yoshida et al., 2010) tested the development of grouping preferences in Japanese and English infants. Their results showed that at 5-6 months neither Japanese nor English infants display a grouping bias in non-speech durational contrasts. However, at 7-8 months English infants reveal a preference for iambs, whereas Japanese infants reveal no preference, in line with Iversen et al. (2008) adults' results[5]. These findings showed the grouping preference for non-speech stimuli develops early in infancy, giving rise to the cross-linguistic difference found in adults.

Grouping preferences and the Iambic/Trochaic law will not be further discussed. However, for the purpose of the present work, it is important to keep in mind that the attribution of a rhythmic/meter structure is a critical operation when studying human behaviour and language for many reasons which will be extensively discussed in the next section.

[5] In a Japanese-Italian cross-linguistic study, Gervain, Nespor, Mazuka, Horie, & Mehler (2008) showed that8-month-old infants display a preference for word order in accordance with their native language.

2.4 What is rhythm for?

2.4.1 Generation of prediction

In Paragraph 2.3 we discussed the principles governing grouping and we saw that grouping events into higher-level chunks is a process already exploited by 2-3-months old infants. But why is the perception of regularities so important? The perception of regularities crucially improves the **generation of prediction** (Arnal, Doelling, & Poeppel, 2014; Fujioka, Trainor, Large, & Ross, 2012; Winkler, Denham, & Nelken, 2009). Winkler et al. (2009) focused on the auditory modality and argued that "regularity representations play an essential role in parsing the complex acoustic input into discrete object representations and in providing continuity for perception by maintaining a cognitive model of the auditory environment" (p. 532). In other words, the processing of regularities, which are intrinsically predictive, enhances the construction of auditory perceptual objects, which are used to continuously anticipate forthcoming stimuli (see also Bendixen, Roeber, & Schröger, 2007; Bendixen, Schröger, & Winkler, 2009). Therefore, regularities are extracted by the brain, which are consequently exploited to build prediction of future acoustic events.

Beyond the strictly auditory modality, we are, as human beings, constantly predicting future states of the world and the ability to make prediction is essential for adapting our behavior to consequences of our own action and of external events. When we cross a street, we have to predict the position of the cars at the moment when we are likely to meet their trajectories. When serving during a tennis competition, we have to anticipate the location of the tennis ball to hit it at the right time and at the right angle in order to do a successful serve. We also constantly make predictions in language. Consider filler-gap dependencies, such as (2), reporting *wh*-movement. The processor predicts the presence of a gap (empty base-position where the moved constituent receives its interpretation) as soon as the filler (the moved constituent) is encountered (Frazier & D'Arcais, 1989)[6].

(2) Cosa ha mangiato ___ Pietro?
    What has eaten __ Pietro?

We also usually anticipate the phi-features of a noun upon hearing (or reading) a determiner, such as an article, which in some languages is marked for gender and/or number and, upon hearing and adjective, we usually have an expectancy of which word can combine with it (cloudy can be followed by morning/afternoon/day but not table/bottle). In other words, this means that during language processing (and production) we have an expectancy of forthcoming information, at different level (phonological, syntactic and semantics levels). If we finally consider language production, the generation of prediction is evident in the case when the replacement of the error with the correct word occurs with almost no delay between the utterance of the error and the correct form, thus revealing that an internal model of the word has been generated before overt production and, consequently, that the error must have been detected before it was overtly spoken (Postma, 2000).

Thus, prediction is a key ability in our everyday life. Now the question is: why is prediction so important? The most plausible answer is that prediction reduces memory load through the pre-activation of the sensory system. We have already seen that from early in life the prediction of regularities are used by infants in the acquisition of different aspects of language. Likewise, the motor system generates prediction from an early age, since it has been shown that twelve-month-old children make prediction about motor actions they observe (Stapel, Hunnius, van Elk, & Bekkering, 2010).

[6] The active filler strategy proposed by Frazier & D'Arcais (1989) states that the filler should be assigned to the leftmost position from which it might have been extracted (p. 332).

The present dissertation is particularly concerned with predictive timing that is to say with the generation of temporal prediction. Crucially, an accurate prediction of "when" the next event is going to happen entails having an abstract representation of the timing of the events. Predictive timing has recently received a lot of interest from the scientific community, but still its computation and neurophysiological mechanisms are not completely clear (Arnal et al., 2014; Arnal & Giraud, 2012; Arnal, 2012; Fujioka et al., 2012). In a recent MEG study, Arnal et al. (2014) examined the neurophysiological mechanism at the basis of the generation of temporal predictions by means of a delayed-target detection task. The authors recorded the brain neuromagnetic activity while participants were listening to a sequence of 4 or 5 beats and were asked to decide whether the last tone (target) was delayed or not with respect to the tone. By contrasting correct and incorrect trials, the authors observed that ~200 ms prior to stimulus occurrence, the power in delta (1–3 Hz) and beta (18–22 Hz) frequency bands was significantly higher for correct trials and that the oscillations of these two frequency bands were coupled. They also found that angle distributions in the delta band for correct and incorrect trials were in opposite phases, thus showing that delta oscillations also need to be in a specific phase at stimulus occurrence. In summary, this experiment shows that prediction is reflected in the pre-stimulus brain activity and that coupled delta-beta oscillations are involved during the process of predicting the timing of a sound occurrence. Along the same lines, Stefanics and colleagues (Stefanics et al., 2010) found that the more predictable the target tone is, the more accurately the phase of the delta oscillations is locked to the predicted time of stimulus onset. The potential role of the beta-band oscillation in predictive timing has also been shown by Fujioka et al. 2012. In a MEG study, neural activity was recorded while participants listened passively to an isochronous auditory rhythm while watching a silent movie. In the first three conditions, the beats were rhythmically presented with onset-to-onset intervals of 390 (2.5 Hz), 585 (1.7 Hz), and 780 ms (81.3 Hz). In the fourth condition the sounds were presented at random onset-to-onset intervals within the interval of 390 and 780 ms. The findings showed that, in the regular conditions, the beta-band oscillations showed a modulation in power and phase-coherence reflecting the rate of the isochronous stimuli in auditory cortices and motor-related areas (sensorimotor cortex, inferior-frontal gyrus, supplementary motor area, and the cerebellum) despite the absence of actual movement (remember that participants were asked to listen passively to the sounds) (see also Bengtsson et al., 2009; Chen, Penhune, & Zatorre, 2008, for studies showing the activation of motor areas during listening to auditory rhythm without the intention to move). These results are particularly surprising if we consider that beta-band oscillations (~13-30 Hz) are attested to reflect changes in the sensorymotor system. On the contrary, in irregular condition, the beta rebound was significantly earlier compared to the isochronous conditions. This indicates that the beta rebound (synchronization after desynchronization) before the onset of the beat appears to encode an internal representation of the stimulus rate. The beta amplitude reaches its maximum just before the occurrence of the next tone only with regular stimuli, whereas when the time of the next tone is unpredictable, the system makes ready for the likelihood of an early beat rather than assuming the occurrence of the next beat at the mean time of previous tones. This last finding points to a very important aspect of the processing of predictive timing, since it suggests that the system has a tendency to pre-activate even when the timing of future event is uncertain, therefore in the absence of an internal representation. Similar evidence has been replicated in an EEG study testing 7-year-old children, though only in the two slower tempi (585 and 780 ms) (Cirelli et al., 2014). Therefore, the time course of beta modulation that encodes a mechanism of predictable time intervals is already in place for children as young as 7 years. In summary, the results of Fujioka et al. (2012) and Cirelli et al. (2014) suggest that the motor system is recruited in the predictive timing of a beat even in the lack of any intention to move in synchrony with the stimulus. Moreover, Arnal et al. (2014) and Fujioka et al. (2012) findings suggest that oscillations in the delta and the beta bands are instrumental in predictive timing processing since oscillations in these frequency bands need to be in a specific phase when the beat occurs in order to make accurate temporal judgment.

To summarize, these findings suggest that:

- Prediction is mirrored in pre-stimulus activity.
- Delta and beta oscillations play an instrumental role in the predictive timing of rhythmic events.
- The motor system plays a role in the prediction of temporal regularities even when in the absence of any intentional synchronized movement.
- The coupling between the auditory and the motor systems configures the sensorimotor network involved in the communication and coordination of the auditory and the motor system.

A detailed investigation of the neurophysiological mechanisms underpinning predictive timing is beyond the purpose of the present thesis, as they would deserve an ad hoc study. Nevertheless, the notions presented in this paragraph are very important for the rationale of the studies discussed in the following chapters and I believe they will be of crucial interest in the next future.

To conclude, although most of the above-mentioned studies focus on the auditory stimuli, the importance of the results span over the auditory perception fields since they shed light on the predictive mechanisms underlying many cognitive processes.

2.4.2 Entrainment between auditory and sensorimotor systems

In the previous paragraph, we saw that the auditory and the motor systems are more interconnected than it is usually thought.

The entrainment between auditory and sensorimotor systems is enhanced with the attribution of a metrical structure to a given rhythm existing in the environment. In the literature, *the coordination of movement with an external rhythm* is usually called sensorimotor synchronization (henceforth SMS) (Repp & Su, 2013). SMS has been mostly studied by finger tapping to an external simple metronome. The preferred tapping rate is 2 – 2.4 Hz, hence there is a preference for beats that occur roughly every 500 - 700 ms. People usually experience problems in following beats faster than 5 Hz (beats occurring every 200 ms) and slower than 1.2 Hz (every 1.2 sec) (Patel, 2008). SMS skill develops over years and reaches adult-like performance at the age of 6-7 (McAuley, Jones, Holub, Johnston, & Miller, 2006). One key feature of SMS is **anticipation** (for a review see Repp & Su, 2013; Repp, 2005). In facts, when asking to tap to a simple sequence of auditory tones, there is a systematic tendency for tap response to anticipate signal by 30-50 ms (Aschersleben & Prinz, 1995). In the tapping literature, it is usually referred to as negative mean asynchrony[7] (henceforth NMA). Crucially, synchronization is clearly distinct from a reaction time task, since it entails generation of a prediction regarding the timing occurrence of a future event. Considering that the shortest reaction time is 150 ms, any positive asynchrony shorter than 150 ms indicates an anticipatory behavior.

In the last two decades, the SMS abilities of individuals with developmental dyslexia (DD) received a lot of attention. Overall, these studies showed that both children and adults with DD are impaired in rhythmic tasks. The methodologies and results of these experiments will be reviewed in details in Chapter 6 and 7.

2.4.3 Rhythm and language

In Paragraph 2.3 we discussed the perception of grouping in the light of linguistic-specific preferences. This point is particularly important when considering the role of rhythm in language acquisition. Besides grammar and vocabulary, speaking a language implies mastering the pattern of timing that

[7]NMA is smaller or absent in musicians and, in general, there is a great individual difference.

characterizes the stream of syllables in a sentence, i.e., rhythm. The inherently rhythmic property of language is evident from the very first babies' babbling, at around 7 months of age. In fact, infants' vocalizations "bababa" are produced with the rhythmic pattern of natural languages, such as rhythm, timing and stress and also manual babbling of profoundly deaf babies or hearing babies acquiring sign language is produced with general prosodic contours of natural sign languages (Petitto, Holowka, Sergio, & Ostry, 2001; Petitto, Holowka, Sergio, Levy, & Ostry, 2004; Petitto & Marentette, 1991). Thus, humans are inborn with a tacitly sensitivity to specific rhythmic patterns in language which are exploited to discover the phonetic and syllabic repertoires in the linguistic stream.

Rhythm in language is determined by the alternation of stressed and unstressed elements. This alternation at different levels of speech forms a hierarchy. At word level languages differ in elements that recur periodically establishing temporal organization. According to Pike (1945), languages split in syllable-timed languages (such as Spanish and Italian) and stress-timed languages (such as English and Dutch). Subsequently, a third category of languages, namely mora-timed languages, has been proposed to describe the rhythms of languages such as Japanese or Tamil (Abercrombie, 1967). In a stress-timed language the units are feet, which have great temporal variability though having roughly equal temporal intervals between stresses. In a syllable-timed language every syllable has roughly equal temporal intervals. In mora-timed languages, the units are moras, which have roughly regular pacing. Moras are smaller than syllables and can be formed by a consonant and a vowel or by a single consonant or vowel. Dauer (Dauer, 1983, 1987) further suggested that languages vary with respect to phonological properties, which influence their rhythmic pattern. These phonological properties mainly depend on the diversity of the syllabic structures. In particular, stress-timed languages allow a broader range of syllable types than syllable-timed languages and mora-timed languages. Moreover, since stress-timed languages have vowel reduction, unstressed vowel tends to be shorter in duration.

Finally, in stress-timed syllable stress has a stronger effect on the duration of a vowel than in syllable–timed languages. Ramus et al. (1999) observed that the proportion of vocalic intervals and the variability of consonantal intervals are congruent with the notion of rhythmic classes, thus finding at one end English, Dutch and Polish with more than 15 syllable types and Japanese with 4 syllable types at the other end. Interestingly, experimental results of infants revealed that infants and newborn can discriminate languages that belong to different rhythmic classes (Mehler, Dupoux, Nazzi, & Dehaene-Lambertz, 1996; Mehler et al., 1988) even when none of the languages to be discriminated was their mother tongue language (Nazzi, Bertoncini, & Mehler, 1998). Moreover, the ability to discriminate languages belonging to different rhythmic class (Dutch vs. Japanese), when the sentences are played forward but not backward, has also been found in cotton-top tamarin monkeys (Ramus, Hauser, Miller, Morris, & Mehler, 2000; Tincoff et al., 2005) and in rats (Toro, Trobalon, & Sebastián-Gálles, 2003). Stepping back to language acquisition, it has been proposed that rhythm type might help to acquire some phonological properties, such as vowel reduction, lexical stress and syllable structure, which in turn might help speech segmentation (Cutler & Mehler, 1993; Cutler, Mehler, Norris, & Segui, 1986). In fact, segmentation strategies of fluent speech are the first step into language development and into the development of lexicon (Jusczyk, Cutler, & Redanz, 1993). The segmentation of speech into words is a particularly challenging task for infants if we consider that in fluent speech word boundaries are not divided by pauses and that speech sounds are co-articulated, so their realizations are usually influenced by the previous or the following sound irrespective of word boundaries. During language acquisition, the syllabic repertories may lead to conjecture the mean size of the more frequent words, since it is more likely that words will tend to be monosyllabic in a language which has a rich repertoires of syllables (i.e., stress-timed languages), rather than in a language with a small repertoire of syllable (which in turn will tend to be on average longer) (Mehler & Nespor, 2004). Moreover, the beginning of a new word is usually marked by a stress syllable in English, and it is no coincidence that American 9-month-old infants listened significantly longer to disyllabic words with strong/weak stress patterns than to disyllabic words with weak/strong stress patterns (Jusczyk et al., 1993). Thus, the rhythm characteristics of a language might help to acquire some phonological properties, which in turn can play a crucial role in speech segmentation and therefore the development of lexicon.

If we now turn to consider the phrasal level, the relative prominence of prosodical elements has been argued to play a role in the setting of syntactic parameters, what it is usually referred to as the **Phonological bootstrapping of syntax hypothesis** (Morgan & Demuth, 1996). In other words, the Phonological bootstrapping of syntax hypothesis proposes that higher level of rhythmic organization can support the acquisition of syntax. Each phonological phrase (which roughly corresponds to the syntactic phrase) has a prosodically prominent element, which is the complement, and it is usually determined by the stressed vowel of the word. In head-complement languages (such as Italian, French and English), the most phonological prominent element is usually at the right. In complement-head languages (such as Turkish and Japanese), the most phonological prominent element is usually at the left. Therefore, as it is evident, there is a correlation between the prosodic structure and the syntactic structure[8].

According to Nespor et al. (2008), the Iambic/Trochaic law defines the physically acoustical realization of the main salient element of a phonological phrase (composed by more than one element). The authors run an acoustic analysis of pitch, intensity and duration for the prominent word of French and Turkish speech materials. French and Turkish have the same lexical primary stress but they differ in head-direction parameter, the former being a head-complement language, the latter a complement-head language. Their results showed that in Turkish, the phonological phrase prominence is

[8] The presence of phonological phrase (and intonational phrase) has also been attested in Israeli Sign Language (Nespor & Sandler, 1999).

realized through a combination of higher pitch and intensity, whereas in French the phonological phrase prominence is realized through a combination of increased duration and intensity. In the light of these results, Nespor et al. (2008) suggested that the different realization of prominence within phonological phrases might be used to acquire word order by infants. The prediction made by Nespor et al. (2008) was borne out by experimental evidence. By means of a nonnutritive sucking paradigm, Christophe and colleagues (Christophe, Nespor, Guasti, & Ooyen, 2003) showed that 2-3-month-old infants can discriminate two languages that differ in head-direction (French and Turkish) on the basis of prosodic structure. This result revealed that infants are sensitive to prominence and therefore it is possible that the physical realization at phrase level might be early exploited for the acquisition of the relative order of heads and complements.

In a nutshell, linguistic rhythm is a crucial cue that helps the acquisition of different aspects of language, such as the acquisition of the phonological repertories, the development of the lexicon and the acquisition of syntax.

2.4.4 Rhythm and handwriting

Throughout this dissertation, handwriting will be considered in its motor and kinematic aspects. In fact, besides involving manifold linguistic aspects, handwriting is a very complex motor skill that requires the organization of different components, such as strokes and letters. Strokes, letters and words are not produced as a succession of distinct acts, but they are an ordered sequence of hierarchically organized motor events (Lashley, 1951; van Galen & Teulings, 1983). This means that each individual motor component occupies a precise place in a larger unit and that its place depends upon the positions occupied by previous (and future) elements. In other words, writing is characterized by a temporal structure, which needs to be available before effective execution. Handwriting (as well as other motor activities) is ruled by two principles of rhythmic organization: isochrony and homothety. The **principle of isochrony** (Binet & Courtier, 1984; Stetson & McDill, 1923; Viviani & Terzuolo, 1982) states that the speed of movement execution is proportionally related to the length of its trajectory in order to keep the movement duration approximately constant. Previous studies have shown that the total writing duration remains invariant irrespective of the size of the word or letter (Freeman, 1914; Laquaniti, Terzuolo, & Viviani, 1983; Viviani & Terzuolo, 1983). This implies that there is a compensatory mechanism whereby writing speed changes in accordance to the size of what is being written, i.e., the writer naturally increases the speed of handwriting when asked to write bigger. Beyond handwriting (Freeman, 1914; Viviani & Terzuolo, 1983), this compensatory mechanism has been attested in various motor activities, such as drawing (Laquaniti et al., 1983; Vinter & Mounoud, 1991; Viviani & McCollum, 1983; Viviani & Schneider, 1991) infants' kicking activity (Thelen & Fisher, 1983), manual pointing (Fitts, 1954) and it has also been observed in non-human primates (Sartori, Camperio-Ciani, Bulgheroni, & Castiello, 2013). The **principle of homothety** (Lashley, 1951; Viviani & Laissard, 1996; Viviani & Terzuolo, 1980, 1982) guarantees the invariance of the temporal relationship among the single motor events that compose a motor act. When applied to handwriting, this principle predicts that the relative durations of the individual letters that compose a word are kept constant despite changes in the global duration, thus preserving the temporal relationships. If we suppose that it takes 1000 ms to write the word 'cat', decreasing to 500 ms when the writer writes faster and increasing to 1500 ms when the writer writes slower and if we further suppose that the relative duration of the letter 'c' is 50% of the total duration, of the letter 'a' is 20%, of the letter 't' is 30%, the principle of homothety predicts that the relative durations of individual letters will remain constant despite the variations of the global duration. For instance, in the three aforementioned conditions, the letter 'c' will take 500 ms in the spontaneous condition, 250 ms in the faster one and 750 ms in the slower one, but these durations always remain 50% of the total duration.

In a nutshell, these two mechanisms are features of the motor planning system. They predict that an abstract motor representation needs to be available before factual execution: the length of the trajectory needs to be anticipated in order to adjust the speed of motor execution and the duration of each single letter needs to be allocated according to a timing frame that is not limited to the single letter but that rather includes the word (or the group of words) the letter is part of. The principle of isochrony rules the timing of a handwriting act as a whole, e.g., word. The principle of homothety governs the timing of its sub-components, e.g., individual letters.

Chapter 3

The developmental of handwriting and language in the first years of school: a cross-sectional study

3.1 Introduction

In Paragraph 2.2 we mentioned that there is a frequent co-occurrence between dyslexia and motor problems, although it is often neglected. The comorbidity between reading/language and motor disorders suggest that their development might be more interrelated than it has been previously thought. In turn, this calls for a search of the source of this interrelation; is there some representational format, some shared mechanisms or some common principles? The study illustrated in the current Chapter aims at investigating the developmental path of reading and handwriting (considered in its motor and kinematic features, not in the spelling domain) in children in their first years of school.

Reading and handwriting are two fundamental abilities to succeed in the contemporary society. In the last decades, less stress has been placed on handwriting due to the increased use of computers, keyboards, tablets and instructional programs attempting to focus on typing in replacement of handwriting have been introduced in some schools (Herron, 1995). This trend notwithstanding, both reading and handwriting keep taking place regularly in our everyday life. Learning to write and to read are also the very first challenges that children have to face in their early school career and the successful accomplishments of these two activities have a great impact in children's school life, with important repercussions in the long term. When reading and writing are compared, some common features can be noticed. Both reading and writing require automaticity at cognitive level, which is normally reached through constant practice in individuals with no history of reading or neurological disorders. This means that, once completely automatized, reading and handwriting do "not require conscious effortful monitoring" (Nicolson & Fawcett, 1990, p. 163). Another shared feature is seriality, since both handwriting and reading are carried out in a serial way. At the level of the motor program, the handwriting gesture is represented as an ordered sequence of movement units, hierarchically organized (Lashley, 1951; van Galen & Teulings, 1983). At the level of execution, strokes and ultimately letters are generated in a prevalent serial way (van Galen, 1991): each letter stroke is traced singularly, the serial concatenation of single strokes forms letters and the concatenation can apply again to letters to form words, to words to produce phrases and to phrases to form sentences. As for reading, aside from the vocal output, which is obviously serial, the phonological representations are accessed through a serial process (see Coltheart & Rastle, 1994, for a serial processing model of reading process). Despite these observations, reading and handwriting have been manly studied separately. Traditionally, they have been considered as independent phenomena, though their development occurs in the same individual approximately over the same time span. Only recently, research about possible neural links between reading and writing has received growing attention from the scientific community. In a series of imaging studies on preliterate children and adults, it has been showed that brain regions recognized to be engaged during reading are activated more strongly after handwriting training rather than typing (James & Atwood, 2009; James & Engelhardt, 2012; Longcamp et al., 2008). Similarly, behavioral studies demonstrated that handwriting training, contrary to typing training, boosts recognition of new character in pre-reading children (Longcamp, Zerbato-Poudou, & Velay, 2005) and adults (Longcamp et al., 2008; Longcamp, Boucard, Gilhodes, & Velay, 2006). In the Procedural Learning Deficit Hypothesis, Nicolson and Fawcett (2011) assumed an interrelation between the language neural circuit and the motor neural circuit in their account for the comorbidity between motor (such as Dysgraphia) and cognitive disorder (such as Developmental Dyslexia) (see Alamargot et al., 2014; Berninger, Nielsen, Abbott, Wijsman, & Raskind, 2008; Capellini et al., 2010; Cheng-Lai et al., 2013; Lam et al., 2011). According to Nicolson and Fawcett, the language procedural learning system and the motor procedural learning system share a neural circuit that includes the basal ganglia, the frontal cortex (in particular Broca's area and pre-motor regions), the parietal cortex, the superior temporal cortex, and the cerebellum. The dissimilarity between the two systems is that the motor procedural learning system interacts with the primary motor cortex while the language procedural learning system interacts with the language-based regions of the frontal lobe. Thus, dyslexic and dysgraphic children may suffer from an impairment of procedural learning circuit (that involves the cerebellum), and the extent and the prominence of language or motor difficulties depend on the degree of the impairment of the language or motor procedural learning circuits. Along these lines, Diamond (2000) proposed that motor development and cognitive development are more interconnected than it has been previously suggested since linguistic, cognitive and motor disorders often co-occur in the same person (Hill, 2001; Kaplan et al., 1998; Robinson, 1987). It is worth noticing that language, cognitive and motor disorders are comorbid in some, but not all, children. Some speculations can be directed this way. The comorbidity of difficulties only in a sub-group of the population raises the hypothesis that a malfunction of an underlying mechanism, which is common among these abilities, cause difficulties across the language and the motor domain. Nevertheless, it is possible that some children are compensated in one domain, thus showing surface difficulties only in one restricted area.

The aim of our explorative study is to investigate the developmental trajectory of reading and handwriting in pupils in their first years of school. We also considered phonological memory abilities, since these have been shown to be related to children's reading capacities (Gathercole & Baddeley, 1993; Gathercole, Willis, & Baddeley, 1991; Goswami & Bryant, 1990). We expect a parallel developmental pathway for reading, phonological memory and handwriting. In the first years of school, reading becomes automatized and therefore we expect dissociation between reading words and reading non-words. Children can activate the lexical route to convert a printed word, whereas they have to convert sequentially letter to sound in order to be able to read correctly non-words. The activation of the lexical route is quicker than the non-lexical one. Therefore children who are becoming skilled readers are expected to read quicker words than non-words as an index of automatism. If language and motor development are related, we expect that handwriting follows the same developmental steps as reading and phonological memory and becomes automatized. Finally, we expect correlations between reading and handwriting measures. Our hypothesis is grounded on two assumptions, namely that the motor and the language maturational processes rest on shared neuroanatomical mechanisms (Diamond, 2000; Gimenez et al., 2014) and that the language procedural learning system and the motor procedural learning system share a common neural circuit (Nicolson & Fawcett, 2011). To investigate this question, reading skills and phonological memory were assessed by means of standardized tests. As regards handwriting, we considered the motor aspect, not the spelling. The maturation of handwriting skills was estimated through the examination of a set of kinematic and dynamic descriptors of the writing gesture that are indices of automatization and fluency, which have been collected by means of a digitizing tablet.

In summary, the present explorative study aims at:

- Studying the developmental pathway of reading and phonological memory abilities.
- Studying the developmental pathway of handwriting abilities (considered in their motor aspects).
- Studying the relation of the maturation of reading and handwriting skills.

3.2 Method

3.2.1 Participants

We tested 102 pupils, ranging from the first to the fourth grade of primary school: 15 first grade children (Grade 1), 34 second grade children (Grade 2), 26 third grade children (Grade 3), 27 fourth grade children (Grade 4). Children in each school grade group were approximately evenly divided as for gender. The children were all born in Italy. They were all Italian monolingual and used Italian as their first oral and written language. The children were recruited from different schools in the province of Milan. We recruited pupils from different schools in order to minimize effects due to a particular teaching method. Since the Italian system is not uniform regarding the introduction of cursive script, we selected schools that introduce the cursive script from the second semester of the first grade. All subjects were tested in the second semester of the academic year (from end of January to May). Demographic information of the subjects is reported in Table 3.1.

Table 3.1
Demographic information on age, gender, and hand dominance of the participants.

Grade	Grade 1 (n = 15)	Grade 2 (n = 34)	Grade 3 (n = 26)	Grade 4 (n = 27)
Mean age in years (SD in brackets)	6;7 (0.29)	7;6 (0.3)	8;4 (0.3)	9;5 (0.46)
Age range	6;3 – 7;2	7;08 – 8;08	7;9 – 9;17	8;25 – 10;25
Gender				
Male	10	17	13	12
Female	5	17	13	15
Hand dominance				
Left	2	4	3	2

Testing was preceded by a preliminary consultation with the teachers and all children completed the nonverbal IQ Raven's test (Raven, Court, &

Raven, 1998). Therefore we screened participants and only tested those who had a non-verbal IQ Raven's test score equal or above the 25 percentile and who were not reported for cognitive, reading, auditory, writing and language problems.

Ethical approval according to standards of the Helsinki Declaration (World Medical Association, 2013) was obtained from the board of the University of Milano-Bicocca. Participants' parents signed informed consent before the testing session.

3.2.2 Materials

Reading and phonological skills were assessed by means of Italian standardized tests ((1), (2)). Handwriting data were collected by means of a digitizing tablet (3). Children were asked to write an Italian word in different conditions.

Reading words and non-words task. One list of words (list a.a.) and one list of non-words (list a) from Part 2 and 3 of the *Batteria per la valutazione della Dislessia e della Disortografia evolutiva-2, DDE-2* (Sartori, Job, & Tressoldi, 2007) were administered to assess reading proficiency. Children were asked to read aloud single words and single non-words consistent with the phonotactic constraints of Italian. Reading speed (syllables per second) and errors' score were considered as variables. Reading speed was measured by dividing the total syllables of each list (71 for the words; 40 for non-words) for the seconds employed to read each subtest. The errors' score corresponded to the number of words and non-words read incorrectly. Self-correction was not counted as mistake.

Repetition of non-words. *VAUMeLF Batterie per la Valutazione dell'Attenzione Uditiva e della Memoria di Lavoro Fonologica nell'Età Evolutiva* (Bertelli & Bilancia, 2006) was used to assess phonological memory. Forty non-words ranging from two to five syllables in length are included in the test. All non-words comply with the Italian phonotactic rules. Children were asked first to listen to the recorded non-word and then to repeat it out loud immediately afterwards. The accuracy score corresponded to the number of words correctly repeated. A self-corrected word was counted as mistake.

Writing task. Children were asked to write on an unruled A4 paper size with landscape orientation rested on the recording surface of an Intuos 3 Wacom tablet. Children were invited to grasp the wireless pen of the digitizing tablet with their dominant hand as if it was a common pen and to write wherever they wanted on the paper surface (Figures 1a and 1b). During handwriting, the digitizing pen produced an ink trace, which allowed participants to visually control the trace. Therefore the children were in the same situation as they were when writing at school. Our experimental design included two conditions where the size and the speed of the target word were manipulated. We considered the two extremes of each condition: Big/Small (size) and Fast/Slow (speed), with spontaneous condition as a baseline. This procedure is frequently used to evaluate a participant's ability to control handwriting size and tempo (Galen, 1991; Mayor Dubois, Zesiger, Perez, Ingvar, & Deonna, 2003; Teulings & Schomaker, 1993; Zesiger, 2003). Indeed, this experimental method has been used in previous studies with targets word of different languages (Arabic: Bouamama, 2010; French: Mayor Dubois et al., 2003; Zesiger, 1995; Italian: Chapter 4). Therefore, children were asked to write the Italian word *burle* (English translation 'jokes') in two different scripts, cursive and block in all capitals and for each script, in five different conditions: spontaneously (without any additional instructions, i.e., as the child usually writes in class), very big, very small, very fast and very slow with respect to the Spontaneous condition. Thus, the word *burle* was written ten times in total (Figure 3.1). We chose *burle* as target word because it can be written without any detachment of the pen from the surface when writing in cursive script. Children were not provided with any templates of handwriting. Our main concern here was to foster modulation and to contrast two extreme conditions (Big/Small and Fast/Slow). The Spontaneous condition functioned as baseline. The data collected in the Small and the Slow condition were not included in the analysis since some children wrote too small (also when writing in the Slow condition) and data were not usable for the estimation of velocity, dysfluency etc., due to the resolution limits of the digitizing tablet (±0.25 mm). The Big and Fast conditions do not have resolution limitation, except paper size. We expected children to show significant differences in the opposite conditions, if they had understood the task and above all if they had the fine motor ability to tailor their handwriting movement.

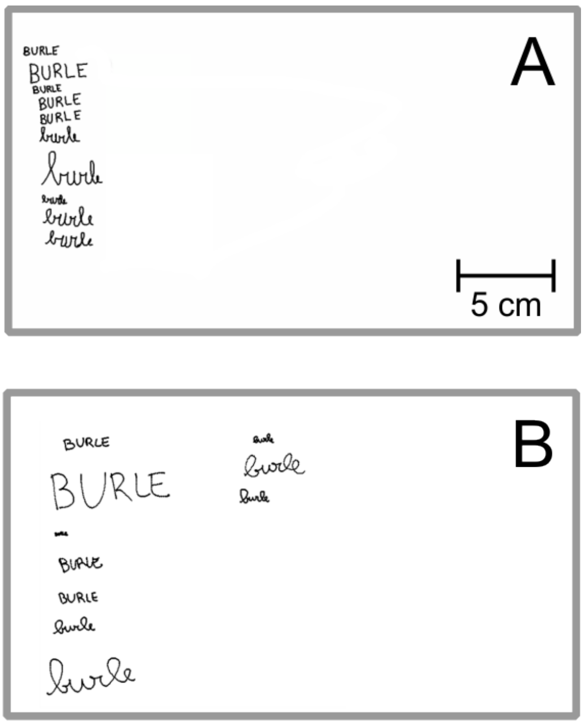


Fig. 3.1. Writing samples. Panel A displays a writing sample of a 1st grade girl. Panel B display a writing sample of a 4th grade girl.

3.2.3 Instruments used for collecting data on writing

A rich set of geometric, kinematic and dynamic descriptors of handwriting was collected by means of the digitizing tablet connected to a computer controlled by VBDigitalDraw 2.0 software (Toneatto, 2012). VBDigitalDraw 2.0 is the evolution of VBDD, which was firstly developed at the Department of Psychology of the University of Milano-Bicocca to investigate performances of Arabic handwriting (Bouamama, 2010), and has been recently used to investigate the handwriting abilities of Italian dyslexic children with and without dysgraphia (Chapter 4). VBDigitalDraw 2.0 is composed of two independent modules both working on Windows Platform: one module is dedicated to data acquisition and one is a post-processed computational algorithm module. Data were collected by means of an Intuos 3 Wacom digitizing tablet used with a wireless pen (Sampling rate: 200 Hz; physical size (W×D×H): 440 × 340 × 14 mm; active area (W×D): 305 × 231 mm; pressure sensitivity: 1.024; levels resolution: 5.080 lpi; pen accuracy: ±0.25 mm; mouse accuracy: ±0.5 mm; tilt: ±60 degrees; maximum reading height with Pen: 6 mm).

The handwriting path was recorded as (*x, y*) Cartesian coordinates. The handwriting path was recorded both when the tip of the pen physically touched the surface and when the tip of the pen was closed but not touching the digitizer active area, thus exercising pressure equal to zero, i.e., when the subject was not writing but preparing for the next handwriting movement. The force exerted on the surface's axis was a numeric value comprised between 0 and 1023. VBDD 2.0 Software permits to collect trajectory, speed and pressure data on-line, then displayed as ".txt" file. The segments of interest (i.e., word) were selected off-line starting from an automatic raw segmentation obtained through the software grounded on speed and pressure. For the purpose of the current study, the continuous handwriting strings were segmented by word. A tag was assigned to each selected segment according to the script (block or cursive) and to the experimental conditions (Spontaneous, Big, Small, Fast, Slow). The total length (i.e., the summation of the length of all the strokes measured in cm) and velocity gain factor (which can be considered a robust estimator of the mean velocity, see *Appendix*) were considered in a preliminary analysis to check whether children complied with the task, i.e., if they modulated their writing performance according to task demands.

3.2.4 Procedure

Children were tested individually in a quiet room at their school. Reading, phonological memory and handwriting tasks were administered in a 30-minutes testing session with pauses whenever required. The outputs of the reading and phonological memory tests were recorded in a ".wav" file and double-checked later by another experimenter.

3.2.5 Data analysis

Statistical analyses of the reading measures were performed using a Generalized Linear Model (GLM) analysis mixed-design with Grade (Grade 1, Grade 2, Grade 3, Grade 4) as between-subject factor (henceforth BS) and Item (Word, Non-Word) as within-subject (henceforth WS) and between-item factors. Similarly, the analyses of the phonological memory score were run using a GLM mixed-design with Grade as BS and Item as WS.

