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Dyslexic children fail to comply with the rhythmic constraints of handwriting

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ABSTRACT

In this study, we sought to demonstrate that deficits in a specific motor activity, handwriting, are associated to Developmental Dyslexia. The linguistic and writing performance of children with Developmental Dyslexia, with and without handwriting problems (dysgraphia), were compared to that of children with Typical Development. The quantitative kinematic variables of handwriting were collected by means of a digitizing tablet. The results showed that all children with Developmental Dyslexia wrote more slowly than those with Typical Development. Contrary to typically developing children, they also varied more in the time taken to write the individual letters of a word and failed to comply with the principles of isochrony and homothety. Moreover, a series of correlations was found among reading, language measures and writing measures suggesting that the two abilities may be linked. 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.

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1. Introduction

From the first studies on Developmental Dyslexia (DD), anecdotes and experimental evidence have reported that children with DD often suffer from fine and gross motor difficulties, like motor coordination, poor balance and clumsiness (Capellini, Coppede, & Valle, 2010; Nicolson & Fawcett, 1990). In addition, increasing evidence suggests that children at familial risk for DD show slow motor development at infancy (Viholainen, Cantell, Lyytinen, & Lyytinen, 2002). 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, & Frith, 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 dyslexia is the automaticity/cerebellar hypothesis of Nicolson and Fawcett (Nicolson & Fawcett, 1990, 2011), which states that a dysfunction at the level of the cerebellum is responsible for the comorbidity between dyslexia and dysgraphia (see also Lam, Au, Leung, & Li-Tsang, 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, and Goswami (2006) (see also Thomson & Goswami, 2008). In this line of research, it is reported that dyslexic students anticipated an isochronic-pacing metronome signal when tapping by significantly longer intervals than controls did 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 point out the importance of rhythmic timing for both language and motor skills and suggest that the link between reading and motor deficits is mediated by rhythm. Timing is also the main feature of Llinás's (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 principles of isochrony and homothety (see Section 1.5 for an exhaustive discussion of the key questions of this study).

1.1. Principles of the rhythmic organization of handwriting

Handwriting (and other motor activities) is ruled by two principles of rhythmic organization: isochrony and homothety. The principle of isochrony (Binet & Courtier, 1893; Stetson & McDill, 1923; Viviani & Terzuolo, 1982) asserts that the speed of movement execution is proportionally related to the length of its trajectory in order to keep the movement duration approximately constant. This relation between movement velocity and its linear extent, which seems to be an ordinary feature of different types of movement, has been observed both in humans (e.g., Freund & Büdingen, 1978; Viviani & Terzuolo, 1982) and in non-human primates (Sartori, Ciani, Bulgheroni, & Castiello, 2013). Previous studies have shown that the total writing duration remains invariant irrespective of the size of the word or letter (Freeman, 1914; Lacquaniti, Terzuolo, & Viviani, 1983; Viviani & Terzuolo, 1983). This implies that there is a compensation 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. The principle of homothety (Lashley, 1951; Viviani & Terzuolo, 1982) guarantees the invariance of the relative duration of a movement's components under a number of possible variations in the duration of the very same movement. In handwriting, this principle predicts that the relative duration of the components of the whole movement (e.g., the individual letters of a word) will remain invariant across changes in duration. Consider a fictitious example. Suppose that it takes 1000 ms to write the word 'dog', decreasing to 500 ms when one has to write faster and increasing to 1500 ms when one has to write slower. Further suppose that the relative duration of the first letter is 50% of the total duration, the second letter is 20%, the third letter is 30%. The relative durations of individual letters will remain constant despite the variations of the global duration. For instance, in the three conditions mentioned above, the letter (d) 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. Thus, the isochrony principle ensures that the time it takes to write a word tends to remain constant under different writing conditions (especially when one has to write bigger) and the principle of homothety guarantees that the relative duration of individual letters remains invariant despite the variations of the duration of the whole word. Therefore, if both homothety and isochrony are respected, the absolute and relative durations of individual letters are kept constant across variations in size and speed. However, at this point, it is worth noting that a violation of the isochrony principle does not involve the violation of the homothety principle (nor vice versa). Isochrony governs the timing of a handwriting event as a whole, e.g., a word, and homothety, that of its components, e.g., individual letters.

