Do Children with Dyslexia Present a Handwriting Deficit? Impact of Word Orthographic and Graphic Complexity on Handwriting and Spelling Performance

Key words

dyslexia;
handwriting;
spelling;
writing development;
graphomotor abilities;
learning disability

Abstract

Several studies have demonstrated that children with dyslexia frequently show poor and slow handwriting skills. It is not clear whether these difficulties are a consequence of their spelling deficit or if they arise from graphomotor difficulties. The present study aims to test the hypothesis of the presence of handwriting difficulties in dyslexia, through the investigation of the impact of graphic and orthographic complexity of words on writing. Participants were all monolingual French-speaking children. Twenty-three children with dyslexia (DYS) were compared to two groups of typically developing children: 23 chronological-age (CA) matched children and 23 spelling-age (SA) matched children. They were assessed on a single-word dictation task of 40 words on a digital tablet. The target words varied in orthographic complexity and in graphic complexity (simple vs. difficult). This task was scored on spelling accuracy, handwriting quality and handwriting speed. General Linear Mixed Model analyses revealed no global differences between the three groups for handwriting quality. However, the DYS children were more impacted by the graphic complexity of words than both the CA and SA children. These findings support the idea that children with dyslexia struggle with the graphomotor aspects of writing and have potential implications for educational and clinical supports.

What This Paper Adds?

The present paper reports relevant findings to the field of writing research and dyslexia. More precisely, it brings elements allowing a better understanding of children with dyslexia's handwriting difficulties. In terms of method, this study used an original experimental single-word dictation task on a digital tablet. Until the present experiment, no study had ever manipulated the graphic complexity of words to assess its impact on spelling accuracy and handwriting performance, and no experiment had ever been conducted on the writing skills of children with dyslexia in a dictation context. By including two typically developing groups matched to the dyslexic group on both age and orthographic abilities, our experiment was designed to determine whether children with dyslexia show deviant or delayed handwriting acquisition. Our results demonstrated similarities in the way children with dyslexia and younger spelling-matched children behaved, which highlights a delay rather than deviance. However, data also demonstrated that children with dyslexia were more impacted by the graphic complexity of words for handwriting quality, which is a sign of deviant development. Therefore, even if spelling abilities are likely to explain to some extent handwriting outcomes, they may not be a sufficient explanation for the handwriting difficulties met by children with dyslexia. These results convey practical implications, relevant to the speech therapists and school teachers. They encourage therapeutical and pedagogical approaches that better integrate the graphomotor side and the spelling side of writing.

Do Children with Dyslexia Present a Handwriting Deficit? Impact of Word Orthographic and Graphic Complexity on Handwriting and Spelling Performance

1. Introduction

Teaching how to spell accurately and how to handwrite efficiently and legibly are major concerns at the beginning of primary school (Puranik, Al Otaiba, Sidler, & Greulich, 2014). Word-writing is a complex ability, which takes time to develop since it requires the acquisition of processes that need to function in parallel: spelling retrieval processes (Rapp, Epstein, & Tainturier, 2002) and motor processes (Van Galen, 1991). Learning to write is a challenge for every individual, especially for children with dyslexia who experience great difficulty with the acquisition of the foundations of writing: spelling (Bernstein, 2009) and handwriting (Søvik, Arntzen, & Thygesen, 1987).

The presence of handwriting difficulties in dyslexia is not well documented within the literature but the idea that children with dyslexia show slow handwriting execution and poor handwriting quality is accepted (Rose, 2009). For example, in an experiment conducted by Berninger, Nielsen, Abbott, Wijsman, and Raskind (2008), US English-speaking children with dyslexia wrote fewer legible alphabet letters from memory in 15 seconds than typically developing children. The origin of those difficulties is debated, and it is not clear if they are the consequence of the spelling deficit (Kandel, Lassus-Sangosse, Grosjacques, & Perret, 2017; Sumner, Connelly, & Barnett, 2014), or if children with dyslexia encounter an additional motor deficit, which leads to handwriting difficulties (Fawcett & Nicolson, 1992). The present experiment investigated the writing difficulties in dyslexia, by comparing writing outcomes of children with and without dyslexia. This study was conducted in a French-speaking context, which implies that children learned to spell in an opaque orthography and that the handwriting instruction they received was exclusively in cursive style. Children performed a writing task with words varying in terms of orthographic and graphic difficulty, allowing determining how each complexity influences spelling and handwriting outcomes.

1.1. Writing Difficulties in Children with Dyslexia

The difficulties experienced by children with dyslexia in writing have been documented more frequently with orthographic skills rather than graphomotor skills. Indeed, the existence of a spelling deficit in dyslexia is indisputable (Afonso, Suárez-Coalla, & Cuetos, 2015; Chilosi et al., 2009, Snowling, 2000). On the contrary, even though the presence of motor difficulties in children with dyslexia has been highlighted in the literature for decades (Nicolson & Fawcett, 1990), numerous questions remain concerning the impact that dyslexia can have on spelling and graphomotor development (Arfé, Dockrell & Berninger, 2014).