Focusing on handwriting, to investigate the abilities and the maturation of handwriting of the subjects, we analyzed velocity gain factor, dysfluency, pressure and duration. Previous studies showed that these measures are suitable indices of automatization and fluency (Accardo, Genna, & Borean, 2013a; Accardo, Genna, & Borean, 2013b; Blöte & Hamstra-Bletz, 1991; Hamstra-Bletz & Blöte, 1990). Moreover, they are good measures to discriminate between proficient and non-proficient handwriters (Di Brina, Niels, Overvelde, Levi, & Hulstijn, 2008; Kushki, Schwellnus, Ilyas, & Chau, 2011; Pagliarini et al., 2015; Parush, Levanon-Erez, & Weintraub, 1998;

Rosenblum, Weiss, & Parush, 2003; Smits-Engelsman & van Galen, 1997). These measures are:

- *Velocity gain factor*, i.e., the measure of the average velocity of the handwriting movement. See the *Appendix* for a detail definition.
- *Average pressure*, i.e., the average axial pen pressure measured as a numeric value comprised between 0 and 1023 (in which 0 corresponds to absence of pressure, and 1023 corresponds to maximum pressure).
- *Dysfluency*, i.e., the logarithm of the number of the maxima and the minima of the curve of instantaneous velocity.
- *Word duration*, i.e., the time measured in seconds to write the word *burle*, considering exclusively the time in which the tip of the pen touched the sheet of paper.

As for the writing data, square root transformations were performed on the data to meet the normality requirements of linear modeling.

A preliminary analysis was performed to determine whether children complied with the task, i.e., if they modulated their writing performance according to task demands. Therefore a GLM mixed-design on total length and velocity gain factor as writing variables with Grade as BS factor, Condition (Spontaneous, Big, Small, Fast and Slow) and Script (Cursive, Block) as WS factors was performed. After the preliminary analysis, only Spontaneous, Big and Fast conditions were analyzed to assess main effects (see Paragraph 3.2.2). The analysis was performed on words as selected segment. Velocity gain factor, pressure, dysfluency and duration were analyzed in a GLM mixed-model design with Grade as BS factor, Condition (Spontaneous, Big, Fast) and Script (Cursive, Block) as WS factors. Significant main effects and interactions were followed up using Bonferroni's post-hoc comparisons. We reported only significant main effects and interactions, and partial eta squared (η^2_p) as a measure of effect size. Post-hoc significant values are always meant to be minor than 0.5. Finally, correlations between reading, phonological and writing data were run to estimate the relation between reading and writing abilities.

3.3 Results

3.3.1 Linguistic test results

Reading words and non-words tasks[9]. Figure 3.2 illustrates the growing trend of reading speed with grade, both for words and non-word. The GLM analysis on reading speed (syll/sec) of words and non-words revealed a main effect of Grade, $F(3, 98) = 32.44$, $p < .001$, $\eta^2_p = .50$. The post-hoc tests showed that Grade 1 read fewer syllables per second than Grade 2, 3 and 4; Grade 2 read fewer syllable per second than Grade 3 and 4. Grade 3 and 4 did not differ between them. A main effect of Item, $F(1, 98) = 156.50$, $p < .001$, $\eta^2_p = .61$, was also found, showing that participants read more syllables per second when reading words than reading non-words. Interestingly the significant interaction Grade x Item, $F(3, 98) = 18.51$, $p < .001$, $\eta^2_p = .36$, revealed that, from the second grade, children start progressively to read more rapidly words than non-words, as an indication that they are starting to automatize reading (Figure 3.2). In fact, post-hoc tests revealed that reading speed of words differs from reading speed of non-words in Grade 2, 3 and 4 but not in Grade 1, for which no difference between reading words and non-words was found.

[9] We also run a GLM analysis on the reading speed of words and non-words with raw seconds as dependent variable. It revealed a main effect of Grade, $F(3, 98) = 27.26$, $p < .001$, $\eta^2_p = .45$. The post-hoc comparisons showed that the seconds for Grade 1 were greater than Grade 2, 3 and 4. No other difference was found among Grades. It also revealed a main effect of Item, $F(1, 98) = 77.63$, $p < .001$, $\eta^2_p = .44$ due to more seconds needed to read words than non words. Finally, it also showed a significant interaction Grade x Item, $F(3, 98) = 25.53$, $p < .001$, $\eta^2_p = .44$. Post hocs showed that words reading speed differed from non-words reading speed in Grade 1 and Grade 2.

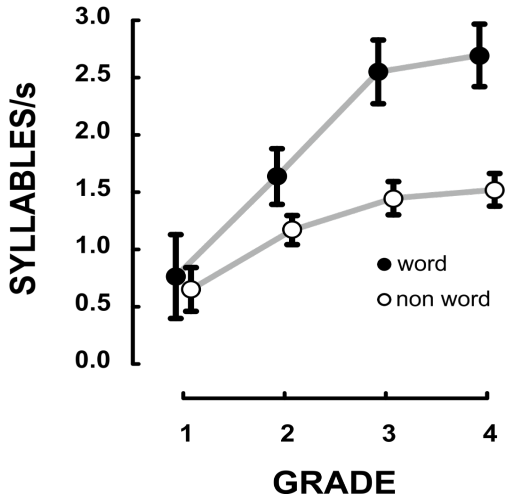


Fig. 3.2. Reading words and non-words of children from the first to the fourth grade of primary school. Reading speed counted in syllables read per second for words and non-words is reported for the 4 experimental groups (1 = Grade 1; 2 = Grade 2; 3 = Grade 3; 4 = Grade 4). Vertical bars represent 95% confidence interval.

The results of the GLM analysis on error score in reading words and non-words showed a main effect of Grade, $F(3, 98) = 7.53$, $p < .001$, $\eta^2_p = .18$. Post-hoc tests revealed that Grade 1 made more errors than Grade 3 and Grade 4. Grade 2 made more errors than Grade 3. No significant difference was found between Grade 1 and Grade 2 and between Grade 3 and Grade 4. A main effect of Item was also found, $F(1, 98) = 38.27$, $p < .001$, $\eta^2_p = .28$, due to more errors made in reading non-words than reading words. A significant interaction Grade x Item was also found, $F(3, 98) = 3.34$, $p < .05$, $\eta^2_p = .09$. This interaction showed that the number of errors made when reading words differ significantly from that made when reading non-words for Grade 2 and Grade 4, whereas for Grade 1 and 3 no difference was found between errors score in reading words and non-words.

Notice that despite third grade children did not show an improvement in accuracy in reading non-words, they are significantly faster in reading words than non-words, thus indicating that they are in the process of automatized reading.

Repetition of non-words task. Figure 3.3 shows the number of non-words accurately repeated for the 4 experimental groups (grade 1 - 4). The GLM analysis performed on the correct repeated non-words showed a main effect of Grade, $F(3, 98) = 6.78$, $p < .001$, $\eta^2_p = .17$. Post-hoc tests revealed that Grade 1 was less accurate than Grade 3 and Grade 4. No statistical difference was found between Grade 1 and 2. Grade 2 did not differ from Grade 3 and 4.

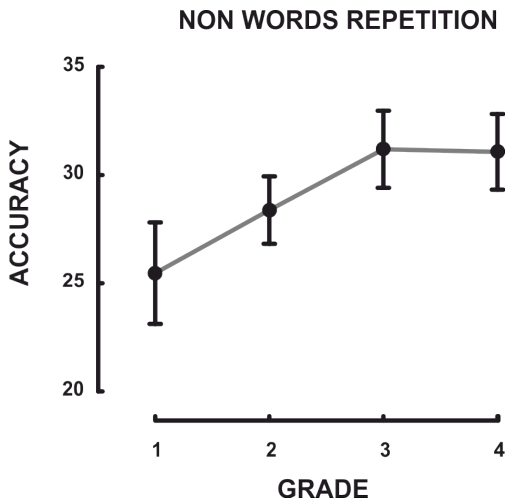


Fig. 3.3. Non-words repetition of children from the first to the fourth grade of primary school. The number of non-words accurately repeated is reported for the 4 experimental groups (1 = Grade 1; 2 = Grade 2; 3 = Grade 3; 4 = Grade 4). Vertical bars represent 95% confidence interval.

3.3.2 Preliminary results of the writing task

A preliminary analysis was run to determine whether subjects adjusted their handwriting as requested by the different experimental conditions therefore complying with the experimental task. Two variables were analyzed: total length and velocity gain factor (see Appendix). We expected a significant difference between the Small and the Big condition in the total length and a significant difference between the Slow and the Fast condition in the velocity gain factor.

Total length. The GLM analysis revealed a main effect of Condition, $F(4, 392) = 234.82$, $p < .001$, $\eta^2_p = .70$. Post-hoc tests revealed that Spontaneous condition was statistically different from Small, Big and Fast conditions; Small, Big and Fast conditions differ from each other and all the other conditions. The total length was longer in the Big condition compared to the Small and Slow conditions. Spontaneous and Slow conditions were not statistically different. A main effect of Script was found, $F(1, 98) = 27.65$, $p < .001$, $\eta^2_p = .22$, as the summation of the length of all the strokes of the word *burle* written in cursive script was longer than the length of the word *burle* written in block script in all capitals. The significant interaction Grade x Script, $F(3, 98) = 7.35$, $p < .001$, $\eta^2_p = .18$, showed that the difference between the total length of cursive and block script in all capitals was considerable for Grade 1 and that the divergence between the two scripts started to smooth from Grade 2 and reached a plateau in Grade 3. A significant interaction Script x Condition was also found, $F(4, 392) = 26.64$, $p < .001$, $\eta^2_p = .21$, due to a longer length in the cursive compared to the block script in all capitals in the Small and in the Fast condition.

Velocity gain factor. The GLM analysis showed a main effect of Condition, $F(4, 392) = 217.86$, $p < .001$, $\eta^2_p = .69$. The velocity gain was slower in the Slow condition compared to the Fast condition. Each condition differed from the others, but the Small and Slow conditions did not differ from each other. A main effect of Script was also found, $F(1, 98) = 11.96$, MS $= 1.16$, $p < .001$, $\eta^2_p = .11$, as children wrote systematically faster when asked to write in block script in all capitals than when asked to write in cursive script.

The results of the preliminary analysis confirmed our expectations. The significant difference between the Small and the Big condition in the total length and the difference between the Slow and Fast condition in the velocity gain confirmed that children complied with the task requirement and adjusted the size and the speed of their writing in accordance with the different conditions.

So, after checking that the subjects accomplished the experimental task as required, we considered only Spontaneous, Big and Fast conditions to assess main effects and interactions (for the Small and Slow conditions see comment on Paragraph 3.2.2).

3.3.3 Writing (whole word) tasks results

Velocity gain factor. Figure 3.4 displays the significant interaction Grade x Script x Condition, $F(6, 196) = 3.01$, $p < .01$, $\eta^2_p = .08$. Notice that the partial eta squared of the interaction is very low, and, as well as it appears from the figure, this interaction does not affects the interpretations of the main effects.

Figure 3.4 mainly shows that velocity gain tends to increase with grade, both for cursive and block script. On the three panels of Figure 3.4 the three different analyzed experimental conditions (Spontaneous, Big, and Fast) are represented, showing that not only did children write more rapidly when asked to write faster (Fast condition), but they increased writing speed also when asked to write bigger than usual. A main effect of Grade was found, $F(3, 98) = 6.19$, $p < .001$, $\eta^2_p = .16$. Post-hoc tests revealed that Grade 1 wrote slower than both Grade 3 and Grade 4 and Grade 2 wrote slower than Grade 4, as shown in Figure 3.4. No difference was found between Grade 1 and 2 and between Grade 3 and 4. We also found a main effect of Script, $F(1, 98) = 44.78$, $p < .001$, $\eta^2_p = .31$, as subjects wrote slower when asked to write in cursive script than when asked to write in block script in all capitals. We also found a main effect of Condition, $F(2, 196) = 274$, $p < .001$, $\eta^2_p = .74$. Post-hoc comparisons showed that each condition differs from the other: the Fast condition was executed with the greatest gain and the Spontaneous condition was performed with the lowest gain. Therefore, children increased the velocity when asked to write bigger than usual besides than when required to write faster.

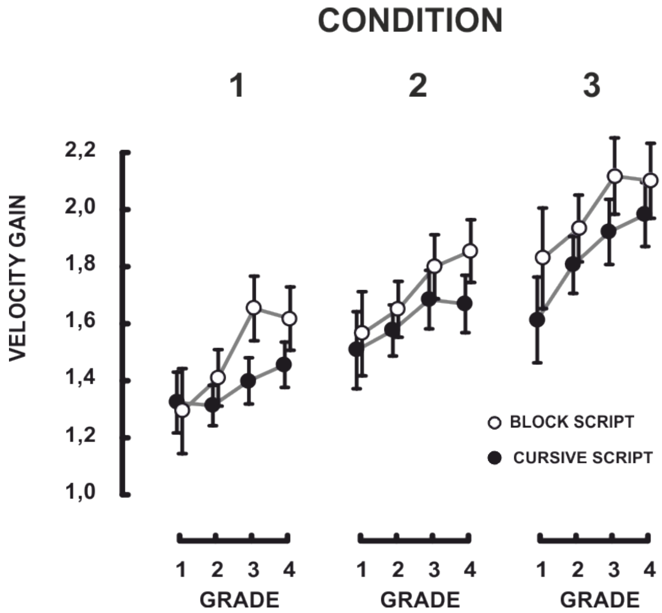


Fig. 3.4. Velocity gain of children from the first to the fourth grade of primary school. The second order interaction Script (cursive, block) by Condition (1 = Spontaneous, 2 = Big, 3 = Fast) by Grade (1 = Grade 1, 2 = Grade 2, 3 = Grade 3, 4 = Grade 4) of the velocity gain factor is reported. Vertical bars represent 95% confidence interval.

Dysfluency. The GLM analysis on the dysfluency showed a significant interaction Grade x Condition, $F(6, 196) = 2.38$, $p < .05$, $\eta^2_p = .06$, due to Grade 1 and 2 being more dysfluent than Grade 3 and 4 in the Spontaneous condition whereas the difference among groups was neutralized in the Big and Fast conditions. A significant interaction Script x Condition was also found, $F(2, 196) = 4.95$, $p < .05$, $\eta^2_p = .05$, due to a greater dysfluency of cursive than block script in the Spontaneous and Fast condition. The analysis also revealed a significant interaction Grade x Script x Condition, $F(6, 196) = 2.64$, $p < .05$, $\eta^2_p = .07$. It is worth noticing that the partial eta squared of the aforementioned interactions is small, and therefore it is safe to assume that these interactions do not affect the interpretations of the main effects. A main effect of Grade was found, $F(3, 98) = 9.42$, $p < .001$, $\eta^2_p = .22$, as displayed in Figure 3.5. Post-hoc tests revealed that Grade 1 and Grade 2 were more dysfluent than Grade 3 and Grade 4, with no significant statistical difference between Grade 1 and 2 and between Grade 3 and 4. We also found a main effect of Script, $F(1, 98) = 111.9$, $p < .001$, $\eta^2_p = .53$, as children turned out to write more dysfluent when requested to write in cursive than in block script in all capitals. Condition was also significant, $F(2, 196) = 241.33$, $p < .001$, $\eta^2_p = .71$. Post-hoc test showed that children were more dysfluent in the Spontaneous and the Big conditions than in the Fast condition.

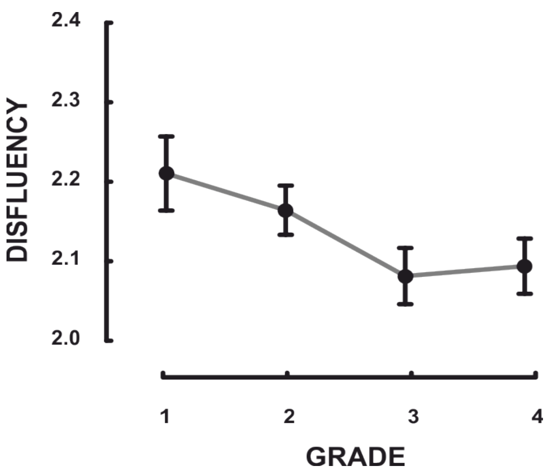


Fig. 3.5. Dysfluency of children from the first to the fourth grade of primary school. The main effect of Grade for the four groups (1 = Grade 1, 2 = Grade 2, 3 = Grade 3, 4 = Grade 4) of the dysfluency is reported. Vertical bars represent 95% confidence interval.

Pressure. The GLM analysis on writing pressure showed a significant interaction Script x Condition, $F(2, 196) = 3.06$, $p < .05$, $\eta^2_p = .03$, revealing a difference in pressure between cursive and block script in all capitals in Big and Fast conditions, but not in Spontaneous condition. No significant group difference was found in the pressure exerted on the surface. We found a main effect of Script, $F(1, 98) = 52.74$, $p < .001$, $\eta^2_p = .35$, due to greater pressure applied to the surface when writing in cursive script than in block script in all capitals. Condition was also significant, $F(2, 196) = 36.40$, $p < .001$, $\eta^2_p = .27$, due to higher pressure exerted when writing in Big and Fast conditions than in Spontaneous condition and greater pressure applied when writing in Big than Fast condition.

Word duration. We found a significant interaction Grade x Script, $F(3, 98) = 7.92$, $p < .001$, $\eta^2_p = .19$, as the difference between cursive and block script in all capitals was significantly different in Grade 1, but this difference started to smooth over from Grade 2. We found a main effect of Grade, $F(3, 98) = 10.90$, $p < .001$, $\eta^2_p = .25$, in the time measured in seconds to write the word *burle*. Post-hoc comparisons showed that Grade 1 and Grade 2 differed from Grade 3 and 4, with no statistical difference between Grade 1 and 2 and between Grade 3 and 4. We also found a significant interaction Script x Condition, $F(2, 196) = 12.91$, $p < .001$, $\eta^2_p = .11$, as the divergence between cursive script and block script in all capitals was greater in the Spontaneous and Fast conditions than Big condition. Script was significant, $F(1, 98) = 129.35$, $p < .001$, $\eta^2_p = .57$, as the cursive script took a longer duration than block script in all capitals. Condition was also significant, $F(2, 196) = 204.21$, $p < .001$, $\eta^2_p = .67$. Post-hoc comparisons showed that each condition differed from each other: Big condition had the longest duration and Fast condition had the shortest duration.

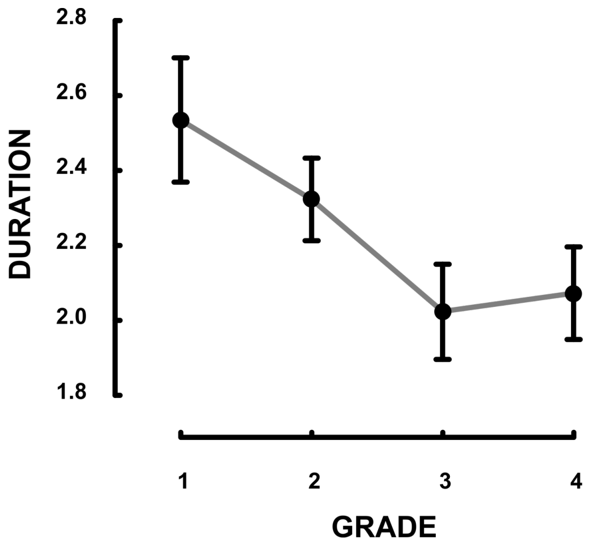


Fig. 3.6. Word duration of children from the first to the fourth grade of primary school. The main effect of group for the four groups (1 = Grade 1; 2 = Grade 2; 3 = Grade 3; 4 = Grade 4) of the duration is reported. Vertical bars represent 95% confidence interval.

3.3.4 Correlation analysis between writing and language descriptors

Correlations were found among handwriting variables (velocity gain factor, dysfluency and duration) and scores of reading and phonological memory tasks. The four groups of children were aggregated. Significant correlations ($p < .05$) are reported in Table 3.2, 3.3 and 3.4.

Table 3.2
Correlations between *velocity gain* as writing variable and all reading/linguistics variables.

	1	2	3	4	5	6	7	8	9	10	11
1. Cursive spontaneous	-	.67***	.58***	.55***	.57***	.45***	.17	- .05	.20*	-.07	-.17
2. Cursive big		-	.70***	.55***	.74***	.55***	.13	.00	.18	.04	.00
3. Cursive fast			-	.57***	.63***	.65***	.31**	-.09	.36***	-.00	-.06
4. Block spontaneous				-	.71***	.65***	.33**	-.13	.26**	-.16	.14
5. Block big					-	.70***	.23*	-.11	.20*	-.08	.05
6. Block fast						-	.20*	-.08	.19	-.01	.07
7. Speed reading words							-	-.58***	.79***	-.44***	.38***
8. Errors reading words								-	-.45***	.54***	-.57***
9. Speed reading non-words									-	-.37***	.20*
10. Errors reading non-words										-	-.37***
11. Accuracy non-word repetition											-

Pearson correlation coefficients are displayed

(*$p < .05$; **$p < .01$; ***$p < .001$)

Table 3.3
Correlations between *dysfluency* as writing variable and all reading/linguistics variables.

	1	2	3	4	5	6	7	8	9	10	11
1. Cursive spontaneous	-	.73***	.58***	.54***	.59***	.22*	-.37***	.15	-.33***	.00	-.17
2. Cursive big		-	.52***	.48***	.75***	.18	-.22*	.04	-.21	-.03	-.04
3. Cursive fast			-	.31**	.38***	.28**	-.42***	.28**	-.41***	.12	-.17
4. Block spontaneous				-	.55***	.14	-.35***	.10	-.34***	.12	-.14
5. Block big					-	.16	-.22*	.06	-.18	.09	.07
6. Block fast						-	-.26**	.19	-.26**	.04	-.11
7. Speed reading words							-	-.58***	.79***	-.44***	.38***
8. Errors reading words								-	-.44***	.54***	-.57***
9. Speed reading non-words									-	-.37***	.20*
10. Errors reading non-words										-	-.37***
11. Accuracy non-word repetition											-

Pearson correlation coefficients are displayed

(*$p < .05$; **$p < .01$; ***$p < .001$)

Table 3.4
Correlations between *duration* as writing variable and all linguistics variables.

	1	2	3	4	5	6	7	8	9	10	11
1. Cursive spontaneous	-	.73***	.67***	.61***	.54***	.41***	-.48***	.30**	-.42***	.16	-.33***
2. Cursive big		-	.47***	.53***	.75***	.22*	-.29**	.11	-.22*	.08	-.10
3. Cursive fast			-	.35***	.30**	.37***	-.48***	.34***	-.47***	.17	-.31**
4. Block spontaneous				-	.50***	.29**	-.30**	.06	-.29**	.10	-.16
5. Block big					-	.14	-.19*	.04	-.17	.10	.11
6. Block fast						-	-.32***	.21*	-.32***	.09	-.22*
7. Speed reading words							-	-.58***	.79***	-.44***	.38***
8. Errors reading words								-	-.45***	.54***	-.57***
9. Speed reading non-words									-	-.37***	.20*
10. Errors reading non-words										-	-.37***
11. Accuracy non-word repetition											-

Pearson correlation coefficients are displayed
($*p < .05$; $**p < .01$; $***p < .001$)

Velocity gain in handwriting positively correlated with speed in reading words and non-words (Table 3.2). Dysfluency and duration negatively correlated with speed in reading words and non-words (Table 3.3 and Table 3.4 respectively). Negative correlations were also found between duration in writing and accuracy in the repetition of non-words (Table 3.4).

3.4 Discussion

This cross-sectional study aimed at investigating the developmental pathway of reading, phonological memory and handwriting abilities in Italian children from the first to the fourth grade of primary school. As regards handwriting, it is worth reminding that we conceived handwriting as a fine-motor skill, thus neglecting the spelling domain. Based on previous findings, showing that the motor and language/reading maturational processes rely on common brain mechanisms (Diamond, 2000; Gimenez et al., 2014), and that the language neural circuit and the motor neural circuit are interrelated (Nicolson &

Fawcett, 2011), we predicted a parallel developmental pathway for reading, phonological memory and handwriting.

The results of the reading tasks reveal a developmental change in the second grade of the primary school. From this grade, the speed of reading words diverges from the speed of reading non-words, as words are read faster than non-words. Similarly, words are read more accurately than non-words. Therefore, from the second grade, children start to rely on lexical knowledge and the process of reading gradually becomes more automatized. The third grade turns out to be the turning point for reading skills. Children's performance levels off as shown by the absence of statistical difference between Grade 3 and 4 both in reading speed and in reading error scores. The results of the non-word repetition task, which was our phonological memory measure, shows that the main change occurs between the first and the second grade, and similarly to the performance of the reading task, the performance evens out at the third grade of primary school.

Focusing on handwriting, our analysis concerned the quantitative (not qualitative) aspects of handwriting, more specifically: velocity gain, dysfluency, pressure and duration (as already mentioned in Paragraph 2.2, the descriptors were chosen according to previous studies: (Accardo et al., 2013; Accardo et al., 2013; Blöte & Hamstra-Bletz, 1991; Di Brina et al., 2008; Hamstra-Bletz & Blöte, 1990; Kushki et al., 2011; Pagliarini et al., 2015; Parush et al., 1998; Rosenblum et al., 2003; Smits-Engelsman & van Galen, 1997, among others).

We found that velocity gain increased considerably from the second grade to the third grade, in line with the results from Blöte and Hamstra-Bletz (1991), and from the third grade velocity gain seems to reach a plateau at least in some conditions. Consistently with the trend in velocity gain, the duration taken to write the whole word decreased considerably from the second grade to the third grade and again was even out after the third grade. Finally, dysfluency revealed a similar pattern in the opposite direction, i.e., towards a more fluent handwriting, starting at the second grade and stabilizing at the third grade. The pressure exerted on the surface did not differ across the different grades. Therefore, it seems that the pressure is not a relevant quantitative index, in line with results from the literature about non-proficient handwriters (Kushki et al., 2011; Pagliarini et al., 2015). Across different variables, children generally wrote slower when asked to write in cursive script than when asked to write in block script in all capitals. The difference between the two scripts started to smooth from Grade 2 and was leveled off from Grade 3. This effect was expected since block script in all capitals is introduced beforehand the cursive script in the Italian educational system and it is commonly more trained, especially in the first years of primary school. Finally, the correlation analysis revealed that reading/phonological performance is correlated to handwriting skills. Children who wrote faster and were more fluent were also faster in reading words and non-words. Children whose duration in handwriting was shorter, also read faster words and non-words and were more accurate in the non-word repetition.

In summary, the investigation of quantity handwriting descriptors showed that from the end of the second grade of primary school the handwriting movement is performed in a ballistic and automatized way, in line with previous studies (Blöte & Hamstra-Bletz, 1991; Di Brina et al., 2008; Feder & Majnemer, 2007; Hamstra-Bletz & Blöte, 1993). These results, taken together with the findings from the reading and the phonological memory task, showed that children make a remarkable improvement from grade 2 to grade 3, both in reading, phonological memory, and the fine motor ability required in writing, followed by stagnation between Grade 3 and 4. Therefore, our findings suggest that the motor and the language development follow a similar pathway, in line with our prediction. Our results have strong implication for the study of developmental disorders, as high comorbidity between language and motor disorders has been well-attested for decades (Hill, 2001; Kaplan et al., 1998; Robinson, 1987) and there is increasing evidence that children at familiar risk for developmental dyslexia are slow in their motor development at infancy (Viholainen et al., 2002). The evidence of a similar developmental trajectory for phonological, reading and handwriting skills are compatible with the presence of a common procedural learning circuit (Nicolson & Fawcett, 2011), whose malfunctioning might cause difficulties in learning to read, write or spell, with variation depending on the extent of the impairment of the language or motor procedural learning as well as with the hypothesis that language and motor abilities rest on a common mechanism. These conjectures are corroborated by recent studies, showing that children with dyslexia are slower and more dysfluent in writing than typically developing children in an alphabetic language (Pagliarini et al., 2015) and less accurate in characters writing in a logographic language (Lam et al., 2011). Ultimately, handwriting and reading are automatized acquired skills, therefore it is plausible to conjecture that handwriting (and more general motor) and reading impairments may be caused by a failure in the acquisition of automatized skills (Nicolson & Fawcett, 1990). Following on from these observations, the present results suggest to reconsidering the current practice of developmental disorders diagnosis. Frequently, psychologists and speech therapists tend to restrict their medical survey on one aspect of cognition, either language or motor aspect, disregarding well-attested data showing that there is a high co-occurrence of developmental disorders within an individual and that handwriting problem are often associated with developmental dyslexia (Alamargot et al., 2014; Berninger et al., 2008; Capellini et al., 2010; Cheng-Lai et al., 2013; Lam et al., 2011; Nicolson & Fawcett, 2011; Pagliarini et al., 2015). An alternative account of the data discussed above might take into consideration the influence of handwriting in learning to read (and vice versa). Recent evidence from behavioral studies showed that handwriting training, but not typing practice, improves recognition of new characters both in preliterate children (Longcamp et al., 2005) and adults (Longcamp et al., 2008, 2006). Similar evidence comes from imaging studies. A functional MRI study showed that the inferior frontal gyrus, the left anterior cingulate cortex and the fusiform gyrus during letter perception were recruited more after handwriting experience than after typing or tracing training in 5 years old preliterate children (James & Engelhardt, 2012). Analogous evidence has been found in adults, as letters and pseudoletters trained through handwriting caused a stronger activation of the left Broca's area (Longcamp et al., 2008), left fusiform and dorsal precentral gyrus (James & Atwood, 2009) than letters and pseudoletters trained through typing during a visual letters (and pseudoletters) processing task. Moreover, not only has the role of motor knowledge been shown to be particularly important for letter recognition and letter perception, but also for letter processing. It has been found that the handwriting quality of 5 – 6 years old beginner writers/readers is positively associated with gray matter volume in an overlapping region of the pars triangularis of right inferior frontal gyrus during a phonological task using functional MRI (Gimenez et al., 2014). The influence of motor knowledge in speech perception is already active at infancy, since 4-months-old children can discriminate their native language from an unfamiliar language by relying only on facial speech information (Weikum et al., 2007). It is undisputed that handwriting practice facilitates the visual recognition of letters thus reinforcing the brain's visual-object processing system as argued by the authors of the studies mentioned above (James & Atwood, 2009; Longcamp et al., 2008, 2006, 2005), but yet the inferior frontal gyrus and the fusiform gyrus are brain regions recognized to be involved in phonological processing and reading (Dietz, Jones, Gareau, Zeffiro, & Eden, 2005; McCandliss, Cohen, & Dehaene, 2003; Shaywitz & Shaywitz, 2008). Therefore, it is possible that a specific motor-sensory network is engaged during handwriting practice but not when using the keyboard. This motor-sensory link is likely to contribute to the development of cortical circuits associated with phonological and visual process in the developing brain, ultimately facilitating reading acquisition in young children. Conversely, a longitudinal study of pupils assessed annually from grade 1 to grade 4 showed that children applied the knowledge in reading to their writing and that this relation is unidimensional (in other words, reading influences writing, but writing does not improve reading) (Ahmed, Wagner, & Lopez, 2014). Although our study does not allow us to disentangle among these alternatives (but not incompatible) explanations, yet it shows that motor and language development follow similar curves.

Finally, caution is warranted in interpreting the data reported in this chapter due to several limitations of our explorative study. First and most importantly, the relationship between reading and handwriting has not been explicitly tested. Neither the fact that the developmental curves of reading and writing are similar nor the correlations are a direct evidence of the existence of a link and a shared neural circuit between these two skills. Future studies should address this question more directly, by means of an appropriate experimental design. Second, reading was measured by means of only one test assessing the reading of single words and non-word. Future studies should test the reading in longer passages. Finally, the sample size was very small.

Chapter 4

Dyslexic children fail to comply with the rhythmic constraints of handwriting

4.1 Introduction

[10]The findings of the experiment presented in Chapter 3 showed that the development of phonological, reading and handwriting skills follows a similar trajectory in the first years of school and that children make a remarkable improvement from grade 2 to grade 3, in reading, phonological memory, and the fine motor ability required in writing. Altogether, these results suggest that motor development and language development are more interrelated than it has been previously suggested and that the development of these domain may hinge on common processes, a topic that will deserve considerable attention in future studies. Nevertheless, this pattern of findings is relevant if we consider that a high comorbidity between language and motor disorders has been recognized for decades, as already mentioned in Paragraph 2.3 and Chapter 3.

From the first studies on DD, anecdotes and experimental evidence have reported that children with DD often suffer from fine and gross motor difficulties. When the association between DD and motor disorders is examined, it is often narrowed to a comorbidity between DD and other developmental disorders, such as Attention Deficit Hyperactivity Disorder (ADHD) and Developmental Coordination Disorder (DCD) (Ramus, Pidgeon, et al., 2003; Rochelle, Witton, & Talcott, 2009). These observations notwithstanding, prior research on DD has focused on reading problems while neglecting motor problems. One exception that links motor deficits to

[10] A slightly modified version of this article has been published as Pagliarini, E., Guasti, M. T., Toneatto, C., Granocchio, E., Riva, F., Sarti, D., Molteni, B. & Stucchi, N. (2015). Dyslexic children fail to comply with the rhythmic constraints of handwriting. *Human movement science*, *42*, 161-182. Here, it is reprinted with the kind permission from Elsevier and from all the authors.

dyslexia is the automaticity/cerebellar hypothesis of Nicolson and Fawcett (Nicolson & Fawcett, 1990; Nicolson & Fawcett, 2011) (see also Chapter 3), which states that a dysfunction at the level of the cerebellum is responsible for the comorbidity between dyslexia and dysgraphia (see also Lam et al., 2011). Other exceptions are Wolff (2002), where some motor skills are studied in relation to dyslexia, (see also Wolff, Michel, Ovrut, & Drake, 1990) and Thomson, Fryer, Maltby, & Goswami (2006) (see also Thomson & Goswami, 2008). In this line of research, it is reported that dyslexic students anticipated an isochronic-pacing metronome signal by significantly longer intervals than controls did in a tapping task and showed difficulties in reproducing patterned rhythms of tones separated by a sequence of long and short inter-tap-intervals (Wolff, 2002). Thomson et al. (2006) and Thomson and Goswami (2008) further developed this line of research and found within-individual variability in the internal consistency of a tapping rate and an association between motor and auditory rhythmic sensitivity on the one hand and literacy on the other (see also Flaugnacco et al., 2014 for the relation between rhythmic perception and reading). These studies highlighted the importance of rhythmic timing for both language and motor skills and suggested that the link between reading and motor deficits is mediated by rhythm, as already extensively discussed in Paragraph 2.3 and 2.4. Timing is also the main feature of LLinás (1993) physiological account for dyslexia. Llinás defined dyslexia as “dyschronia” since, aside from their strictly linguistic deficits, dyslexic participants show difficulties in generating fast recurring sequences of movements. According to Llinás, rhythmicity is the ability to generate a sequence of rhythmic events that are time locked to each other. In Llinás’s model, the lack of appropriate triggering or resetting of neuronal oscillations at 40 Hz or 10 Hz might affect certain temporal aspects of cognition. Here, we study handwriting, a motor activity which requires the generation of rapid repeated events and is ruled by principles of rhythmic organization. We explore the hypothesis that children with DD experience a deficit in the temporal binding of events, which discloses a difficulty to comply with the **principle of isochrony** (the speed of movement execution is proportionally related to the length of its trajectory in order to keep the movement duration approximately constant) and **principle of homothety** (the internal temporal relation of each motor units is kept invariant despite changes in the global duration, thus preserving temporal relationship) (see Paragraph 2.4.4 for a detailed description of these two principles).

4.1.1 Dysgraphia and the Assessment of handwriting proficiency in Italian.

Studies on Chinese language have shown that dyslexic children write significantly slower, with greater average character size and that they make more stroke errors (Lam et al., 2011; see also Cheng-Lai et al., 2013). In these studies, the handwriting process was measured by means of a computerized system connected to a digitizing tablet, thus allowing the authors to collect on-line a series of kinematic parameters.

In the clinical practice, the assessment of handwriting proficiency in Italy is firstly performed through an evaluation of the legibility of the handwriting output produced during school activities. Second, the quality of handwriting and its speed are evaluated during formal testing with paper-and-pencil. The most commonly used test is the *Batteria di Valutazione della Scrittura e della Competenza Ortografica* 2 (BVSCO 2 Tests for assessing writing and orthographic competence, Tressoldi, Cornoldi, & Re, 2013). Writing speed is usually assessed by means of three writing subtests in which children are asked to write sequences of the syllables LE and UNO, and sequences of numbers. Speed is determined by calculating the number of legible graphemes written over one minute. The *BHK - Scala sintetica per la valutazione della scrittura in età evolutiva* (Di Brina & Rossini, 2011), which is the Italian version of the Dutch *Beknoptebeoordelingsmethode voor kinderhandschriften: BHK* (Concise Evaluation Scale for Children's Handwriting: BHK; Hamstra-Bletz, de Bie, & den Brinker, 1987) is also used. It is composed of 13 items measuring different aspects of handwriting quality, such as word alignment, word spacing, collision of letters and ambiguous letter forms beyond writing speed. So, it is possible that handwriting problems are present also in children with DD having an alphabetic language as mother tongue, but these problems are subtle and undetectable by means of paper-and pencil tests. It is also noteworthy that, although the definition of DD does not make reference to handwriting difficulties in Western countries (World Health Organization, 1992), the Hong Kong Education Bureau considers deficiencies in handwriting in the definition of developmental dyslexia (Suk-Han Ho, Wai-Ock Chan, Lee, Tsang, & Luan, 2004), in addition to impairments in phoneme awareness, rapid naming of characters, non-word reading and word repetition.