1.2. Developmental Dyslexia

Developmental Dyslexia (DD) is currently defined as a learning disorder characterized by a specific difficulty in learning to read accurately and fluently despite conventional instruction, adequate intelligence and socio-cultural opportunity (DSM-IV, American Psychiatric Association, 1994). The percentage of the school population affected by DD is around 3–7% depending on the language. In Italian, the percentage ranges from 1.5% to 5% (Cornoldi, 1991; Cornoldi & Tressoldi, 2007; Stella, 1999; see also Barbiero et al., 2012). It is widely agreed that DD is a language disorder (Vellutino, 1979), specifically due to phonology related processes (e.g., Castles & Coltheart, 2004), although the exact etiology is still a matter of debate (Ramus, Marshall, Rosen, & van der Lely, 2013). Individuals with DD experience particular difficulties in phonological tasks (Ramus, Rosen, et al., 2003; Snowling, 2000) and in tasks demanding rapid automatized naming (Wolf & Bowers, 1999). Beside the undisputed core phonological deficit, other cognitive impairments have been observed in individuals with DD (and this has led to the proposal of new approaches to developmental disorders, e.g., Pennington, 2006). These deficits affect different cognitive domains, such as rapid auditory processing (Tallal, 1980), visual perception (Stein & Walsh, 1997), attention (Facoetti et al., 2003), amplitude modulation, beat perception and production (Goswami et al., 2002), motor control, automatization and handwriting problems (Chang & Yu, 2013; Cheng-Lai, Li-Tsang, Chan, & Lo, 2013; Lam et al., 2011; Nicolson & Fawcett, 1990). 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 DD (Ho, Chan, Lee, Tsang, & Luan, 2004; Ho, Chan, Tsang, & Lee, 2002), in addition to impairments in phoneme awareness, rapid naming of characters, non-word reading and word repetition.

1.3. 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 is proposed, according to which linguistic spelling errors are included (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, Parush, & Weiss, 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, Schwellnus, Ilyas, & Chau, 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, Levanon-Erez, and Weintraub (1998) and Di Brina, Niels, Overvelde, Levi, and Hulstijn (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.

1.4. Assessment of handwriting proficiency in Italian

Italian uses alphabetic lettering that comprises block script and cursive script. Cursive requires connecting characters in a smooth, fluent and continuous movement. Conversely, block script has no smoothness requirement, since each character is written separately. For the last 30 years the Italian mainstream educational practice has been to start teaching block script in all capitals first and cursive later.

The assessment of handwriting proficiency 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 is 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.

1.5. Key questions of this 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 explore the conjecture that handwriting difficulties are linked to rhythmic deficits. 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. 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. (2011), 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. 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 requires smoothness and continuity, especially in cursive. Therefore, in light of previous results highlighting the presence of handwriting difficulties in Chinese DD children (Lam et al., 2011), we predicted 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, 2006a; Rosenblum, Dvorkin, & Weiss, 2006b; 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 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. In accordance with 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/language and 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 sum, our study is an extension of the Lam et al. study (2011), which focused only on handwriting. Ours further 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.

2. Methods

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 a 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, whereas those with DD and DD_DY were recruited from the Developmental Neurology Unit of the Neurological Institute Carlo Besta in Milan. Demographic information of the participants is shown in Table 1.

A qualified team of psychologists and speech therapists of the Developmental Neurology Unit 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 (2010). The diagnosis was made by means of standardized tests and, to complete the diagnosis

Table 1
Demographic information on age, time of instruction, gender, and hand dominance of the participants.

Group	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)
Range in age	7.5–10.1	8–12	8–11.2
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

DD: children with Developmental Dyslexia; DD_DY: children with both Developmental Dyslexia and dysgraphia; TD: children with Typical Development.

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, Court, & Raven, 1998) and obtained a score equal to or above the 25th percentile.

Ethical approval according to standards of the Helsinki Declaration (World Medical Association, 2009) was obtained from both the board of the University of Milano-Bicocca and the board of the Developmental Neurology Unit of the Neurological Institute Carlo Besta. Before each testing session, informed consent was signed by the participants and by their parents.