In the early nineties, Nicolson and Fawcett (1990) proposed the deficit in automatisation hypothesis, which stipulates that children with dyslexia would struggle to make any new skill automatic. Throughout their work, Fawcett and Nicolson gathered evidence that children and adults with dyslexia demonstrate signs of cerebellar impairment (Fawcett & Nicolson, 1992; Fawcett, Nicolson, & Dean, 1996; Nicolson, Fawcett & Dean, 2001) and those signs were confirmed with fMRI studies (Stoodley & Stein, 2011). However, these motor theories of dyslexia have been disputed within the literature. First, those studies do not allow confirmation of the relation of causality between motor difficulties and the deficit in written language. For instance, the difficulties in motor abilities could be attributed to the comorbidity between dyslexia and attention deficits (Ramus, 2003). Moreover, the evidence of motor difficulties in dyslexia can only be found in a percentage of children with dyslexia. Iversen, Berg, Ellertsen, and Tønnessen (2005) reported that motor coordination difficulties were found in over 50% (but not all) of their sample composed of 20 Norwegian-speaking children with dyslexia and 17 poor readers.

Recent studies have given an alternative explanation regarding the presence of handwriting difficulties in dyslexia. Authors demonstrated that the difficulties in handwriting observed in children with dyslexia can be interpreted as the consequence of their deficit in spelling with the following explanation: since they have poor orthographic abilities, they need to take longer pauses inside and between words during writing. This was demonstrated thanks to the use of digital tablets in a text composition task in UK English (Sumner, Connelly, & Barnett, 2013) and in a sentence-copying task (Sumner, et al., 2014). In these experiments, children with dyslexia executed handwriting at the same speed as typically developing children but needed to pause more often. Such conclusions were also reached in a French-speaking sample of children with dyslexia in a study conducted by Kandel et al. (2017), who also used digital tablets for data collection. This experiment revealed that the interaction between orthographic and motor processes during writing had a negative impact on handwriting outcomes (movement duration and fluency), stronger in the group composed of children with dyslexia than in a control group. These results do not support the hypothesis of an actual motor deficit in dyslexia and highlight the need to better understand children with dyslexia's writing difficulties.

1.2. Handwriting Acquisition in Cursive Context

Children have to develop their graphomotor abilities to accurately produce the shapes of the alphabet letters on paper, which imply various demands in terms of graphomotor abilities. They will need to acquire a good level of handwriting speed to be able to keep up with school's requirements. Before automatisation, children's resources are largely required by the graphomotor processes (Jones & Christensen, 1999). Therefore, handwriting automatisation is an important stage since it will allow children to allocate more resources to higher-processes (Pontart et al., 2013) such as spelling, idea generation, syntax, etc. According to the Capacity Theory of Writing, the lower processes (i.e. the graphomotor gesture) must be automatised to allow higher-level writing processes to develop, by using the available resources (McCutchen, 1996). There is no consensus on the stage at which handwriting becomes an automatised skill with research suggesting it would occur at the beginning of primary school (Overvelde & Hulstijn, 2011) and others in secondary school (Graham, Berninger, Weintraub, & Schafer, 1998). It may also depend on the learning context according to the children's country (e.g. script in English speaking countries *vs*. cursive in French speaking countries). Indeed, cursive style requires more advanced fine-motor skills compared to script style (Anonymous, 2018; Paoletti, 1999). As shown in a previous experiment conducted by Anonymous (2018), some graphic aspects lead to handwriting difficulties, like abrupt changes of pen stroke trajectory. In cursive handwriting style, children have to join all the letters within the words together, and the main difficulty arises from the modification of the link between two letters.

1.3. Learning to Spell in an Opaque Language

During learning to write, children have to deal with different levels of orthographic complexity. Regarding orthographic complexity, some words are very easy to spell and are mastered very early like the regular words (i.e. high level of consistency of the correspondences between phonemes and graphemes). Conversely, especially in the less transparent languages, some words will require more time to be mastered by children because they comprehend complex sounds and inconsistencies (Alegria & Mousty, 1996). Therefore, in the less transparent languages (e.g. English and French), the challenge is even bigger for children because mastering the correspondences between phonemes and graphemes is not sufficient to reach correct spelling. Children must also develop their lexical orthographic knowledge to be able to successfully write irregular words. Those challenges will be even greater in children with dyslexia. They struggle to learn the correspondences (phonological dyslexia) or to add new words to their orthographic lexicon in memory (surface dyslexia) or both (Castles & Coltheart, 1993).

