Reading, phonological memory and handwriting develop in parallel in the first years of school: evidence from a cross-sectional study

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Abstract: This study attempted to bring together the investigation of reading and writing, which have been traditionally considered separately. In particular, our cross-sectional study aimed at outlining the developmental trajectory of reading abilities and handwriting kinematic aspects of children in their first years of school. We collected reading, phonological memory and handwriting data from 102 Italian monolingual children ranging from Grade 1 to Grade 4 of primary school. Reading skills and phonological memory were assessed by means of standardized tests, whereas handwriting was assessed through the examination of a set of kinematic and dynamic descriptors collected by means of a digitizing tablet. The results of the present study provide evidence for a parallel developmental pathway of reading, phonological memory and handwriting (considering the motor features, not the spelling). The implications of these findings are discussed in the context of the understanding of developmental disorders and the influence of handwriting in learning to read.

Keywords: reading; handwriting; kinematic analysis; development; language acquisition.

1 Introduction

Reading and handwriting are two fundamental abilities to succeed in contemporary society. In the last decades, little stress has been placed on handwriting due to the increased use of computers, keyboards and tablets. Additionally, instruc-

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tional 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 abilities have a great impact in children's school life, with important repercussions on the general cognitive and linguistic functioning.

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 & Teuling, 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 Coltherart & Rastle, 1994, for a serial processing model of reading process).

Despite these observations, reading and handwriting have been mainly 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, Boucard, Gilhodes, Anton, Roth, Nazarian & Velay, 2008). Similarly, behavioral studies demonstrated that handwriting training, contrary to typing training, boosts recognition of new character in prereading children (Longcamp, Zerbato-Poudou & Velay, 2005) and adults (Longcamp, Boucard, Gilhodes & Velay, 2006; Longcamp, *et al.*, 2008).

In a different approach, 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, Morin, Pontart, Maffre, Flouret & Simard-Dupuis, 2014; Berninger, Nielsen, Abbott, Wijsman & Raskind, 2008; Capellini, Coppede & Valle, 2010; Cheng-Lai, Hill, 2013; Lam, Au, Leung & Li-Tsang, 2011; Pagliarini, Guasti, Toneatto, Granocchio, Riva, Sarti, Molteni, Stucchi, 2015, for the co-occurrence of developmental dyslexia and grapho-motor difficulties). 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 premotor 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 the 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 of motor procedural learning circuits. Along these lines, Diamond (2000) proposed that motor development and cognitive development are more interconnected than has been previously suggested since linguistic, cognitive and motor disorders often co-occur in the same person (Hill, 2001; Kaplan, Wilson, Dewey & Crawford, 1998; Johansson, Forssberg & Edvardsson, 1995; Robinson, 1987).

The aim of our study was 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 (Goswami & Bryant, 1990; Gathercole, Willis & Baddeley, 1991; Gathercole & Baddeley, 1993). We expected a parallel developmental pathway for reading, phonological memory and handwriting. Our hypothesis grounds in two assumptions, namely that the motor and the language maturational processes rest on shared neuroanatomical mechanisms (Diamond, 2000; Gimenez, Bugescu, Black, Hancock, Pugh, Nagamine, Kutner, Mazaika, Hendrenl, McCandliss & Hoeft, 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, which have been collected by means of a digitizing tablet.

2 Methods

2.1. *Participants*

We tested 102 pupils, ranging from the first to 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 area 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 participants were tested in the second semester of the academic year (from end of January to May). Demographic information of participants is reported in Table 1.

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;5
Gender				
Male	10	17	13	12
Female	5	17	13	15
Hand dominance				
Left	2	4	3	2

Table 1: Demographic information about age, gender, and hand dominance of the participants.

The 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, 2009) was obtained from the board of the University of Milano-Bicocca. Participants' parents signed informed consent before the testing session.