To date, the handwriting performance of dyslexic children having an alphabetic language has not been investigated yet. Noticeably, an alphabetic script has different requirements than a logographic script such as Chinese. In fact, the handwriting of Chinese characters requires the command of complex geometric configurations, the arrangement of strokes within a square area (Chow, Choy, & Mui, 2003) and the visual discrimination of fine differences in form and position of strokes. By contrast, handwriting in alphabetic languages, such as Italian, requires smoothness and continuity, especially in cursive. Cursive requires connecting characters in a smooth, fluent and continuous movement. Conversely, block script has no smoothness requirement since each character is written separately.

In addition to a group of children with a diagnosis of DD, we included in our study a group of DD children diagnosed also for dysgraphia. Dysgraphia was defined as a "written-language disorder that concerns mechanical writing skills. It manifests itself in poor writing in children of at least average intelligence who lack a distinct neurological disability and/or an overt perceptual-motor handicap" (Hamstra-Bletz & Blöte, 1993, p. 690). This definition is adopted in our study, although in the literature sometimes another definition including linguistic spelling errors is proposed (DSM-IV, American Psychiatric Association, 1994). It has been observed that children with dysgraphia, who are not proficient in handwriting, produce poor quality script due to variable letter shapes and spacing. More specifically, their handwriting product is characterized by more variability in size (Hamstra-Bletz & Blöte, 1993; Smits-Engelsman & van Galen, 1997), dysfluency (Hamstra-Bletz & Blöte, 1993; Smits-Engelsman & van Galen, 1997) bad alignment, inadequate spatial organization (Rosenblum, Aloni, & Josman, 2010; Tseng & Cenmark, 1993), longer in-air time (Rosenblum et al., 2003), increased pause time per stroke and an increased number of directional changes in velocity (Chang & Yu, 2013). Nevertheless, some results are controversial. On the one hand, non-proficient hand writers have been found to write fewer characters per minute with an overall slower writing speed than proficient controls (Rosenblum et al., 2003). On the other hand, it has been observed that not only do children with dysgraphia show the same average writing speed as controls (Hamstra-Bletz & Blöte, 1993), but also that more proficient hand writers write at a slower rate compared to children with dysgraphia (Feder, Majnemer, & Synnes, 2000; Kushki et al., 2011). Some authors attempted to account for the slowness of skilled writers as a higher level of self-monitoring during the writing action (Ziviani & Wallen, 2006), though a consistent account for these data is not yet available. Other debatable findings regard pressure, since Kushki et al. (2011) found no significant difference in pen pressure exerted on the surface between children with dysgraphia and typically developing children, in contrast to Parush et al. (1998) and Di Brina et al. (2008). These puzzling findings reveal inconsistencies in the study of dysgraphia largely due to the adoption of different and approximate tools, such as the use of carbon copy-paper (Parush et al., 1998) and subjective handwriting scales, which again highlight the weakness on study on handwriting.

The purpose of adding to the experiment a group of dyslexic children with overt handwriting problems was to investigate whether we could detect differences in handwriting between this latter group and children with only dyslexia.

4.1.2 Key questions of the present study

This study had three main aims:

- The first aim was to establish whether children with DD experience handwriting problems that are veiled and undetectable by means of paper-and pencil tests.
- The second was to examine whether children with DD comply with the rhythmic principles of handwriting (principle of isochrony and homothety)
- The third was to establish whether measures of reading and writing are correlated and whether rhythm is involved in these correlations.

To test these hypotheses, we investigated the handwriting performance of Italian dyslexic children (DD) and DD children with dysgraphia (DD_DY) and we compared it to that of typically developing children (TD).

We collected a series of quantitative kinematic variables by means of an objective, computerized tool developed to study the handwriting process to verify whether kinematic measures can detect subtle difficulties that escape off-line testing. As already mentioned, Lam et al. (2011) established that a group of Chinese DD children, who were already known to have writing problems, performed less well than TD children on various dynamic handwriting measures such as speed, average size of characters and total number of stroke errors. Differently from Lam et al. (2001), we compared the performance of children with DD_DY and that of children with only DD with no diagnosis of handwriting difficulties. Moreover, our study is concerned with the alphabetic script, which has different requirements than Chinese. Therefore, in light of previous results highlighting the presence of handwriting difficulties in Chinese DD children (Lam et al., 2011), the prediction was that DD and DD_DY children would write slower than TD children.

Meanwhile, we expected DD_DY children to write more dysfluently than children with DD. This hypothesis hinges on findings from previous studies (Hamstra-Bletz & Blöte, 1993; Rosenblum, Chevion, & Weiss, 2006; Rosenblum, Dvorkin, & Weiss, 2006; Smits-Engelsman & van Galen, 1997) which consistently showed that the handwriting of children with dysgraphia is characterized by sharp turns in size and direction.

Our second goal was to investigate whether DD and DD_DY children have difficulties in timing when translating the linguistic code into a series of motor events (i.e., individual letters). We hypothesized that DD and DD_DY children do not comply as well as TD children with the principles of isochrony and homothety, which describe the rhythm of the writing activity. In order to verify this hypothesis, we first ran an analysis by selecting individual letters as segments, then considering the total duration of the letters as the dependent variable. Our experiment required children to adjust their movement, namely handwriting, in accordance with the size (condition Big vs. Small) and the speed (condition Fast vs. Slow) of the letters. In accordance with the isochrony principle, we predicted that the speed of writing increases as a function of words and letter sizes. When children are requested to write bigger, they should also proportionally write faster. According to the homothety principle, we expected the relative duration of individual letters to be invariant across conditions. Finally, in line with our third goal, we aimed at exploring the association between reading and language/writing. If the link between motor skills and reading is mediated by rhythm, as suggested by Thomson et al. (2006), we can conjecture that rhythm mediates the frequently observed association between dysgraphia and dyslexia, since handwriting is ruled by two principles of rhythmic organization, isochrony and homothety.

In summary, our study is an extension of the Lam et al. study (2011), which focused only on handwriting. In addition, the current study under investigation explores the hypothesis that DD children experience a deficit in the temporal binding of events (Llinás, 1993). Since writing a word is a motor activity, which requires timing, i.e., a specific rhythm, we ultimately investigate potential links between language and motor control.

4.2 Method

4.2.1 Participants

Three groups of Italian monolingual children aged 8-11 were tested: a group of children with dyslexia (DD) (N = 17), a group of children with both dyslexia and dysgraphia (DD_DY) (N = 21) and a group of children with typical development (TD) (N = 39). The three groups were matched by gender, age and school grade. One child with DD and one with DD_DY were reported to have Specific Language Impairment. A one-way ANOVA on the age of the three groups revealed no significant differences with respect to their chronological age, $F(2, 74) = 2.02$, $p = .13$, $\eta^2_p = .14$. With respect to time of instruction, the difference approached significance, $F(2, 74) = 3.08$, $p = .05$, $\eta^2_p = .07$, due to more time spent in an educational setting by DD_DY children. The children were all born in Italy and used Italian as their first oral and written language. The TD children were recruited from different schools in the province of Milan. The children with DD and DD_DY were recruited from the Neurological Institute Carlo Besta in Milan. Demographic information of the participants is shown in Table 4.1.

Table 4.1
Demographic information on age, time of instruction, gender and hand dominance of the participants. (DD: children with developmental dyslexia; DD_DY: children with both developmental dyslexia and dysgraphia; TD: children with typical development).

	DD (N = 17)	DD_DY (N = 21)	TD (N = 39)
Mean age in years	9;0	9;5	9;2
(SD in brackets)	(0.6)	(1.17)	(0.81)
Age range	7;5 – 10;1	8;0 – 12;0	8;0 – 11;2
Mean age of time of instruction in years	4;2	4;7	4;2
(SD in brackets)	(0.77)	(1.12)	(0.84)
Gender			
Male	9	19	22
Female	8	2	17
Hand dominance			
Left	1	1	3

A qualified team of psychologists and speech therapists of the Neurological Institute Carlo Besta diagnosed dyslexia and dysgraphia in accordance with the National Guidelines (PARCC DSA, 2011) and the recommendations of the *Congresso Nazionale AIRIPA* (Congresso Nazionale AIRIPA, 2010). The diagnosis was made by means of standardized tests. Moreover, in order to complete the diagnosis of dysgraphia, the writing production of children at school was examined. The same team determined that the DD and DD_DY children had no psychological, neurological or auditory problems, nor did they have Developmental Coordination Disorders.

A preliminary interview with the teachers determined that the TD children had no cognitive, reading, writing, language or auditory problems. Moreover, they completed the nonverbal IQ Raven's test (Raven et al., 1998) and obtained a score equal to or above the 25th percentile.

Ethical approval according to standards of the Helsinki Declaration (World Medical Association, 2013) was obtained from both the board of the University of Milano-Bicocca and the board of the Neurological Institute

Carlo Besta. Before each testing session, informed consent was signed by the participants and by their parents.

4.2.2 Material

Reading and oral language abilities were assessed by means of standardized Italian tests ((1), (2), (3)). Writing and scribbling were tested by means of tasks performed with a digitizing tablet ((4), (5)):

(1) **Task of reading words and non-words.** Parts 2 and 3 of the *Batteria per la valutazione della Dislessia e della Disortografia evolutiva-2, DDE-2* (Sartori et al., 2007) were adopted to assess the students' level of reading competence. Children were asked to read aloud four lists of words and three lists of non-words conforming to the phonotactic rules of Italian.

(2) **Repetition of non-words.** *VAUMeLF Batterie per la Valutazione dell'Attenzione Uditiva e della Memoria di Lavoro Fonologica nell'Età Evolutiva* (Bertelli & Bilancia, 2006) was administered to assess phonological competence and verbal memory. The test included 40 non-words from two to five syllables in length. All non-words conformed to the phonotactic rules of Italian. Children were asked to repeat the non-word after having listened to it.

(3) **Receptive vocabulary.** *Peabody Picture Vocabulary Test - Revised (PPVT-R)* (Italian version: Stella, Pizzioli, & Tressoldi, 2000) was run to measure participants' receptive vocabulary for standard Italian. It consists of 175 vocabulary items of increasing difficulty. Children were asked to listen to a word uttered by the interviewer and then select one of four black-and-white pictures that best described the meaning.

(4) **Writing tasks.** We used the same task adopted in the cross-sectional study which investigated the development of handwriting and language in the first years of school (see Chapter 3). Figure 4.1(A) reports a writing example of a typically developing child. Figure

4.1(B) reports a writing example of a dyslexic child. As a reminder, I report briefly the task. Children were asked to write the Italian word *burle* in five different conditions (Spontaneous, i.e., as the child usually writes in class, then Big, Small, Fast and Slow with respect to the condition), both in block script in all capitals and in cursive. The condition Spontaneous was the baseline. We included two opposite condition pairs (Big/Small and Fast/Slow) in order to test participants' flexibility and ability to adjust the movement to challenging conditions. Our primary aim was to drive the children to write distinctly bigger and faster than in the condition Spontaneous. We did not bind children with templates since our concern here was to obtain as natural a change in size and velocity as possible. Similarly to the previous experiment, because of this procedure, some participants wrote too small in the conditions Small and Slow and data were not reliable for the estimation of velocity, dysfluency etc., due to the resolution limits of the digitizing tablet (±0.25 mm). The conditions Big and Fast do not have technical limitations (except paper size). Therefore, children could adjust their handwriting as much as they wanted and as much as they could. So, provided that children comprehended the task, we expected them to show significant differences in the opposite conditions.

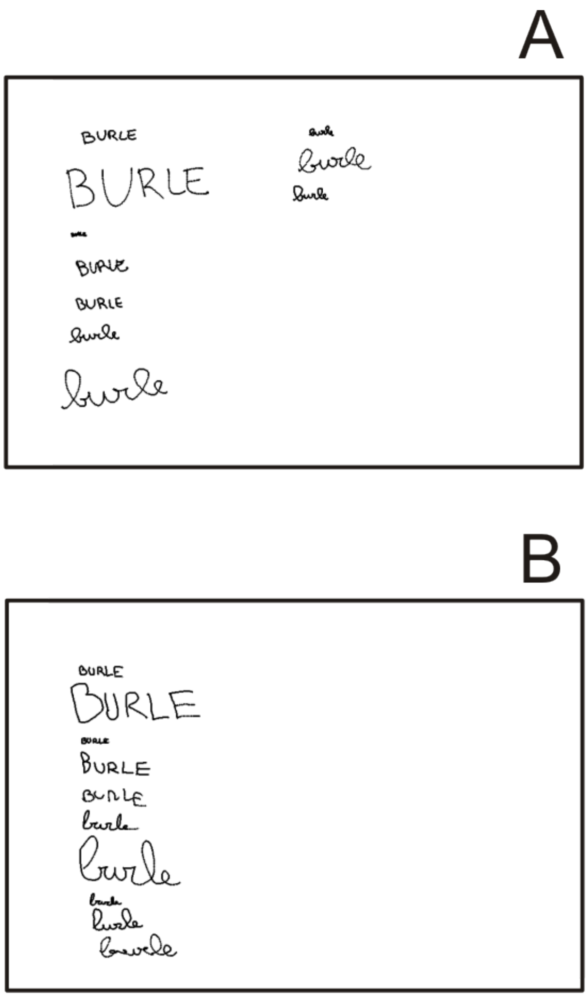


Fig. 4.1. Writing sample of a TD child and a DD child recorded by means of the graphic tablet. Panel A reports the writing production of a typically developing child. Panel B reports the writing production of a dyslexic child. Participants had to write the word ‘burle’ (jokes) on a sheet of paper placed in landscape orientation on the recording surface of an Intuos 3 Wacom ® tablet. They had to vary the size and speed of writing. Five conditions were envisaged: Spontaneous, Big, Small, Fast, and Slow in both cursive and block scripts. Note that no evident feature of the scripts allows us to classify the writing of the dyslexic child as less proficient than the other one.

(5) **Scribbling tasks.** Children were told to sketch a route inside a given circle, imagining that they were drawing a trail blazed during a free bicycle ride in a park. The circle given was 30 cm in diameter. Children were asked to trace only smooth lines without angles and without lifting the pen from the surface. The task lasted about 2

minutes. The general settings were the same as for the writing tasks. This task was implemented to investigate the fine motor skills in a task in which no process of lexical access or orthographic code is required.

4.2.3 Instruments used for collecting data on writing and scribbling

Similarly to the experiment described in Chapter 3, writing and scribbling data were collected by means of the Intous 3 digitizing tablet used with a wireless pen and connected to a laptop controlled by VBDigitalDraw 2.0 software (Toneatto, 2012) (see Paragraph 3.2.3).

For the purpose of the present study, the continuous handwriting strings were segmented by word in the first analysis, and by letter in the second. The individual letters of the cursive script were segmented according to the standard cursive shape of the letter taught at school. The geometrical transition between two consecutive letters was set at the minimum velocity in the transition segment. The final segmentation of handwriting strings in words/letters was checked off-line, starting from an automatic raw segmentation obtained through the software and based on the modulation of speed and pressure. Each selected word/letter was labeled according to the letter when segmentation was done by letter (*b-u-r-l-e*), the script (block capital or cursive) and the experimental conditions (Spontaneous, Big, Small, Fast and Slow).

4.2.4 Procedure

Participants were tested individually in a quiet room either at the Neurological Institute Carlo Besta in Milan (children with DD and children with DD_DY) or at their school (children with TD). Standardized linguistic, oral and handwriting tasks were administered in 40-minute testing sessions with breaks whenever required.

4.3 Data analysis

4.3.1 Selected variables

For tasks of *reading words and non-words*, reading speed and error score were considered as variables. Reading speed was measured in syllables per second. Specifically, for reading words, the total number of syllables in the four lists (281 syllables in total) was divided by the seconds required to read all the four lists, the same holds for reading non-words, in which the total number of syllables was 127. Error score corresponded to the number of words read incorrectly. Self-correction was not counted as a mistake.

For the *repetition of non-words test*, accuracy was measured as the number of words correctly repeated. In this case, a self-corrected word was considered a mistake.

For *receptive vocabulary*, we considered the number of correct answers.

For the *writing* and *scribbling tasks*, the VBDigitalDraw 2.0 system permits one to collect a rich set of geometric, kinematic and dynamic descriptors (see Paragraph 3.2.2). A subset of descriptors was analyzed for both the writing and scribbling tasks, in accordance with previous studies (Di Brina et al., 2008; K. Feder et al., 2000; Hamstra-Bletz & Blöte, 1993; Kushki et al., 2011; Parush et al., 1998; Rosenblum et al., 2003; Smits-Engelsman & van Galen, 1997) and in line with the purposes of the present study. The selected variables were:

- *Length*, i.e., the summation of the length of all the strokes in cm (only for writing tasks).
- *Average speed*, i.e., the average absolute speed of pen movement in cm/sec.
- *Average pressure*, i.e., the average axial pen pressure measured as a numeric value between 0 and 1023 (where 0 corresponds to the absence of pressure, and 1023 corresponds to maximum pressure).

- *Dysfluency*, i.e., the logarithm based on the number of maxima and minima in the curve of instantaneous velocity.
- *Duration*, i.e., the time in seconds to write the word *burle* (or each letter of the word), taking into account only the time when the pen is in contact with the surface (only for writing tasks).

4.3.2 Statistical analysis

Statistical analyses of the reading and oral measures were performed using a Generalized Linear Model (GLM) analysis with Group (DD, DD_DY, TD) as the between-subject factor (henceforth BS), Item (Word, Non-Word) as the within-subject (henceforth WS) and between-item factors and age of instruction as covariate.

As for the writing data, square root transformations were performed to meet the normality requirements of linear modeling, but the original non-transformed measures are reported in Figures 4.3 – 4.9 to demonstrate the real extent of the effects. Control analyses on non-transformed data, however, substantially produced the same results as the analyses reported below. A preliminary analysis was performed to determine whether children complied with the task and modulated their writing performance according to task demands. This assessment was done through a GLM analysis on length and average speed of writing with Group as the BS factor, Condition (Spontaneous, Big, Small, Fast and Slow) and Script (Cursive, Block) as the WS factors and age of instruction as covariate. Next, to assess group differences, only the conditions Spontaneous, Big and Fast were analyzed.

First, the analysis of the writing data was performed on words as the selected segment. Therefore, average speed, pressure and dysfluency were analyzed by a GLM analysis with Group as the BS factor, Condition and Script as the WS factors and age of instruction as the covariate.

Then, the analysis was performed on letters as the selected segment. Therefore duration was analyzed by a GLM analysis with Group as the BS factor, Condition, Script and Letter ((b), (u), (r), (l), (e)) as the WS factors and age of instruction as covariate. Significant main effects and interactions were followed up on using Bonferroni's post-hoc comparisons. Significant values are always meant to be less than 0.5. We reported only significant main effects and interactions; partial eta squared (η^2_p) was reported as a measure of effect size. In the end, correlations among reading, language and writing data were computed to assess the relation between writing and reading performance.

4.4 Results

4.4.1 Language task results

Results from the GLM analysis on reading speed (measured in syll/sec)[11] revealed an effect of Group, $F(2, 73) = 34.1$, $p < .001$, $\eta^2_p = .48$. Post-hoc comparisons showed that TD children read more rapidly than DD and DD_DY and that these two latter groups did not differ from each other. As shown in Figure 4.2, the interaction Group x Item, $F(2, 73) = 22.87$, $p < .001$, $\eta^2_p = .38$, is due to the fact that TD children read words more quickly than non-words.

The analysis of the error score of reading revealed a significant effect of Group, $F(2, 73) = 11.47$, $p < .001$, $\eta^2_p = .24$, due to TD children making fewer errors than DD and DD_DY. It also revealed an effect of Item, $F(1, 73) = 4.06$, $p < .05$, $\eta^2_p = .05$, since reading words elicited fewer errors than reading non-words.

[11] We also run a GLM analysis on the reading speed of words and non-words with raw seconds as dependent variable (and age of instruction as covariate). The analysis showed a main effect of Group, $F(2, 73) = 28.88$, $p < .001$, $\eta^2_p = .44$. Post hocs showed that TD children read faster than both DD and DD_DY children, whereas these two latter groups did not differ from each other. The analysis also revealed a main effect of Item, $F(1, 73) = 11.36$, $p < .001$, $\eta^2_p = .13$ as more seconds were spent to read words than non-words. Finally, a significant interaction Group x Item was found, $F(2, 73) = 14.65$, $p < .001$, $\eta^2_p = .29$. Post hoc tests showed that the seconds in reading words differed from reading non-words for children with DD and DD_DY but not for TD children.

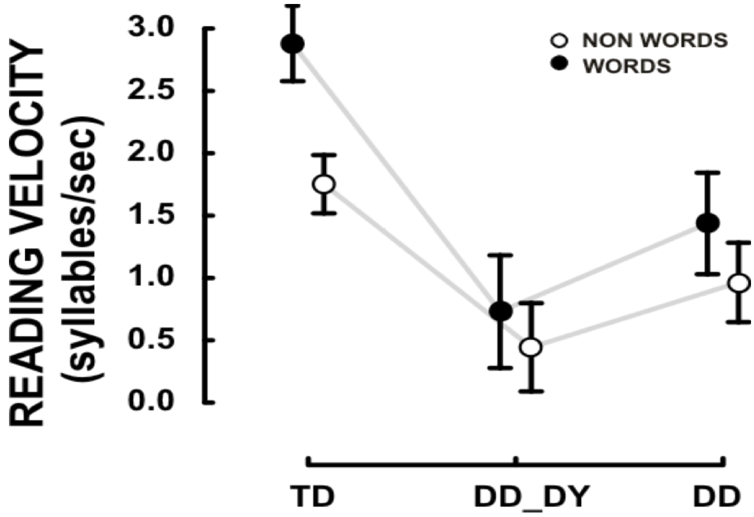


Fig. 4.2. Reading words and non-words task of TD, DD_DY and DD children. (Parts 2 and 3 of the *Batteria per la valutazione della Dislessia e della Disortografia evolutiva-2, DDE-2*, Sartori, Job, & Tressoldi, 2007). Reading speed is reported, expressed in syllables/second for words and non-words in the three experimental groups (DD: Children with Developmental Dyslexia, DD_DY: Children with Developmental Dyslexia and Dysgraphia, TD: Children with Typical Development). Vertical error bars represent standard error.

For the non-word repetition, the GLM analysis on correct repeated non-words revealed a main effect of Group, $F(2, 73) = 9.64$, $p < .001$, $\eta^2_p = .20$, due to TD children being more accurate in repeating non-words than the other two groups, with no difference between the DD and DD_DY group.

For the receptive vocabulary, the GLM analysis on correct responses revealed a main effect of Group, $F(2,73) = 3.69$, $p < .05$, $\eta^2_p = .09$, due to DD and DD_DY children obtaining lower scores than those with TD. In summary, TD children performed better than DD and DD_DY in all the reading and oral language variables.

4.4.2 Preliminary analysis of the writing task (whole word)

Preliminary analyses were conducted to verify whether children had correctly complied with the experimental requirements and had modulated their handwriting according to the task demands.

Length. The GLM analysis on length (Group x Script x Condition) showed an effect of Condition, $F(4, 292) = 8.94$, $p < .001$, $\eta^2_p = .10$. Post-hoc tests revealed that the conditions Big and Small were different from all the other conditions. Moreover, a significant interaction Script x Condition, $F(4, 292) = 3.15$, $p = .02$, $\eta^2_p = .04$ was found, as displayed in Figure 4.3. The conditions Big, Small and Fast differed more in cursive than in block script. This interaction does not affect the interpretation of the main effect, as it is due to the deviation from the parallelism of the curves for the cursive and block scripts.

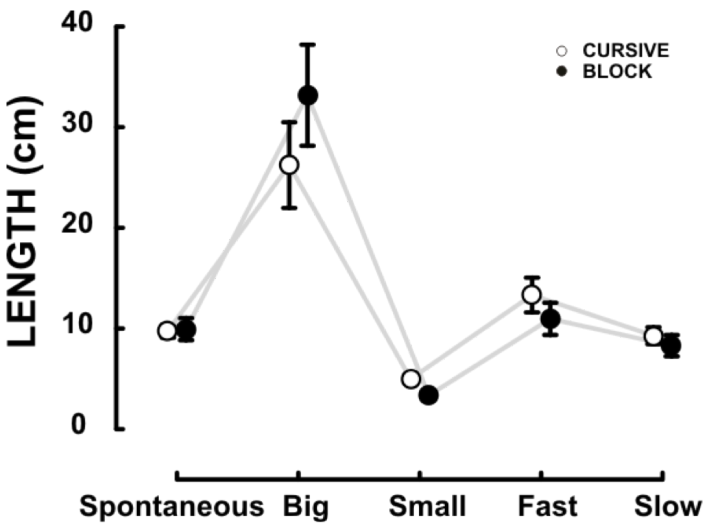


Fig. 4.3. Complying with the task requirements: size modulation. A preliminary analysis was performed to determine whether all the children, without distinguishing the 3 groups ($N = 77$), complied with the task demands and modulated the size of their writing. The average lengths of the word *burle* (with their standard error represented by the vertical bars) are reported for the 5 experimental conditions by the two scripts. The direct instruction of writing Big has a noteworthy effect on length. The instruction of writing Fast does not have the same effect on length. This is not at odds with the isochrony principle, which predicts an increase in velocity along with an increased size of writing, but not an increase in size along with an increase in velocity.

Average speed. The GLM analysis on average speed (Group x Script x Condition) revealed a main effect of Group, $F(2, 73) = 8.54$, $p < .01$, $\eta^2_p = .19$. A post-hoc comparison showed that TD children wrote faster than DD and DD_DY but DD children did not differ from DD_DY. Moreover, a main effect of Condition was found, $F(4, 292) = 7.95$, $p < .001$, $\eta^2_p = .10$ (Figure 4.4). The condition Spontaneous differs from all the other conditions. The condition Big differs from all the other conditions, except for the Fast. The condition Small differs from all the other conditions, except for the Slow. Finally, an interaction Group x Condition was found, $F(8, 292) = 3.75$, $p < .001$, $\eta^2_p = .10$. Post-hoc comparisons showed that TD children wrote faster than DD and DD_DY in the conditions Big and Fast whereas DD children did not differ from DD_DY in these conditions.

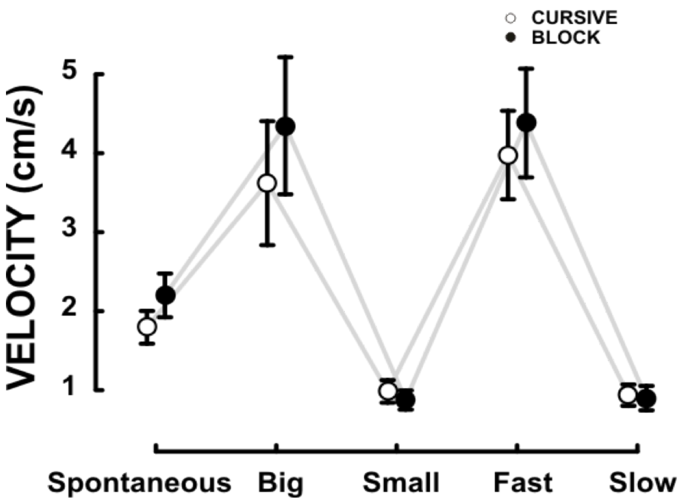


Fig. 4.4. Complying with the task requirements: velocity modulation. A preliminary analysis was performed to determine whether all the children, without distinguishing the 3 groups (N = 77), complied with the task and modulated the velocity of their writing. The average speeds of the word *burle* (with their standard error represented by the vertical bars) are reported for the 5 experimental conditions by the two scripts. Obviously, the direct instruction of writing Fast has a noteworthy effect on speed, and the instruction of writing Big has the same effect on speed as anticipated by the isochrony principle.

For the purposes of our study, it is important to know that children wrote more rapidly in the condition Big than in Small and in the condition Fast than in Slow. Crucially, speed is greater not only in the condition Fast, but also in Big, in line with the isochrony principle (see Paragraph 2.4.4). Thus, all three groups modulated speed as a function of size, but in a different way, as evident from the main effect of Group. The analyses of length and of average speed both confirm that children have complied with the experimental requirements and have modulated their writing according to the task demands. Further analysis on writing will consider only the conditions Spontaneous, Big and Fast.

4.4.3 Results on writing (whole word) and scribbling tasks.

Average speed. We found a main effect of Group, $F(2, 73) = 8.59$, $p < .001$, $\eta^2_p = .19$. Post-hoc comparisons revealed that TD children wrote more rapidly than both DD and DD_DY. DD children did not differ from DD_DY. We also found a main effect of Condition, $F(2, 146) = 4.84$, $p < .01$, $\eta^2_p = .06$. The post-hoc tests revealed that children systematically wrote slower when asked to write spontaneously than when asked to write either bigger or faster. Finally, we found a significant interaction of Group x Condition, $F(4, 146) = 2.71$, $p < .05$, $\eta^2_p = .06$, which can be appreciated by observing Figure 4.5. Post-hoc tests showed that the three groups did not differ from each other in the condition Spontaneous. In the conditions Big and Fast TD children wrote faster than DD and DD_DY whereas DD children were not statistically different from DD_DY.

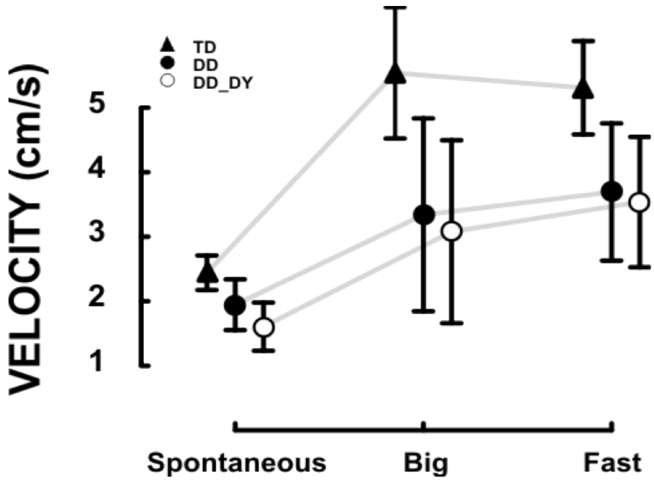


Fig. 4.5. Average writing velocity (whole word) of TD, DD and DD_DY children. The interaction Condition (Spontaneous, Big, Fast) by Group (TD, DD, DD_DY) in writing speed (cm/s) of the whole word *burle* is shown (vertical error bars represent standard error.). TD children are systematically faster than DD and with DD_DY in the conditions Big and Fast.

Dysfluency. A main effect of Group was found, $F(2, 73) = 10.76$, $p < .001$, $\eta^2_p = .23$. Post-hoc comparisons revealed that DD_DY children were more dysfluent than TD, and DD children did not differ from DD_DY in any condition (see Figure 4.6). A main effect of Script was found, $F(1, 73) = 13.2$, $p < .001$, $\eta^2_p = .15$, as it turned out that participants were more dysfluent when asked to write in cursive script. A main effect of Condition was also found, $F(2, 146) = 6.46$, $p < .01$, $\eta^2_p = .08$. Post-hoc tests showed that children were less fluent in the conditions Spontaneous and Big than in Fast. In addition, the conditions Spontaneous and Big also differ from each other, but the non-significant interaction, reported in Figure 4.6, showed that this is mainly due to DD children.

Average pressure. A GLM analysis on the average pressure exerted on the surface showed no significant differences among the groups. Script was significant, $F(1, 73) = 4.6$, $p < .05$, $\eta^2_p = .06$, due to higher pressure exerted when writing in cursive. Condition was also significant, $F(2, 146) = 8.18$, $p < .001$, $\eta^2_p = .10$. This effect was due to higher exerted pressure in the condition Big than in Spontaneous and Fast, and to higher pressure in the condition Fast than in Spontaneous.

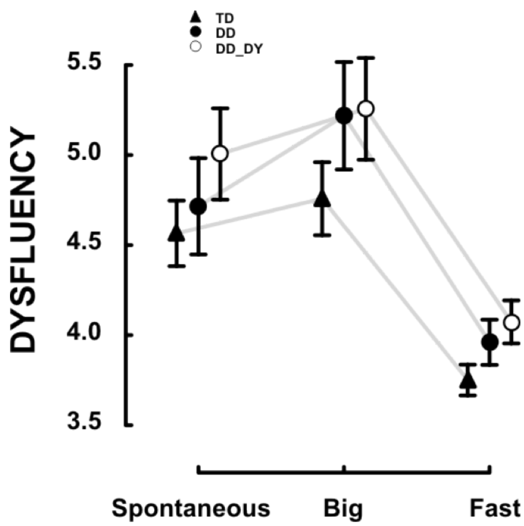


Fig. 4.6. Dysfluency (whole word) of TD, DD and DD_DY children. The non-significant interaction Condition (Spontaneous, Big, Fast) by Group (TD, DD, DD_DY) in dysfluency computed on the whole word *burle* is shown (vertical error bars represent standard error). DD_DY children are less fluent than TD and DD children do not differ from DD_DY in any condition.

4.4.4 Results on scribbling task

Considering the scribbling task, no significant differences among groups were found in any of the variables analyzed (average speed, dysfluency, pressure on the surface).

4.4.5 Results of writing tasks (individual letters)

The analysis on individual letters as selected segments was run to establish whether DD and DD_DY children can comply with the principles of isochrony and homothety (which govern rhythmic writing) as well as TD children can.

Duration. The GLM analysis revealed an effect of Script, $F(1, 73) = 6.07$, $p < .05$, $\eta^2_p = .08$, which is mainly due to the DD_DY group (see Figure 4.7).

The educational program introduces cursive later than block script and does not place much emphasis on it. This is particularly true for children who are known to have writing problems. For these reasons, it seems more appropriate to analyze block and cursive scripts separately as competence is likely to be different between them.

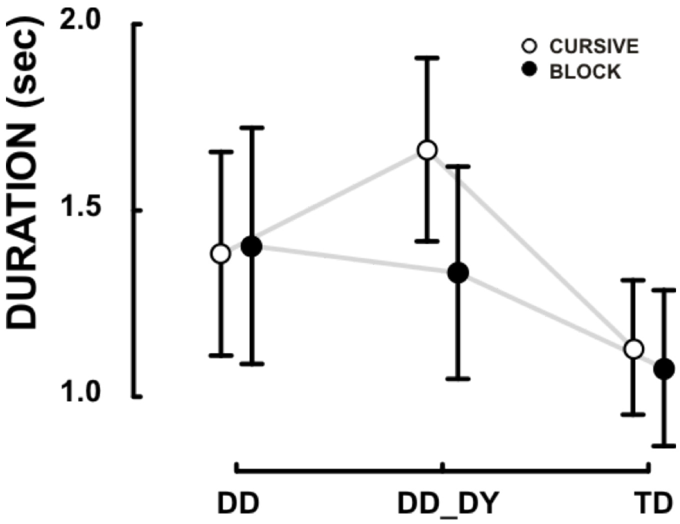


Fig. 4.7. Duration (separate letters) of TD, DD and DD_DY children. The average time (vertical error bars represent standard error) taken to write each individual letter of the word *burle* for cursive and block scripts is shown.

For block script in all capitals, Figure 4.8 displays the effects of Letter and Condition for each Group. We found a main effect of Group, $F(2, 73) = 4.42$, $p < .01$, $\eta^2_p = .11$. TD children differed from DD and DD_DY; DD children did not differ from DD_DY. We also found a main effect of Letter,

$F(4, 292) = 14.25$, $p < .001$, $\eta^2_p = .16$. Each letter differed from the others. TD children spent less time writing each letter than the other two groups, mainly in the condition Big, as confirmed by the significant interaction of Group x Condition, $F(4, 146) = 3.95$, $p < .01$, $\eta^2_p = .10$. The post-hoc comparisons revealed that in the condition Big the durations were longer for DD and DD_DY children than TD ($p = .01$, $p = .07$, respectively) whereas DD children were not statistically different from DD_DY. The three groups did not differ in the condition Spontaneous or Fast. Finally, we found an interaction of Group x Letter, $F(8, 292) = 2.34$, $p < .05$, $\eta^2_p = .06$. Post-hoc tests showed that the duration of the letters (b) and (r) were significantly longer for DD and DD_DY children than for TD. The durations of the letters (u) and (e) were significantly longer for DD children than TD and DD_DY. The three groups did not differ in the letter (l). No statistical differences were found between DD children and DD_DY.