2.2. Material

Reading and oral language abilities were assessed by means of standardized Italian tests ((1), (2), (3)), whereas 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, Job, & Tressoldi, 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 of the word.

(4) *Writing tasks*. Participants were asked to grasp the wireless pen of a digitizing tablet with their dominant hand as they usually hold a normal pen in school. They were invited to write and draw on an unlined A4 size paper with the longer side in the horizontal position. The word *burle* (English translation: 'jokes') was chosen for the writing task because in Italian cursive is usually written without any detachment of the pen from the surface. Thus, children were asked to write the Italian word *burle* in two different scripts, block script in all capitals and cursive (see

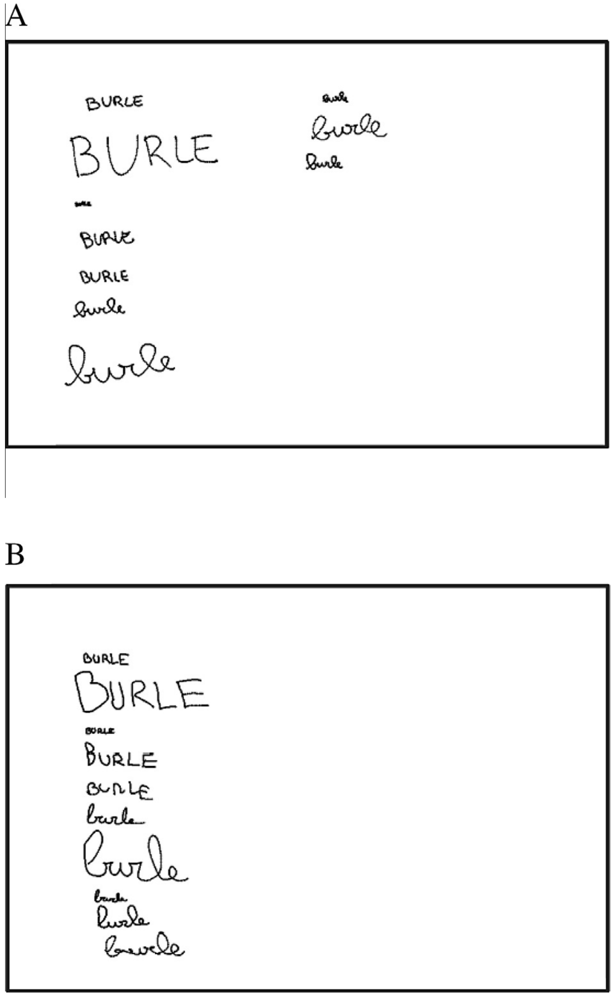

Fig. 1. Writing recordings from a graphical tablet. Participants had to write the word 'burle' (jokes) on a sheet of paper placed in landscape orientation on the recording surface of an Intuos 3 Wacom® tablet. They had to vary the size and speed of writing. Five conditions were envisaged: Spontaneous, Big, Small, Fast, and Slow in both cursive and block scripts. The writing production of a typically developing child (A) and of a dyslexic child (B) are reported. 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.

Fig. 1(A) and (B)). Then, for each script, children were asked to write the word 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 Spontaneous. Thus, children had to write the word *burle* ten times in total. 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. However, 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), and 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.

(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 min. 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.

2.3. Instruments used for collecting data on writing and scribbling

Kinematic and dynamic variables of writing and scribbling were collected by means of a digitizing tablet connected to a computer controlled by the VBDigitalDraw 2.0 system (Toneatto, 2012)[1]. The system consists of two independent modules: one for data acquisition, the other for a post-processed computational algorithm module, both working on Windows Platform XP. Data were acquired by means of the commercial digitizing tablet Intuos 3 Wacom®[2] connected to a laptop and used with a wireless pen. The trajectory of the handwriting gesture was recorded as (x, y) Cartesian coordinates, both when the pen was in contact with the surface and when the pen position was in the air on the digitizer's active area with pressure = 0 i.e., when the writer was not writing but planning or preparing the next movement sequence. The force exerted on the surface's axis was a numeric value comprised between 0 and 1023. Trajectory, speed and pressure were collected on-line, whereas data analysis was conducted off-line. The raw data were collected in a '.txt' file using VBDD 2.0 Software. Then for the purpose of our 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).