2.2. *Materials*

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

Words and non-words reading task. 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 four lists of words (281 syllables in total) and three lists of non-words (127 syllables in total) 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 subtest (281 for the words and 127 for non-words) by the seconds employed to read each subtest. The error score corresponded to the number of words and non-words read incorrectly. Self-correction was not counted as a 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 a 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 (Fig. 1a and 1b). During handwriting, the digitized pen produced an ink trace, which allowed participants to visually control the trace. Therefore, 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), considering the spontaneous condition as a baseline. This procedure is frequently used to evaluate a participant's ability to control handwriting size and tempo (Van Galen, 1991; Teulings & Schomaker, 1993; Mayor Dubois, Zesiger, Roulet Perez, Maeder Ingvar & Deonna, 2003; Zesiger, 2003). Indeed, this experimental method has been used in previous studies, with a different target word in each language (Arabic: Bouamama, 2010. Unpublished doctoral dissertation; French: Mayor Dubois *et al.*, 2003; Zesiger, 1995; Italian: Pagliarini, 2016, Unpublished doctoral dissertation; Pagliarini *et al.*, 2015; Pagliarini *et al.* 2017).

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 (Fig. 1). We chose *burle* as the 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, pressure and duration, due to the resolution limits of the digitizing tablet (±0.25 mm). The Big and Fast conditions do not have resolution limitations, except paper size.

We expected children to show significant differences in the opposite conditions (big vs. small; fast vs. slow), if they had understood the task and above all if they had the fine motor ability to tailor their handwriting movement.

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 (Pagliarini *et al.*, 2015; Pagliarini *et al.* 2017). 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, with a sampling frequency of 200 Hz and a spatial accuracy of ±0.25 mm. The handwriting path was recorded as (x, y) Cartesian coordinates, 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 online, 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.

To investigate the abilities and the maturation of handwriting of the participants, we focused on velocity gain factor, dysfluency, pressure and duration since they are suitable indices of automatization and fluency (Accardo, Genna & Borean, 2013a; Accardo, Genna & Borean, 2013b; Blöte & Hamstra-Bletz, 1991; Hamstra-Bletz & Blöte, 1990) and 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; Pagliarini *et* *al.* 2017, Parush, Levanon-Ere & Weintraub, 1998; Rosemblum, Parush & Weiss, 2003; Smits-Engelsman & Van Galen, 1997):

(1) Velocity gain factor: measure of the average velocity of the handwriting movement. See the Appendix for a detailed definition.
(2) Average pressure: 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).
(3) Dysfluency: the logarithm of the number of the maxima and the minima of the curve of instantaneous velocity.
(4) Duration: 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.

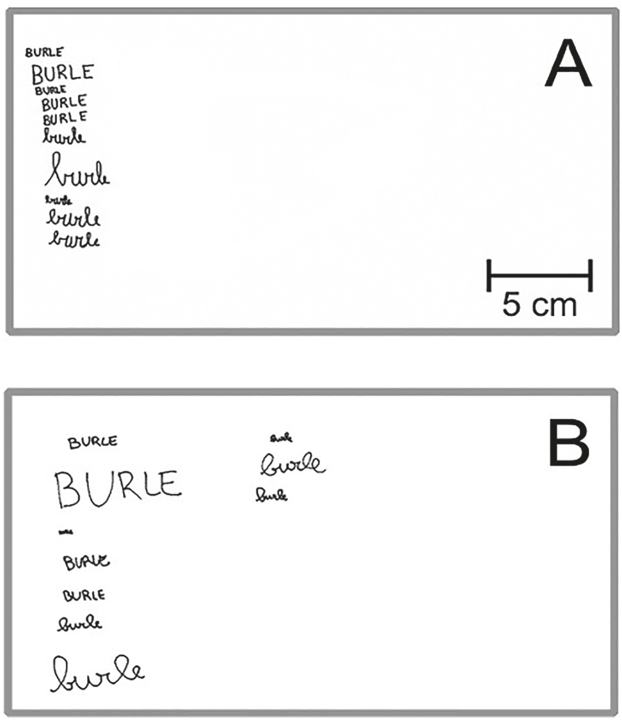

Fig. 1: Writing samples of a 1st grade (a) and a 4th grade girl (b).

2.3. *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.

2.4. *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 subjects factor (henceforth BS) and Item (Word, Non-Word) as within subjects factor (henceforth WS). Similarly, the analyses of the phonological memory score were run using a GLM mixed-design with Grade as BS and Item as WS.