Experiments have demonstrated that handwriting and spelling interact during writing. For instance, it has been demonstrated that children's handwriting skills have an impact on writing and spelling outcomes (Graham, Harris, & Fink, 2000; Jones & Christensen, 1999; Wicki, Lichtsteiner, Geiger, & Müller, 2015), as well as the graphomotor demand induced by writing tasks (Van Reybroeck & Hupet, 2009). An experiment conducted by Kandel and Perret (2015) studied the opposite direction of the relationship, and revealed that the orthographic characteristics of words (e.g. regular vs. irregular words in French) have an impact on handwriting fluency and speed. Previous findings demonstrated that difficulties with spelling lead to poorer quality and fewer quantity of word writing (Abbott, Berninger, & Fayol, 2010). Investigating how the graphic side of writing can influence spelling as well as the opposite relationship is a relevant approach to study the handwriting difficulties of children with dyslexia.

It has been found that children with dyslexia have a deficit in spelling and some studies have also revealed difficulties in handwriting. However, the origin of those handwriting difficulties is not established. There is a need for detailed investigation of the writing production of children with dyslexia. It is essential to compare their performance to one of their typically developing peers, matched on chronological age and also on spelling level (as in Sovik & Arntzen, 1986; Sumner et al., 2014) to shed light on delayed or deviant handwriting development in dyslexia. Recent findings identified the graphic aspects of words that lead to high graphic complexity (Anonymous, 2018). With regard to the orthographic side, words also have different levels of orthographic complexity: some words (i.e. regular words) are easier to spell than others (i.e. irregular words). Manipulating the level of orthographic complexity allows its impact on handwriting outcomes to be evaluated. As far as we know, no study has ever manipulated the graphic complexity of words to investigate its impact on spelling accuracy and handwriting performance. Moreover, no experiment has ever been conducted on the writing skills of children with dyslexia in a single-word dictation context.

2. Objective

The main purpose of this experiment is to better understand the difficulties met by children with dyslexia (DYS) in handwriting, by examining both the orthographic and graphomotor sides of writing. Children took a single word dictation task on a digital tablet, composing words that varied in orthographic and graphic levels of complexity. For each child, measures of handwriting quality, handwriting speed and spelling accuracy were taken. These measures were then compared with two control groups composed of typically developing children: chronological age-matched children (CA) and spelling age-matched children (SA). To fulfil the main purpose, the present experiment will focus on answering three research questions. The research questions and the predictions associated with each question are presented below.

(i) Do DYS children show poorer handwriting quality and slower handwriting execution than CA and SA children?

In the context of the graphomotor deficit in dyslexia hypothesis, we expect them to show poorer handwriting quality and slower handwriting speed than both CA and SA children. If DYS children do not have specific graphomotor difficulties, their handwriting performance should be comparable to the one of CA and SA children.

(ii) Are DYS children more impacted by the graphic complexity of words than CA and SA children?

In the context of the graphomotor deficit in dyslexia hypothesis, we expect the impact of graphic complexity to be higher in the DYS group than in the CA and SA groups. This effect should appear on the three writing variables: handwriting quality, handwriting speed and spelling accuracy. If DYS children do not present specific difficulties arising from the graphomotor side of writing, we expect the impact of graphic complexity to be equivalent in the three groups.

(iii) Are DYS children more impacted by the orthographic complexity of words than CA and SA children?

The SA children were matched on spelling age with DYS children, allowing comparing handwriting outcomes when spelling level is equivalent. In the context of the graphomotor deficit in dyslexia hypothesis, we expect handwriting quality and handwriting speed to be more impacted by orthographic complexity in the DYS group than in the SA group. Observing this result would be in favour of a deviant development of handwriting in dyslexia. If DYS children do not present specific difficulties arising from the graphomotor side of writing, we expect the impact of orthographic complexity on handwriting variables to be equivalent in the DYS and SA groups. In any case, since DYS children have lower spelling abilities than CA children, handwriting quality and speed in the DYS group should be more impacted by orthographic complexity than in the CA group.

3. Method

3.1. Participants

Participants were from two rural French-speaking primary schools in Belgium with a middle socio-economic status. The headmasters and the teachers voluntarily took part in this experiment, and the children's parents gave active consent. No selection criteria were used at the start of the experiment. The ethical commission of the The Psychological Sciences Research Institute of the main experimenter's institution approved the experiment (reference: Anonymous). Data were collected in February and March 2018. Children from eight classes (Grade 2, Grade 3 and Grade 4) were tested (*N* = 136).