2.4. Procedure

Participants were tested individually in a quiet room either at the Developmental Neurology Unit of 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-min testing sessions with breaks whenever required.

2.5. Data analysis

2.5.1. 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.

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[1] The first version of the software, VBDD, was developed in the Department of Psychology of the University of Milano-Bicocca and it was first used to investigate performance of Arabic handwriting (Bouamama, 2010).

[2] Technical details: Physical size (W × D × H): 440 × 340 × 14 mm; active area (W × D): 305 × 231 mm: pressure sensitivity: 1024 levels: resolution: 5080 lpi: pen accuracy: ±0.25 mm; mouse accuracy: ±0.5 mm; tilt: ±60°; maximum reading height with Pen: 6 mm; maximum report rate: 200 points per second; connection: USB; cable length: 2.5 m; weight: 1800 g.

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 as 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 Section 2.3). A subset of descriptors was analyzed for both the writing and scribbling tasks, in accordance with previous studies (Di Brina et al., 2008; 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:

(1) Length, i.e., the summation of the length of all the strokes in cm (only for writing tasks).
(2) Average speed, i.e., the average absolute speed of pen movement in cm/s.
(3) 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).
(4) Dysfluency, i.e., the logarithm based on the number of maxima and minima in the curve of instantaneous velocity.
(5) 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).

2.5.2. 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 factor (henceforth WS) 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 Figs. 3–9 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,

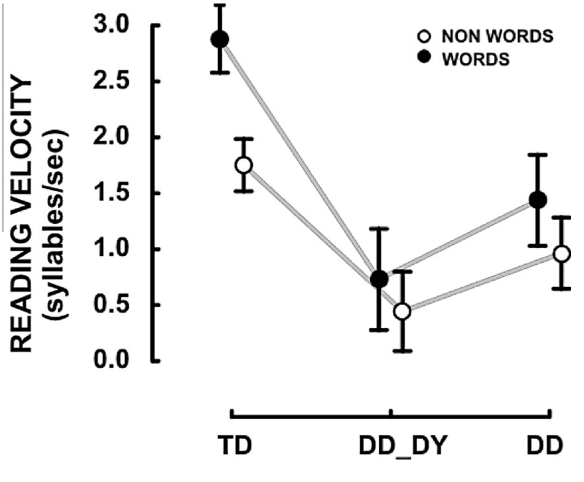

Fig. 2. Reading words and non-words task (Parts 2 and 3 of the *Batteria per la valutazione della Dislessia e della Disortografia evolutiva-2, DDE-2*: Sartori et al., 2007). Reading speed is reported, expressed in syllables/second for words and non-words in the three experimental groups (DD: children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

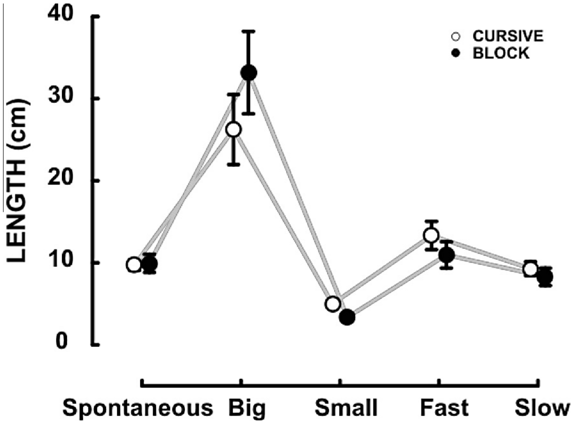

Fig. 3. Complying with the task requirements: size modulation. A preliminary analysis was performed to determine whether all the children, without distinguishing the 3 groups ($N = 77$), complied with the task demands and modulated the size of their writing. The average lengths of the word *burle* (with 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.