Figure 4.8 clearly shows that the relative and absolute durations of individual letters in the three conditions are equal for TD children, suggesting that they comply with the principles of isochrony and homothety. This does not hold for the other two groups. Violation of homothety should be confirmed by the interaction of Condition x Letter in a separate analysis for each group. Violation of isochrony should be confirmed by a main effect of Condition and by some significant differences in the comparison of letters in the conditions Big and Spontaneous.

In the analysis of the DD group, we found a significant interaction of Condition x Letter, $F(8, 128) = 5.07$, $p < .001$, $\eta^2_p = .24$; a main effect of Condition, $F(2, 32) = 14.06$, $p < .001$, $\eta^2_p = .47$ and Letter, $F(4, 64) = 32.62$, $p < .001$, $\eta^2_p = .67$. Some post-hoc comparisons were significant, in particular duration was longer in the condition Big than in Spontaneous for the letters (b), (r) and (e), as appears in Figure 4.8. The analysis of the DD_DY group revealed analogous results, i.e., a significant interaction of Condition x Letter, $F(8, 160) = 7.22$, $p < .001$, $\eta^2_p = .27$; a main effect of Condition, $F\ (2, 40) =$

15.56, $p < .001$, $\eta^2_p = .44$ and Letter, $F(4, 80) = 48.89$, $p < .001$, $\eta^2_p = .71$. Some post-hocs were significant: duration was longer in the conditions Big and Spontaneous than in Fast for the letter (b); duration was longer in the condition Big than in Fast for the letters (u) (r) (e) (see Figure 4.8). The analysis of the TD group showed an interaction of Condition x Letter, $F(8, 304) = 2.14$, $p < .05$, $\eta^2_p = .05$ and a main effect of Letter, $F(4, 152) = 55.53$, $p < .001$, $\eta^2_p = .59$. No post-hoc test was significant, but the duration of the letter (b) in the condition Big was longer than in Fast. This explains the significant interaction of Condition x Letter. Notice that the main factor Condition is not significant and that the partial eta squared of the interaction is considerably smaller than that of the same interaction in the DD and DD_DY groups. These results support the conclusion that TD children tend to keep the absolute and relative durations of individual letters in the different conditions constant, as shown by Figure 4.8.

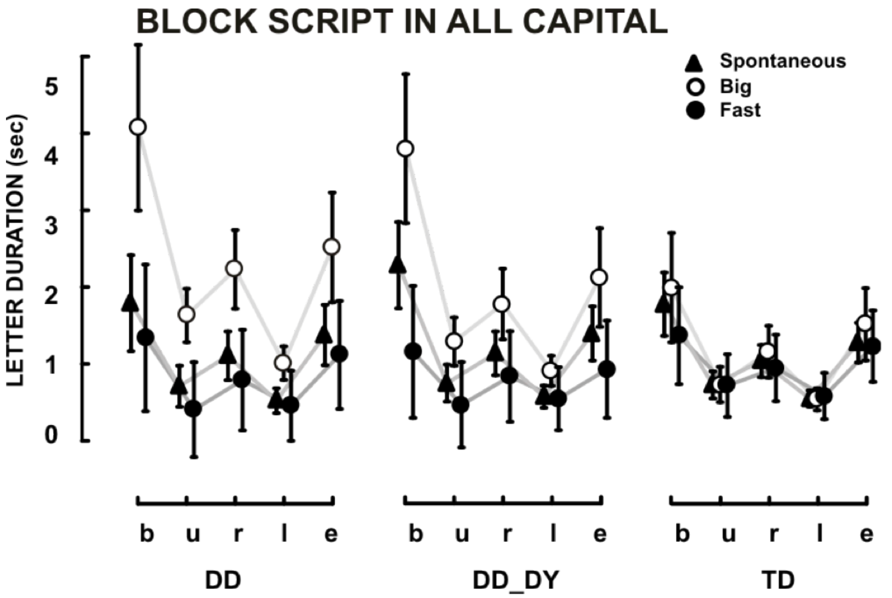


Fig. 4.8. Duration of separate letters in block script in all capitals of TD, DD and DD_DY children. The second order interaction Group (DD, DD_DY, TD) by Condition (Spontaneous, Big, Fast) and by Letter ((b), (u), (r), (l), (e)) is shown for duration (vertical error bars represent standard error). Writing the first letter (b) requires a longer time than the other letters indicating the burden of starting the writing task. The curves representing the performances of TD children superpose very well, indicating that they cope with the isochrony principle (keeping movement duration constant across changes in size) and with the homothety principle (keeping relative durations of movement components constant across changes in speed). This does not hold for DD or DD_DY children, who are less able to adjust their handwriting movement to the experimental size manipulations. Furthermore, in the three conditions the relative durations of the letter of DD and DD_DY children change at variance with the homothety principle.

Focusing on the analysis of writing in cursive, Figure 4.9 displays the effects of Letter and Condition for each Group. The GLM analysis (Group x Condition x Letter) revealed a main effect of Group, $F(2, 73) = 10.22$, $p < .01$, $\eta^2_p = .22$, as the time spent writing each letter was systematically shorter for the TD group than for the DD_DY group, with no difference between TD and DD children, and no difference between DD and DD_DY children. A main effect of Letter, $F(4, 292) = 20.62$, $p < .001$, $\eta^2_p = .22$ was also found, due to the prolonged time spent writing the first letter. This effect holds for all three conditions (Figure 4.9). This extra time to write the first letter of the word might reflect the burden of planning to write the entire word. In addition, the time spent writing the letter (u) was different from all the other letters except (r); the letter (r) differed from all the other letters except (u); the letters (l) and (e) each differed from all the other letters. Although the predicted Group x Condition interaction was not found, two other significant interactions were: Condition x Letter, $F(8, 584) = 3.76$, $p < .01$, $\eta^2_p = .05$ and Group x Letter, $F(8, 292) = 2.29$, $p < .05$, $\eta^2_p = .06$. The post-hoc comparisons of the Condition x Letter interaction showed that the duration of each letter differed across the three experimental conditions, except the letter (e), for which no difference was found between the conditions Spontaneous and Big.

Similarly to the analysis of block script, the duration of individual letters was analyzed separately for each group in order to verify whether children comply with the isochrony and homothety principles. The results basically tell the same story, but they are less clear than the previous analysis of block script in all capitals, due to the particular status of cursive in the educational Italian system. In fact, for the last 30 years the Italian mainstream educational practice has been to start teaching block script in all capitals first and cursive later and not much emphasis has been placed on this latter script. The analysis of the DD group revealed a significant interaction of Condition x Letter, $F(8, 128) = 2.73$, $p < .01$, $\eta^2_p = .15$; a main effect of Condition, $F(2, 32) = 8.38$, $p < .01$, $\eta^2_p = .34$ and a main effect of Letter, $F(4, 64) = 39.01$, $p < .01$, $\eta^2_p = .71$. The condition Big is different from the other two for the letter (b); it is also different from Fast for the letters (u) and (r), as shown in Figure 4.9. In the analysis of DD_DY children we found a significant interaction of Condition x Letter, $F(8, 160) = 3.19$, $p < .01$, $\eta^2_p = .14$; a main effect of Condition, $F(2, 40) = 9.91$, $p < .01$, $\eta^2_p = .33$ and a main effect of Letter, $F(4, 80) = 33.90$, $p < .01$, $\eta^2_p = .63$. Post -hoc comparisons showed that the conditions Spontaneous and Big differ from Fast for the letter (b) (see Figure 4.9). The analysis of the TD group revealed a significant interaction of Condition x Letter, $F(8, 304) = 4.63$, $p < .01$, $\eta^2_p = .11$; a main effect of Condition, $F(2, 76) = 5.53$, $p < .01$, $\eta^2_p = .13$ and a main effect of Letter, $F(4, 152) = 79.66$, $p < .01$, $\eta^2_p = .68$. However, from post-hoc comparisons no difference emerged between the letters in the conditions Spontaneous and Big. The only significant differences are among the conditions Fast, Big and Spontaneous for the letter (b) and between Fast and Big for the letter (u).

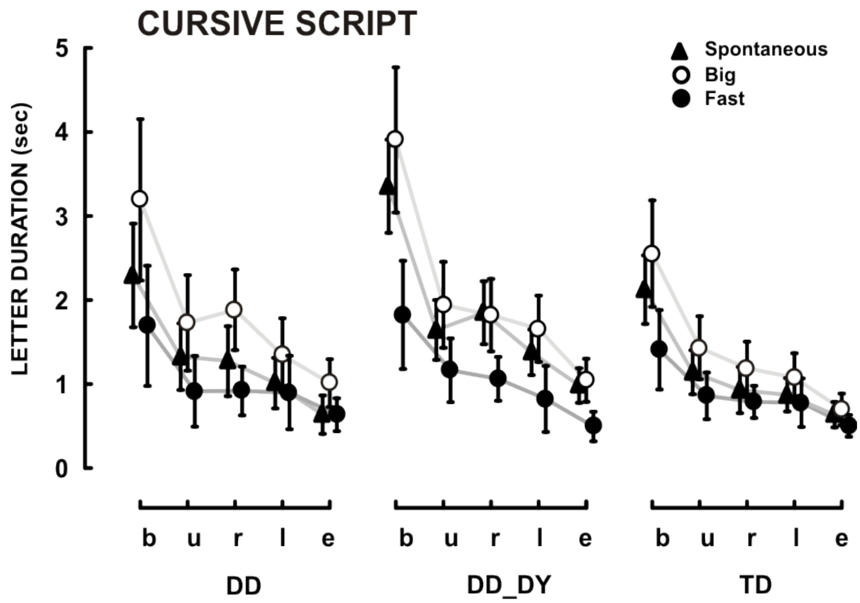


Fig. 4.9. Time taken to write separate letters in cursive script of TD, DD and DD_DY children. The second order interaction of Group (DD, DD_DY, TD) by Condition (Spontaneous, Big, Fast) by Letter ((b), (u), (r), (l), (e)) is shown for duration (vertical error bars represent standard error). Writing the first letter (b) requires more time than the others indicating the burden of starting the writing task. The curves representing the performances of TD children superpose very well, indicating that they cope with the isochrony principle (keeping movement duration constant across changes in size) and with the homothety principle (keeping relative durations of movement components constant across changes in speed). This does not hold for DD and with DD_DY children, who are less able to adjust their handwriting movement to the experimental size manipulations. Furthermore, in the three conditions the relative durations of the letter of DD and DD_DY children change at variance with the homothety principle.

4.4.6 Correlation analysis

Several correlations were found among descriptors of words in writing (average speed, dysfluency and total duration) and scores of the reading/linguistic and oral tasks. Significant correlations ($p < .05$) are reported in Tables 4.2, 4.3 and 4.4.

Most of these correlations were observed when all three groups of children were compared as well as when only the groups DD and DD_DY were considered. We reported the correlations of the groups as a whole. Average speed in writing positively correlated with speed in reading words and non-words, and with the PPVT score (comprehension of lexicon). Average speed in writing negatively correlated with the error score in reading words and non-words (see Table 4.2). Dysfluency and total duration of writing a word positively correlated with the error scores in reading words and non-words and they negatively correlated with speed in reading words and non-words, and with the PPVT score (see Table 4.3 for correlations with dysfluency and Table 4.4 for correlations with total duration). Furthermore, to explore the hypothesis that reading and writing are mediated by rhythmic competence, we ran a correlation analysis between reading speed and speed difference between the conditions Big and Spontaneous ($D_{B\text{-}S}$). The difference between these two conditions is a measure sensitive to the children's ability to comply with isochrony. First, we found a strong correlation between block script in all capitals and cursive ($r = .77$). Second, $D_{B\text{-}S}$ in block script significantly correlated with speed in reading words ($r = .32$) and non-words ($r = .26$). $D_{B\text{-}S}$ in cursive significantly correlated with speed in reading words ($r = .23$) and the correlation with speed in reading non-words approached significance ($r = .21$, $p = .06$).

Table 4.2
Correlation analyses within the three groups including average speed cm/sec as writing variable (based on whole word) and all reading/linguistics variables.

	1	2	3	4	5	6	7	8	9	10	11	12
1. Cursive spontaneous	-	.70***	.67***	.51***	.52***	.40***	.32**	-26*	.30**	-.20	.06	.22
2. Cursive big		-	.76***	.48***	.77***	.55***	.32**	-.23*	.30*	-.15	.01	.20
3. Cursive fast			-	.51***	.68***	.66***	.44***	-.30**	.41***	-.26*	.15	.21
4. Block spontaneous				-	.73***	.72***	.25*	-.23*	.22*	-.23*	.00	.31**
5. Block big					-	.71***	.35**	-.25*	.29**	-.23*	-.09	.23*
6. Block fast						-	.29**	-.20	.25*	-.25*	.07	.19
7. Speed reading words							-	-.78***	.92***	-.71***	-.01	.45***
8. Errors reading words								-	-.84***	.94***	.07	-.36***
9. Speed reading non-words									-	-.78***	-.05	.43***
10. Errors reading non-words										-	.05	-.29**
11. Accuracy non-word repetition											-	.00
12. PPVT												-

Pearson correlation coefficients are displayed

*p < .05
**p < .01
***p < .001

Table 4.3
Correlation analyses within the three groups including dysfluency as the writing variable (based on whole word) and all reading/linguistics variables.

	1	2	3	4	5	6	7	8	9	10	11	12
1. Cursive spontaneous	-	.75***	.61***	.48***	.54***	.26*	-.29**	.18	-.26*	.12	-.22	.07
2. Cursive big		-	.59***	.38***	.65***	.20	-.34**	.27*	-.28**	.20	-.21	.06
3. Cursive fast			-	.27*	.49***	.37***	-.52***	.38***	-.49***	.33**	-.27*	.07
4. Block spontaneous				-	.56***	.30**	-.21	.09	-.17	.09	-.23**	.00
5. Block big					-	.34**	-.39***	.25*	-.33**	.27*	-.28**	.16
6. Block fast						-	-.34**	.20	-.24*	-24*	-.13	-.07
7. Speed reading words							-	.78***	.92***	-.71***	.46***	-.02
8. Errors reading words								-	-.84***	.94***	-.36***	.07
9. Speed reading non-words									-	-.78***	.43***	-.05
10. Errors reading non-words										-	-.28**	.06
11. Accuracy non-word repetition											-	.00
12. PPVT												-

Pearson correlation coefficients are displayed

*p < .05
**p < .01
***p < .001

Table 4.4
Correlation analyses within the three groups including total duration as the writing variable (based on whole word) and all linguistics variables.

	1	2	3	4	5	6	7	8	9	10	11	12
1. Cursive spontaneous	-	.69***	.61***	.41***	.50***	.36***	-.31**	.18	-.27*	.16	-.16	.1
2. Cursive big		-	.52***	.40***	.65***	.21	-.27*	.23*	-.23*	.20	-.07	.16
3. Cursive fast			-	.22*	.40***	.46***	-.50***	.34**	-.46***	.31**	-.24*	.18
4. Block spontaneous				-	.57***	.48***	-.17	.00	-.09	.02	-.05	-.03
5. Block big					-	.35**	-.30**	.16	-.26*	.17	-.18	.20
6. Block fast						-	-.34**	.13	-.21	.12	-.08	-.09
7. Speed reading words							-	-.78***	.92***	-.71***	.46***	-.02
8. Errors reading words								-	-.84***	.94***	-.36***	.07
9. Speed reading non-words									-	-.78***	.43***	-.05
10. Errors reading non-words										-	-.28**	.05
11. Accuracy non-word repetition											-	.00
12. PPVT												-

Pearson correlation coefficients are displayed

*$p < .05$

**$p < .01$

***$p < .001$

4.5 Discussion

The present study demonstrated that handwriting difficulties are associated to DD and that these difficulties can be characterized in terms of compliance with the rhythmic principles of writing. This observation was drawn by comparing the writing performance of children with DD to that of children with DD plus dysgraphia (DD_DY) and that of children with TD. Reading and oral language abilities were also assessed. We aimed at verifying the existence of systematic correlations among writing, reading and some language measures as suggested in previous contributions.

As expected, our results showed that TD children performed better than DD and DD_DY in all reading and oral language variables. Moreover, our results showed that TD children read words more quickly than non-words. This divergence was expected and it suggests that TD children are proceeding towards an automation of reading and rely more on lexical knowledge.

Kinematic and dynamic variables of writing and scribbling were collected by means of a digitizing tablet. We observed that both the DD and DD_DY groups were slower than TD in average writing speed. Interestingly, no significant difference was observed between the DD group and DD_DY. We found that the DD_DY group wrote less fluently than TD, but, in contrast with our prediction, we were unable to show that the DD_DY group differed from DD. The DD and DD_DY groups both wrote less fluently than TD in the conditions Big and Fast, but the overall difference between the DD_DY group and the DD group only approached significance ($p < .09$). There is one plausible explanation for the lack of difference between DD and DD_DY children. Dysgraphic children are rehabilitated for handwriting and, therefore, their fluency is improved, whereas dyslexic children do not undergo any kind of practical intervention for handwriting. Finally, we found that the pressure exerted on the surface did not differ among the groups, in line with the results by Kushki et al. (2011). Writing in cursive turned out to be generally more challenging than block script in all capitals and it is likely to be due to the later introduction of cursive training in the learning program. Overall, these findings support our first hypothesis, which predicted that children with DD with no previous diagnosis of dysgraphia have some latent handwriting problems. These problems cannot be attributed to less handwriting practice since children with dyslexia are not relieved of writing responsibilities because of their reading difficulty. They also confirm the findings by Lam et al. (2011), which established that speed and accuracy in handwriting could discriminate Chinese children with DD from typically developing children (see also Cheng-Lai et al., 2013). Moreover, our remarks extended to an alphabetic script, which has different requirements from Chinese. Handwriting in alphabetic languages requires smoothness and continuity, especially in cursive. By contrast, Chinese requires the command of complex geometric configurations and the arrangement of strokes within a square area (Chow et al., 2003). It also requires visual discrimination of fine differences in form and position of strokes. Thus, although the alphabetic script may be less challenging than the Chinese logographic script, it is still challenging for children with DD. The results of the free scribbling task (a motor task in which no process of lexical access or orthographic code is required) reported no significant group difference. These results seem to suggest that the differences found between the TD group, on the one hand, and DD and DD_DY on the other, do not result from a motor deficit. However, further studies adopting additional sensitive measures of fine motor control (i.e., the Purdue pegboard battery, Tiffin, 1999) are needed to confirm this finding and discern whether children with DD are not affected by a more general deficit in fine motor control.

In light of these results, we considered the possible involvement of the linguistic component, in terms of accessing and retrieving the word to be written. If the problem were due to access to the linguistic code (or to the orthographic form), we would have expected children to struggle especially in the condition Spontaneous. In fact, the Spontaneous condition was the first presented to the participants in the testing sessions and therefore, it was the first time that the orthographic word had to be retrieved. All the other conditions followed Spontaneous, so participants simply had to rewrite the same word. However, even though Spontaneous was the most challenging in terms of access and retrieval, no significant group difference was found in the writing speed. In light of these considerations, we discarded the hypothesis and conjectured that the differences found between the TD group and DD and DD_DY are due to a deficit in transposing the linguistic structure into a motor event. In fact, beyond linguistic competence, specific skills are required to transpose the linguistic structure onto a sequence of motor events, such as motor programming, time estimation, allocation of time to each linguistic event (i.e., individual letters), since writing a word requires timing, i.e., a specific rhythm. In other words, this means that there is a writing rhythm that enhances writing performance particularly as speed and fluency are concerned.

Therefore, our second aim was to establish whether motor difficulties in handwriting are related to rhythm and therefore whether specific rhythmic deficits are associated to DD. If children with DD and DD_DY have problems with the rhythmic organization of writing, then they should be less able to keep the duration of the word constant across changes in size (violation of the isochrony principle) and they should also be less able to maintain the relative duration of individual letters, which is directly tied to the writing rhythm of words when the duration of the word changes across changes in speed (violation of the homothety principle).

As shown by the analysis of the writing speed of the word, average speed differed across groups. DD and DD_DY children did not increase writing speed in the Big condition, contrary to the principle of isochrony. TD children, however, were generally able to modulate their handwriting movement since when they had to write big, they also wrote more rapidly. Following on this, we found that TD children were able to keep the duration of the letters remarkably constant across the conditions Spontaneous, Big and Fast. Thus, in accordance with the isochrony principle, when they were asked to write bigger, they wrote more quickly in order to keep the absolute duration of letters constant. On the contrary, as shown by the main effect of Condition of the duration of individual letters (both in cursive and in block script), children with DD and DD_DY did not vary their movement to the change in size in contrast with the isochrony principle (see Figure 4.8 and 4.9). This suggests that they experience some difficulties in adapting their handwriting movement to various experimental size manipulations. Moreover, Figures 4.8 and 4.9 show that TD children keep the absolute and relative duration of individual letters remarkably constant regardless of the experimental request of writing Spontaneous, Big or Fast, as it can be appreciated by the superposition of the curves. On the contrary, DD and DD_DY children showed greater timing variability and were less able than TD children to maintain the relative duration of individual letters constant across conditions. In summary, these figures show that TD children comply with the isochrony principle and the homothety principle. On the other hand, DD and DD_DY children conform less to the principle of isochrony than TD children as the duration of the word varies across conditions. They also fail to comply with the homothety principle, as the relative duration of their individual letters varies across conditions. This pattern of findings is consistent with the hypothesis that DD and DD_DY children lack the ability to keep the rhythm of writing across the different experimental requests. This is in line with findings by Ben-Pazi, Kukke, & Sanger, (2007) showing that variability in a simple tapping task correlated with handwriting variability.

Our third aim was to investigate the association between reading and writing. We found a series of correlations among handwriting measures (average speed, dysfluency and duration) and reading/language measures (speed and errors in reading words and non-words, receptive vocabulary), thus confirming our third hypothesis. In fact, children who wrote fast also read fast; they made fewer errors in reading both words and non-words and had a larger receptive vocabulary. Moreover, children who wrote less fluently turned out to read more slowly, made more errors and had a poorer receptive vocabulary. These results are consistent with those in Cheng-Lai et al., (2013), according to which handwriting speed predicted impairments in rapid automatic naming. Finally, our correlation analysis revealed that speed difference between the conditions Big and Spontaneous, which was considered a measure sensitive to children’s ability to comply with isochrony, correlated with speed in reading words and non-words, thus supporting the hypothesis that reading and writing are mediated by rhythmic competence. Although correlation is not causality, these findings are compatible with the hypothesis of a common source for reading and handwriting problems. However, a more suitable design should be envisaged with a larger number of participants in order to carry out a more sophisticated correlation analysis (e.g., structural equation modeling).

Our study showed that individuals with dyslexia display rhythmic motor difficulties in handwriting beyond auditory rhythmic deficits (e.g., Flaugnacco et al., 2014; Goswami, 2011) and impairment in tapping in time to a metronome (Thomson et al., 2006; Wolff et al., 1990)Returning to the hypotheses raised at the outset, we suggest that DD children experience a deficit in generating serial sequences of rhythmic events time locked to each other, which is likely due to a physiological abnormality of resetting neural oscillations at higher frequencies, as argued by Llinás (1993).

Our outcomes have important implications for the clinical diagnosis of handwriting deficits and for practical intervention. In terms of clinical diagnosis, our results suggest that the handwriting skills of children with dyslexia require careful evaluation, since no evident features of the script allow for the estimation of a dyslexic child as less proficient than a typically developing child. The present data also suggest the need for the implementation of new, more sensitive tools to identify handwriting deficits in addition to the current paper-and-pencil tests. In terms of practical intervention, the latent handwriting problems disclosed in DD children recommend handwriting-based activities besides the more traditional reading interventions. Ultimately, intervention based on rhyme, rhythm and more generally musical activities might boost the maturation of crucial timing skills and, consequently, language and reading skills.

Before concluding, we think that some critical comments should be addressed about the limitations of this study. The research was conducted on a small number of DD and DD_DY children. Replication studies are indeed needed as well as a larger number of participants in order to conduct a more sophisticated correlation analysis between language scores and writing scores.

In conclusion, the current study showed that:

- ❖ children with DD suffer from handwriting difficulties, similar to those observed in children with DD plus dysgraphia;
- ❖ the absolute and relative durations of the individual letters were more variable across conditions in DD and DD_DY children than in TD children, suggesting that the former

groups were less skilled than the latter in complying with the principles of isochrony and homothety;

- reading/language and writing measures were correlated supporting the idea of a common origin of these disorders.

In the face of these results, we suggest that children's impairments are mediated by rhythm, which is at the basis of language/reading and handwriting, and are due to difficulties in generating serial sequences of rhythmic events time locked to each other.

Chapter 5

The isochrony and the homothety principle at work from the age of 6: evidence from a cross-sectional study.

5.1 Introduction

In Chapter 4 we saw that children with DD (with and without dysgraphia) were less able to comply with the principles of isochrony and homothety than typically developing children. These results suggest that children with DD do not pre-activate an abstract representation of the event they have to produce, thus affecting the temporal estimation both at a global (word) and a relative (letter) level. As already mentioned in Paragraph 2.4.4, these two principles are features of the motor planning system. They postulate that an abstract representation is available before actual execution. The length of the trajectory needs to be estimated in order to adjust the speed of motor execution and the duration of each single letter needs to be allotted according to a timing frame that is not restricted to the single letter but that rather includes the word (or the group of words) the letter is part of.

It might be objected that these principles of rhythmic organization develop after some experience in reading or handwriting and that the problems experienced by children with DD are consequences of the fact that these children have less experience in both reading and handwriting. In previous studies investigating drawings, it has been shown that children as young as 5 years comply with the isochrony principle (Vinter & Mounoud, 1991; Viviani & Schneider, 1991). The results of these studies are compatible with the idea that the adherence to the principle of isochrony is not the result of motor learning, but rather an innate constraint. However, this finding is also compatible with the hypothesis that these constraints are the results of a learning process, since children aged 5 were tested in drawing task, an activity which is rather natural for young children. The aim of our cross-sectional study was to establish whether the isochrony and homothety principles are the byproduct of practice or rather innate principles. In case they turned out to be learned constraints, we were interested in studying the development with age of these principles. In this study, we investigated the isochrony and homothety principles in handwriting. Contrary to scribbles and drawings, which are rather spontaneous production especially during infancy, handwriting is a fine-motor ability which requires many years of training in order to be performed ballistically and automatically (Blöte & Hamstra-Bletz, 1991; Di Brina et al., 2008; Feder & Majnemer, 2007; Hamstra-Bletz & Blöte, 1993; see also Chapter 3). For these reasons handwriting is a particularly interesting and appropriate context to ascertain whether these constraint are inborn or learned through practice. If isochrony and homothety are learned, we expect a developmental change of these principles in handwriting throughout the first years of school. Alternatively, if they are inborn, we expect no developmental variation. It is worth stressing that, to our knowledge, no previous study examined the development of the principle of homothety.

In summary, the key questions of the present study are:

- Determine if isochrony and homothety are innate mechanisms or if they are learned through practice.
- In case isochrony and homothety turned out to be learned mechanisms, we aim at determining at what age children start to adhere to these principles.

5.2 Method

5.2.1 Participants

Two hundred ninety-eights Italian children participated in the experiment. Children were all born in Italy, were all Italian monolingual speakers and used Italian as their first oral and written language.

Children were divided into five groups, according to their school grade: a group of first grade children, henceforth G1 (*N* = 57); a group of second grade children, henceforth G2 (*N* = 72); a group of third grade children, henceforth G3 (*N* = 61); a group of fourth grade children, henceforth G4 (*N* = 68); a group of fifth grade children, henceforth G5 (*N* = 40). Children in each school grade group were approximately evenly divided as for gender. Demographic information of the subjects is shown in Table 5.1. Children were recruited from three different schools in the province of Milan (Italy), in order to reduce possible effects due to a specific teaching and training method. In the Italian system, handwriting starts to be trained in the first grade of primary school, when children are around 6-year-old. The teaching of block script precedes the teaching of cursive script, and the time of introduction of this latter script is not uniform throughout schools, as some schools start the training of the cursive script at the end of the second semester of the first grade of primary school whereas others introduce it at the beginning of the second grade. Therefore, in order to have homogeneous cohorts in term of exposition to the cursive script, we selected schools that introduce the training of cursive script at the end of the second semester of the first grade. Moreover, in order to further control the time of exposition to the cursive script, all subjects were tested in the second semester of the Italian academic year (from end of January to May).

Table 5.1
Demographic information on age, gender, and hand dominance of the participants.

Grade	1 grade (n = 57)	2 grade (n = 72)	3 grade (n = 61)	4 grade (n = 68)	5 grade (n = 40)
Mean age in years (SD in brackets)	6;8 (0.3)	7;7 (0.3)	8;6 (0.3)	9;6 (0.4)	10;7 (0.3)
Age range	6;1 – 7;6	6;4 – 8;3	7;9 – 9;3	8;2 – 10;7	10 – 11;2
Gender					
Male	28	40	34	36	19
Female	29	32	27	32	21
Hand dominance					
Left	8	6	4	12	8

All subjects had a nonverbal IQ score (Raven's Coloured Progressive Matrices, Raven et al., 1998) equal or above the 25 percentile and, in addition, a prior consultation with the teachers determined that the pupils had no cognitive, neural, motor, writing and language problems.

Ethical approval according to standards of the Helsinki Declaration (World Medical Association, 2013) was obtained from the board of the University of Milano-Bicocca. Informed consent was signed by subjects' parents before the testing session.

5.2.2 Material

We used the same writing task adopted to test the development of handwriting skills in typically developing children (see Paragraph 3.2.2) and to test handwriting abilities in children with DD (see Paragraph 4.2.2). Thus, children were asked to write the Italian word *burle* (English translation "jokes") in two different scripts, cursive and block in all capitals, and for each script in five different conditions. The word *burle* was chosen as the target word because it is usually written in a continuous, smooth line when writing in cursive script. Children were not given any template. Two opposite conditions (*Big* versus *Small*; *Fast* versus *Slow*) were included in the experimental design in order to foster a natural change in size and velocity, along with the size and the speed of the experimental conditions.

The baseline condition was *Spontaneous*, i.e., children were asked to write as they habitually write in class, with no further instruction. Therefore, children were asked to write smaller (*Small* condition), bigger (*Big* condition), slower (*Slow* condition) and faster (*Fast* condition) with respect to the *Spontaneous* condition. Thus, the word *burle* was written ten times in total (Figure 5.1), varying in script, size and speed. This experimental method has been adopted in previous studies to assess participants' ability to control the handwriting size and tempo, with targets word of different languages (Arabic: Bouamama, 2010; French: Mayor Dubois et al., 2003; Zesiger, 1995; Italian: Pagliarini et al., 2015).

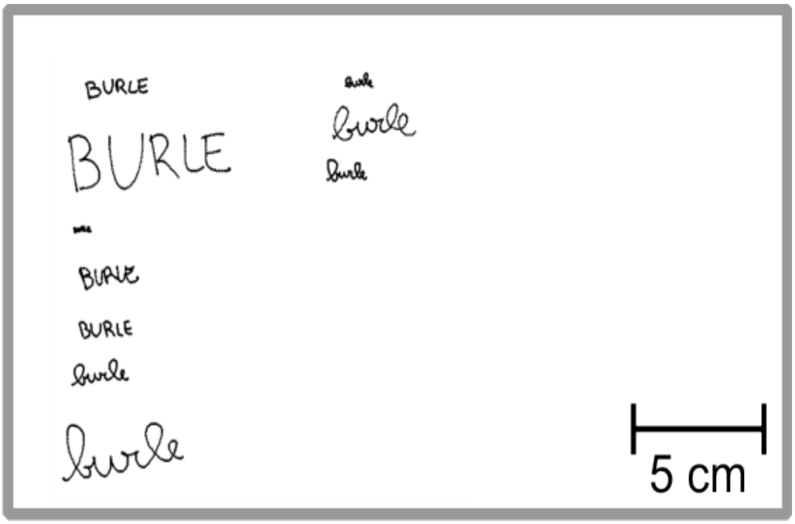


Fig. 5.1. Writing sample of a 4th grade girl recorded by means of the graphic tablet. The writing output of a 4th grade girl is reported. Children were asked to write the Italian word *burle* (English translation *jokes*) on an A4 landscape sheet of paper rested on the surface of an Intuos 3 Wacom tablet (sampling frequency: 200 Hz, spatial accuracy: ±0.25 mm). Children were asked to write *burle* in five different conditions (*Spontaneous*, *Big*, *Small*, *Fast*, *Slow*) both in cursive and block script.

5.2.3 Procedure and apparatus

Each participant was tested individually in a quiet room at their school, in a testing session lasting approximately 15 minutes.

The apparatus was the same of the two previous studies reported in Chapter 3 and 4. Children were asked to write on an unruled A4 paper size rested on landscape orientation on the recording surface of an Intuos 3 Wacom tablet. Children were required to grasp the wireless pen of the digitizing tablet with their dominant hand as if they were normally writing with a common pen. The digitizing pen left a visible ink trace on the paper and therefore the handwriting activity took place in a very realistic context. The digitizing tablet was connected to a computer via an USB cable. The data were acquired by VBDigitalDraw 2.0 software (Toneatto, 2012). The VBDigitalDraw 2.0 Software permits to collect an ample set of geometric, kinematic and dynamic descriptors of handwriting, and the system has been recently employed to investigate the handwriting abilities of Italian dyslexic children with and without dysgraphia (Pagliarini et al., 2015).

VBDigitalDraw 2.0 software recorded the trajectory of the handwriting as (*x, y*) Cartesian coordinates, both when the pen tip was in contact with the surface of the digitizing table and when the pen tip position was in the air above the digitizer active area with pressure = 0 i.e., when the writer was temporary pausing or planning the next movement sequence.

The continuous string of the handwriting performance was segmented into single words (to investigate the principle of isochrony) and letters (to study the principle of homotethy). We started from a semi-automatic segmentation gained from VBDigitalDraw 2.0 software. The semi-automatic segmentation segmented the trace on the basis of the detachment of the pen tip from the tablet surface, that is to say when pressure was equal to 0. Moreover, it considered a temporal detachment greater than 5000 ms as the end of a segment. Afterwards the end of a segment, the detection of pressure greater than 0 was considered as the beginning of a new segment. Therefore, the semi-automatic segmentation didn't add any criteria besides the deletion of segments shorter than 40 ms, as considered as artifacts. As for the single letters of the cursive script, the semi-automatic segmentation was double-checked by two different experimenters. In the event of a mismatch between the parameters of the semi-automatic segmentation and the letter geometry, the experimenters corrected manually the segmentation. The geometrical passage between two adjacent letters was stipulated at the minimum of velocity in the transition segment.

5.2.4 Data analysis

For the purpose of the present study, we considered total duration of the word, length and mean velocity for the examination of the principle of isochrony. We examined the duration of the single letter of the target word *burle* to investigate the principle of homothety.

Therefore, we focused on the following kinematic measures:

- *Word duration*: i.e., the time expressed in seconds to write the whole word *burle.* It comprises both the seconds during which the pen tip is in contact with the surface of the digitizing tablet and the seconds during which the pen tip is in the air above the digitizer active area.
- *Word Mean velocity*: the mean absolute velocity of pen movement expressed in cm/sec.
- *Word Length:* i.e., the sum of the length of all the strokes expressed in cm.
- *Letter duration*: i.e., the time expressed in seconds to write each letter of the word *burle*. It comprises only the time during which the pen tip is in contact with the surface of the digitizing tablet.

Some participants wrote too small both in the *Small* and *Slow* conditions, and because of the resolution limits of the digitizing tablet (±0.25 mm), the data collected in these two conditions were not reliable for the estimation of velocity, length and duration and were therefore excluded from data analysis (see also Pagliarini et al., 2015).

5.3 Results

5.3.1 Isochrony

To investigate the principle of isochrony, the analysis was performed on words as the selected segment. In order to detect outliers, we applied the rejection criterion of 3 standard deviations above the mean of the total duration. As a result, the 1.78% of the observations was eliminated. Linear regression analyses were used to examine the relationship between length (logarithmic value) and total duration and between length and mean velocity (both in logarithmic values). Significant main effects and interactions were followed up using Bonferroni's post-hoc comparisons. Significant values were reported ($p < .05$) for main effects and interactions. Partial eta squared (η^2_p) were reported as a measure of effect size.