Amongst those, 13 children in Grade 3 and 10 children in Grade 4 were identified as having dyslexia (DYS, n = 23, 13 girls, M age = 9;1 years, age range: 8;10 – 10;10 years). They had all been diagnosed by a speech therapist and they all performed below two standard deviations in the standardised spelling measure Chronosdictées (Beneath, Boutard, & Alberti, 2006). They were matched to typically developing children on either chronological age (CA children, n = 23, 13 girls, M age = 9;2 years, age range: 8;10 – 10;10 years) or spelling age (SA children, n = 23, 11 girls, M age = 7;6 years, age range: 7;4 – 8;7). To accurately match the DYS children and the SA children, their raw scores at the standardised spelling task was first taken into account. Each DYS child was matched with a 2nd grader who had performed similarly at the spelling task, who came from the same school and, as much as possible, of the same sex. Therefore, the present sample was composed of 69 French-speaking Belgian children. A series of one-way analyses of variance (ANOVAs) demonstrated no differences between the three groups in non-verbal IQ ability assessed through matrices subset of the WISC-IV (Weschler Intelligence Scale for Children – Fourth Edition; Weschler, 2005) ($F(2, 66) = 2.56$, p = .08) and in receptive vocabulary ability assessed with the EVIP designation task (Echelle de vocabulaire en images Peabody [Peaboby picture vocabulary scale]; Dunn, Dunn, & Theriault-Whalen, 1993) ($F(2, 66) = 1.45$, p = .24). A difference in age was observed between the three groups ($F(2, 66) = 55.65$, p = < .001). Bonferroni Post hoc comparisons revealed that the DYS and CA group were accurately matched on age (p = 1.00) and that SA were significantly younger than both DYS and CA (*all p*s < .001). The analysis also revealed a difference in spelling accuracy assessed with the Chronosdictées standardised task (Beneath et al., 2006) ($F(2, 66) = 24.48$, p < .001). Bonferroni post hoc comparisons revealed that the DYS children were accurately matched on spelling ability with the SA children (p = 1.00), and that both DYS and SA children performed significantly lower than

CA children (*all p*s < .001). More details regarding participants' characteristics and differences between groups are presented in Table 1.

3.2. Materials

To complete the dictation task, each child was given a digital tablet and a digital pen (Wacom Intuos Pro Medium and Wacom Inking Pen). The tablets' size was 380 x 251 x 12 mm, with an active area of 224 x140 mm. The single-word dictation task was composed of 40 words. The words were selected according to their levels of orthographic and graphic complexity, and they were matched on several variables as shown in Table 2.

3.2.1. Orthographic complexity (O-simple and O-difficult).

The orthographic level of complexity refers to the spelling demands of words. To determine the words' level of orthographic complexity, word regularity and word success rate for children in Grade 2 in the French database EOLE (Echelle d'acquisition en orthographe lexicale [lexical spelling acquisition scale]; Pothier & Pothier, 2003) were taken into account. Regular words with a high success rate (> 75% in EOLE for Grade 2) were selected for the lists *orthographically simple* (O-simple). On the contrary, words with complex or irregular phoneme-grapheme correspondences and with a lower success rate (< 50% in EOLE for Grade 2) were selected for the lists *orthographically difficult* (O-difficult).

3.2.2. Graphic complexity (G-simple and G-difficult).

The graphic level of complexity refers to the graphomotor demands required by handwriting words. Words that include abrupt changes in pen stroke trajectory are more complex than words mostly containing curvy segments. This information came from a previous experiment conducted by Anonymous (2018) in which the authors determined how children were influenced by those characteristics for handwriting speed and legibility. The authors also quantified each characteristic complexity by coefficients. This led to a formula applied to a complete French lexical database (LEXIQUE, New, Pallier, Brysbaert, &

Ferrand, 2004), giving a value for each word's graphic complexity. To determine the reference values for low and high levels of complexity (G-simple vs. G-difficult), the percentiles 25 and 75 of the entire database were used as thresholds. This revealed a maximum threshold for G-simple of 15.6 (Percentile 25) and a minimum threshold for G-difficult of 19.4 (Percentile 75).

The first list was composed of words simple on both dimensions (O-simple; G-simple), the second list was composed of words difficult to spell and easy on the graphomotor dimension (O-difficult; G-simple), the third list was composed of words easy to spell and complex in terms of graphomotor gesture (O-simple; G-difficult) and the fourth list was composed of words complex on both dimensions (O-difficult; G-difficult).

Table 2 presents the four lists characteristics as well as an example to illustrate each list. Equivalence and differences between lists are also presented.

3.3. Measures

In the present experiment, children were administered several control tasks as well as the single-word dictation experimental task. The control tasks were used to match the DYS children to CA and SA children and to provide information about the participants in general cognitive abilities and written language skills. The experimental task was exclusively used to answer the research questions.

3.3.1. Control Measures

Word reading. Reading ability was assessed with a single-word reading test administered to the children, (LUM, Lecture en Une Minute [One minute reading]; Khomsi, 1999), which consisted of reading a maximum of the words in one minute. The test is composed of 105 words. Children's scores were calculated by counting the number of words correctly read within one minute. Their scores were then compared to the test's norms.

Handwriting speed in copying task. Participants' handwriting speed was assessed with a text copying task taken from a standardised test, in the limited time of five minutes (BHK, [Concise evaluation scale for children handwriting]; Charles, Soppelsa, & Albaret, 2004). The number of letters correctly copied was scored, and then compared to test age norms as an indicator of handwriting speed.

Handwriting quality in copying task. The quality of the handwriting was also assessed with the standardised test BHK, through the use of precise aesthetic criteria (e.g. size of the letters, correction of letter forms, letter distortion). Each sentence was scored according to those criteria. The presence of one of the graphical errors leads to attributing 1 point. Therefore, low scores refer to good handwriting quality, whereas high scores reflect poor handwriting quality. BHK (Charles et al., 2004) is a standardised test, allowing the comparison of participants' performances with their school level norms for both speed and quality. The task has a very high reported interrater reliability ($r = 0.90$), and the internal reliability in the current sample given by Cronbach's alpha is .83.