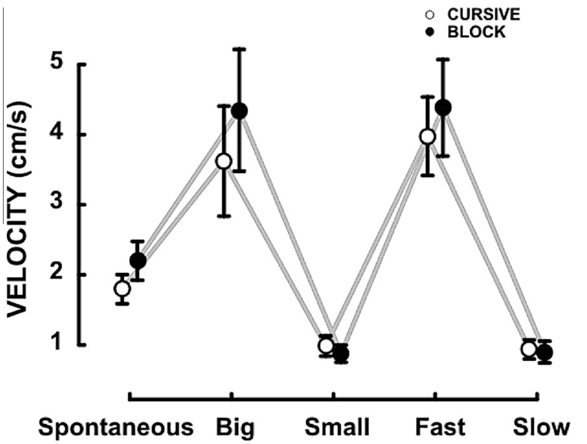

Fig. 4. Complying with the task requirements: velocity modulation. A preliminary analysis was performed to determine whether all the children, without distinguishing the 3 groups ($N = 77$), complied with the task and modulated the velocity of their writing. The average speeds of the word *burle* (with 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.

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

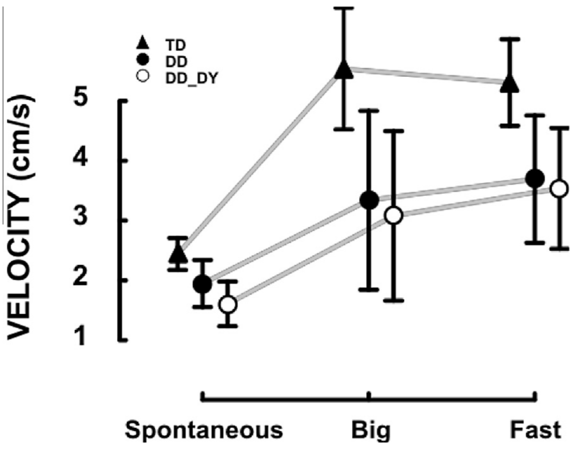

Fig. 5. Average writing velocity (whole word). The interaction Condition (Spontaneous, Big, Fast) by Group (TD, DD, DD_DY) in writing speed (cm/s) of the whole word *burle* is shown (vertical error bars represent standard error). TD children are systematically faster than DD and with DD_DY in the conditions Big and Fast.

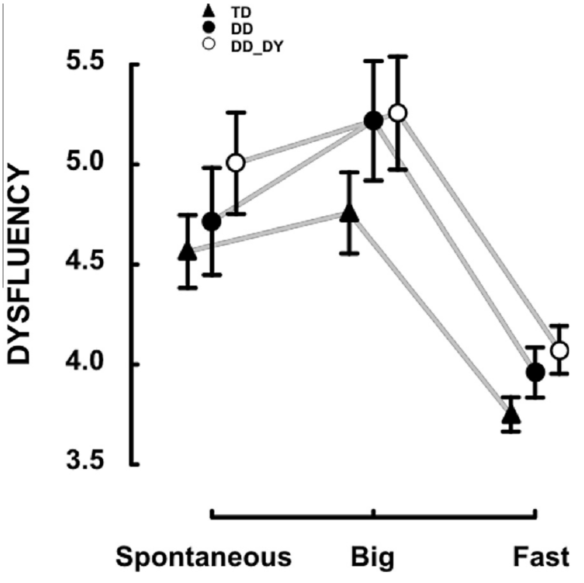

Fig. 6. Dysfluency (whole word). The non-significant interaction Condition (Spontaneous, Big, Fast) by Group (TD, DD, DD_DY) in dysfluency computed on the whole word *burle* is shown (vertical error bars represent standard error). DD_DY children are less fluent than TD and DD children do not differ from DD_DY in any condition.

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 .5. We reported only significant main effects and interactions; partial eta squared ($\eta^2{}_p$) was reported as a measure of effect size. In the end, correlations among reading, linguistic and writing data were computed to assess the relation between writing and reading performance.

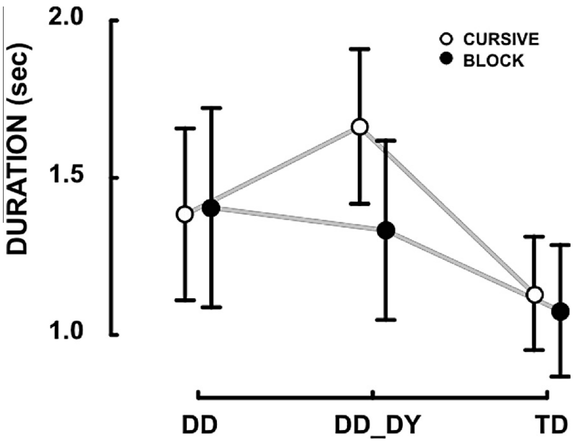

Fig. 7. Duration (separate letters). The average time (vertical error bars represent standard error) taken to write each individual letter of the word *burle* for cursive and block scripts is shown.