Figure 5.2, Panel A reports the semi-log plot on the entire set of data (including the five groups of participants all together and the conditions *Spontaneous*, *Big*, *Fast* both in cursive and block script in all capitals) of word length against word duration. The relationship between the two variables is expressed by the equation $y = 3.17 + 1.89x$, with r = .31, $p < .001$. Figure 5.2, Panel B reports the log-log plot on the whole set of data of word length against word mean velocity (cm/sec) of the trace of the word *burle*. The equation $y = -1.01 + 0.71x$ explains the relationship between the two variables. It has r = .67 and $p < .001$. The results give evidence for the adherence of the principle of isochrony in handwriting, as the velocity of the handwriting movement is proportionally related to the length of its trajectory in order to keep the movement duration approximately constant across changes in size. In other words, when participants are requested to write bigger, they increase the velocity in order to keep constant the duration. As shown by Figure 5.2, Panel A, length needs to be increased by 20 times in order to double the duration.

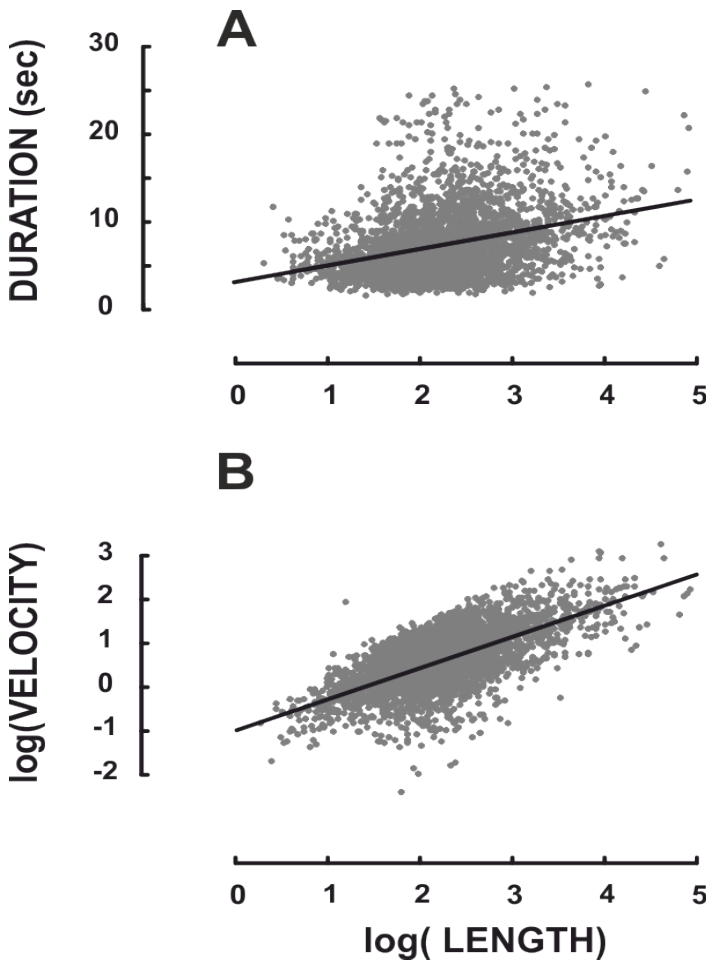


Fig. 5.2. Isochrony. Panel A reports the semi-log plot on the entire set of data (including the five groups of participants and the conditions *Spontaneous*, *Big*, *Fast* both in cursive and block script all capitals) of word length (cm) against word duration (*x* axis in log unit). Panel B reports the log-log plot on the whole set of data of word length (cm) against word mean velocity (cm/sec) of the trace of the word *burle* (*x* and *y* axes are in log unit). As predicted by the isochrony principle, the velocity of the handwriting motion is proportionally related to the length of its trajectory in order to maintain the movement duration approximately constant across changes in size. Therefore, when participants are asked to write bigger, they increase the velocity in order to keep constant the duration. Length needs to be increased by 20 times in order to double the duration.

Figure 5.3 reports the log-log plot of word length against word mean velocity (cm/sec) for each group when writing in block and cursive scripts, respectively. Table 5.2 reports the slopes and the coefficients of correlations of the log-log regression between the length and velocity, for each group.

For each group, the mean velocity correlates positively with the linear extent of the corresponding trajectory, both when writing in cursive and in block script all capitals. The pairwise comparisons between all the coefficients of correlation (r) were not significant (block script, *p* > .25; cursive script, *p* > .09). Thus, these results show that all the five groups of children equally complied with the isochrony principle.

Table 5.2.
Coefficient of correlation (r) and slopes of the log-log regression model which explains the relationship between word length and word mean velocity (cm/sec) for each group.

	Block script	Block script	Cursive script	Cursive script
Grade	**Slope**	**r**	**Slope**	**r**
G1	$.80x$	.72	$.91x$	.78
G2	$.75x$	.75	$.84x$	.74
G3	$.79x$	.73	$.94x.$	.71
G4	$.69x$	.66	$.72x.$	.62
G5	$.65x$	.74	$.82x.$	.75

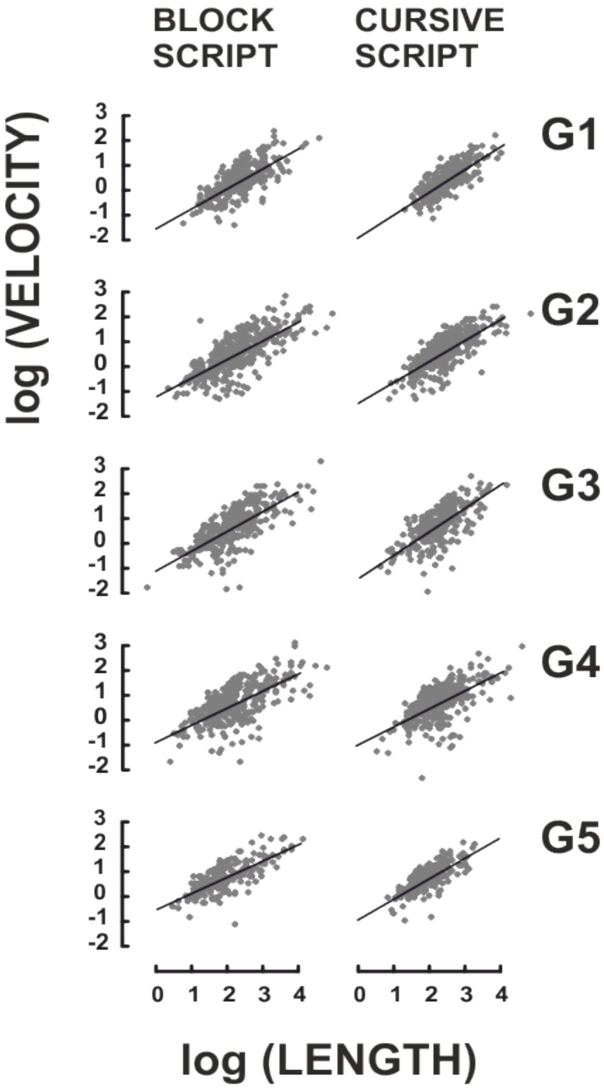


Fig. 5.3. Development with age of the isochrony principle. The log-log plot of word length (cm) against word mean velocity (cm/sec) is reported for each group of children (G1: first grade; G2: second grade; G3: third grade; G4: four grade; G5: five grade) when writing in block and cursive scripts, respectively (x and y axes in log unit). Each data point represents the word *burle* written in one of the experimental conditions (*Spontaneous*, *Big*, *Fast*) by each individual subject. The pairwise comparison between all the coefficients of correlation (r) were not significant (block script, $p > .25$; cursive script, $p > .09$). All the five groups of children adhere to the isochrony principle, as for each group the mean velocity correlates positively with the linear extent of the corresponding trajectory.

5.3.2 Homothety

To study the principle of homothety, the analysis was performed on letters as selected segment. Letter duration was analyzed by a Generalized Linear Model (GLM) analysis, with Grade (G1, G2, G3, G4, G5) as the between subject factor, Script (Cursive, Block), Condition (*Spontaneous*, *Big*, *Fast*) and Letter (*b*, *u*, *r*, *l*, *e*) as the within-subject factors. Next, letter duration was converted into percentage separately for each participant and experimental condition by dividing the duration of single letter by the duration of the entire word. Block and cursive script were analyzed separately. Relative letter duration was analyzed by a Generalized Linear Model (GLM) analysis, with Grade (G1, G2, G3, G4, G5) as the between-subject factor, Condition (*Spontaneous*, *Big*, *Fast*) and Letter (*b*, *u*, *r*, *l*, *e*) as the within-subject factors.

Significant main effects and interactions were followed up using Bonferroni's post-hoc comparisons. Significant values were reported ($p < .05$) for main effects an interactions and partial eta squared (η^2_p) were reported as a measure of effect size.

Figure 5.4 reports the significant interaction Grade (G1, G2, G3, G4, G5) by Script (Cursive, Block) of the letter duration, $F(4, 293) = 35.56$, $p < .001$, $\eta^2_p = .33$. Post-hoc comparisons revealed that the first and the second grade children took longer when writing in cursive script than block script. The GLM analysis also revealed a significant main effect of Grade, $F(4, 293) = 29.54$, $p < .001$, $\eta^2_p = .29$. Post-hoc tests showed that each group differed from the other with the exception of G2 and G3, which did not differ from G4. Script was significant, $F(1, 293) = 125.57$, $p < .001$, $\eta^2_p = .29$, as duration was longer when writing in cursive script. Letter was significant, $F(4, 1172) = 1015.6$, $p < .001$, $\eta^2_p = .78$. The duration of each letter was significantly different from the other, but no difference was found between the letter *l* and *e*.

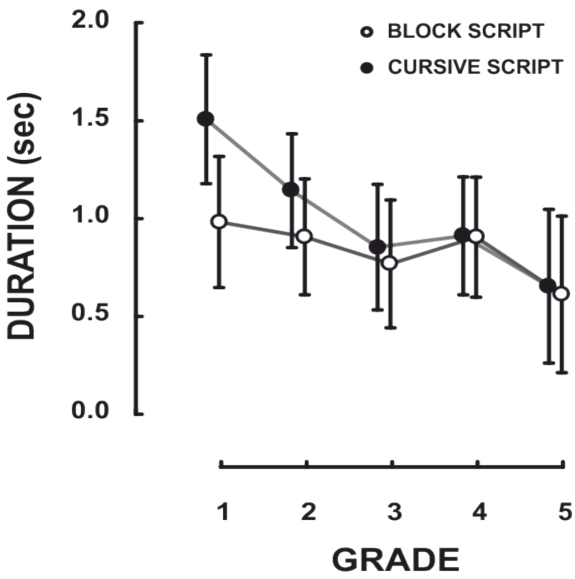


Fig. 5.4. Grade difference. The significant interaction Grade (G1, G2, G3, G4, G5) by Script (Cursive, Block) is reported for the durations of the single letters. Post-hoc comparisons showed that the first and the second grade children took longer when writing in cursive script than block script. Vertical error bars represent 95% confidence interval.

Subsequently, letter duration was transformed into percentage for each participant by dividing the duration of single letter by the duration of the entire word.

Since the previous analysis highlights a considerable difference between the two scripts, we analyze the relative letter duration of block and cursive script separately.

This difference might be due to structural differences between the two scripts. The handwriting of cursive script requires the connection of letters in a smooth and frictionless motion. The handwriting of block script in all capitals doesn't have smoothness requirements, since each letter is written separately from each other, but it requires adequate word spacing. Moreover, the difference might be due to different time of start of instruction (see Paragraph 5.2.1).

As already mentioned, letter duration was converted into percentage for each participant by dividing the duration of single letter by the duration of the entire word.

Main effect of Grade and Condition are obviously not calculated, because the normalization flattens grade and conditions differences.

Figure 5.5, reports the interaction Condition x Letter (Panel A) and Grade x Letter (Panel B) of the duration in percentage taken to write each letter in cursive script. The GLM analysis revealed a significant interaction Condition x Letter, $F(8, 2344) = 34.95$, $p < .001$, $\eta^2_p = .11$. Post-hoc tests are reported in Figure 5.6. The interaction Grade x Letter was also significant, $F(16, 1172) = 4.54$, $p < .001$, $\eta^2_p = .06$. Post-hoc comparisons revealed some significant differences, reported in Figure 5.7.

Figure 5.5, also reports the interaction Condition x Letter (Panel C) and Grade x Letter (Panel D) of the duration in percentage taken to write each letter in block script. The GLM analysis revealed a significant Condition x Letter, $F(8, 2344) = 45.29$, $p < .001$, $\eta^2_p = .13$. Post-hoc tests showed that the *Fast* condition diverged from the Spontaneous and the *Big* conditions for all the letters.

We also found a significant interaction Grade x Letter, $F(16, 1172) = 2.87$, $p < .001$, $\eta^2_p = .04$. However, post-hoc comparisons showed that the respective duration of each letters did not differ among the five experimental groups.

Though the analysis on block and cursive script revealed significant interactions, their partial eta squared are very low. Thus, as clearly shown by Figure 5.5, all the group of children kept the internal temporal relations of each letter constant despite changes in the global duration, in accordance with the homothety principle.

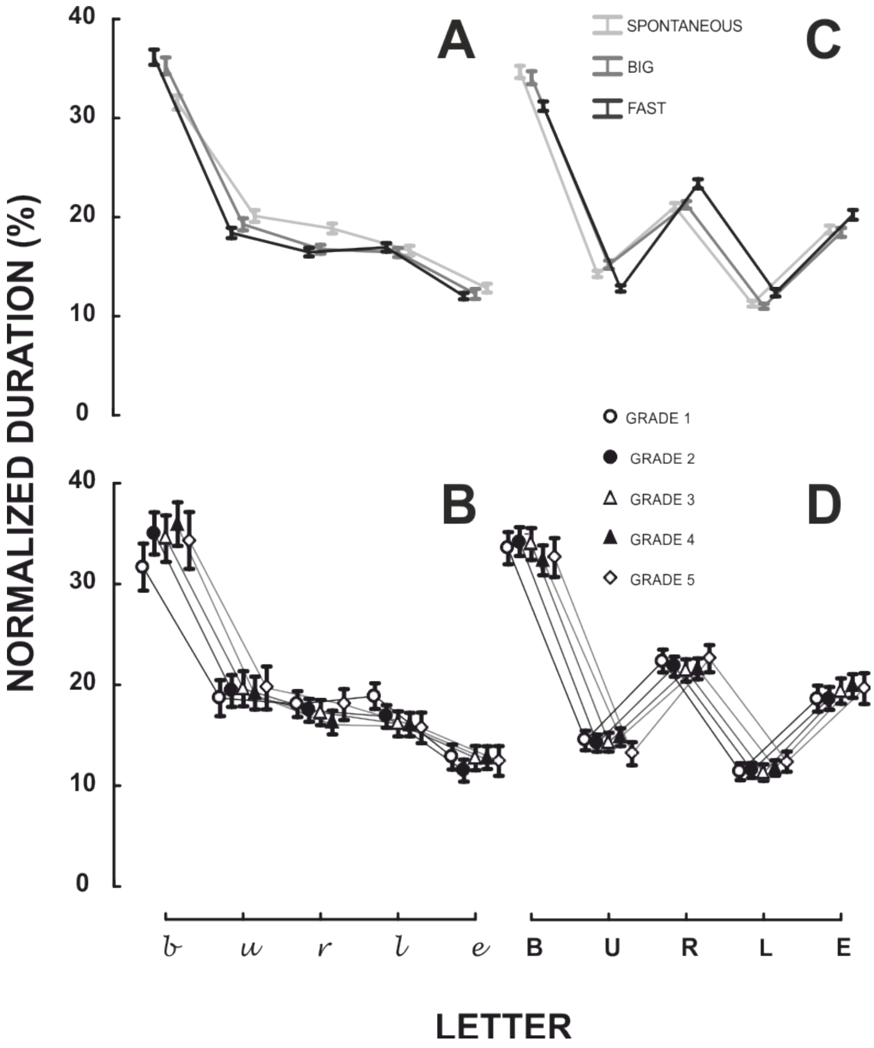


Fig. 5.5. Homothety. The interactions Condition (Spontaneous, Big, Fast) by Letter (*b*, *u*, r, *l*, *e*) (cursive: Panel A; block script: Panel C) and Grade (G1, G2, G3, G4, G5) by Letter (*b*, *u*, *r*, *l*, *e*) (cursive: Panel B; block script: Panel D) are shown for the duration in percentage taken to write each letter. The relative durations of movement components (i.e., letters) are kept constant across changes in speed by all the five groups of children, both when writing in cursive and block script, in accordance with the homothety principle. Vertical error bars represent 95% confidence interval.

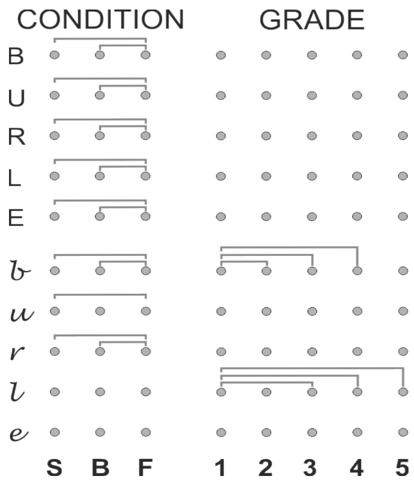


Fig. 5.6. Post hoc comparisons. The post hoc comparisons of the Condition x Letter and the Grade x Letter interactions are reported, both for block and cursive script. Significant differences are indicated by straight line connecting two points, where each point represents a level of a factor. S stands for *Spontaneous*, B for *Big*, F for *Fast*. 1 stands for G1, 2 for G2, 3 for G3, 4 for G4, 5 for G5.

5.4 Discussion

In this study, we aimed at determining whether the principles of isochrony and homothety are innate or learned mechanisms. The prediction behind this cross-sectional study was that a developmental effect should emerge if these principles are learned mechanisms. In order to outline the developmental path of these two mechanisms, we collected handwriting samples of Italian children from the first to the fifth grade of primary school by means of a digitizing tablet. Children were asked to write the Italian word *burle* in cursive and block script in all capitals, and for each script in five different conditions. Besides a baseline condition (*Spontaneous* condition), the design included two opposite conditions (*Big* versus *Small*; *Fast* versus *Slow*) to favor modulation and to evaluate participants' capacity to regulate the size and the tempo of handwriting.

First, we will consider the principle of isochrony. The results of the analysis on the whole word showed that when children are required to write bigger (as in the case of the *Big* condition), they increase the velocity in order to keep constant the duration, as precisely predicted by the principle of isochrony. In particular, the results of the analysis on the whole word showed that the mean velocity(log) covariates with the length(log) and that the length needs to be increased by twenty times in order to double the time. Figure 5.3 clearly shows that the principle of isochrony holds for all the grades and for both scripts. Thus, our findings demonstrate that isochrony characterizes the handwriting movement from the first grade of primary school, thus from an early age, when children are around 6-year-old (our group of first grade children had a mean age of 6;8 and an age range of 6;1 – 7;6 years). Contrary to previous findings, we did not find sizable differences among the five groups of children both in block and cursive script, since all groups of children comply fairly well with the isochrony. Freeman (1914) argued that children were less likely than adults to increase the speed of writing with an increase in size. However, his method raises some concerns. First, the author tested only 10 children, ranging in age from 9 to 15. Second, the apparatus adopted by the author poses some issues in regards to accuracy of data acquisition. Handwriting was collected by means of typewriter ribbon placed underneath a sheet of paper on which the participant wrote down. The speed of the typewriter ribbon was determined by an electric marker, which wrote tenths of a second on it. Therefore, all these things considered, the claim that children do not modulate speed in accordance with the size seems to be unreliable. Other studies focused on the principle of isochrony in drawing movements (Vinter & Mounoud, 1991; Viviani & Schneider, 1991). These studies showed that the principle was already active from the age of 5 and this result is compatible with our finding, since our youngest participants had an age of 6 years and eight months. However, contrary to our results, these studies reported that the improvement with age was non-monotonic since 7-year-old children exhibited a developmental disrupt in the adherence to isochrony and that the adult performance was not yet fully achieved by 12-year-old children. Another significant result of our study is that the principle of isochrony manifests both in cursive and in block script all capitals. This is particularly important if we consider that at the time of the testing session first grade children had few months of training in cursive script. Thus, our results showed that the principle of isochrony is at work from the age of 6, it is preserved throughout ages and its compliance does not depend on the time of practice.

We now turn to the principle of homothety. The preliminary results of the duration of the single letters revealed a developmental effect, since first and second grade children spent significantly more time when writing in cursive than in block script all capitals. From the third grade the difference between the two scripts is evened out. However, it is worth pointing out that this development effect does not affect the compliance with the rhythmic principles of handwriting. The analysis of the relative duration of the single letters revealed that all groups of children keep the relative durations of individual letters constant despite the changes in speed or size, as shown in Figure 5.5. In the graph, the curves representing the performances of the different grades superpose very well, indicating that not only do all group of children adhere to the principle of homothety, but they also comply well with the principle of isochrony, thus confirming the results previously discussed. Children comply well with the homothety principle both when writing in cursive and in block script all capital. However, the results of the cursive script appear less clean than those in block script. It is possible that, since children tend to write slower when writing in cursive (see Chapter 3 and Chapter 4), they are more likely to modulate the durations. Finally, the post-hoc comparisons of the Grade x Letter interaction in block script all capitals show that the duration of all letters in *Fast* condition differed from the duration of the letters in *Spontaneous* and *Big* condition. One possible account for this result is that the velocity reaches its maximum when writing fast, thus narrowing the possible modulation of the duration. In summary, our study showed that the adherence to the principle of isochrony and homothety are at work in children by the age of 6, both when writing in block and cursive script. On the basis of these results, it is plausible to argue that these principles are neither the outcome nor influenced by the time of training. Thus, the outcome of our study gives further evidence for the innatism of principle of isochrony, as previously claimed by Viviani & Schneider (1991) and Vinter & Mounoud (1991). Likewise, it seems legitimate to suggest for the first time that also homothety is an innate mechanism of the human motor-control system. Therefore, our results suggest that from the age of 6 children have an abstract representation of the word and of its components. In fact, they have the capacity of modulating the velocity when asked to write bigger than usual (principle of isochrony) and they are able to keep invariant the temporal relationship of each units despite changes in size and tempo (principle of homothety). If we consider our findings in the light of traditional research on the development of handwriting, our results suggest that these mechanisms are respected before handwriting movement turns to be ballistic and automatized, since motor automation in writing has been attested to be reached around the third grade of primary school (Accardo et al., 2013a, 2013b; Blöte & Hamstra-Bletz, 1991; Di Brina et al., 2008; Hamstra-Bletz & Blöte, 1993).

The assumption of the nativism of these two constraints is particularly noteworthy if we consider recent results showing that children with Dyslexia and children with Dyslexia plus Dysgraphia comply less well with the isochrony and homothety principle than age matched control children (see Chapter 4). In our previous study, the experimental design was the same as the one adopted in the present experiment. Both groups of children with Dyslexia were less able to keep the movement duration constant across changes in size (isochrony) and were less able to keep the relative durations of the letters constant across changes in size and speed. If we assume that the length of the trajectory needs to be anticipated in order to adjust the speed of motor execution (thus adhering to isochrony) and that the duration of each letter needs to be allocated according to a timing frame the letter is part of (thus adhering to homothety), the results of dyslexic children suggest that these children experience difficulties in building an abstract representation of the gesture they have to produce. From this line of reasoning, it is plausible to argue that humans are endowed with these compensatory mechanisms to deal with change of size and speed of movements and with a natural tendency to anticipate later movement of the basis of previous ones. However, as shown by the study reported in Chapter 4, these compensatory mechanisms appear disrupted in some populations, such as individuals with DD. In future studies, it might be interesting to further investigate the compliance with the isochrony and homothety principle in the dyslexic population by looking at different motor tasks, to extend those studies to other atypical populations and to investigate whether the subtle difficulties in adhering with these principles by children with DD persist into adulthood.

In a nutshell, the current study showed that:

- ❖ The principle of isochrony and homothety do not emerge after some years of handwriting (or reading) practice, as children comply with both principles from the age of 6.
- ❖ No developmental effect was found.
- ❖ Children as young as 6 years old are able to construct an abstract representation of the handwriting movement which allows them to adjust the speed of writing to changes in sizes (principle of isochrony) and to keep constant the relative duration of each single letter across changes in speed (principle of homothety).

Chapter 6

Timing prediction in adults with Developmental Dyslexia

6.1 Introduction

The results of the experiment reported in Chapter 4 showed that children with DD are less able to comply with the rhythmic principles of handwriting. The correlations among reading/language measures, writing measures and a measure sensitive to the children's ability to comply with the principle of isochrony suggest that the motor and the language systems appear to be linked and that this link in mediated by rhythm. The results reported in Chapter 5 rule out the hypothesis that the principles of rhythmic organization emerge after reading or handwriting experience. In fact, isochrony and homothety are at work from the age of 6, at the time children enter primary school. Moreover, all groups of children respected these principles in equal terms. This fact suggests that isochrony and homothety are not the result of training, but rather are innate mechanisms. In the light of this evidence, the results of Chapter 4 are strengthened. They suggest that children with DD experience some difficulties in exploiting the rhythmic structure of handwriting to anticipate the occurrence of future sensory events. In the case of handwriting, events can be letters, words, phrases. Therefore children with DD appear unable to construct an internal representation of timing events, and this inability to form an abstract representation might prevent children with DD to timely anticipate the occurrence of these events. Whether children can build an abstract representation of an event they have to produce but can not use it to make prediction or whether an abstract representation is readily available but still is not exploited to make timing prediction is still an open question.

The proposal of a rhythmic timing deficit as a cause of Developmental Dyslexia has already been released by Goswami in the last decade (Goswami, 2011; Goswami et al., 2002; see also Paragraph 2.1). The latest version of her proposal is referred to as the **Temporal Sampling**

Framework for Developmental Dyslexia (TSF) (Goswami, 2011). The TSF is a framework based on oscillations. It is grounded on the multi-time resolution model (MTRM) by Poeppel and colleagues (Hickok & Poeppel, 2007; Poeppel, Idsardi, & van Wassenhove, 2008; Poeppel, 2003). According to the MTRM, speech analysis occurs at different time scales. Slower temporal frequencies (which correspond to the syllabic level) drive Theta sampling, predominantly in the right non-primary auditory cortex. Fast temporal frequencies (which correspond to the phonemic level) are coded bilaterally by Gamma sampling. On the basis of the MTRM, the TSF claimed that the cause of the phonological deficit in Developmental Dyslexia is due to impairment in the phase locking of slower modulations in the speech signal, particularly in Theta (4 - 8 Hz) and Delta (0.5 - 4 Hz) bands. Theta band tracks the temporal integration at syllable level. Delta band tracks the prosodic level (Ghitza & Greenberg, 2009). According to Goswami and colleagues, this theory is supported by studies showing that children with DD are impaired in discriminating amplitude envelope rise time (which is the time taken for a sound to reach its maximum amplitude), results that hold across languages having different rhythmic structure (English: Goswami et al., 2002; Chinese and Spanish: Goswami et al., 2011; Hungarian: Surányi et al., 2009; Finnish: Hämäläinen, Leppänen, Torppa, Müller, & Lyytinen, 2005; French: Muneaux et al., 2004). In Goswami's framework, the deficit in the amplitude modulation is linked to the deficit in the processing of speech at the syllable level. From a theoretical perspective, the detection of beats in amplitude modulation sequences coincides to the detection of perceptual centers (P-center) in acoustic signals. In speech, the P-center occurs at around the onset of the syllable vowel, which is usually the nucleus of the syllable (Scott, 1998). P-centers are used as mechanism for segregating syllable onsets and rhymes and are therefore important for accurate phonological representation. In summary, the impairment to entrain to temporal modulation at lower frequency (1.5 - 7 Hz) is atypical from birth in individuals with DD. According to such framework, this impairment affects the recovery of the prosodic and syllabic structure and it is likely to cause an impoverished perception of speech rhythm and syllable stress since early phonological development. Indeed, there is evidence of impaired rhythmic tapping to a beat in children with DD (Thomson & Goswami, 2008; Wolff, 2002; see also Corriveau & Goswami, 2009, for impaired rhythmic entrainment in children with Specific Language Impairment). There is also evidence that this impairment persists in adulthood (Thomson et al., 2006). In these experiments, rhythmic motor ability was assessed by means of a tapping task. Participants were asked to tap along to 10 ms pure tone metronome beats at rates of 1.5, 2 and 2.5 Hz. The findings of the above-mentioned studies showed that children with DD were highly variable in the 2 and 2.5 Hz paced condition as compared to controls (Thomson & Goswami, 2008). Adults with DD were more variable in 1.5 and 2 Hz paced condition (Thomson et al., 2006). In all the experiments reviewed above, participants display a tendency to over-anticipate the occurrence of the beat. Moreover, individual differences in the tapping task were related to individual differences in reading and spelling tasks (see also Flaugnacco et al., 2014). Goswami linked the recurring tapping instability at 2 Hz to stressed syllable rate (2 Hz), since stressed syllables occur nearly every 500 ms. Behavioral findings have been corroborated by neural studies. Hämäläinen and colleagues showed that adults with DD have reduced phase-locking to amplitude modulation at the delta rate of 2 Hz in the right auditory cortex and that they have a more bilateral phase locking distribution as compared to their controls (Hämäläinen, Rupp, Soltész, Szücs, & Goswami, 2012)[12]. In line with these results, Soltész and colleagues found that the inter-trial coherence of delta phase was significantly weaker in adults with DD as compared to adult controls for stimuli presented at 2 Hz (Soltész, Szücs, Leong, White, & Goswami, 2013).

In the light of the results reviewed above, it seems evident that individuals with DD suffer from a rhythmic timing deficit.

[12] The authors also found that the phase locking in the left hemisphere at 10 Hz was greater for participants with DD than control participants.

Nevertheless, the results of the experiment reported in Chapter 4 show that the impairment is extended to the motor domain and then it is not delimited to the auditory domain.

The aim of the present study is to further elaborate Goswami's proposal[13] by investigating the possibility that the rhythmic timing deficit might affect the construction of an abstract representation of a timing structure, which by consequence prevents the ability to timely anticipate a highly predictable forthcoming rhythmic event. In the experiment reported in Chapter 4, children with DD were tested in a task tapping on handwriting in which the temporal and rhythmic properties were implicit. Here, adults with DD have been engaged in a task requiring entrainment to a given rhythm, in which the temporal and rhythmic properties are more explicit than the handwriting task.

This study aims also at investigating language competence in adults with DD. Previous behavioral and electrophysiological evidence have shown the existence of morpho-syntactic difficulties in adults with DD (Cantiani, Lorusso, Guasti, Sabisch, & Männel, 2013a; Cantiani, et al., 2013b; Rispens et al., 2006). Here, the hypothesis is that an inability to predict incoming sensory events would also impact language performance, as language processing is built on predictions.

In Paragraph 2.2 we have seen that children with DD frequently encounter fine and gross motor problems. The current study aims at studying whether subtle fine motor difficulties are also observed in adults with DD.

In summary, during the present study three main questions will be addressed:

- Are adults with DD able to exploit input regularities to predict the occurrence of a future event?

[13] Goswami (2002) sketched the issue that rhythmic entrainment impairment can unsettle internal representations with consequences in other domains. Although, to date, she has not further explored this hypothesis.

- Does the language competence of well-compensated adults with DD display subtle impairments?
- Are fine motor skills impaired in well-compensated adults with DD?

6.2 Method

6.2.1 Participants

We tested 20 participants diagnosed with Developmental Dyslexia (DD) (mean age 22.31, SD = 2.8, 8 female) and 21 control participants (mean age 23.4 years, SD = 1.1, 16 female). These two groups did not differ in age (p = .1). All participants were born in Italy, were Italian monolingual speakers and used Italian as their first oral and written language. They were all right-handed and with normal hearing. Participants with DD were students at the University of Milano-Bicocca and were recruited through the university learning disabilities center. They had a formal diagnosis of Developmental Dyslexia. This diagnosis was given in accordance to Italian criteria. That is: reading speed below 2 SD from the mean with respect to age, and/or reading accuracy below 5 percentile; absence of neurological and sensorial disorders; IQ within 1 SD from the mean; adequate socio-cultural opportunities (AIRIPA, 2010).

Control participants were also university students at the University of Milano-Bicocca. Inclusion criteria were as follows: absence of neurological, psychiatric and auditory deficits; absence of learning disabilities.

For the purposes of our study, only participants with instrumental musical practice equal or less than 5 years were included. This criterion held for both participants with DD and control participants. Following this criterion, only one participant with DD was excluded from the analysis. In addition to this excluded participant with DD, another participant with DD was not included in the analysis since he did not comply with the task (he consistently tapped in downbeat). We also excluded one control participant because his performance in the rhythmic task had a mean ≥ 3 SD from the mean of the group (see Paragraph 6.3.2 for further details). The subject was considered an outlier.

Finally, we retained data from 20 control participants (mean age 22.3 years, SD = 1.2, 15 female) and 18 participants with DD (mean age 22.4 years, SD = 3.5, 7 female). Demographic and mean characteristics for these 38 participants are listed in Table 6.1

The study was approved by the Ethics Committee according to standards of the Helsinki Declaration (World Medical Association, 2013). Prior to each testing session, participants signed an informed consent to take part in the experiment. Following the written consent, the goals of the study were further explained to the participants.

Table 6.1.
Mean participant characteristics.

Group	DD (n = 18)	Controls (n = 20)	One-way Anova F(1, 36)	Partial Eta-square
Chronological age in years	22;3 (2.9)	23;4 (1.06)	2.5	ns
Age range in years	18 - 19	22 - 26	-	-
Reading speed	0.27 (0.05)	0.15 (0.02)	84.19***	0.70
Reading error scores	6.91 (3.5)	1.72 (0.89)	39.05***	0.52
Comprendo accuracy %	0.87 (0.04)	0.92 (0.04)	7.98**	0.18
Comprendo number of sentences processed	70.5 (18.86)	86.1 (11.5)	9.23**	0.20
PPB RH	14.3 (1.86)	15.8 (1.57)	6.60*	0.15
PPB LH	13.39 (2.67)	15.0 (1.51)	5.08*	0.12
PPB Both	11.28 (1.56)	12.35 (1.42)	4.66*	0.11
PPB RH + LH + Both	39.0 (5.12)	43.15 (3.52)	8.15**	0.18
PPB Assembly	37.05 (6.05)	32.83 (7.5)	3.47	0.08

Note. Standard deviations in parentheses

*$p < .05$

**$p < .01$

***$p < .001$

6.2.2 Materials

Reading task. The *Prova di velocità di lettura di brani per la Scuola Media Superiore* (Judica & De Luca, 2005) was used to assess reading abilities. Participants were asked to read out loud the first of the two texts included in the test battery (the text was "Funghi in città", from Marcovaldo, by Italo Calvino (1963)). Reading speed and error score were considered as dependent variables.

Reading speed was scored in seconds for reading a syllable. The text had 571 syllables in total. Therefore reading speed was calculated as *(tot. reading time/571)*. Error score corresponded to the number of the errors done while reading. These errors were counted as follows: 1 point for each word incorrectly read (irrespective of the number of errors made in the same word); 0.5 point for: shift of accent (e.g., cittadìno → cittàdino); lexical substitution (e.g., mutamenti → cambiamenti); same error reiterated in a word presented more time in the text (e.g., di → da; di → da); uncertainty (e.g., desideri → desi-desideri) Self-correction was counted 0.5 point. The maximum time participants were given to complete the test was 4 minutes.

Receptive grammar. Receptive grammar was measured by means of the *Comprendo, Test for Reception of Grammar* (Comprendo, Batteria per la comprensione di frasi negli adulti, Cecchetto, Di Domenico, Garraffa, & Papagno, 2012). This test consists of 10 different *types of sentences* (I. active transitive; II. active dative; III. passive; IV. right-branching subject relative clauses; V. right-branching object relative clauses; VI. center-embedded subject relative clauses; VII. center-embedded object relative clauses; VIII. sentences with coordinate object complements; IX. sentences with coordinate verb phrases; X. coordinate sentences) with 10 sentences for type. The test was computer administered for a pre-established duration of 10 minutes. Each item contained four pictures, one of which corresponds to the target sentence, whereas the other three were grammatical foils. Participants heard the target sentence through headphones and were asked to match the given sentence with the picture that best represented the meaning of the sentence. The *types of sentence* were presented in a random order. The total number of sentences performed in ten minutes (number of sentences) and the percentage of correct answers (accuracy %) were measured as dependent variables.