Spelling accuracy. Spelling ability was assessed with a sentence dictation task (Chronosdictées, Beneath et al., 2006). The task includes regular words and words with complex phoneme-grapheme correspondences, allowing scoring the productions on both phonological and lexical spelling. This test also considers grammatical spelling since it includes several instances of verb and noun agreement. Low raw scores refer to few spelling errors, while high scores refer to more spelling mistakes committed. Test length gradually increases through primary school grades. It consisted of three sentences in Grade 2, five sentences in Grade 3 and seven sentences in Grade 4. Children's scores were compared to the norms for their grade, on phonological spelling, lexical spelling and grammatical spelling as well as their total score. For clarity, the present experiment will only report the children's total score.

3.3.2. Experimental Measures

The three experimental measures presented below were extracted within the same single-word dictation task.

Handwriting quality in experimental task. Scoring of the experimental task was inspired by the BHK scale, (Charles et al., 2004), from which we selected five handwriting quality criteria that were suitable to the context of single-word writing that all referred to a type of graphical error. The words were assessed in a binary way, with the score of 1 attributed in the case of the presence of a graphic abnormality, and 0 being the score of expected handwriting performance. In other words, an item with a score of 0 referred to excellent handwriting quality, whereas a score greater than or equal to 1 referred to poorer handwriting quality. The presence of one of the following abnormal elements was systematically noted: (1) distortion of a letter, ending up with an abnormal letter form; (2) inconsistent letter size, referring to a situation where there is an abnormal variation of the letter size within the same word (3); inconsistent relative height of letters, meaning that small letters (e.g. "*a*", "*i*", "*s*") are produced at the same height of tall or tail letters (e.g. "*y*", "*t*", "*h*") and vice-versa; (4) correction of letter forms, noticeable by the presence of a graphic correction on paper; and (5) bad letter alignment within the word, when horizontality of the handwriting is violated. The examiner was given detailed guidelines on how to assess the children's handwriting performances, with precise judgement criteria. A total score per word was computed, by adding the score for each criterion, leading to a maximum score of 5 per word written. For handwriting quality, high scores refer to poor handwriting while lower scores refer to better legibility. Percentages of agreement between the three scorers were calculated in a sample of 160 words (17.25% of the total sample coded by the three scorers). They revealed high percentage of agreement amongst raters for each criterion: for distortion of letters (92%), inconsistent letter size (90%), inconsistent relative height of letters (85%), correction of letter forms (80%) and bad letter alignment (94%).

Handwriting speed in experimental task. Each word's production time was directly extracted from the tablets, measured in milliseconds, giving a value for handwriting speed. The recording started at the very beginning of each word's pen stroke, until the very end of the word. The pauses inside the words and in air phases (i.e. pen lifts) are not taken into consideration. The values for speed refer to the distance covered while the pen was on the sheet of paper (cm/s). A low value refers to slow handwriting, whereas high values refer to fast handwriting execution.

Spelling accuracy in experimental task. Children were given one point for each word correctly spelled and the score 0 in the case of a spelling error. The internal reliability in the current sample given by Cronbach's alpha is .86.

3.4. Procedure

The whole experimental phase occurred in an empty classroom within the children's respective schools. Three experimenters administered the control tasks. They lasted approximately 30 minutes and were administered to each child individually. One of the experimenters also administered the experimental single-word dictation task in the presence of an engineer in charge of the tablets and computers. The experimental task lasted approximately 20 minutes and was administered in groups of four children, and testing took place over six weeks. The children were simply asked to write down the words they heard, at their usual speed. The experimenter emphasised the fact that the dictation task would have nothing to do with their school results and that even if some words seemed too difficult for them, they should try to write them down to the best of their ability. It was explained that their writing was recorded inside the tablets and that the engineer would then be able to analyse all their productions on his computer. The children were not informed about the focus on handwriting quality and speed. In order to have enough space to write down the 40 words, three testing A4 sheets were provided for each child. The writing task was completed on unlined paper, which was attached on top of the tablet with tape. The testing conditions were close to how they usually write since children had to write down on white paper, with an ink pen. To make sure the children would write within the active zone, it was clearly marked out by a frame drawn on each sheet. Additionally, in order to guide the children throughout the task and to make sure they would write in the correct space, dashes followed by each word's determiner (either – *le* or – *la* [the], or either – *un* or – *une* [a]) were placed vertically, according to the order used for the dictation. Children had to fill in the blank following each determiner. Their productions were recorded in real time, with a sample frequency of 7/8ms.

3.5. Data Analysis

All statistical analyses were run on IBM SPSS Statistics 24. Since the shape of the distributions for the measure of speed was asymmetric (Sk = 52 and Ku = 2747), handwriting average speed per word was transformed (LN transformation) to reach distributions within acceptable levels of peakedness and symmetry. Preliminary analyses on all the other dependent variables revealed no distributional problems, with data meeting the normality assumption for parametric procedures (all Sk < 2 and Ku < 7).