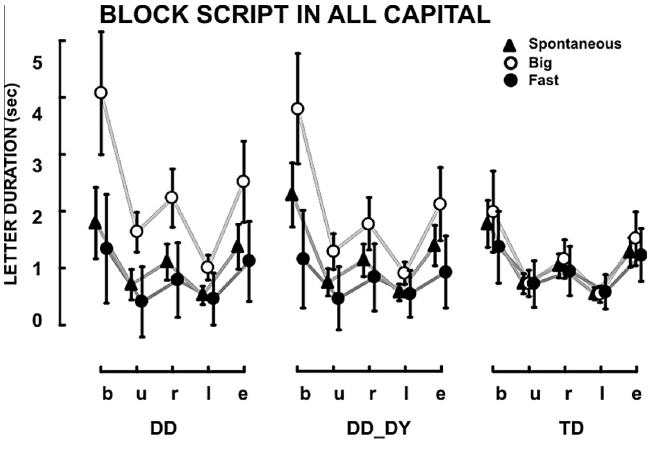

Fig. 8. Duration of separate letters in block script in all capitals. The second order interaction Group (DD, DD_DY, TD) by Condition (Spontaneous, Big, Fast) and by Letter ((b), (u), (r), (l), (e)) is shown for duration (vertical error bars represent standard error). Writing the first letter (b) requires 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 and 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.

3. Results

3.1. Language task results

Results from the GLM analysis on reading speed 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 Fig. 2, the interaction Group × 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.

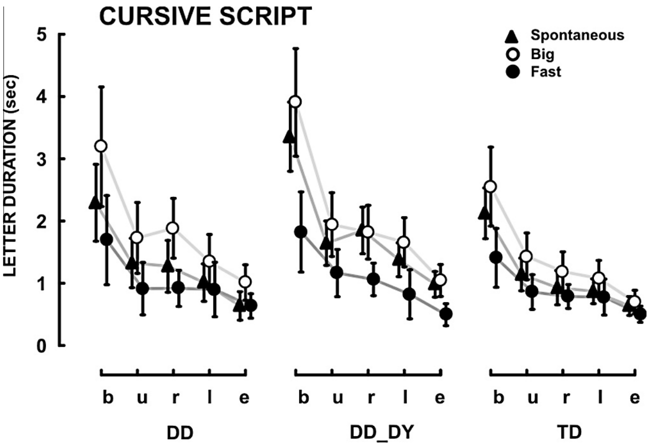

Fig. 9. Time taken to write separate letters in cursive script. The second order interaction of Group (DD, DD_DY, TD) by Condition (Spontaneous, Big, Fast) by Letter ((b), (u), (r), (l), (e)) is shown for duration (vertical error bars represent standard error). Writing the first letter (b) requires more 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 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.

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.

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.

3.2. 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.

3.2.1. Length

The GLM analysis on length (Group × Script × 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 × Condition, $F(4,292) = 3.15$, $p = .02$, $\eta^2_p = .04$ was found, as displayed in Fig. 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.

3.2.2. Average speed

The GLM analysis on average speed (Group × Script × 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, $F(4,292) = 7.95$, $p < .001$, $\eta^2_p = .10$ (Fig. 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 × 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.

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 Section 1.1). 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.

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

3.3.1. Writing task

3.3.1.1. 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 × Condition, $F(4,146) = 2.71$, $p < .05$, $\eta^2_p = .06$, which can be appreciated by observing Fig. 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.

3.3.1.2. 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 Fig. 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 Fig. 6 showed that this is mainly due to DD children.

3.3.1.3. 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.

3.3.2. 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).

3.4. 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.

3.4.1. 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 Fig. 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.

For block script in all capitals, Fig. 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 × 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 × 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.