Fine-motor abilities. The *Purdue Pegboard Battery* (PPB) (Tiffin, 1999) was adopted to measure the fine movements of the fingers, hands, arms and the fine fingertip dexterity required in assembly tasks. The pegboard had two rows of thirty holes and four cups at the top of the board. The two external cups contain 25 pins in each. For right-handed participants, the cup to the right of the center contains 40 washers and the cup to the left of the center contains 40 collars (for left-handed the location of these latter cups is reversed). The test procedure consisted of 5 sub-tasks: I. Right hand (RH); II. Left hand (LH); III Both hands (Both); IV. Right+Left+Both hands (this is not a practical test, but a mathematical sum calculation) (RH+LH+Both); V. Assembly (Assembly). In RH sub-task, participants were asked to pick up one pin at a time from the external right-handed cup with the right hand and to place as many pins as possible in the right-handed row in a 30 second time frame, starting from the top hole. The same procedure was followed for the LF sub-task, but pins were picked from the external left-handed cup with the left hand and placed in the left-handed row. In the Both sub-task, participants were asked to use both their right and left hands and again were asked to insert as many pins in the holes in a 30 second time frame. For the RH and LH tasks, the score was the number of pins inserted in the holes. For the Both sub-task the score was the number of pairs of pins inserted in the rows. In the Assembly sub-task, participants were asked to form as many assemblies as possible by conforming to the following procedure: participants were asked to pick up a pin from the external right-handed cup and to place it in the top hole of the right-handed. Simultaneously, they were required to pick up a washer with the left hand and to drop it over the pin. While the washer was placed over the pin, they had to pick up a collar with the right hand and to drop it over the washer. Finally, while the collar was dropped over the washer, participants had to pick up another washer with the left hand and to drop it over the collar. Thus, participants were required to move both hands at the same time and to alternate them. The Assembly task lasted 1 minute. The score is the total number of parts assembly. Since each single part of the assembly counted as a point, supplementary parts correctly placed were also added to the score. Each test session was preceded by a practice session. Each sub-task was administered only once, contrary to the standard procedure, requiring three repetitions of each sub-task.

Rhythm anticipation task. In order to assess participants' ability to generate timing prediction according to a given rhythm, we used a warning-imperative paradigm (Walter, Cooper, Aldridge, McCallum, & Winter, 1964). The warning (henceforth WB) and imperative (henceforth IB) beats are pairs of adjacent tones, in which the WB is predictive about the timing of the IB (Figure 6.1). Participants were trained to tap the left mouse button in response to the IB. Crucially, the WB gives advance notice of the occurrence of the IB and therefore, if participants are able to generate temporal prediction on the basis of the presented rhythm, they are expected to tap exactly on time to the IB (or even to anticipate the IB).

Four different rhythmic conditions were presented to the participants, ranging from the simplest to the most complex (Figure 6.2). These rhythmic conditions were presented in the following order:

- **Rhythm 1**: **Spondee (**tactus, *metronome tempo*) had a reference tempo of 80 bpm. The beats were 440 Hz pure tones with 8 ms rise and fall times and 200 ms steady-state duration. Beats were presented with onset-to-onset intervals of 750 ms. Sequences of tones were presented in trains of 6000 ms of duration and each train contained 6 basic tones and one WB-IB couple tones.

- **Rhythm 2**: **Stressed spondee** (strong beat – long interval – weak beat – long interval). The strong beats were 440 Hz pure tones with 8 ms rise and fall times and 200 ms steady-state duration. The weak beats were 440 Hz pure tones with 4 ms rise and fall times and 100 ms steady-state duration. The intensity of the weak tone was half of the strong one. Beats were presented with onset-to-onset intervals of 750 ms. Sequences of tones were presented in trains of 6000 ms, and each train contained 6 basic tones and one WB-IB couple tones.
- **Rhythm 3**: **Trochee** (– ∪) (strong beat – long interval – weak beat – short interval). The strong beats were 440 Hz pure tones with 8 ms rise and fall times and 200 ms steady-state duration. The weak beats were 440 Hz pure tones with 4 ms rise and fall times and 100 ms steady-state duration. Beats were presented with onset-to-onset intervals of 990 ms (long interval) and 510 ms (short interval). Sequences of tones were presented in trains of 6000 ms, and each train was consisted of 6 basic tones and one WB-IB couple tones.
- **Rhythm 4**: **Unpredictable beats sequence**. Auditory stimuli were 440 Hz pure tones with 8 ms rise and fall times and 200 ms steady-state duration. Sounds were presented with a mean onset-to-onset intervals of 750 ms ± a random error of 30% of the reference duration of 750 ms. Sequences of tones were presented in trains of 6000 ms, and each train contained 6 basic tones and one WB-IB couple tones. Rhythm 4 serves as control condition. Given the unpredictable timing, participants had no opportunity to predict the timing. In this condition, there is no group differences expected.

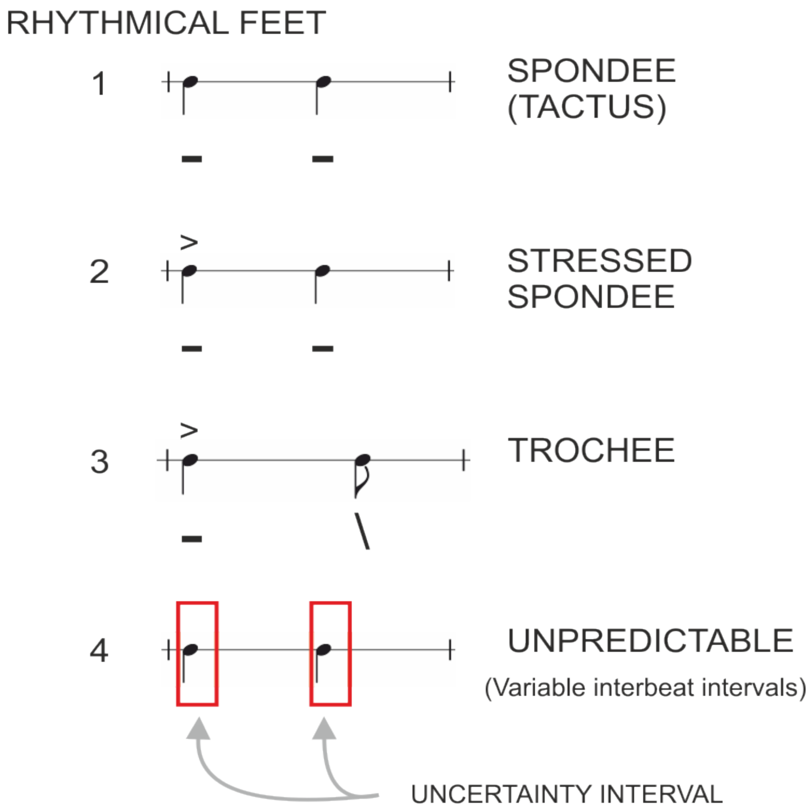


Fig. 6.1. Rhythmic conditions included in the adult study. Participants were presented four different rhythmic conditions, ranging from the simplest to the most complex. For the purpose of the present study, Rhythm 1, Rhythm 2 and Rhythm 4 will be analyzed.

For the purpose of our study, we analyzed Rhythm 1, Rhythm 2 and Rhythm 4. The dependent measures were: the *Synchronization Error*; the *Absolute value of the synchronization error;* the *Group consistency*; the *Subject consistency* (see Paragraph 6.3.2).

6.2.3 Procedure

Participants were tested individually in a quiet room at the University of Milano Bicocca.

Tasks were administered in a forty minutes test session, with breaks whenever required. The tasks presented in Paragraph 6.2.2 were administered according to the following fixed order: 1) Reading task; 2) Rhythm anticipation task; 3) Purdue Pegboard Battery; 4) The Test for Reception of Grammar (Comprendo).

The procedure of the *Rhythm anticipation task* is displayed in Figure 6.2. For each rhythmic condition, participants were presented a familiarization phase (indicated by a red dot) followed by a target trial phase (indicated by a green dot). The interval between the familiarization and test phase was 3000 ms.

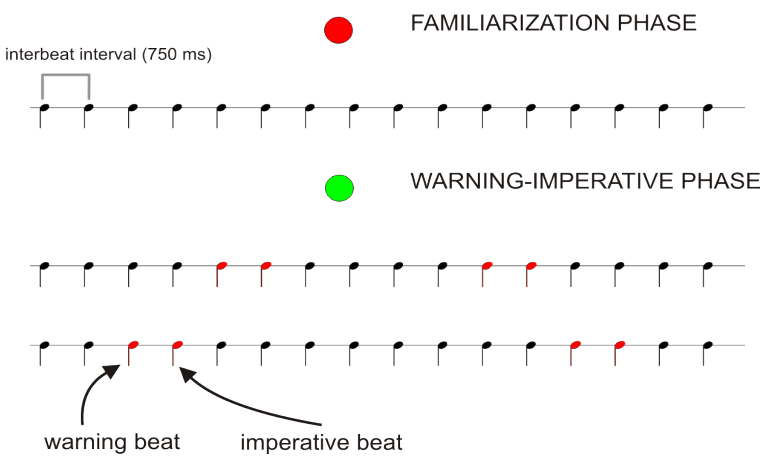


Fig. 6.2. Experimental procedure of the rhythm anticipation task. For each rhythmic condition, participants were presented a familiarization phase (indicated by a red dot) followed by a target trial phase (indicated by a green dot). During the familiarization phase, participants were asked to listen attentively to the rhythm (no actual task was required). During the target trial phase, participants were presented the rhythmic pattern they were previously familiarized with and were asked to tap the left mouse button in response to the IB. In the figure the WB and the IB are marked in red for illustration purposes; in the experiment they were obtained by adding a harmonic to the sound used to present the rhythmic pattern.

During the familiarization phase, participants were asked to listen attentively to the rhythm (no actual task was required). During the target trial phase, participants were presented the same rhythmic pattern they were previously familiarized with and were asked to tap the left mouse button in response to the IB. The WB and IB beats were randomly distributed throughout the rhythmic sequence. In all rhythmic conditions, they were obtained by adding a harmonic to the basic sound used to present the rhythmic pattern. Thus, the WB and IB beats had a frequency of 880 Hz, which is double the frequency of the basic ones.

In the familiarization phase, one train was presented 2 times per condition; in the target trial phase, one train was presented 10 times per condition. In the analysis the 10 WB-IB couples for each rhythm will be referred as Repetitions.

The *Rhythm anticipation task* test session was preceded by a practice block where participants were trained using a shorter version of the experiment, in which one train was presented 2 times per condition during the familiarization phase and 5 times per condition during the target trial phase.

The *Rhythm anticipation task* was presented using MATLAB (MathWorks, R2013a) and Psychtoolbox Version 3.0.11 (developed by Mario Kleiner and colleagues). All sound were generated by MATLAB and played via loudspeakers.

6.3 Results

6.3.1 Reading, language and fine motor tasks results

All participants completed the reading task within the time limit. As reported in Table 6.1, the reading task confirmed the dyslexia diagnosis for the experimental group. In fact, the participants with DD and control participants differed significantly in the reading speed, expressed in seconds per syllable ($p < .001$)[14], and reading errors ($p < .001$).

Interestingly, despite the absence of a previous diagnosis of Specific Language Impairment, participants with DD performed more poorly than control participants in the receptive grammar task, both in terms of accuracy ($p < .01$) and in terms of number of sentences performed in the given time of 10 minutes ($p < .01$). An individual analysis of the speed of sentence processing revealed that 8 out of 18 adults with DD fell more than 1.5 SD below the control group mean of the number of sentences performed.

As regards to manual dexterity, participants with DD differed from control participants when using the right hand (which is the dominant hand for all participants, $p < .05$), the left hand (which is the non-dominant hand for all participants, $p < .05$) and in the arithmetical sum of right, left and both hands ($p < .01$). In all these pegboard sub-tasks, participants with DD inserted fewer pins than control participants (see Table 6.1 for the mean of pins inserted in each sub-task).

In addition, we analyzed the performance of each adult with DD individually. An adult with DD was considered impaired in fine-motor skills if his/her score was more than 1.5 SD below the mean of the performance of the control group in at least 2 out of 4 sub-tasks of the Pegboard test (excluding the arithmetical sum of right, left and both hands condition). According to this cut-off, 7 out of 18 adults with DD fell more than 1.5 SD below the control group mean in at least two sub-tasks of the test. Four participants scored lower than 1.5 SD as compared to control group in two sub-tasks. Two participants scored more than 1.5 SD below the mean of the control group in three sub-tasks. One participant had a performance lower than 1.5 SD as compared to the control group in one sub-task. It is also interesting to note that, according to the set cut-off, 6 out of 7 participants with DD were impaired in the left hand condition.

[14] Adults with DD differed significantly from controls in reading speed also when the raw seconds were used as dependent variable ($p < .001$).

6.3.2 Rhythm anticipation task.

In order to detect outliers, we filtered the data of all participants using the Median Absolute Deviation (MAD) of the 10 Repetitions (Hoaglin, Mosteller, & Tukey, 1983) for Rhythm 1 and Rhythm 2 separately. We calculated the z point:

$$z_i = \left| \frac{0.6745 \cdot (x_i - M)}{MAD} \right|$$

When z was > 3 and the error synchronization was greater than -350 ms, the data point was replaced by the median calculated on the remaining values (in other words the values without the excluded point). As a result, the 17.4 % of the observations was substituted.

We decided to limit the analysis to Rhythm 1, Rhythm 2 and Rhythm 4 (this latter condition serves as control condition). The standard deviation (SD) of the synchronization error of Rhythm 3 was remarkable (*SD* = 199.15), when compared to the SD of Rhythm 1 (14.49) and to the SD of Rhythm 2 (69.1), suggesting that Rhythm 3 was challenging for both groups.

In order to find out outlier participants among the control group, we calculated the mean and standard deviation of the control group for Rhythm 1 (*M* = 14.48, *SD* = 74.85) and Rhythm 2 (*M* = 2.19, *SD* = 68.18) and the means of the 10 Repetitions of the Rhythm 1 and 2 for each subject. Participants with a mean ≥ 3 SD from the mean of the group were considered outliers. As a result, one subject was discarded.

As previously mentioned, three dependent variables were considered for the analysis: *Synchronization Error*, *Absolute value of the synchronization error, Group consistency*, *Subject consistency.*

Synchronization Error. In order to determine whether the timing of participants tapping was synchronous with the occurrence of the IB, the synchronization error was measures by calculating the difference between the time of the subject's tapping response and the occurrence of the IB (see Figure 6.3 for a schematic representation of the synchronization error calculation).

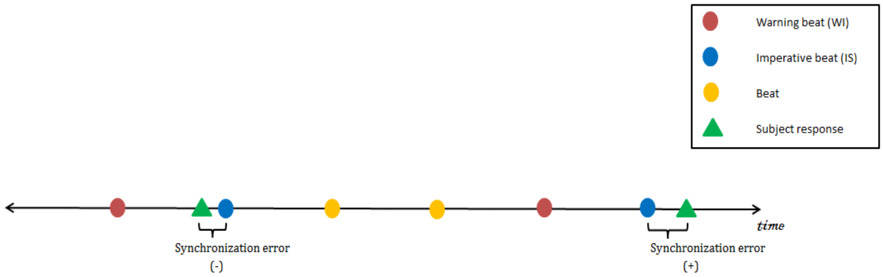


Fig. 6.3. Schematic representation of the calculation of the synchronization error. A negative error (-) indicates a response before the IB, i.e., anticipation. A positive error (+) indicates a response after the IB, where depending on the ms, can still be consider as anticipation (< 120-140 ms) or reaction time (> 150 ms).

Figure 6.4 shows the performance of a participant with DD (Panel A) and the performance of a control participant (Panel B), here given as examples. The participant with DD shows poor anticipatory skills. In Rhythm 1 and Rhythm 2, the delayed responses (around 200 ms) indicate that he/she tapped in response to the IB, being unable to generate prediction of the timing of occurrence of the IB. Moreover the response pattern shows variability across repetitions. On the contrary, the control participant displays good anticipatory skills. In Rhythm 1 and Rhythm 2, the control participant mostly responds in synchrony with the IB (in sporadic cases the response has few milliseconds of anticipation or delay). In Rhythm 4, which is meant to be the unpredictable rhythm and thus our control condition, participants of both groups have difficulties in anticipating the IB. The strategy of both participants is to respond after having heard the IB.

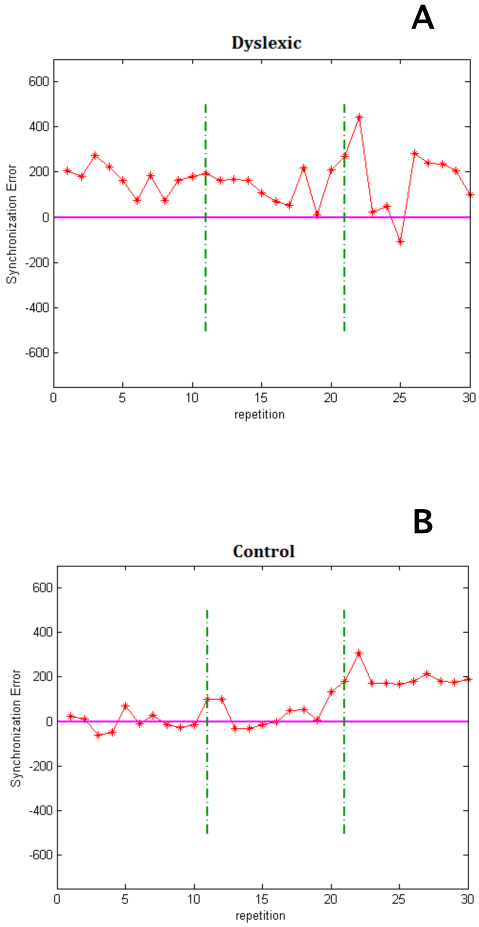
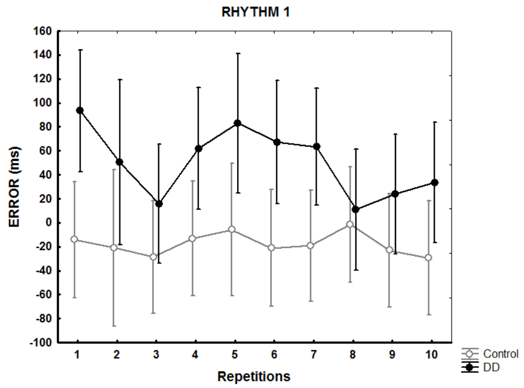


Fig. 6.4. Example of performance of adult participants (with and without DD). Panel A reports the performance of a participant with DD. Panel B reports the performance of a control participant. On the X-axis, the 30 repetitions of IB (10 for Rhythm 1, 10 for Rhythm 2, 10 for Rhythm 4) are reported. On the Y-axis, the synchronization error (ms) is reported. Positive errors represent delayed responses; negative errors represent anticipated responses; zero errors represent flawless synchrony. Time zero represents the time of occurrence of the IB. Green vertical lines separate the three analyzed rhythmic condition, in the following order: Rhythm 1, Rhythm 2, Rhythm 4. The participant with DD shows poor anticipatory skills. In Rhythm 1 and Rhythm 2, the delay responses (around 200 ms) indicate that he/she is unable to generate prediction of the timing of occurrence of the IB, and thus is unable to anticipate the IB. Moreover the response pattern displays variability across repetitions. The control participant displays good anticipatory skills. In Rhythm 1 and Rhythm 2, the control participant mostly responds in synchrony with the IB (in sporadic cases the response has few milliseconds of anticipation or delay). In Rhythm 4, which is meant to be the unpredictable rhythm and thus our control condition, participants of both groups have difficulties in anticipating the IB. Their strategy is to respond after having heard the IB.

The GLM analysis on Synchronization Error with Group (DD, Control) as between subject factor and Rhythm (1, 2) and Repetitions as within subject factor showed a significant effect of Group, $F(1, 36) = 7.06$, $p < .01$, $\eta^2_p = .16$. The synchronization error was greater for participants with DD than control participants. No significant Repetition effect was found.

Subsequently, GLM analyses were carried out for each rhythmic condition, with Synchronization error as the dependent variable, Group (DD, Control) as the between-subject factor and Repetitions as within subject factor. The results are shown in Figure 6.5 for Rhythm 1 (Panel A) and Rhythm 2 (Panel B). In Rhythm 1, significant group difference were found, $F(1, 36) = 9.33$, $p < .01$, $\eta^2_p = .20$. As illustrated in Figure 6.5 (Panel A), controls are synchronous or anticipate the IB within a maximum of 30 ms, whereas participants with DD display a tendency of tapping after the occurrence of the IB with a delay between 20 and 90 ms. In Rhythm 2, group difference is not significant, $F(1, 36) = 3.05$, $p = .09$, $\eta^2_p = .07$. Although, as displayed in Figure 6.5 (Panel B), participants with DD showed a similar tendency as in Rhythm 1, i.e., they tapped after the IB. Thus, Figure 6.5 demonstrates that participants with DD were not able to anticipate the IB, but rather tapped after the occurrence of the beat, contrary to controls that were perfectly synchronous or anticipated the IB by few milliseconds. No significant Repetition effect was found at any rhythmic condition.

A



B

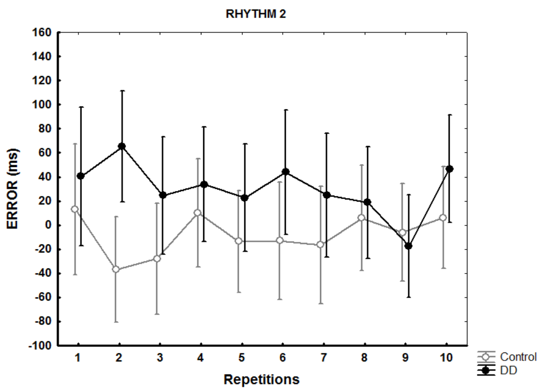


Fig. 6.5. Synchronization error in Rhythm 1 and 2 of adult participants. The non-significant interaction Group x Repetition is reported for Rhythm 1 (Panel A) and Rhythm 2 (Panel B). On the X-axis the mean of the 10 repetitions is reported. On the Y-axis the synchronization error (which is calculated as the difference between the expected time, namely the imperative time, and the actual time, namely the time of the key press on the IB) is reported. In Rhythm 1 (Panel A), the two groups were significantly different. Controls are synchronous or anticipate the IB within a maximum of 30 ms, whereas participants with DD tapped after the incidence of the IB (with a delay between 20 and 90 ms) and displayed more deviation from the expected IB. In Rhythm 2, group difference was not significant, although participants with DD showed a similar tendency as in Rhythm 1, i.e., they tapped after the IB. Vertical error bars represent 95% confidence interval.

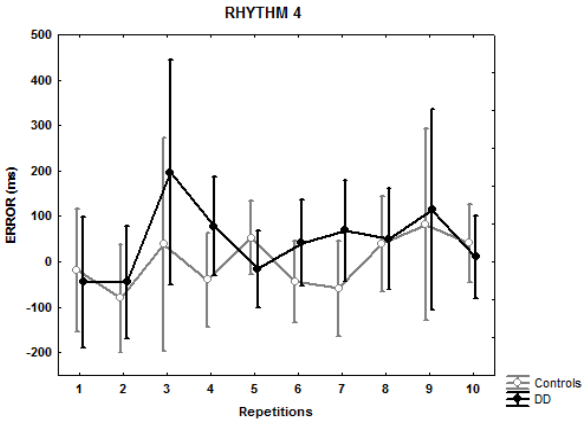


Fig. 6.6. Synchronization error in Rhythm 4 of adult participants. The non-significant interaction Group x Repetition is reported. On the X-axis the mean of the 10 repetitions for Rhythm 4 is reported. On the Y-axis the synchronization error (which is calculated as the difference between the expected time, namely the imperative time, and the actual time, namely the time of the key press on the IB) is reported. As predicted, the error of the two groups did not differ. Participants of both groups display a similar reaction time in response to the IB, as the unpredictability of the beat occurrence did not permit the prediction of the IB. Vertical error bars represent 95% confidence interval.

Figure 6.6 displays the Synchronization Error of Rhythm 4, which in our experimental design serves as a control condition. The GLM analysis on Synchronization Error with Group (DD, Control) as between-subject factor, Rhythm 4 and Repetitions as within-subject factor did not show a significant effect of Group, $F(1, 36)=1.07$, $p = .30$, $\eta^2_p = .0$, in line with our prediction. Participants of both groups display a similar reaction time in response to the IB, as the unpredictability of the beat occurrence did not permit the prediction of the IB. Repetition was not significant.

Absolute value of the synchronization error. We calculate the mean of the absolute values of the synchronization error of the ten repetitions of Rhythm 1, Rhythm 2 and Rhythm 4, separately, which indicates the time interval between the IB and the tapping response regardless of whether the response was given before or after the IB. This means that the greater the synchronization error, the greater the time interval between the awaited response (i.e., the occurrence of the IB) and the subject's response. The GLM analysis on absolute value of the synchronization error with Group (DD, Control) as between subject factor, Rhythm (1, 2) and Repetitions as within subject factor showed a significant effect of Group, $F(1, 36) = 19.47$, $p < .001$, $\eta^2_p = .35$. Adults with DD had a greater error than control participants. The analysis also revealed a significant interaction Group x Rhythm, $F(1, 36) = 5.59$, $p < .05$, $\eta^2_p = .13$. Post-hoc comparisons revealed that adults with DD had a greater error in Rhythm 1 than in Rhythm 2, whereas the error between Rhythm 1 and 2 was not significantly different for control participants. Rhythm and Repetition were not significant. No significant differences emerged from the GLM analysis on the absolute value of synchronization error of Rhythm 4, with Group (DD, Control) as between-subject factor, Rhythm 4 and Repetitions as within-subject factor.

A GLM analysis was also carried out for Rhythm 1 and Rhythm 2 distinctly, with the mean of the absolute values of the synchronization error as the dependent variable, Group (DD, Control) as the between-subject factor and Repetitions as within subject factor. In Rhythm 1 and Rhythm 2, a significant effect of Group was found (Rhythm 1: $F(1, 36) = 20.63$, $p < .001$, $\eta^2_p = 0.36$; Rhythm 2: $F(1, 36) = 8.48$, $p < .001$, $\eta^2_p = 0.19$), as the error turned out to be bigger for the adults with DD than the controls in both conditions.

Group consistency. This measure characterized the group internal consistency of IB tapping response across the ten repetitions, independently of whether or not the response occurred at the right IB timing per se. We tested whether the variance of the two groups, in each condition, was different, by means of the standard test of the homogeneity of variances (probability of the ratio of two variances evaluated by means of the *F* distribution). The variance of the two groups differed in Rhythm 1, Rhythm 2 and also when the synchronization error of Rhythm 1 and Rhythm 2 were summed up, as shown by the mean and standard deviation (SD) reported in Table 6.2. The variance of the two groups did not differ in Rhythm 4.

Table 6.2
Mean of synchronization error and p. value for Rhythm 1, Rhythm 2, Rhythm 1 + Rhythm 2 and Rhythm 4.

Group	DD (n = 18)	Controls (n = 20)	p. value
Rhythm 1	50.28 (86.41)	- 17.72 (41.62)	< .001***
Rhythm 2	22.28 (82.2)	- 15.89 (45.40)	< .01**
Rhythm 1 + Rhythm 2	36.28 (85.48)	- 16.80 (43.56)	< .01**
Rhythm 4	26.65 (143.17)	-17.38 (110.84)	= .14

Note. Standard deviations in parentheses

*$p < .05$
**$p < .01$
***$p < .001$

Subject consistency (precision). This measure characterized an individual's coherence of IB tapping response across the ten repetitions, and it is independent of whether or not the response occurred at the right IB timing in itself. Subjects' consistency was measured by calculating the standard deviation of each participant's tapping response to the IB in the 10 repetitions for Rhythm 1, Rhythm 2 and Rhythm 4. GLM analyses were carried out for each Rhythm, with Subject Consistency as the dependent variable and Group (DD, Control) as between-subject factor. Significant group difference was found only in Rhythm 1, $F(1, 36) = 6.17$, $p < .05$, $\eta^2_p = .14$, as adults with DD turned out to be less consistent within their responses across the ten repetitions than control participants. In Rhythm 2 and in Rhythm 4 the two groups did not differ.

6.3.3 Correlation among anticipatory, reading, language and fine motor skills.

The investigation of correlations, which included the entire group of 38 subjects, showed that the variables of the anticipatory task were related to measures of reading, of fine motor skills and of language (see Table 6.3). We use the mean of absolute value of the synchronization error of the ten repetitions of Rhythm 1 and Rhythm 2, respectively, which indicates the time interval between the awaited response, i.e., IB occurrence, and the participant's tapping response, irrespective of whether the participant's response occurred before or after the IB. Therefore the greater the synchronization error, the greater the time laps between the occurrence of the IB. The analyses showed that the error of both Rhythm 1 and Rhythm 2 strongly correlates with reading speed (expressed in seconds for syllable). This result suggests that participants who displayed a greater synchronization error, required more seconds to read a syllable, i.e., they were slower in reading. Moreover, the error of both Rhythm 1 and Rhythm 2 negatively correlated with some fine motor skills measures. Specifically, participants who had a greater synchronization errors inserted fewer pegs in the Pegboard task when using the left hand (non-dominant) and in the assembly sub-task. The correlation with the summation of RH + LH + Both was also significant, but only for Rhythm 1. Finally, participants who reported a greater synchronization error handled fewer sentences in the receptive grammar task.

Table 6.3
Correlation analyses of reading, language, fine motor and anticipatory skills measure.

	1	2	3	4	5	6	7	8	9	10	11
1. |Error Rhythm 1|	-	.61***	.40**	.26	-.17	-.53***	-.14	-.31*	-.32*	-.46*	-.28
2. |Error Rhythm 2|		-	.37*	.20	-.08	-.37*	-1.14	-.19	-.34*	-.26	-.22
3. Reading speed (sec/syll)			-	.74***	-.31	-.56***	-.38*	-.44**	-.29	-.32*	-.34*
4. Reading error				-	-.25	-.37*	-.36*	-.39**	.01	-.04	-.36*
5. PPB RH					-	.42**	.59***	.79***	.47**	.04	.31
6. PPB LH						-	.61***	.75***	.41**	.33*	.41**
7. PPB Both							-	.87***	.50***	.02	.33*
8. PPB RH + LH + Both								-	.51***	.02	.40**
9. PPB Assembly									-	.27	.25
10. Comprendo number of sentences										-	.23
11. Comprendo accuracy %											-

Pearson correlation coefficients are displayed

**p* < .05

***p* < .01

****p* < .001

6.4 Discussion

This study primarily set out to explore the ability to make prediction upon the timing of occurrence of rhythmic regular stimuli by adults with DD. It also aims at investigating language and fine motor abilities of adults with DD as well as relationship between prediction abilities, reading/language competence and fine motor skills. For the mere purpose of confirmation of the diagnosis of Dyslexia, a reading task was administered to both groups. As expected, participants with DD read slower and made more errors in reading than controls.

In regards to language competence, previous studies have shown that children and adults with DD experience difficulties with the comprehension and production of complex syntactic structures, such as passive and relatives sentences (e.g., Bar-Shalom, Crain, & Shankweiler, 1993; Reggiani, 2009; Robertson & Joanisse, 2010) and with the processing of morpho-syntactic features (e.g., for electrophysiological evidence see Cantiani, Lorusso, Guasti, Sabisch, & Männel, 2013a; Cantiani et al., 2015; Cantiani et al., 2013b;

Rispens et al., 2006; for behavioral evidence see Joanisse, Manis, Keating, & Seidenberg, 2000; Rispens & Been, 2007). In our study, adults with DD were administered a test for reception of grammar. The results revealed that participants with DD scored significantly poorer and were slower than controls. An individual analysis revealed that among adults with DD, only a sub-group of participants scored more than 1.5 SD below the mean of number of sentences processed by control participants. Therefore, despite participants with DD were well-compensated (they were university students) and did not report a diagnosis for Specific Language Impairment, they did reported subtle problems with the processing of syntactic structures. These results replicate Cantiani et al.'s findings (Cantiani, et al., 2013a), showing that German adults with DD were slower than controls in a grammaticality judgment task and replicate another finding by Cantiani and colleagues (Cantiani, et al., 2013b) showing that Italian adults with DD are less accurate than controls in a grammaticality judgment task.

Significant differences were also found in terms of fine motor abilities. At group level, adults with DD inserted fewer pegs when using the dominant hand (right), the left hand and both hands. By consequence significant difference was found in the RH+LH+Both score, which is a mathematical sum. These results are partly consistent with Thomson et al., 2006 study. In their study, they found significant differences between adults with DD and controls only in the dominant hand condition. The reason for the difference between the results of the present study and Thomson et al., 2006 study is unclear. This is even more puzzling considering the task in Thomson et al. as well as the age of the participants are similar to the present study under investigation. Further investigations are therefore needed in order to shed light on the nature of fine motor difficulties in adults with DD. Nevertheless, our individual analysis of the performance of adults with DD revealed that only 7 out of 18 participants with DD fell within the cut-off of 1.5 SD below the mean performance of the control group in at least two sub-tasks of the Pegboard test. Therefore, in the light of the individual analysis, fine-motor skill impairments appear limited to a sub-group of adults with DD.

Let us now focus on the main concern of the present study, namely the timing prediction abilities in adults with DD. In order to investigate whether adults with DD can anticipate an upcoming rhythmic event, we engaged participants in a task requiring entrainment to a given rhythm using a warning-imperative paradigm. The findings showed that the synchronization error is greater for dyslexic participants than for controls in Rhythm 1. Rhythm 1 can be considered a *cadence*, i.e., an isochronous repetitions of beats, all of them having the same characteristics (see Paragraph 2.3 for a definition of cadence). More specifically, DD participants showed a tendency for tapping after the occurrence of the target beat (IB) both in Rhythm 1 and in Rhythm 2, even though no group difference was found in this latter condition. This is a novel result, inconsistent with the totality of the results reported in the literature about rhythmic entrainment in individuals with DD. As already mentioned, both children and adults with DD usually displayed a tendency to over-anticipate the beat. However, it is worth stressing that a direct comparison among our results and the findings reported by previous studies cannot be drawn, considering the important differences in the adopted methodologies. As already mentioned in Paragraph 6.1, rhythmic abilities in individuals with DD have been mainly investigated by means of the tapping paradigm (see Paragraph 6.1 for details about this paradigm). Wolff (2002) asked 12 students with DD (age range: 10 – 16 years) to tap in time with a metronome signal. His findings showed that all participants tend to anticipate the metronome signal. Controls anticipated the metronome beats by a mean interval of 41 ms, similarly to the pattern of response of the controls participants of the present study, whereas participants with DD showed an anticipation time of 130 ms. In another study, Thomson and colleagues (2006) modeled their tapping task on Wolff's work to study the rhythmic abilities of 19 adults with DD (age range: 18 – 31 years) and found no effect of group in anticipation time. Leong & Goswami (2014) investigated rhythmic abilities in dyslexia by tested the entrainment to speech rhythm of 21 adults with DD (age range: 19;6 – 29;7 years). In this experiment, participants were presented with nursery rhymes (speech samples that display a strong rhythmic beat) and were asked to tap along to the beat they perceived. Their results revealed that whilst adults with DD tapped with regular intervals, they entrained their tapping to a significantly earlier syllable amplitude modulation phase than controls, i.e., they were generally shifted earlier in time. In order to account for their results, Leong and Goswami (2014) suggested that adults with DD perceive the perceptual onset of the beats as occurring beforehand as compared to controls.

Therefore, one very plausible reason for the different response pattern by participants with DD in our experiments when compared with results from previous experiments could be the different methodologies adopted. In the aforementioned studied, participants were asked to tap along a metronome signal in the case of Wolff (2002) and Thomson et al. (2006), and along the beat of a nursery rhyme, in the case of Leong and Goswami (2014). Therefore, it is possible that once participants with DD understood the task, they tendency to over-anticipate might simply be a manifestation of their anxiety for the performance. As already mentioned, in the warning – imperative paradigm, participants are asked to make prediction on the basis of the given rhythmic structure which should enhance the extraction of regularities. Therefore, the response to the IB discloses whether the timing to the beat has been correctly predicted (leading to anticipation) or not. In our study, the response pattern displayed by participants with DD showed that they react to the IB, thus they tapped once they heard the IB, thus failing to make prediction based on the rhythmic configuration of the stimuli.