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 2.2). The analyses were performed on words as a 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 first level effects and interactions were followed up using Bonferroni's post-hoc comparisons. We reported only significant effects and interactions, and partial eta squared (η2p) 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 Results

3.1. *Linguistic test results*

Reading words and non-words tasks. Fig. 2 illustrates the growing trend of reading speed with grade, both for words and non-word. The GLM analysis on reading speed of words and non-words revealed a main effect of Grade, $F\ (3, 98) = 32.44$, $p < .001$, $\eta^2p = .50$. The post-hoc test showed that Grade 1 read fewer syllables per second than Grade 2, 3 and 4; Grade 2 read fewer syllables per second than Grade 3 and 4. Grade 3 and 4 did not differ between them. A main effect of Item, $F\ (1, 98) = 156.50$, $p < .001$, $\eta^2p = .61$, 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, $F\ (3, 98) = 18.51$, $p < .001$, $\eta^2p = .36$, revealed that, from Grade 2, children start progressively to read more rapidly words than non-words, as an indication that they are starting to automatize reading (Fig. 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.

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 Grade 3 children not showing an improvement in non-words reading accuracy, they were significantly faster in reading words than non-words, thus indicating that they were in the process of automatizing reading.

Repetition of non-words task. Fig. 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.

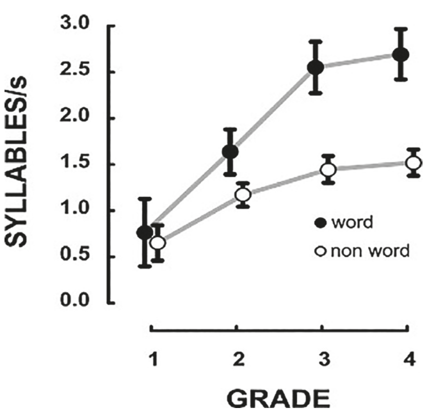

Fig. 2: Reading speed counted in syllables read per second for words and non-words is reported for the 4 experimental groups (1 = Grade 1; 2 = Grade 2; 3 = Grade 3; 4 = Grade 4). Vertical bars represent 95% confidence interval.

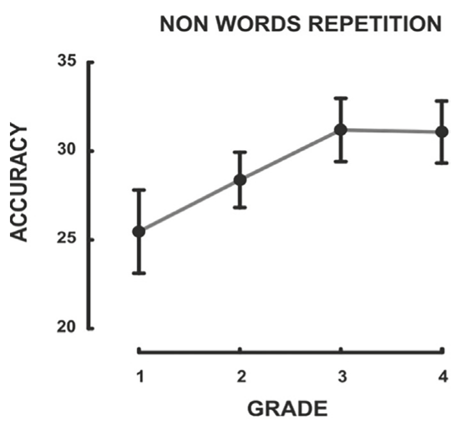

Fig. 3: The number of non-words accurately repeated is reported for the 4 experimental groups (1 = Grade 1; 2 = Grade 2; 3 = Grade 3; 4 = Grade 4). Vertical bars represent 95% confidence interval.

3.2. *Preliminary results of the writing task*

A preliminary analysis was run to determine whether participants 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. The total length was consistently 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 participants 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 2.2).

3.3. *Writing (whole word) tasks results*

Velocity gain factor. Fig. 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 it appears from the figure, this interaction does not affect the interpretations of the main effects. Fig. 4 mainly shows that velocity gain tends to increase with grade, both for cursive and block script. On the three panels of Fig. 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 Grade 3 and Grade 4 and Grade 2 wrote slower than Grade 4, as shown in Fig. 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 participants 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.

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 Fig. 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.

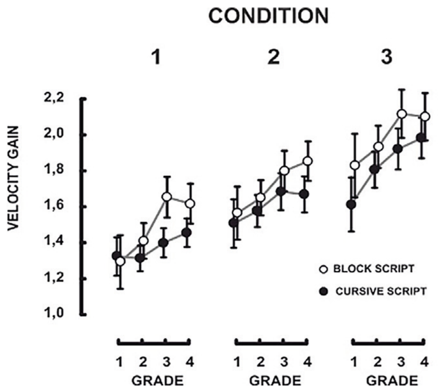

Fig. 4: The second order interaction Script (cursive, block) by Condition (1 = Spontaneous, 2 = Big, 3 = Fast) by Grade (1 = Grade 1, 2 = Grade 2, 3 = Grade 3, 4 = Grade 4) of the velocity gain factor is reported. Vertical bars represent 95% confidence interval.