To answer the present experiment's research questions, the three scores from the single-word dictation task were used (three dependent variables: handwriting quality, handwriting speed and spelling accuracy). Descriptive statistics are presented in Table 3 to provide readers with details on the children's performances. The analyses conducted to answer the present experiment's aims will be reported below. Generalised Linear Mixed Models (GLMM) associated with repeated measures ANOVAs were used to answer the experiment's questions: (i) Do DYS children show poorer handwriting quality and slower handwriting execution than CA and SA children?; (ii) Are DYS children more impacted by graphic complexity of words than CA and SA children?; and (iii) Are DYS children more impacted by orthographic complexity of words than CA and SA children?

The GLMM analyses allow accounting for both the variability induced by children and that induced by the items within the same analyses. In the GLMM, participants ($N = 69$) were entered as random factor. Group (three levels: DYS, SA and CA), Orthographic complexity (two levels: simple and difficult) and Graphic complexity (two levels: simple and difficult) were entered as fixed factors. We also checked whether the interactions were significant between Group × Orthographic Complexity and between Group × Graphic Complexity. When the main effect of group was significant, the post-hoc sequential Bonferroni given by the GLMM were reported to locate the differences between our three groups. When interactions were significant, simple effects were examined with repeated measures ANOVAs, which allowed comparing the performances within group between the conditions (O-simple vs. O-difficult and G-simple vs. G-difficult). To report effect sizes, partial eta squared values from the ANOVAs models were used for main effects and interactions (cf. Table 4), and additional Cohen's *d* were calculated in the case of pairwise comparisons.

To complete the experimental single word dictation task, the 69 participants each wrote 40 words, leading to 2760 words produced. The 3 × 2 × 2 GLMM analysis for spelling accuracy was thus run on 2760 items. A very low percentage ($n = 12$; 0.4%) of the handwritten words could not be correctly handled and segmented because of technical recording issues. Therefore, the 3 × 2 × 2 GLMM for handwriting speed was conducted on 2748 words.

Moreover, a precaution was taken regarding the analysis of the variable handwriting quality, due to the high proportion of misspelled words. Out of the 2760 words written by the children, only 1334 words were accurately spelled. This could bias our findings regarding the handwriting quality measures. Indeed, when words were too difficult to spell for the children, they simplified the spelling and shortened the words in most cases. Since the graphic complexity of words was determined on the basis of the letters making up the words, when a production was misspelled and shortened, handwriting scoring could disadvantage the children who produced accurate spelling. For example, the word *brebis* (ewe) was spelled accurately by Child 1 but Child 2 produced *bebi*. In this case, Child 2 simplified the target word, since he only wrote four letters out of the six target letters. Consequently, the chance of finding aesthetic errors in Child 2's production was reduced compared to Child 1 who produced accurate spelling. By conducting the GLMM for handwriting quality on correctly spelled words only (n = 1334), we ensured that the exact same productions were compared between children. Those accurately spelled words were mainly from the condition orthographically simple, since only 13% of the orthographically complex words were spelled successfully. For this reason, orthographic complexity was not entered as a fixed effect in the GLMM for handwriting quality, leading to a 3 × 2 GLMM.

4. Results

Preliminary correlational analyses were carried out, revealing the associations between children's performances in the different control tasks and the experimental word-dictation task. Handwriting quality in the experimental task was positively related to spelling (Chronosdictées, Beneath et al., 2006), meaning that poor spelling abilities were associated with poor legibility. Handwriting speed in the experimental task did not relate to any of the other measures. A strong and expected correlation was found between the two measures of spelling accuracy (in the control task, Chronosdictées, Beneath et al., 2006; and in the experimental task). Pearson's correlation coefficients are presented in Table 4.

The CA and DYS groups were composed of children coming from two different grades: grades 3 and 4, whereas the SA group was composed of 2^{nd} graders only. To check whether this plurality of grades within group would influence the results, ANOVAs were run on the CA and DYS samples. They revealed no effect of grade in the way children were impacted by orthographic and graphic complexity on the three variables. Indeed, for the interactions Grade × Graphic Complexity and Grade × Orthographic Complexity were not significant for handwriting quality ($F(1, 43) = 0.07$, $p = .79$; $F(1,43) = 2.46$, $p = .12$), handwriting speed, ($F(1,43) = 2.43$, $p = .13$; $F(1, 43) = 0.19$, $p = .67$) and spelling accuracy, ($F(1, 43) = 3.29$, $p = .08$; $F(1, 43) = 1.19$, $p = .28$). Therefore, grade was not introduced in the following GLMM analyses.

4.1. General Linear Mixed Models

The GLMM was run separately for each dependent variable, leading to three models: spelling accuracy, handwriting quality on words correctly spelled, and handwriting speed. The results are reported in Table 5.