We then considered the mean difference between the actual response and the expected response (IB), independently of whether the response was given earlier or later than the IB. The results showed that the mean of the absolute values of the synchronization error was greater for DD participants as compared to control both in Rhythm 1 and in Rhythm 2.

Group differences in Rhythm 1 and Rhythm 2 were also found when considering group consistency, i.e., group internal consistency of response to IB across the ten repetitions, without regard to the right IB timing per se, in contrast with Leong and Goswami's study (2014) which surprisingly reported more variability for the control group.

Finally, subject's precision (i.e., individual's consistency of response to IB across the ten repetitions, without regard to the right IB timing per se) revealed that participants with DD were less consistent within their response across the ten repetitions in Rhythm 1, as compared to controls, in line with Thomson et al. (2006) results (Wolff, 2002 did not report this measure).

The correlation analyses revealed that prediction skills are related to reading and language processing (i.e., participants who were good in making timing prediction were also faster in reading and in the processing of syntactic structures) and to motor dexterity. The link is particularly strong with the scores of the non-dominant hand, i.e., participants who were good in making timing prediction inserted more pegs. Moreover, participants who were faster in reading were also faster in the insertion of the pins in the fine motor task. Again the correlation is particularly strong when the scores of the non-dominant hand are considered.

Overall, the results of this study showed that well-compensated adults with DD are not able to exploit temporal regularities to anticipate the next sensory event, despite the high predictability of the stimulus. Moreover, our results revealed there are significant links between prediction timing skills, motor skills and reading/language abilities. The responses of participants with DD were systematically delayed as compared to controls and were more similar to a simple reaction time in response to an auditory signal, rather than a response built upon a prediction. Our results are consistent with Soltész et al. study (2013), which is to date the only experiment that looked at preparatory brain activity in individuals with DD. The researchers of this study presented dyslexic adults (mean age 25.8) with a stream of 500 Hz tones of 200 ms duration at two different isochronous rates, 2 Hz and 1.5 Hz and asked participants to press a button in response to the target beat (target beats were white noise and had an occurrence of fifteen percent out of the total of the beats presented). The authors found that the contingent negative variation (CNV) amplitude 30 ms before the occurrence of the beat in the 2 Hz condition was significantly smaller in participants with DD as compared to controls. The CNV is an event-related component that reflects anticipatory attention and motor preparation in anticipation of the forthcoming stimulus (Walter et al., 1964). Moreover, the authors of this study found that the pre-stimulus delta phase angle (- 2 ms) of the target trials (white noise) was predictive of the reaction time of the control group, but not for dyslexic group. Taken together, these findings support the hypothesis of impairment in predictive ability caused by an inefficient preparatory brain activity. An impairment to timely predict the occurrence of future events can potentially also account for the recent findings by Huettig and Brouwer (2015). These authors engaged Dutch adults with DD (age range: 18 - 25 years) in an eye-tracking experiment in which they were shown a quadrant with four objects, one of which was the target object and the other three were distractors. At the same time, participants were listening to a sentence such as "look at the displayed piano", where the information of the target object was already available at the article (as the gender of the article was compatible only with the target object and no similar morpho-syntactic information was available on the adjective). It was found that adults with DD shifted their eye gaze to the target objects substantially later than control participants. In another words, the adults with DD were unable to use the morpho-syntactic information from the article to anticipate the target object. In the light of Huetting & Bouwer (2015) results and our findings, it is plausible that an inefficient framework for predicting future sensory events is the cause of the frequent difficulties in the processing of morpho-syntactic features and of complex syntactic structures experienced by individuals with DD (this hypothesis will be further investigated in Chapter 7 and discussed in Chapter 8).

Crucially, in the current investigation the results of the control condition (Rhythm 4) ruled out the possibility that individuals with DD are generally delayed in their responses. In this condition, the occurrence of the IB was unpredictable, and no regularity could be exploited in order to predict the incidence of the IB. No significant group differences were found in any of the measures considered. Both groups of participants showed a similar response pattern, i.e., they tapped in response to the IB. Therefore, when no predictive timing is involved, no differences emerge between groups. This argument is consistent with results emerging from a simple reaction time task, which showed that two groups of adolescents with DD (aged 15 and 11) did not differ from their control when asking to press a button as soon as they could after having heard a tone (Nicolson & Fawcett, 1994). Similarly, Soltész et al. (2013) did not find difference in RT in adults with DD as compared to their controls when asked to press a button in response to the target beat.

Moreover, it is interesting to observe that adults with Dyslexia displayed a better performance in Rhythm 2 than in Rhythm 1. Recalling the details of the conditions, Rhythm 1 can be considered a cadence (repeated beats at isochronic interval, see Paragraph 2.3) whereas Rhythm 2 can be considered a rhythm (a repeated pattern of alternating ‘strong’ and ‘weak’ elements, Lerdahl & Jackendoff, 1983). Notice also that in previous studies participants with DD have always been present with ‘cadence’ rather than rhythm (Corriveau & Goswami, 2009; Hämäläinen et al., 2012; Leong & Goswami, 2014; Thomson et al., 2006; Thomson & Goswami, 2008; Wolff, 2002, among others). Therefore, our result suggests that rhythm helps extraction of a metrical structure, thus enhancing entrainment and consequently timing prediction. Future studies should be conducted to explore more deeply this aspect, since it might have important consequence for both a better understanding the nature of the impairment and the developing of rhythmic training intervention for both children and adults with Dyslexia.

As already discussed in Paragraph 6.1, the Temporal Sampling Framework by Goswami (2011) argued that individuals with DD suffer from subtle impairment in the neural oscillatory phase locking mechanisms of slower temporal modulations which in turn affects the perception and expression of rhythm and the neural representation of prosody and syllabic structure of speech (Corriveau & Goswami, 2009; Goswami, 2011; Leong & Goswami, 2014; Thomson et al., 2006; Thomson & Goswami, 2008; Wolff, 2002). On the basis of the present evidence it seems that it is specifically the predictive timing mechanism to be impaired in Dyslexia. On the basis of the results reported in Chapter 4, showing that children with DD are more variable in a motor activity such as handwriting timing, it seems that the impairments does not lie exclusively in the auditory perception domain contrary to what it has been suggested so far.

Our results also call into question Tallal's rapid auditory processing theory (Tallal, 1980; Tallal & Piercy, 1973). According to Tallal, individuals with DD are not able to integrate sensory information that converges in rapid succession in the central nervous system. The theory was based on findings showing that children with DD could discriminate basic acoustic information (tones of 75 ms) on par with typically developing children when the inter-stimulus-interval (ISI) was 428 ms, but not when the ISIS was 150 ms. However, in our experiment adults with DD struggle to anticipate the forthcoming beat even though the onset-to-onset interval was 750 ms (ISI 550), thus suggesting that it is not frequency to be the source of the difficulties. Similarly, the frequently reported impairment at 2 Hz, which is the fulcrum of Goswami's framework, appear limited, as in our study the frequency of the beats was 1.8 Hz.

Nevertheless, the present study has some limits. In the present study only one frequency of occurrence, namely 1.8 Hz, was tested. Future studies should be designed to test prediction of beats presented at different frequencies in order to determine which is the range of frequencies compromised in individuals with DD. Moreover, the current data do not reveal whether deficit in timing prediction is due to impairment in the construction of a model for the extraction of regularities or whether the extraction of regularities is spared, but these regularities are not exploited to efficiently predict future events.

In conclusion, the current investigation found that:

- Adults with DD were systematically late when asked to anticipate an upcoming auditory stimulus. Their response is similar to a simple reaction time in response to an auditory signal.
- A sub-group of adults with DD was slower in processing sentences of different syntactic complexity.
- Adults with DD inserted fewer pins than control participants in the fine motor skill task.
- Participants who turned out to have good anticipatory skills (i.e., they anticipated the IB or they were synchronous with the IB) they were also faster in reading, more accurate and faster in the receptive grammar task. Moreover, participants who had a greater synchronization error inserted fewer pegs in the Pegboard task.

Chapter 7

Timing prediction and language competence in children with Developmental Dyslexia

7.1 Introduction

The results of Chapter 6 suggested that dyslexic adults are less able than controls to predict the timing occurrence of highly predictable rhythmic events that are time locked to each other. The findings also revealed that they experience subtle deficit in the processing of syntax as they turned out to be less accurate and slower in the receptive grammar task as compared to controls. Finally, adults with DD inserted fewer pins as compared to controls in the fine motor skill task. We posited that the predictive timing mechanism seems to be impaired in well-compensated adults with DD. To date, one theory of Dyslexia, the Temporal Sampling Framework for Developmental Dyslexia (TSF) by Goswami (2011) highlights the importance of temporal coding (see Paragraph 6.1 for an extensive overview of the TSF). Briefly, the TSF suggests that individuals with DD are affected by deficits in low-frequency phase locking mechanism in auditory cortex. The theory is mostly based on findings showing that children as well as adults with DD experience specific difficulties in hearing the rate of change of amplitude envelope onset and in synchronizing motor behavior to an external auditory rhythm, especially at the metronome rate of 2 Hz, which is the stressed syllable rate in speech. Moreover, in these studies, individuals who are particularly inconsistent in tapping show the poorest literacy and phonological awareness. In its present form, the TSF narrows the deficits to the auditory domain and to slow rate (~ 2 Hz.). However, in the light of the results presented in Chapters 4 and 6, it is plausible to conjecture that the impairments are not limited to the auditory perception domain. In fact, we have seen that adults with DD displayed a slower performance in a fine motor task and children with DD varied more in the time taken to write the individual letters of a word in a motor activity such as handwriting (Chapter 4). As an extension to children with DD of the study presented in Chapter 6, we hypothesize that children with DD might be less able to predict when a highly predictable beat is going to occur. We will use the same method used with adults in Chapter 6. Therefore, children with DD will be engaged in a task requiring entrainment to a highly predictable rhythmic sequence and will be asked to tap in synchrony to the target beat (which is the imperative beat). Here, we return to the hypothesis raised in Chapter 6 and we propose that individuals with DD predict less efficiently "when" an event is going to happen in a specific modality (here we have evidence for the auditory and the motor modality). Crucially, if participants are able to build an internal representation of the rhythmic sequence, they will be in the position of predicting (and thus anticipating) the occurrence of the imperative beat. To date, this is the first study that investigates predictive timing abilities in children with DD.

We are also interested in further investigating the oral language abilities of children with DD. This point is particularly relevant since it has been shown that children at familial risk for DD produced shorter sentences as compared to their peers at 2 years and displayed a significantly poorer performance than controls in object naming and in inflectional morphology skills at 3;5 years (Lyytinen, Poikkeus, Laakso, Eklund, & Lyytinen, 2001). These results have been replicated by Viholainen and colleagues (Viholainen et al., 2002) who found that children at familial risk for DD had a smaller vocabulary and produced shorter utterances than controls (Viholainen et al., 2002). Moreover, oral language difficulties are frequently attested in children with DD without Specific Language Impairment (see Arosio, Pagliarini, Perugini, Barbieri, & Guasti, in press; Bar-Shalom, Crain, & Shankweiler, 1993, among others) and there is increasing evidence showing that Dyslexia and Specific Language Impairment often overlaps (Cantiani et al., 2015; Catts, Adlof, Hogan, & Weismer, 2010; McArthur, Hogben, Edwards, Heath, & Mengler, 2000).

In this study, we also aim at verifying whether the fine-motor deficits observed in adults with DD are also observed in children with DD. Finally, we will investigate whether predictive timing abilities are associated to reading skills, phonological awareness and fine motor abilities, since previous studies showed that inter-subject variability in finger tapping abilities are associated to reading competence and phonological awareness (Flaugnacco et al., 2014; Thomson & Goswami, 2008). Additionally, past research revealed that musical metrical sensitivity predicts phonological awareness and reading development (Huss, Verney, Fosker, Mead, & Goswami, 2011) and that poorer synchronization ability (determined as the ability to synchronize drumming to an external acoustic beat having approximately that phonemic rates) is associated to poorer phonological processing, auditory short-term memory, rapid automatized naming also in preschooler children (Woodruff Carr, White-Schwoch, Tierney, Strait, & Kraus, 2014).

At the present time this study is still on going, so we will present some preliminary results.

In summary, the key questions that will be addressed in the present study are:

- Are children with DD able to predict the timing occurrence of highly predictable rhythmic events?
- Do children with DD suffer from subtle morpho-syntactic deficits?
- Are fine motor skills impaired in children with DD?
- Are there associations among predictive timing abilities, reading skills, phonological awareness and fine motor abilities?

7.2 Method

7.2.1 Participants

Fourteen children with DD (henceforth DD) (7 male; Mean age 9;75; SD 0.89) and seven children with typical development (henceforth TD) (4 male;

Mean age 9;40; SD 0.44) were studied. The two groups were matched by gender, age and school grade. A one-way ANOVA on the age of the three groups revealed no significant differences with respect to their chronological age, $F(1, 19) = .92$, $p = .34$, $\eta^2_p = .04$ and no difference with respect to age of instruction, $F(1, 19) = 1.19$, $p = .29$, $\eta^2_p = .05$.

One child with DD was reported to have also Specific Language Impairment. All children were Italian monolingual speakers and they attended a school in Northern Italy. Typically developing children were recruited from the Istituto Comprensivo Franco Cappa in the province of Verona. Seven of the DD children were recruited from the Centro di Psicomotricità in Lodi and seven were recruited from the Unità Operativa di NeuroPsichiatria dell'Infanzia e dell'Adolescenza (UONPIA) of the Ospedale Maggiore Policlinico in Milan. These children received a diagnosis of DD from a qualified team of psychologists and speech therapists, according to the Italian National Guidelines (PARCC DSA, 2011) and the recommendations of the Congresso Nazionale AIRIPA, (2010). The criteria for a diagnosis are as follows: reading speed at least 2 standard deviations below the mean with respect to age and/or reading accuracy below the 5th percentile; absence of neurological and sensorial disorders; I.Q. within 1 Standard Deviation from the mean; adequate socio-cultural opportunities. In addition, all children had no neurological or auditory problems and had average or above average non-verbal intelligence. The criterion for children with DD was an I.Q. score above 84 either on the WISC III or on WISC IV. The criterion for control children was a score above the 25th percentile on the Raven's progressive matrices.

The study was approved by the Ethics Committee of the University of Milano-Bicocca and of the Instituto Neurologico Besta di Milano, according to standards of the Helsinki Declaration (World Medical Association, 2013). Participants' characteristics are shown in Table 7.1.

Table 7.1
Demographic information on age, gender and hand dominance of the participants.

Group	DD (n = 14)	TD (n = 7)
Mean age in years	9;75 (0.89)	9;40 (0.44)
Age range	8;58 – 11;5	8;66 – 10
Mean age of time of instruction in years	4.0 (0.96)	3.57 (0.53)
Gender		
Male	7	4
Female	7	3
Hand dominance		
Left	3	1

Note. Standard deviations in parentheses

7.2.2 Materials

Reading words and non-words task. Part 2 and 3 of the *Batteria per la valutazione della Dislessia e della Disortografia evolutiva-2, DDE-2* (Sartori et al., 2007) were used to measure single word reading. Children were asked to read aloud four lists of words and three lists of non-words that adhere to the phonotactic constraints of Italian. The dependent variables considered are reading speed and errors' score. Reading speed is expressed in syllables/second (281 for the words and 127 for non-words). The errors' score corresponded to the number of words and non-words read incorrectly. Self-correction was not counted as mistake.

Phonological awareness. The Spoonerism task of the *Test Metafonologici* battery (IRCSS E. Medea – Ass. La Nostra Famiglia di Bosisio Parini, unpublished) was used to test explicit phonological awareness. The examiner provided an auditory presentation of pairs of one-syllable non-words (spaced 1 second from each other) and children were required to swap the initial phonemes of two syllables (e.g., for "bif" - "pun" where the answer is "pif" - "bun"). Children were asked to give an oral answer. Accuracy score was calculated with respect to each correct phoneme replacement out of 18. Answer speed was also recorded.

Morphological and morpho-syntactic skills. Test 1 (part A and part B) and Test 2 (part A, part B and part C) of the *Co.Si.Mo. Batteria di Valutazione delle Competenze Sintattiche e Morfologiche* (Lorusso, 2009) was used to assess implicit morphological and morpho-syntactic skills. All tasks focused on bound morphology. Test 1 taps on nominal inflectional morphology. Words (part A) and non-words (part B) in the singular form with their respective determiner were auditory presented to children. The task was to produce the plural form, of both the determiner and the noun (e.g., Word: for "l-**a**$_{SingFem}$ cas-**a**$_{SingFem}$" [the house] the expected answer is "l-e$_{PlurFem}$ cas-e$_{PlurFem}$" [the houses]; Non-Word: for "l-a$_{SingFem}$ tomeg-a$_{SingFem}$" the expected anwer is "l-e $_{SingFem}$ tomegh-e $_{SingFem}$"). Accuracy scores were computed separately for words and non-words. One point was assigned if both the determiner and the noun were correctly inflected; 0.5 point was assigned if only the noun was correctly inflected. Scores were out of possible 6 points both for words and for non-words. Test 2 taps on nominal derivational morphology (part A and part C) and verbal inflectional morphology (part B). Children were auditory presented with non-words (and non-verbs). They were asked to produce plural form (e.g., for "prico" the expected answer is "prichi"); diminutive form (e.g., for "prico" the expected answer is "prichino"); augmentative form (e.g., for "prico" the expected answer is pricone) and other morphological manipulations. The verbal inflectional morphology manipulation requested were: creation of the infinitive (e.g., for "ho rencato" the answer is "rencare"), the gerund form (e.g., for "ho rencato" the answer is "rencando"), the conditional form (e.g., for "ho rencato" the answer is "rencassi"), derivation (only one item: "quelli che rencano si chiamano?" the answer is "rencatori"). Part A included 7 manipulations in total. Part B included 7 manipulations in total. Part C included 8 manipulation in total. One point was given for each correct manipulation whereas 0.5 point was assigned for all other neologisms correctly formulated provided that they were understandable and semantically acceptable.

Short-term memory. The Digits Forward and Digits Backward tasks of the *Wechsler Intelligence Scale for Children—Fourth Edition* (WISC-IV, 2003) were used to measure auditory short-term memory and sequencing skills. In the Digit Forward task children were required to repeat numbers in the same order as read aloud by the experimenter. In the Digit Backward task children were asked to repeat the numbers in the reverse order of that presented by the experimenter. For both the Digits Forward and Digits Backward tasks the score was the total number of items correctly repeated.

Fine-motor abilities. The *Purdue Pegboard Battery* (PPB) (Tiffin, 1999) was adopted to measure the fine movements of the fingers, hands, arms and the fine fingertip dexterity required in assembly tasks. The test procedure consisted of 5 sub-tasks: I. Right hand (RH); II. Left hand (LH); III Both hands (Both); IV. Right+Left+Both hands (RH+LH+Both - which was not a practical test, but a mathematical sum calculation); V. Assembly (Assembly). For the RH and LH tasks the score was the number of pins inserted in the holes. For the Both sub-task the score was the number of pairs of pins inserted in the rows. The score for the Assembly task was the total number of parts assembly. Since each single part of the assembly counted as a point, supplementary parts correctly placed were also added to the score. The duration of each sub-task was 30 seconds, but the Assembly task lasted 1 minute. Each test session was preceded by a practice session. Each sub-task was administered only once, contrary to the standard procedure, requiring three repetitions of each sub-task. See Paragraph 6.2.2 for a more detailed description of each sub-task.

Rhythm anticipation task. In order to assess participants' ability to generate timing prediction according to a given rhythm, we used a warning-imperative paradigm (Walter et al., 1964). The warning beat (henceforth WB) and imperative beat (henceforth IB) are pairs of adjacent tones, in which the WB is predictive about the timing of the IB. Participants were trained to tap the left mouse button in response to the IS. Crucially, the WB pre-alerts about the occurrence of the IB and therefore, if participants are able to build a prediction on the basis of the presented rhythm about the timing of the next beat, they are expected to tap exactly on time with the IB (or to anticipate the IB).

Three different rhythmic conditions were presented to the participants (Figure 7.1). The conditions were presented in the following order:

1. **Spondee (**tactus, *metronome tempo*) had a reference tempo of 80 bpm. The beats were 440 Hz pure tones with 8 ms rise and fall times and 200 ms steady-state duration. Beats were presented with onset-to-onset intervals of 750 ms. A train had a duration of 6000 ms and consisted of 6 basic tones and one WB-IB couple tones.
2. **Stressed spondee** (strong beat – long interval – weak beat – long interval). The strong beats were 440 Hz pure tones with 8 ms rise and fall times and 200 ms steady-state duration. The weak beats were 440 Hz pure tones with 4 ms rise and fall times and 100 ms steady-state duration. The intensity of the weak tone was half of the strong one. Beats were presented with onset-to-onset intervals of 750 ms. Sequences of tones were presented in trains of 6000 ms, and each train contained 6 basic tones and one WB-IB couple tones.
3. **Unpredictable sequence of beats**. Auditory stimuli were 440 Hz pure tones with 8 ms rise and fall times and 200 ms steady-state duration. Sounds were presented with a mean onset-to-onset intervals of 750 ms ± a random error of 30% of the reference duration of 750 ms. Sequences of tones were presented in trains of 6000 ms, containing 6 basic tones and one WB-IB couple

tones. This condition serves as control condition. Given the unpredictable timing, participants were in a situation where no timing prediction was possible. No difference between groups was expected.

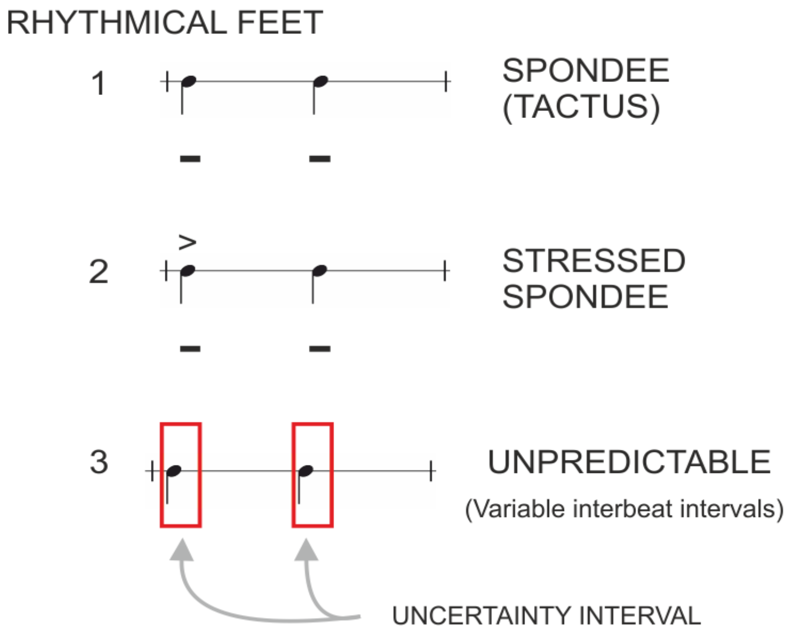


Fig. 7.1. Rhythmic conditions included in the study with children. The figure graphically exemplifies the three different rhythmic conditions presented to the participants: Spondee, Stressed Spondee and an unpredictable sequence, which serves as control condition.

The dependent measures considered in the data analysis are: the *synchronization error*, the *absolute value of the synchronization error*, the *group consistency* and the *subject consistency* (precision).

7.2.3 Procedure

Children with DD were tested individually in a quiet room of the clinic they were recruited from. TD children were tested individually in a quiet room at school.

Tasks were administered to TD children in two separate sessions, each of them lasting thirty minutes, with breaks whenever required. Children with DD were tested in one session lasting one hour.

Figure 7.2 graphically represents the *Rhythm anticipation* task procedure. For each rhythmic condition, participants were presented a familiarization phase (indicated by a red dot) followed by a target trial phase (indicated by a green dot). The interval between the familiarization and test phase was 3000 ms.

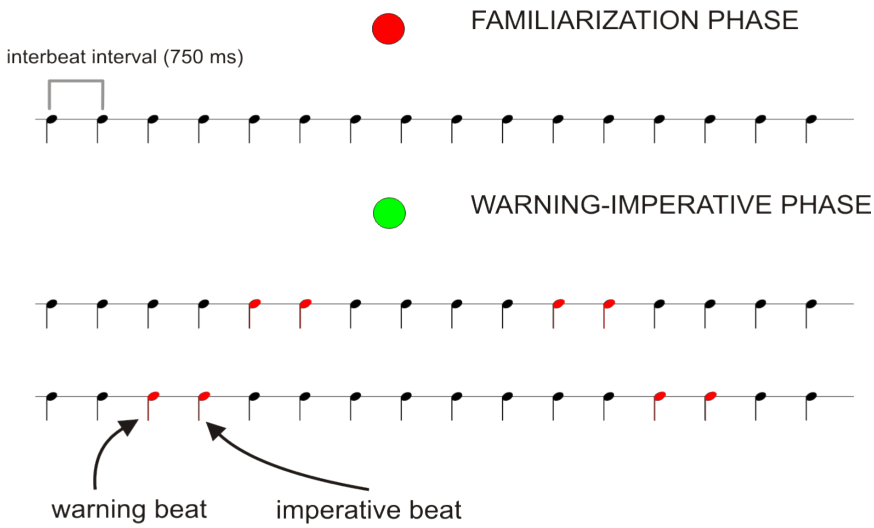


Fig. 7.2. Experimental procedure of the rhythm anticipation task. In the figure, the WB and the IB are marked in red for illustration purposes; in the experiment they were obtained by adding a harmonic to the basic sound used to present the rhythmic pattern.

During the familiarization phase, participants were asked to listen attentively to the rhythm (no actual task was required). During the target trial phase, participants were presented the rhythmic pattern they were previously familiarized with and were asked to finger tap with the left mouse button in response to the IB. The WB and IB beats were randomly distributed throughout the rhythmic sequence. In all rhythmic conditions, they were obtained by adding a harmonic to the basic sound used to present the rhythmic pattern. Thus, the WB and IB had a frequency of 880 Hz, which is double the frequency of the basic ones.

In the familiarization phase, one train was presented 2 times per condition; in the target trial phase, one train was presented 10 times per condition. In the analysis the 10 WB-IB couples for each rhythm will be referred as Repetitions.

Before the testing session, all participants underwent a practice session of the *Rhythm anticipation* task, during which they were trained using a shorter version of the experiment. In the practice session, one train was presented 2 times for each condition during the familiarization phase and 5 times per condition during the target trial phase. Before the presentation of the unpredictable sequence, children were explicitly told that this rhythm was "hard to follow" and that it didn't follow a clear rhythmic pattern.

This experiment was presented using MATLAB (MathWorks, R2013a) and Psychtoolbox Version 3.0.11 (developed by Mario Kleiner and colleagues). All sound were generated by MATLAB and played via loudspeakers.

7.3 Results

7.3.1 Reading words and non-words task

The means and standard deviations for the performance on the reading task are shown in Table 7.2. The GLM analysis on reading speed (syll/sec)[15] with Group (DD, TD) as the between-subject factor, (Words, Non-words) as within-subject and between-item factors and age as covariate revealed a main effect of Group, $F(1, 18) = 45.03$, $p < .001$, $\eta^2_p = .70$. It also revealed a significant interaction Group x Item, $F(1, 18) = 43.47$, $p < .001$, $\eta^2_p = .70$. As expected, DD children read slower than TD children and the interaction is due to the fact that TD children read words faster than non-words (whereas DD children were slow both when reading words and when reading non-words). The GLM analysis on reading errors (syll/sec) with Group (DD, TD) as the between-subject factor, Item (Words, Non-words) as within-subject factors and age as covariate showed a main effect of Group, $F(1, 18) = 25.46$, $p < .001$, $\eta^2_p = .58$, as children with DD made more errors than TD children.

Table 7.2.
Mean performance in the reading task.

Group	DD (*n* = 14)	TD (*n* = 7)
Reading speed words (syll/sec)	1.12 (0.51)	3.09 (0.83)
Reading speed non-words (syll/sec)	0.88 (0.39)	1.94 (0.53)
Reading errors words	10.07 (5.58)	1.57 (1.39)
Reading errors non-words	11.92 (6.43)	2.28 (2.05)

Note. Standard deviations in parentheses

[15] A GLM analysis was run on the reading speed of words and non-words with raw seconds as dependent variable (with age as covariate). A main effect of Group was found, $F(1, 18) = 14.70$, $p < .001$, $\eta^2_p = .45$, as children with DD read slower than TD children. We also found a main effect of Item, $F(1, 18) = 6.36$, $p < .05$, $\eta^2_p = .26$, due to more syllable spent in reading words than non-words. Finally, we found a significant interaction Group x Item, $F(1, 18) = 18.41$, $p < .001$, $\eta^2_p = .51$. Post hoc comparisons showed that the speed of reading words differed from the speed of reading non-words for children with DD but not for TD children.

7.3.2 Phonological awareness.

The GLM analysis on spoonerism score as dependent variable, Group (DD, TD) as the between-subject factor and age as covariate revealed a main effect of Group, $F(1, 18) = 20.47$, $p < .001$, $\eta^2_p = .53$ as TD children obtained a high score than children with DD. In line with the diagnosis of dyslexia, DD children performed poorly in the phonological measure.

7.3.3 Morphological and morpho-syntactic task

Z-scores were used as they allowed controlling for age variability. To look for potential differences in **nominal inflectional morphology**, we run two separate GLM analyses on the z-scores of plural formation of words (Test 1, part A of the Co.si.mo) and plural formation of non-words (Test 1, part B of the Co.si.mo) with Group (DD, TD) as the between-subject factor. Group was significant, $F(1, 19) = 5.10$, $p < .05$, $\eta^2_p = .21$ for the plural formation of words. For the plural formation of non-words no main effect of Group was found. When the analysis on the plural formation of words was run excluding the child with DD plus SLI, the effect of Group was approaching significance, $F(1, 18) = 4.29$, $p = .053$, $\eta^2_p = .19$.

To investigate performance in **nominal derivational morphology**, we run a GLM analysis on a composite score formed by the summation of the z-scores of part A and part C of Test 2, with Group (DD, TD) as the between-subject factor. No significant effect was found. Finally, a GLM analysis was run on the z-scores of part B of Test 2 with Group (DD, TD) as the between-subject factor, in order to examine the performance in **verbal inflectional morphology**. The analysis showed a main effect of Group, $F(1, 19) = 4.76$, $p < .05$, $\eta^2_p = .20$. However, the main effect of Group disappeared when the analysis was run excluding the child with DD plus SLI, $F(1, 18) = 3.96$, $p = .06$, $\eta^2_p = .18$. We then analyzed the performance of each child individually. A child with Dyslexia was considered disabled in oral language if his/her score was more than 1.5 standard deviation below the average level for children of their age in at least two sub-parts of the test. According to this cutoff, 7 out of 14 children with DD fell more than 1.5 SD below the age mean norms in at least two sub-parts of the test (one of these children had a previous diagnosis of SLI). In addition, one child with DD scored > 1.5 SD below the age mean norms in only one sub-task.

Table 7.3.
Mean performance in the Morphological and morpho-syntactic task

Group	DD (*n* = 14)	TD (*n* = 7)
Plural formation (words)	- .27 (.98)	.69 (.61)
Plural formation (non-words)	- .05 (.96)	.46 (.95)
Nominal derivational morphology*	- .47 (2.56)	.77 (1.1)
Verbal derivational morphology	- .72 (1.18)	.43 (.88)

Note. Standard deviations in parentheses

*Sum of the z-scores of part a and c of Test 2.

7.3.4 Short-term memory task

The means and standard deviations for the performance of the short-term memory task are reported in Table 7.4. The GLM analysis on span score as dependent variable, Group (DD, TD) as between-subject factor, (Forward, Backward) as within-subject and between-item factors and age as covariate revealed a main effect of Group, $F(1, 18) = 18.03$, $p < .001$, $\eta^2_p = .50$. Both forward and backward span score was lower for children with DD.

Table 7.4.
Mean performance in the short-term memory task

Group	DD (*n* = 14)	TD (*n* = 7)
Forward digit span	6.07 (1.59)	8.86 (1.96)
Backward digit span	4.14 (1.64)	7.75 (2.07)

Note. Standard deviations in parentheses

7.3.5 Fine motor skill task

Table 7.5 reports mean scores for each of the Pegboard sub-tasks. A GLM analysis was carried out for each of the sub-task, with number of pins inserted as the dependent variable, Group (DD, TD) as the between-subject factor and age as covariate. Results are reported in Table 7.5. No main effect of Group emerged. Therefore, manual dexterity did not differ between children with DD and TD children.

Table 7.5.
Mean performance in the pegboard task

	DD (n = 14)	**TD (n = 7)**	**One-way Anova $F(1, 18)$**	**Partial eta-square**
PPB RH	12.64 (1.39)	12.14 (2.19)	.006	< .001
PPB LH	11.71 (1.58)	11.42 (1.51)	.10	.005
PPB Both	10.21 (1.47)	10.14 (2.34)	.25	.013
PPB RH + LH + Both	34.57 (3.77)	33.71 (5.08)	.12	.007
PPB Assembly	21.85 (3.31)	21.85 (2.73)	.38	.020

Note. Standard deviations in parentheses

* $p < .05$
** $p < .01$
*** $p < .001$

7.3.6 Rhythm anticipation task.

Synchronization error. The difference between the time of the subject's response and the occurrence of the IB was calculated to determine whether the response was in synchrony with the occurrence of the IB. Figure 7.3 displays the typical performance of a child with DD (Panel A) and the performance of a control child (Panel B), here given as examples.

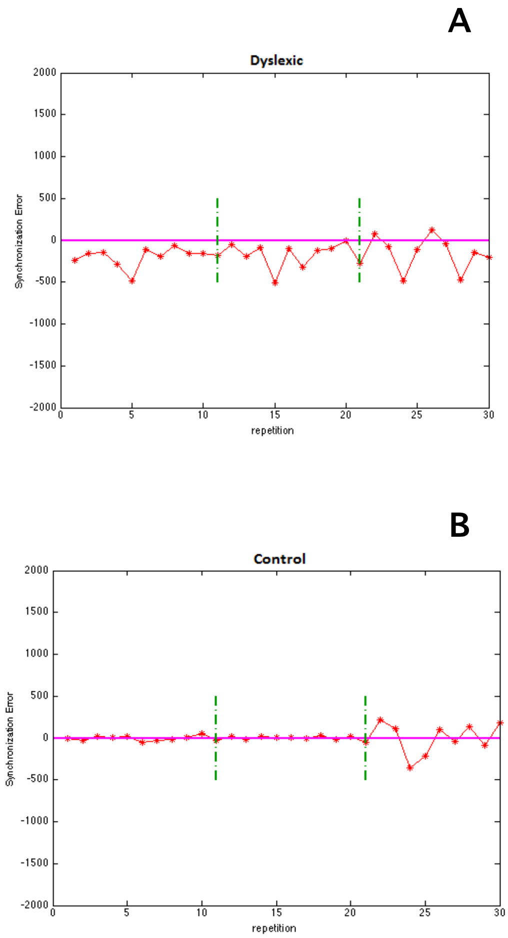


Fig. 7.3. Example of performance in the rhythmic anticipation task of children participants. Panel A reports the performance of a child with DD. Panel B reports the performance of a TD child. On the X-axis, the 10 repetitions of IB for each condition are reported. The experimental conditions, separated by green vertical lines, are displayed in the following order: Spondee condition, Stressed Spondee, Unpredictable condition. On the Y-axis, the synchronization error (ms) is reported. Positive errors represent delayed responses. Negative errors represent anticipated responses. Zero errors represent flawless synchrony. Time zero represents the time of occurrence of the IB. The child with DD anticipates the IB in all the three conditions and is variable across the ten repetitions. The TD child responds in perfect synchrony with the IB in the Spondee and the Stressed Spondee condition and is very consistent across repetitions. As expected, the TD child is very variable in the unpredictable condition (control condition), since no cues can be exploited to predict the IB.

Figure 7.4 reports the non-significant interaction Group x Repetition for Spondee (Panel A), Stressed Spondee (Panel B) and Unpredictable sequence (Panel C) of the synchronization error, which clearly depict the different behaviors of the two groups. In the Spondee condition (Panel A), the children with DD over-anticipated the IB by a means of 150 ms whereas typically developing children anticipated the IB by a means of 20-30 ms. In the Stressed Spondee condition, children with DD responded closer to time 0 (IB) as compared to the Spondee condition, but still they tended to over-anticipate the IB. In the Unpredictable sequence, the performance of the two groups was more similar, and both groups tended to anticipate the IB to the same extent.