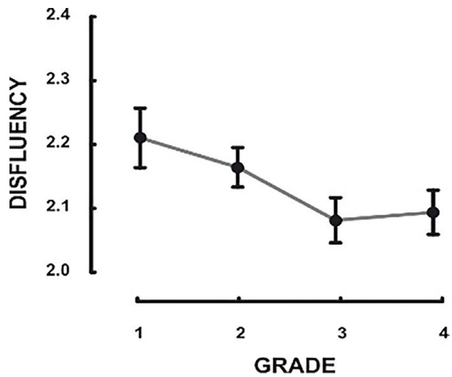

Fig. 5: The main effect of Grade for the four groups (1 = Grade 1, 2 = Grade 2, 3 = Grade 3, 4 = Grade 4) of the dysfluency is reported. Vertical bars represent 95% confidence interval.

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.

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.

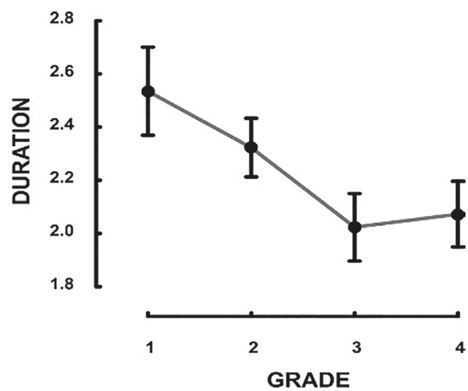

Fig. 6: The main effect of group for the four groups (1 = Grade 1; 2 = Grade 2; 3 = Grade 3; 4 = Grade 4) of the duration is reported. Vertical bars represent 95% confidence interval.

3.4. *Correlation analysis between writing and language descriptors*

Correlations were found between 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 coefficient (Pearson r; $p < .05$) are reported in Table 2, 3 and 4. Velocity gain in handwriting positively correlated with speed in reading words and non-words (Table 2). Dysfluency and duration negatively correlated with speed in reading words and non-words (Table 3 and Table 4 respectively). Negative correlations were also found between duration in writing and accuracy in the repetition of non-words (Table 4).

Script	Condition	Speed reading words	Errors reading words	Speed reading non-words	Errors reading non-words	Accuracy in non word rep.
Cursive	*Spontaneous*	n.s.	n.s.	0.20	n.s.	n.s.
Cursive	*Big*	n.s.	n.s.	n.s.	n.s.	n.s.
Cursive	*Fast*	0.31	n.s.	0.36	n.s.	n.s.
Block	*Spontaneous*	0.33	n.s.	0.26	n.s.	n.s.
Block	*Big*	0.24	n.s.	0.20	n.s.	n.s.
Block	*Fast*	0.20	n.s.	n.s.	n.s.	n.s.

Table 2: Correlations between *velocity gain* as writing variable 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 rep.
Cursive	*Spontaneous*	- 0.37	n.s.	- 0.34	n.s.	n.s.
Cursive	*Big*	- 0.22	n.s.	- 0.21	n.s.	n.s.
Cursive	*Fast*	- 0.42	0.29	- 0.41	n.s.	n.s.
Block	*Spontaneous*	- 0.34	n.s.	- 0.34	n.s.	n.s.
Block	*Big*	- 0.22	n.s.	n.s.	n.s.	n.s.
Block	*Fast*	- 0.26	n.s.	- 0.26	n.s.	n.s.

Table 3: Correlations between *dysfluency* as writing variable 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 rep.
Cursive	*Spontaneous*	- 0.48	0.30	- 0.42	n.s.	- 0.33
Cursive	*Big*	- 0.29	n.s.	- 0.22	n.s.	- 0.40
Cursive	*Fast*	- 0.48	0.34	- 0.47	n.s.	- 0.31
Block	*Spontaneous*	- 0.30	n.s.	- 0.29	n.s.	n.s.
Block	*Big*	- 0.19	n.s.	n.s.	n.s.	n.s.
Block	*Fast*	- 0.32	0.21	- 0.33	n.s.	- 0.23

Table 4: Correlations between *duration* as writing variable and all linguistics variables.