4.1.1. Handwriting Quality

Regarding handwriting quality, the GLMM analyses were conducted on words with accurate spelling only ($n = 1334$), leading to a 3 × 2 GLMM with Group [DYS, CA, SA] × Graphic Complexity [simple, difficult] entered as fixed effects. This analysis did not demonstrate any significant effect of group ($p = .35$). The DYS children ($M = 1.53$, $SD = 0.60$) had the same handwriting quality as the CA children ($M = 1.31$, $SD = 0.51$) and SA children ($M = 1.54$, $SD = 0.43$). The model revealed an effect of the word's graphic complexity on handwriting quality ($p < .001$). High levels of graphomotor demand negatively influenced all the children, leading to more aesthetic errors committed on the graphically difficult words than on the graphically simple words. A significant interaction Group × Graphic Complexity was found ($p = .007$). Simple effects analyses revealed that all children were impacted by graphic complexity on handwriting quality, but the effect size was higher in the DYS group than in the two typically developing groups. Indeed, the effect size in the DYS group was medium ($F(1, 22) = 18.57$, $p < .001$, $\eta p^2 = .46$, $d = 0.49$) whereas they were small in the CA group ($F(1, 22) = 9.97$, $p = .005$, $\eta p^2 = .31$, $d = 0.32$) and in the SA group ($F(1, 22) = 13.12$, $p = .002$, $\eta p^2 = .37$, $d = 0.42$). This interaction is represented in Figure 1.

4.1.2. Handwriting Speed

Regarding speed of handwriting, as shown in Table 5, the 3 × 2 × 2 GLMM demonstrated a significant effect of group ($p = .007$). Post hoc sequential Bonferroni showed that the DYS ($M = 0.43$, $SD = 0.36$) and CA children ($M = 0.44$, $SD = 0.48$) wrote at the same speed ($t(2739) = 0.137$, $p = .89$). DYS and SA children ($M = 0.22$, $SD = 0.39$) also wrote at the same speed ($t(2739) = 1.970$, $p = .09$). The SA children were slower than the CA children ($t(2739) = 2.784$, $p = .02$, $d = 0.50$). The GLMM also revealed a significant effect of both orthographic (O-simple vs. O-difficult) and graphic complexity (G-simple vs. G-difficult), with the difficult words written significantly more slowly than the simple words (all $ps < .001$). The interactions Group × Orthographic Complexity ($p = .007$) and Group × Graphic Complexity ($p < .001$) were both significant. For orthographic complexity, the simple effects analyses revealed that the DYS ($F(1, 22) = 30.61$, $p < .001$, $\eta p^2 = .58$, $d = 0.24$) and CA children ($F(1, 22) = 13.58$, $p = .001$, $\eta p^2 = .38$, $d = 0.18$) had significantly faster handwriting for the orthographically simple than for the difficult words. The SA children were not influenced by orthographic complexity ($F(1, 22) = 0.99$, $p = .76$). Speed of handwriting was impacted by graphic complexity in the DYS group ($F(1, 22) = 46.52$, $p < .001$, $\eta p^2 = .68$, $d = 0.36$) and in the CA group ($F(1, 22) = 18.91$, $p < .001$, $\eta p^2 = .46$, $d = 0.27$). On the contrary, the 2nd grade SA children were not influenced by graphic complexity of words for handwriting speed ($F(1, 22) = 1.98$, $p = .17$). These results are illustrated in Figures 2 and 3.

4.1.1. Spelling Accuracy

The 3 × 2 × 2 GLMM conducted on spelling accuracy is presented in Table 5. It revealed a significant effect of words' graphic complexity, meaning that graphically complex words led to more spelling mistakes than graphically simple words. A similar and significant expected effect of orthographic complexity was also found, meaning that orthographically complex words led to more spelling mistakes than orthographically simple words. The analysis demonstrated that the effect of Group was significant. The DYS children ($M = 0.43$, $SD = 0.49$) and SA children ($M = 0.42$, $SD = 0.49$) performed significantly lower than the CA children ($M = 0.60$, $SD = 0.49$); respectively $t(2751) = 6.364$, $p < .001$, $d = 0.35$ and $t(2751) = 6.614$, $p < .001$, $d = 0.37$. No differences were found for spelling accuracy between the DYS and SA children ($t(2751) = 0.155$, $p = .98$). The interaction Group × Orthographic Complexity ($p = .007$) was significant. The DYS ($F(1, 22) = 944.78$, $p < .001$, $\eta p^2 = .98$, $d = 2.4$) and SA children ($F(1, 22) = 703.60$, $p = <.001$, $\eta p^2 = .97$, $d = 2.19$) were equally impacted by orthographic complexity. They were more influenced than the CA children ($F(1, 22) = 344.31$, $p = <.001$, $\eta p^2 = .94$, $d = 1.83$) by orthographic complexity. The interaction Group × Graphic Complexity was also significant ($p < .001$). Spelling accuracy was impacted in the DYS group by graphic complexity ($F(1, 22) = 22.11$, $p = < .001$, $\eta p^2 = .50$, $d = 0.25$), whereas the CA children did not react to this manipulation ($F(1, 22) = 3.96$, $p = .06$). The SA children's spelling outcomes ($F(1, 22) = 82.29$, $p = < .001$, $\eta p^2 = .58$, $d = 0.31$) were also impacted by graphic complexity. These two interactions are represented in Figures 4 and 5.