The GLM analyses on the synchronization error as the dependent variable for Spondee, Stressed Spondee, and Unpredictable conditions (analyzed separately), with Group (DD, TD) as the between-subject factor, Repetitions as within subject factor and age as covariate revealed neither a main effect of Group nor of Repetition, probably due to the high variability of both groups.

Absolute value of the synchronization error. We calculate the mean of the absolute values of the synchronization error of the ten repetitions of Spondee, Stressed Spondee and the Unpredictable conditions, respectively, which indicates the time interval between the expected IB time and the tapping response, regardless of whether the response was given before or after the IB. This means that the greater the synchronization error, the greater the time interval between the occurrence of the IB and the subject's response.

A GLM analysis was carried out for each condition distinctly, with the mean of the absolute values of the synchronization error as the dependent variable and Group (DD, Control) as the between-subject factor, Repetitions as within subject factor and age as a covariate. Group was significant in the Spondee condition, $F(1, 18) = 11.94$, $p < .01$, $\eta^2_p = .40$; in the Stressed Spondee condition, $F(1, 18) = 9.7$, $p < .01$, $\eta^2_p = .35$, and in the Unpredictable condition, $F(1, 18) = 4.81$, $p < .05$, $\eta^2_p = .21$. In all conditions, the absolute value of the synchronization error of children with DD was greater than their controls. Thus, contrary to our expectation, the synchronization error of children with DD turned out to be greater as compared to their peers also in the control condition (see Figure 7.6). Repetition was not significant.

Subsequently a GLM analysis was run on the mean of the absolute values of the synchronization error as the dependent variable, with Group (DD, Control) as the between-subject factor, Condition (Spondee, Stressed Spondee) and Repetition as within subject factor and age as a covariate. It revealed a main effect of Group, $F(1, 18) = 11.88$, $p < .01$, $\eta^2_p = .40$. The absolute value of the synchronization error of children with DD was greater than their controls (see Figure 7.5). We also found a significant interaction Group x Repetition, $F(9, 162) = 1.94$, $p < .05$, $\eta^2_p = .1$, reported in Figure 7.5. The difference between the two groups decreased in the last two repetitions. It is possible that children with DD were familiarizing with the task towards the end of the experiment. However, it is worth noticing that the value of eta square is very small. Repetition was not significant.

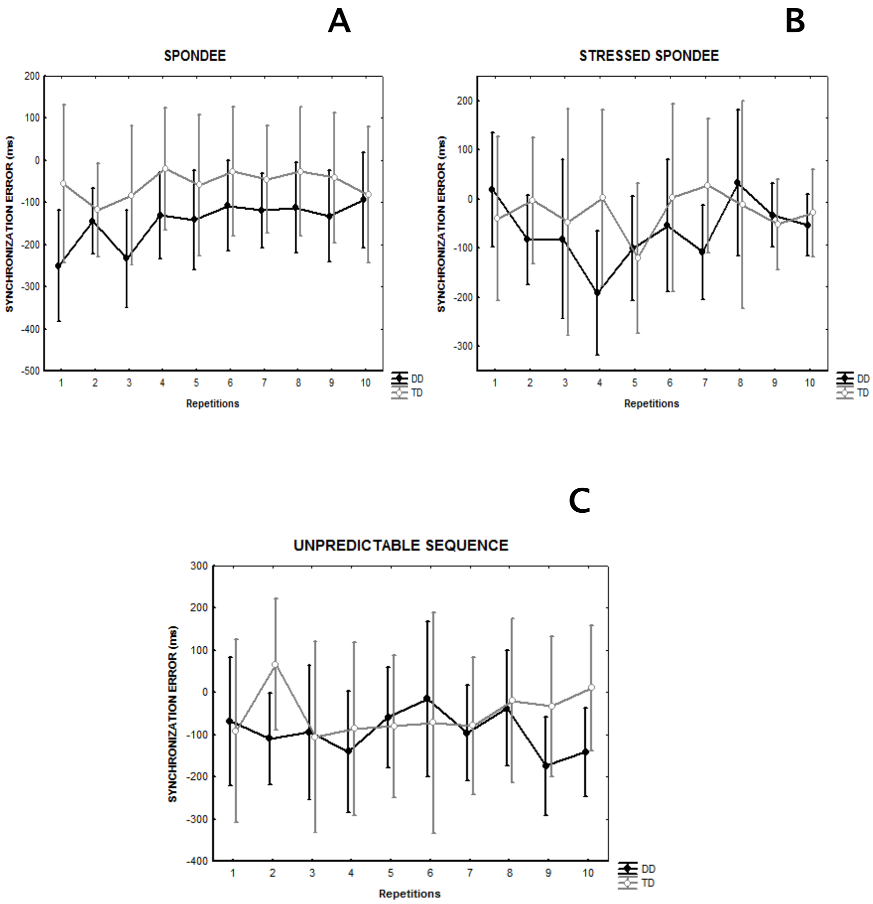


Fig. 7.4. Synchronization error of Spondee, Stressed Spondee and Unpredictable condition. The non-significant interaction Group x Repetition is reported for Spondee (Panel A), Stressed Spondee (Panel B) and Unpredictable sequence (Panel C). On the X-axis the mean of the 10 repetitions is reported. On the Y-axis the synchronization error is reported. The synchronization error is calculated as the difference between the expected time, namely the IB, and the actual time, namely the time of the key press on the IB. In the Spondee condition (Panel A), children with DD over-anticipated the IB by a means of 150 ms whereas TD children anticipated the IB by a means of approximately 50 ms. In the Stressed Spondee condition (Panel B), there was less consistency across the ten repetitions for both groups, however children with DD anticipated less the IB as compared to the Spondee condition, i.e., they performed slightly better. In the Unpredictable sequence (Panel C), both groups showed a similar response pattern by anticipating the IB to the same extent. Vertical error bars represent 95% confidence interval.

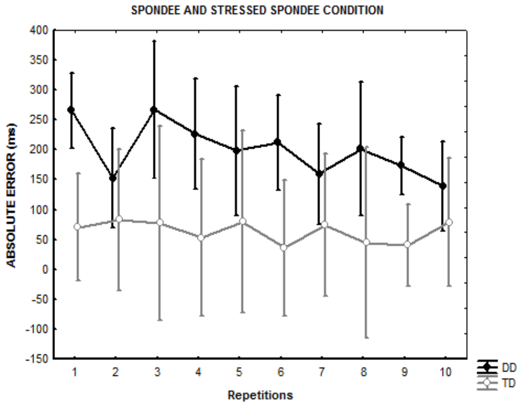


Fig. 7.5. Absolute value of the synchronization error Spondee and Stressed Spondee condition. The significant interaction Group x Repetition is reported. On the X-axis the mean of the 10 repetitions of Spondee and Stressed Spondee condition is reported. On the Y-axis the mean of absolute value of the synchronization error is reported. Children with DD displayed a bigger synchronization error as compared to their peers. The interaction shows that children with DD had a lower error towards the end of the experiment, probably due to a familiarization effect. Vertical error bars represent 95% confidence interval.

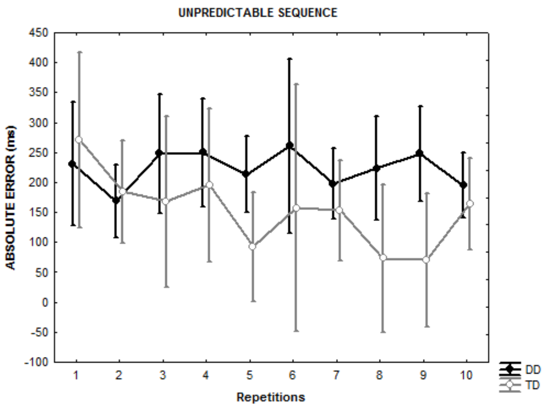


Fig. 7.6. Absolute value of the synchronization error Unpredictable sequence. The non-significant interaction Group x Repetition is reported. On the X-axis the mean of the 10 repetitions is reported. On the Y-axis the mean absolute value of the synchronization error is reported. In this condition, where the unpredictability of the beat occurrence did not allow the prediction of the IB, the performance of the two groups was more similar. Vertical error bars represent 95% confidence interval.

Group consistency. This measure characterizes the group internal consistency of response to the target beat (IB) across the ten repetitions, independently of whether or not the response occurred at the expected IB time. We tested whether the variance of the two groups was different in Spondee, Stressed Spondee and Unpredictable sequence respectively, by means of the standard test of the homogeneity of variances (probability of the ratio of two variances evaluated by means of the *F* distribution). The variance of the two groups differed in all three conditions, as shown by the mean and standard deviation (SD) reported in Table 7.6.

Table 7.6
Mean, standard deviation (in parentheses) and p. values of synchronization error for Spondee, Stressed Spondee and Unpredictable sequence.

Group	**DD (n = 14)**	**Controls (n = 7)**	**p. value**
Spondee	-148.52 (140.79)	-51.73 (54.43)	< .05*
Stressed Spondee	-68.60 (154.73)	-20.53 (30.09)	< .05*
Unpredictable sequence	-99.67 (158.69)	-36.66 (27.85)	< .001***

*$p < .05$
**$p < .01$
***$p < .001$

Subject consistency (precision). This measure describes an individual's coherence of IB tapping response across the ten repetitions, independently of whether or not the response occurred at the expected IB timing. Subjects' consistency was measured by calculating the standard deviation of each participant's tapping response to the IB in the 10 repetitions for each condition separately. GLM analyses were carried out for each Condition, with Subject Coherence as the dependent variable, Group (DD, Control) as between-subject factor and age as covariate. In the Spondee condition, we found a main effect of Group, $F(1, 18) = 11.76$, $p < .01$, $\eta^2_p = .39$, as children with DD had greater variability across the ten repetitions than TD children. In the Stressed Spondee, Group is approaching significance, $F(1, 18) = 4.37$, $p = .053$, $\eta^2_p = .19$. In the Unpredictable sequence condition, no significant effect was found.

7.3.7 Correlation among anticipatory, reading, language and fine motor skills.

Correlations among the absolute value of the synchronization error of the Spondee condition and all the reading, languages and fine motor skill variables are reported in Table 7.7. They revealed that the absolute value of the synchronization error of Spondee condition correlates negatively with reading speed (syll/sec) of both words and non-words, with forward and backward digit spans, with the verbal morphology score and the spoonerism score. This means that children who showed a bigger synchronization error, were also the ones that read fewer syllables/seconds, that recalled fewer digits, that performed worse in the verbal morphology task and that had a greater phonological impairment. The absolute value of the synchronization error of Spondee condition correlates positively with errors in the reading tasks, showing that children who did not have good predictive skills made more errors in reading. Moreover, the phonological awareness score strongly correlates with all the reading variables, consistently with the hypothesis that the reading impairments are associated to (and probably caused by) a phonological disorder. We also run a correlation analysis between the subject's coherence values of the Spondee condition and all the reading, languages and fine motor skill measures. This analysis revealed that subject's coherence is positively correlated to the absolute value of the synchronization error ($p < .01$), and negatively correlated with word reading speed ($p < .05$) and with digit span forward ($p < .05$).

Overall, the correlations reported in Table 7.7 suggest that there are strong correlations among prediction skills, reading outcomes, phonological awareness and short-memory outcomes.

Table 7.7

Correlation analyses of reading, language, fine motor and anticipatory skills measure.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1. |Error Spondee condition|	-	-.52*	.44*	-.43*	.55**	-.44*	-.43*	.18	.05	-.12	.04	.16	-.38	-.05	.10	-.45*	-.25	-.58**
2. Word Reading speed (syll/sec)		-	-.74***	.95***	-.77***	.62**	.79***	.13	.11	.22	.18	.19	.55**	.40	.31	.26	.47*	.75***
3. Word Reading error			-	-.71***	.87***	-.50*	-.49*	-.05	-.34	-.26	-.26	-.38	-.68***	-.58**	-.41	-.08	-.54**	-.68***
4. Non-word reading speed (syll/sec)				-	-.72***	.48*	.72***	.11	.11	.25	.19	.16	.54**	.43*	.37	.20	.42	.43*
5. Non-word reading error					-	-.47*	-.65**	.03	-.31	-.34	-.24	-.39	-.59**	-.50*	-.28	-.30	-.54**	-.65***
6. Forward digit span						-	.70***	-.02	-.07	.01	-.03	.06	.64**	.23	.43*	.26	.46*	.65***
7. Backward digit span							-	-.08	-.18	.20	-.01	.03	.60**	.25	.41	.50*	.50*	.65***
8. PPB RH								-	.60**	.55**	.85***	.52*	.10	.14	.18	-.10	.29	-.02
9. PPB LH									-	.53*	.83***	.76***	.12	.29	.19	-.18	.33	-.08
10. PPB Both										-	.83***	.62**	.39	.13	.29	.25	.30	.23
11. PPB RH + LH + Both											-	.75***	.25	.22	.26	-.00	.37	.06
12. PPB Assembly												-	.29	.18	.21	-.03	.18	.11
13. Cosimo 1a z-score													-	.44*	.58**	.37	.56**	.67***
14. Cosimo 1b z-score														-	.40	.02	.75***	.21
15. Cosimo 2a z-score															-	.09	.64**	.31
16. Cosimo 2b z-score																-	.30	.35
17. Cosimo 2c z-score																	-	.31
18. Spoonerism																		-

Pearson correlation coefficients are displayed

*$p < .05$

**$p < .01$

***$p < .001$

7.4 Discussion

The present study was an extension to children with DD of the study presented in Chapter 6 done on adults with DD. The main questions were: (i) to verify whether the predictive timing deficit observed in adults with DD is observed also in children with DD; (ii) to assess the morpho-syntactic abilities of children with DD; (iii) to investigate the fine motor abilities of children with DD; (iv) to investigate the association among predictive timing abilities, reading skills, phonological awareness and fine motor abilities. To start with the latter question, we observed that the manual dexterity of children with DD did not differ from that of their peers, in line with Thomson and Goswami's finding (2008). A similar results has been found for children with SLI, as they did not differ from age and language matched control children in the number of pins inserted in the pegboard task (Corriveau & Goswami, 2009). The comparison between children and adults with DD suggests that the Pegboard task is a valid task for the discrimination of individuals with DD from individuals with typical development in adulthood (Chapter 6, Thomson, Fryer, Maltby, & Goswami, 2006) but not in childhood (Thomson & Goswami, 2008).

Considering the morpho-syntactic abilities of children with DD, we tested the ability to generalize abstract rules that can be applied to generate novel words. Children with DD performed significantly poorer than age matched controls in the plural formation of words (nominal inflectional morphology) and in the production of verbal inflectional morphology. However, significance decreases when the child with a previous diagnosis of SLI was excluded from the analyses. Despite this observation, the results of our study suggest that children with DD have difficulties in extracting regularities from the input in order to form rules that can be applied for the creation of new words. These findings partly replicate those by Cantiani and colleagues (Cantiani et al., 2015) who used the same tasks (Test 1 and 2 of the Co.Si.Mo). The authors created a composite scores by averaging the Z-scores results of the all sub-parts (a + b + c) of Test 2 - therefore they summed together derivational and verbal inflectional morphology scores. They showed that children with DD obtained a significant lower performance than controls. Here, we considered more appropriate to analyze separately the scores of nominal derivation morphology and verbal inflectional morphology. Our findings are in line with previous studies showing that children with DD have compromised morpho-syntactic abilities (for an overview of the areas of weakness of Italian dyslexic children see Belletti & Guasti, 2015). Results from ERP studies (Cantiani et al., 2015; Cantiani et al., 2013b) investigating agreement violations, showed an anomalous N400 rather than a P600 in Italian children and adults with DD, suggest that these participants resort to memorized lexical chunks rather than exploiting grammatical rules, thus providing further support to our results. It has been shown that children with DD produced more subject-agreement errors than their peers in spontaneous speech (Rispens, Roeleven, & Koster, 2003; see also Rispens & Been, 2007 for subject-agreement problems in children with DD) and that they showed impaired past tense marking (Joanisse et al., 2000). The development of inflectional morphology of children with DD appears delayed since their early infancy, as showed by Lyytinen, Poikkeus, Laakso, Eklund, & Lyytinen (2001) and Scarborough (1990). However, the individual analysis of the performance of our dyslexic children revealed that only 7 out of 14 children with DD fell within the cut-off of 1.5 SD below the age mean norms in at least two sub-parts of the test. The other half of children with DD performed equally as control children. Thus, only half of the children with DD experienced problems in oral language. It is possible this sub-group of children with DD were also affected by Specific Language impairment, although they did not receive any formal diagnosis (besides for one child). Indeed, the fact that language impairments are not affecting all children with DD but only a sub-group, has been found in several studies investigating morpho-syntactic abilities in this population. Arosio and colleagues (Arosio, Pagliarini, Perugini, Barbieri, & Guasti, in press) showed that 10 out of 24 children with DD (mean age 9;3 years) scored 1.5 standard deviation below the mean score of aged matched control children in a direct object clitic production task. Rispens and colleagues (Rispens, Roeleven, & Koster, 2004) tested the sensitivity to subject-verb agreement of 26 children with DD (mean age 8;09) by means of an auditory grammaticality judgment task. Their results showed that half of the children with DD were less accurate in detecting agreement violations as they performed at least 2 SD below the mean of the control groups (age matched controls and language matched controls). In this study, the other half of children with DD had an equivalent performance to the control groups. Similarly, McArthur and colleagues (McArthur et al., 2000) tested the oral language of 110 children with specific reading disability by means of the CELF. The authors of this study found that half of the children with DD displayed compromised oral ability (the cut-off was set as > 1 SD below the mean of the Total Language score for children of the same age). All together, these results further suggest that in some children Dyslexia and Specific Language Impairment seem to be comorbid.

Let's now focus to the main question of the study, which was the predictive timing ability of children with DD. We engaged children in a task requiring entrainment to a given rhythm. In the current study under investigation, we adopted the same methodology used in Chapter 6 to test adults with DD. Participants were expected to extract the timing regularity of a high predictable rhythmic sequence which should enable them to timely predict when the target beat (imperative beat) was going to occur. Overall, participants of both groups displayed a tendency to anticipate the IB, though anticipation was always greater for children with DD particularly in the Spondee condition. In fact, in the Spondee condition children with DD over-anticipated the IB by a means of 150 ms contrary to their aged matched controls who anticipated the IB by a means of 50 ms. However, when the synchronization error was analyzed, no main effect of Group emerged - probably due to the high variability found in the TD group. In the Stressed Spondee condition and in the control condition (unpredictable sequence), the pattern of response of the two groups was more similar as both groups of children tend to anticipate the IB to the same extent. Over-anticipation in children with DD has been found in previous studies using a tapping task (Thomson & Goswami, 2008; Wolff, 2002). Thomson and Goswami (2008) assessed the rhythmic motor ability in 25 children with DD (mean age 10;8) by asking them to tap to a 10 ms pure tone metronome beat at three different rates: 1.5, 2 and 2.5 Hz. The authors found that the mean anticipation score was greater for children with DD, though it did not statistically differ from those of control children. In a similar experiment, Wolff (2002) asked 12 students with DD (age range: 10 – 16 years) to tap to a metronome beat at 1.5 and 2 Hz rates and found that all participants (both controls and participants with DD) tend to anticipate the metronome beat at both rates. However, control participants anticipated by a mean interval of 41 ms whereas participants with DD anticipated by a mean interval of 130 ms.

Interestingly, the mean of synchronization error at the group level reported in Table 7.6 revealed that both DD and TD children responded closer to the expected time in the Stressed Spondee condition. Therefore, the performance of both groups improved when participants were asked to entrain to a rhythmic sequence, rather than a simple cadence of beats.

When the performance of children with DD is compared to those of adults with DD in the warning-imperative task (see the results reported in Chapter 6), it is interesting to notice that the behavior of the two groups is different: adults with DD displayed a delayed response with respect to the IB, whereas children with DD showed over-anticipation with respect to the occurrence of the IB. How can we explain the difference between children and adults behavior? At this moment, we can only speculate. It is possible that the children patter might be the reflection of their eagerness to tap to the beat as they realized to be involved in a task requiring rhythmic ability. On the contrary, it is possible that adults with DD might have understood that the task tapped on prediction ability, however being unable to predict the occurrence of the beat, they responded after having heard the IB as a last resort. But again, these are only speculations as from the present data this question cannot be answered.

We then considered the absolute value of the synchronization error. We observed that in all three conditions the absolute value of the synchronization error was greater for children with DD as compared to control children. The result of the control condition was unexpected. Assuming a predictive timing deficit in children with DD, we expected no difference between dyslexic children and typically developing children in this unpredictable condition, as no timing prediction was possible due to the uncertain timing occurrence of the beat. It is plausible to conjecture that children did not fully internalize the fact that that sequence was unpredictable, despite the fact they were explicitly told that the rhythm was “hard to follow” because it didn’t follow a clear rhythmic pattern. Nevertheless, our prediction was borne out when we looked at the individual subject precision, as both groups of children were equally variable.

At the group level, children with DD were less consistent across the ten repetitions in all conditions.

At the individual level, the individual subject precision of children with DD was lower than their aged matched controls in the Spondee condition. This result is consistent with Thomson and Goswami’s findings (2008) which reported a higher inter-subject variability in children with DD as compared to their controls when tapping to a metronome beat at 2 and 2.5 Hz (which is a cadence likewise our Spondee condition). In the Stressed Spondee, the difference between the two groups was approaching significance. The fact that the individual subject consistency of children with DD improves in the Stressed Spondee (rhythmic sequence) condition as compared to the Spondee condition (cadence) further suggest that the exposure to stimuli having a clear rhythmic structure enhances the predictive abilities of children with DD. However, caution is needed in the interpretation of this finding. It is worth noticing that our experiment included only a trochaic pattern, therefore it is unclear if it is the entrainment to a rhythmic structure per se that improves predictive abilities or if it is the entrainment to specifically the trochaic pattern that boosts these abilities. Future studies should investigate whether iambic rhythms have the same effects of predictive timing. Nevertheless, the enhancement of predictive timing abilities with rhythmic stimuli highlights the importance of rhythmic and music training in children with DD, in accordance with the findings of some recent studies (Bonacina, Cancer, Lanzi, Lorusso, & Antonietti, 2015; Flaugnacco et al., 2015). Crucially, as already commented, no significant effect was found in the Unpredictable sequence condition in line with our prediction, as both groups turned out to be equally variable.

Finally we investigated possible correlations among the absolute value of the synchronization error of the Spondee condition and all the reading, languages and fine motor abilities. The correlation analysis revealed a rich set of correlations (reported in Table 7.7) among prediction skills, reading outcomes, phonological awareness and short-memory outcomes, which further strengthens the hypothesis that predictive timing ability is linked to language competence. Contrary to previous studies (Flaugnacco et al., 2014; Thomson & Goswami, 2008) which found strong correlations among inter-subject tapping variability reading and phonological abilities, in the present study subject coherence was not a very strong predictor of language and motor abilities. The different tasks adopted, namely tapping task vs. warning-imperative task, may explain the discrepancy between our data and the two abovementioned-studies.

In general, the child data of the present study under investigation are less clear than the adult data reported in Chapter 6. Nevertheless, we can substantially draw similar conclusions. Taken together, the data of the present study suggest that the predictive timing deficit found in adults with DD can be also extended to children with DD. In the light of these results, I would like to propose the Predictive Timing Framework (PTF). According to this proposal, adults and children with DD suffer from a difficulty in extracting regularities and thus in forming an internal model that can be used to anticipate the occurrence of an event. A deficit in the extraction of regularities from the input might also explain the handwriting variability (see Chapter 4, Pagliarini et al., 2015) as well as the difficulties in morphosyntax and in more complex syntactic structures attested in individuals with DD (Huettig & Brouwer, 2015). Importantly, evidence in support of this hypothesis is strengthened from the results of the Co.Si.Mo, which are reported in the present Chapter, as the application of regularities previously extracted is required in order to correctly complete the task.

In summary, this study showed that:

- ❖ children with DD are less able than age matched controls to use temporal regularities in an auditory stimulus to anticipate the occurrence of a high predictable beat.
- ❖ A sub-group of children with DD are impaired in the production of inflectional morphology.
- ❖ Children with DD did not differ from their peers in the number of pins inserted in the pegboard task.
- ❖ Children who showed a bigger synchronization error, also read fewer syllables/seconds, recalled fewer digits both, and performed worse in the verbal morphology and phonological awareness task.

Chapter 8

General discussions and Conclusions

In this thesis, a novel framework for Developmental Dyslexia (DD) is proposed, namely the **Predictive Timing Framework** (PTF). The basic ingredient of the framework is the assumption that language and motor actions have a rhythmic structure, which enhances the extrapolation of temporal regularities. On the basis of these temporal regularities an internal representation can be formed upon which predictions about upcoming events are generated. We posit that the mechanism at the basis of temporal prediction may be compromised in children and adults with DD, and that a breakdown of this mechanism may be the cause of reading in individuals with DD and of subtle language and motor problems frequently attested at least in some dyslexic individuals. In fact, in order to speak, to read efficiently and to perform a motor task, children and adults need to generate a self-paced rhythm that is used to make prediction. It is likely that the generation of this rhythm is compromised (beyond the coding of the orthographic form). Thus, at the moment two possibilities remain open: either the generation of the rhythmic representation is compromised or this representation can be generated but cannot be used for prediction of a particular structure.

At the present time it is hard to give a satisfactory account of the brain mechanisms and the nature of the processing timing impairment of individuals with DD, since brain mechanisms underlying predictive timing processing are mainly unknown. Nevertheless, despite being in a very early formulation, the PTF offers great potentialities. The PTF raises the possibility that the difficulties in different domains attested in individuals with DD are the reflections of a single underlying deficit affecting the predictive timing processing, whereas the language representations and the motor control system themselves are intact in individuals with DD. Therefore, another important ingredient of the PTF is the distinction between process and representations. A similar approach has been offered by Shankweiler and Crain (Shankweiler & Crain, 1986) in interpreting the difficulties in oral language experience by poor readers. Shankweiler and Crain attribute these difficulties to working memory limits. Here, we do not mean to defend this hypothesis. We just mention it as an example of an approach that attributes language problem to low-level processing failures. Recent studies in language acquisition support this PTF. Throughout this dissertation we have seen that children as well as adults with DD encounter difficulties in some syntactic and morpho-syntactic aspects of language. Nevertheless, children with DD are not impaired in interpreting the quantifiers *some* and *all* in a context that gives rise to scalar implicatures (Arosio et al., in press) and some preliminary results show that children with DD are not compromised in the comprehension of disjunction in the scope of negation (Pagliarini, Guasti, Crain, in progress). Thus, syntactic and morpho-syntactic structures whose elements are intrinsically time-locked to each other are challenging for individuals with DD, though the language representations themselves appear spared. The PTF also highlights the key role of prediction in human language and action. Focusing for a moment on language, I would like to evoke the distinction about the faculty of language in the broad sense (FLB) and the faculty of language in the narrow sense (FLN) proposed by Hauser, Chomsky and Fitch (Hauser, Chomsky, & Fitch, 2002). I would like to argue that predicting timing (as well as predicting coding) should be included in the mechanisms that are considered part of the FLB along with sequencing, theory of mind, short and long-term memory, audition, vision, etc,. This assumption fits well with the hypothesis proposed above, namely that it is the process to be compromised, not the representations themselves. Hauser and colleagues assume that the computational system of the FLN generates internal representations that are then mapped into the sensory-motor interface and into the conceptual-intentional interface, which are both part of the FLB. Accordingly, if we consider our proposal outlined above, it might be that a breakdown of one specific process of the mapping into the sensory-motor interface cause the multiplicity of problems encountered by individuals with DD, whereas the internal representations generated from the computational system are intact.

Throughout the thesis we point out that language and motor problem are not present in all children with DD but rather are experienced only by a sub-set of children. The PTF leaves open the possibility that one common single affected component has different surface manifestations and that children can compensate in one domain.

Let us briefly review the main results in support of this hypothesis.

In Chapter 4, we have shown that children with DD are less able than age matched control children to adhere to two principles of rhythmic organization, which govern handwriting (isochrony and homothety). According to such principles, before execution, the duration of each single letter needs to be allocated according to a timing structure (homothety) and the length of the trajectory needs to be estimated in order to adjust the speed of motor execution (isochrony). The fact that children with DD do not keep the movement duration constant across change in size and especially the fact that they display high variability in the relative durations of the letters across changes in size and speed, suggest that children with DD encounter difficulties in anticipating the rhythmic structure of the handwriting gesture.

Other evidence supporting the PTF comes from the study reported in Chapter 6, which directly tested the predictive abilities of well-compensated adults with DD. When asked to tap in time to a highly predictable beat, participants with DD tend to tap after the occurrence of the target beat (with a delay between 20 and 90 ms), contrary to controls who are synchronous or anticipate the target beat within a maximum of 30 ms. These results show that adults with DD are not able to use the temporal regularities of auditory stimuli to predict the occurrence of the next beat. This result cannot be accounted in terms of a general delay in reaction time, since adults with DD did not differ from controls in the condition whose temporal structure is unpredictable. Moreover, at the group level, adults with DD are less consistent in their responses across the ten repetitions than controls both in the Spondee and the Stressed Spondee conditions whereas at the individual level, they are more variable across the ten repetitions than controls only in the Spondee condition. Likewise, children with DD are less able than controls to exploit temporal regularities to predict the occurrence of a high predictable beat, even though child data are in general less clear than adult data (Chapter 7). Similarly to adults with DD, children with DD are more variable across the ten repetitions than their peers both at the individual and at the group level. One interesting difference emerges when adult and child data are compared: children with DD are incline to over-anticipate the occurrence of the beat in contrast to adults with DD whose answer is generally delayed.

Another main contribution of this thesis regards the oral language problems experienced by some individuals with DD. The results of this thesis show that a sub-group of adults with DD are slower and score poorer than controls in processing sentences of different syntactic complexity (Chapter 6) and that a sub-set of children with DD are significantly impaired in the production of inflectional morphology (Chapter 7). This latter result further supports the PTF since the task used to assess morphosyntax required the use of grammatical-like regularities that children should have extracted from the input.

This thesis also makes a contribution in regards to subtle handwriting difficulties observed in children with DD. Aside from the non-compliance with the rhythmic principles of handwriting, children with DD without a prior diagnosis of dysgraphia (and without a prior diagnosis of ADHD and DCD) write significantly slower that control children and do not differ from children with DD plus dysgraphia. Moreover, children with DD and children with DD plus dysgraphia write less fluently than typically developing children when asked to modulate size and speed of handwriting. Indeed, these results strengthen the validity of using objective tools and on-line methods for the study of handwriting. The digitizing tablet is a very ecological instrument; the recording of handwriting is fast and enjoyable for children. The use of the digitizing tablet permits us to highlight significant differences among groups that could not be detected by a mere observation of the static handwriting output. In addition, the use of the digitizing tablet helps us to discern relevant (e.g., velocity, fluency) from irrelevant (e.g., pressure) quantitative indexes.

The present dissertation also suggests promoting interdisciplinary cooperation, which could better contribute to the understanding of learning disorders and, more broadly, to the computations at the basis of the faculty of language as well as other aspects of cognitions (motor control, attention, memory).

As usual, much is still to be done. The results achieved in this thesis are only the starting point of a line of research that might better accommodate the multifaceted reality of Developmental Dyslexia.

The next more natural step is to manipulate the onset-to-onset intervals of the beats of the warning-imperative experiment described in this dissertation. The aim will be to verify whether the predictive timing difficulties encountered by children and adults with DD are limited to a given range of intervals. Another necessary manipulation to better understanding the processing underlying predictive timing regards the role of rhythm in predictive timing. The results of the experiments reported in Chapter 6 and Chapter 7 show that when DD participants are faced with a rhythmic pattern their performance is higher than when faced with a mere cadence. However, both experiments included only trochaic auditory stimuli. Future studies should include iambic stimuli as well, in order to ascertain whether participants benefit form a rhythmic structure per se, independently of the trochaic and iambic structure or whether it is the entrainment to specifically the trochaic pattern that enhances predictive timing.

In regards to the computations underlying predictive timing, interest in the topic is increasing. As discussed in Paragraph 2.4.1, recent studies show that the phase entrainment of delta and beta band oscillations plays an active role in predictive timing and that pre-stimulus modulation serves as a neural mechanism at the basis of processing of predicted events. Nevertheless, still to date little is known about the brain mechanisms supporting predicting processing and future works are needed to better understand these mechanisms. The warning-imperative experiment described in this thesis is suitable for investigating brain oscillations by means of magnetoencephalography (MEG). A MEG study based on our behavioral experiment could contribute shed light on the predictive timing processing of both the typically developing population and of the population with DD. MEG data from a cohort of 20 adult English participants have already been collected and the data analysis is in progress at the moment (Pagliarini, Guasti, Stucchi, Crain, Johnson, & Sowman, in progress). We plan to collect MEG data from individuals with DD by means of the same paradigm in the very near future.

Concerning prediction in the motor domain, in this dissertation the investigation was restricted to handwriting (in its fine-motor acceptation) in children with DD. At the time we started to investigate this topic, we were unaware of the fact that another group of scientists were working on the kinematic of movement of displacing action in children with SLI (Roy, Curie, Nazir, Paulignan, & Portes, 2013). The authors of this study asked to typically developing children and to children with SLI to reach a bottle and move it to another location while manipulating the children's knowledge of the weight of the bottle. The results showed that whilst typically developing children compensated the extra cost of moving a heavy object by anticipated wrist peaks in the reach sub-phase, children with SLI did not display anticipated wrist acceleration peaks during the reach sub-phase of the heavy object. Moreover, both in the known and unknown conditions object weight effects were restricted to the move sub-phase in children with SLI. In other words, these results showed that children with SLI were not able to modulate their movement in accordance with the mental representation of the weight of the object and by consequence they had difficulties in anticipating their movement according to the pre-existing knowledge. Therefore, children with SLI appeared impaired in anticipating an abstract sequential motor representation, similarly to children with DD. The results reported in this thesis together with the results of this groundbreaking work call for the study of sequential motor abstract representations in children with DD in different motor activities as well as to an extension of this field of study to other atypical population.

The PTF predicts that the core language representations (including phonological representation) are spared in children with DD. Future studies should apply this prediction to the study of language capacities in children with DD. Most of previous studies focused on syntax and morphosyntax. It would be interesting to study other under-investigated language components of children with DD, such as compositional semantics and pragmatics. It would also be interesting to verify whether the computation of scalar implicature is spared in children with DD when its derivation relies on morpho-syntactic features, as for example in the case of imperfective aspect.

Appendix

Velocity Gain Factor

Already at the end of 19^{th} century psychologists were aware of a systematic covariation between the velocity and the geometry of handwriting movements (Binet & Courtier, 1984; Jack, 1895). Afterwards this robust empirical covariation was formalized as a relation between the velocity of the pen along the path of the writing movement, *v(t)*, and the geometrical radius of curvature of this path, *r*, and it is known as two-third power law (Laquaniti et al., 1983; Viviani & Terzuolo, 1982; Viviani & McCollum, 1983; Viviani & Schneider, 1991). This empirical rule dictates that the speed of the pen tip in handwriting depends on the geometrical shape of the script as described as by the radius of curvature:

$$v(t) = kr^{\beta}(t)$$

where the power β is supposed to take a value of about 1/3 and *k* is the so called velocity gain factor which mainly reflects the average velocity of the writing movement. The velocity gain factor (constant *k*) is estimated by the intercept of the linear regression between *log(v)* and *log(r)* with the line *r* =1. If the power β is roughly constant over age groups (factor Grade), it is safe to assume the value of *k* as a substitute for average velocity. There are some not negligible advantages by using the velocity gain instead of the average velocity. The velocity gain is a robust descriptor because it is derived by a least square regression procedure and thus it is less affected than the average velocity by the numerous outliers and extreme values which are unavoidable in child handwriting. To verify that in our case the velocity gain is a safe substitute of the average velocity we run a GLM analysis on β with Grade as BS factor, and no statistical effect emerged ($F(3, 98) = .70$, $p = .55$, $\eta^2_p = .02$). The general average of β is .42 ± .06.

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Il vero viaggio di scoperta non consiste nel cercare nuove terre,
ma nell'avere nuovi occhi.
(Marcel Proust)

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