Fig. 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 × 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 × 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 Fig. 8. The analysis of the DD_DY group revealed analogous results, i.e., a significant interaction of Condition × 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 Fig. 8). The analysis of the TD group showed an interaction of Condition × 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 × 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 Fig. 8.

Focusing on the analysis of writing in cursive, Fig. 9 displays the effects of Letter and Condition for each Group. The GLM analysis (Group × Condition × 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, and this holds for all three conditions (Fig. 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 × Condition interaction was not found, two other significant interactions were: Condition × Letter, $F(8,584) = 3.76$, $p < .01$, $\eta^2_p = .05$ and Group × Letter, $F(8,292) = 2.29$, $p < .05$, $\eta^2_p = .06$. The post-hoc comparisons of the Condition × 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 (see Section 1.4). The analysis of the DD group revealed a significant interaction of Condition × 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 Fig. 9. In the analysis of DD_DY children we found a significant interaction of Condition × 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 Fig. 9). The analysis of the TD group revealed a significant interaction of Condition × 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).

3.5. 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 2–4.

Table 2
Correlation analyses within the three groups including average speed cm/s as writing variable (based on whole word) and all reading/linguistics variables.

Script	Condition	Speed reading words	Errors reading words	Speed reading non-words	Errors reading non-words	Accuracy in non-word repetition	PPVT
Cursive	Spontaneous	0.34	−0.26	0.31	–	–	0.23
Cursive	Big	0.34	−0.23	0.31	–	–	–
Cursive	Fast	0.46	−0.33	0.43	−0.28	0.32	0.23
Block	Spontaneous	0.27	−0.24	0.24	−0.23	–	0.32
Block	Big	0.35	−0.24	0.30	–	–	–
Block	Fast	0.31	–	0.26	−0.26	–	–

Pearson correlation coefficients are displayed.

Table 3
Correlation analyses within the three groups including dysfluency as the writing variable (based on whole word) and all reading/linguistics variables.

Script	Condition	Speed reading words	Errors reading words	Speed reading non-words	Errors reading non-words	Accuracy in non-word repetition	PPVT
Cursive	Spontaneous	−0.30	–	−0.27	–	–	–
Cursive	Big	−0.34	0.26	−0.29	–	–	–
Cursive	Fast	−0.52	0.37	−0.48	0.33	–	−0.27
Block	Spontaneous	–	–	–	–	–	−0.23
Block	Big	−0.38	0.24	−0.33	0.25	–	−0.27
Block	Fast	−0.37	–	−0.26	0.24	−0.25	–

Pearson correlation coefficients are displayed.

Table 4
Correlation analyses within the three groups including total duration as the writing variable (based on whole word) and all linguistics variables.

Script	Condition	Speed reading words	Errors reading words	Speed reading non-words	Errors reading non-words	Accuracy in non-word repetition	PPVT
Cursive	Spontaneous	−0.31	–	−0.27	–	–	–
Cursive	Big	−0.27	–	−0.23	–	–	–
Cursive	Fast	−0.50	0.33	−0.46	0.29	–	−0.23
Block	Spontaneous	–	–	–	–	–	–
Block	Big	−0.29	–	−0.26	–	–	–
Block	Fast	−0.35	–	–	–	−0.23	–

Pearson correlation coefficients are displayed.

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) whereas it negatively correlated with the error score in reading words and non-words (see Table 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 3 for correlations with dysfluency and Table 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-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-S} in block script significantly correlated with speed in reading words ($r = .32$) and non-words ($r = .26$). D_{B-S} in cursive significantly correlated with speed in reading words ($r = .23$) and the correlation with speed in reading non-words approached significance ($r = .21$, $p = .06$).

4. 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, which 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, does 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, since it 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 Figs. 8 and 9). This suggests that they experience some difficulties in adapting their handwriting movement to various experimental size manipulations. Moreover, Figs. 8 and 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 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 sum, 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, and 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, make more errors and have 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.

5. Conclusions

In conclusion, our results suggest that children with DD suffer from handwriting difficulties, similar to those observed in children with DD plus dysgraphia. In addition, 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. Finally, reading/language and writing measures were correlated supporting the idea of a common origin of these disorders. We suggested 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.

Disclosure statement

No financial interest or benefit arises from *direct applications of this research*.

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