4 Discussion

This cross-sectional study aimed at investigating the developmental pathway of reading, phonological memory and handwriting abilities in Italian children from Grade 1 to Grade 4 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 Grade 2 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 Grade 2, children start to rely on lexical knowledge and the process of reading gradually becomes more automatized. Grade 3 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 Grade 2, and similarly to the outcome of the reading task, the performance evens out at Grade 3 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 said in paragraph 2.2, the descriptors were chosen according to previous studies: Accardo *et al.*, 2013a; Accardo, *et al.*, 2013b; Blöte & Hamstra-Bletz, 1991; Di Brina *et al.*, 2008; Hamstra-Bletz & Blöte, 1990; Kushki, *et al.*, 2011; Pagliarini *et al.*, 2015; Pagliarini *et al.* 2017; Parush *et al.*, 1998; Rosemblum *et al.*, 2003; Smits-Engelsman & Van Galen, 1997, among others). We found that velocity gain increased considerably from Grade 2 to Grade 3, in line with the results from Blöte and Hamstra-Bletz (1991), and from Grade 3 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 Grade 2 to Grade 3 and again was even out after Grade 3. Finally, dysfluency revealed a similar pattern in the opposite direction, i.e., towards a more fluent handwriting, starting at Grade 2 and stabilizing at Grade 3. 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 was 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, were also faster in words and non-words reading and were more accurate in the non-word repetition task.

In sum, the investigation of quantity handwriting descriptors showed that from the end of Grade 2 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 implications 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; Johansson *et al.*, 1995; Robinson, 1987) and there is increasing evidence that children at familiar risk for developmental dyslexia are slow in their motor development since infancy (Viholainen *et al.*, 2002). The evidence of a similar developmental trajectory for phonological, reading and handwriting skills may support the presence of a common procedural learning circuit (Nicolson & Fawcett, 2011), whose deficit 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. This conjecture is 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).

In general, since handwriting and reading are automatized acquired skills, it is plausible to conjecture that handwriting (and more general motor abilities) and reading impairments may be caused by a failure in the acquisition of automatized skills (Nicolson and Fawcett, 1990). Following on from these observations, the present results suggest 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, Hill, 2013; Nicolson & Fawcett, 2011; Lam, et al, 2011, Pagliarini *et al.*, 2015).

The data discussed above might offer an additional piece of evidence about the influence of handwriting in learning to read. Recent 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.*, 2006; Longcamp *et al.*, 2008). Similar indications come 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 pseudo-letters trained through typing during a visual letters (and pseudo-letters) 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, Vouloumanos, Navarra, Soto-Faraco, Sebastián-Gallés & Werker, 2007). The identification of the alphabet letters and the association to their equivalent sound also benefit from Visuo-Haptic training, as it has been showed that haptic exploration of letters on letter recognition improves reading acquisition (Bara, *et al.*, 2010; Bara, Frendembach & Gentaz, 2010; Bara, Gentaz & Colé, 2007; Bara, Gentaz, Colé & Sprenger-Charolles, 2004; Gentaz, Colé & Bara, 2003). Handwriting practice and Visuo-Haptic training 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 (Bara *et al.*, 2010; Gentaz, 2009; James & Atwood, 2009; Longcamp *et al.*, 2005; Longcamp *et al.*, 2006; Longcamp *et al.*, 2008); 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 processes in the developing brain, ultimately facilitating reading acquisition in young children.

Our pattern of findings is consistent with both the hypothesis that the motor and language maturational processes rest on common brain mechanisms (Diamond, 2010; Gimenez *et al.*, 2014) and with the hypothesis that handwriting enhances visual and phonological processing, consequently fostering reading acquisition.

Although our study does not allow to disentangle between these two alternatives (but not incompatible) explanations, our findings undoubtedly show that motor development and language development are more interrelated than has been previously suggested.

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Ethical approval

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Disclosure statement

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

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Appendix: Velocity Gain Factor

Already at the end of 19th century psychologists were aware of a systematic covariation between the velocity and the geometry of handwriting movements (Jack, 1895; Binet & Courtier, 1893). 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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