5. Discussion

Children with dyslexia commonly demonstrate a spelling deficit (Snowling, 2000), and past research have also suggested difficulties in handwriting skills (Cheng-Lai, Li-Tsang, Chan, & Lo, 2013; Martlew, 1992; Sovik & Arntzen, 1986). However, this last assumption has received little attention within the literature. The aim of this experiment was to better understand DYS children's writing difficulties, by analysing spelling accuracy, handwriting quality and handwriting speed. For this purpose, DYS, CA and SA children performed a single-word dictation task. In this task, the target words varied in orthographic and graphic complexity. This design allowed the investigation of the impact of the word's graphic complexity and the word's orthographic complexity on writing outcomes. Until the present experiment, no study had ever manipulated the graphic complexity of words to assess its impact on spelling accuracy and handwriting performance, and no experiment had ever been conducted on the writing skills of DYS children in a dictation context. This discussion section will focus on answering the three research questions.

5.1. Do Children with Dyslexia Show Poorer Handwriting Quality and Slower Handwriting Execution than Typically Developing Children?

In the context of the graphomotor deficit in dyslexia hypothesis, we expected DYS children to show poorer handwriting quality and slower handwriting speed than typically developing children. Our findings did not support this hypothesis. Indeed, DYS children wrote as fast as their chronological age matched peers. Our results are in line with recent findings, which demonstrated that DYS children are not slower at handwriting execution than typically developing children (Sumner et al., 2013). The experiment showed that the SA children in Grade 2 were slower than older children in Grades 3 and 4, whether they belonged to the DYS group or not. This demonstrated that handwriting speed depends on school grade, which was expected since it is a skill that needs practice to become more and more automatic throughout the years of writing experience (Jones & Christensen, 1999; Overvelde & Hulstijn, 2011; Wicki et al., 2015). Regarding handwriting quality performance, all groups had equivalent handwriting quality. These results do not support the hypothesis of an additional graphomotor deficit in dyslexia. However, differences were found in the way word graphic complexity impacted writing outcomes, which are developed below.

5.2. Are Children with Dyslexia More Impacted by Graphic Complexity of Words than Typically Developing Children?

In the context of the graphomotor deficit in dyslexia hypothesis, we expected the impact of graphic complexity on writing to be higher in the DYS group than in the CA and SA groups. Our results go in that direction, since differences were found between control children and DYS children in the way graphic complexity impacted both handwriting quality and spelling. Interestingly, results demonstrated that DYS children's handwriting quality was more impacted by graphic complexity of words. Until the present study, no experiment had analysed handwriting quality with such precise criteria on each word written. In our experiment, the difference of handwriting quality between graphically simple words and graphically complex words was greater in DYS children than in typically developing children. Since those typically developing children included a group that was matched on spelling level (SA) with the DYS group, this effect cannot be explained by DYS children's poor spelling abilities. Moreover, it is worth noting that the SA children (Grade 2) were on average a year and a half younger than DYS children (Grades 3 and 4), which implies that DYS children were more experienced in handwriting. Despite this advantage in the DYS group, the negative impact of graphic complexity was still higher. It constitutes evidence that DYS children present signs of a deviant handwriting development, specific to the graphic side of writing. This result is complementary to previous findings in favour of the idea that DYS children are less legible than other children (Berninger et al., 2008; Iversen et al., 2005; Martlew,1992).

Regarding spelling accuracy, another relevant finding from our experiment was that words' graphic complexity also influenced spelling outcomes to a greater extent in the DYS group than in the chronological age matched group. In the group composed of DYS children, the graphically complex words led to lower spelling accuracy than the graphically simple words. This difference between the two graphic conditions was not found in the CA typically developing group. Yet, the DYS and SA groups demonstrated a similar profile, with their spelling accuracy being impacted by graphic complexity to the same extent. This means that when children have low orthographic abilities, spelling is more challenged by the graphomotor demand implied by the words they are handwriting. This can be interpreted within the framework of the Capacity Theory of Writing (McCutchen, 1996). Indeed, young children or DYS children need to dedicate more resources to spelling than skilled-spellers. Therefore, increasing the graphomotor demand has a negative impact on spelling since resources have to be allocated to the graphomotor side of writing. In that sense, the spelling deficit in DYS children could explain the difficulties observed on the graphomotor side of writing. However, as recalled above, DYS children in Grades 3 and 4 had been using handwriting for longer than the SA children, who were only in their second year of primary school. Therefore, it is interesting to observe that DYS and SA were equally impacted by graphic complexity for spelling outcomes, despite the DYS group's advantage of being older and more experienced in handwriting. Keeping in mind this element, the spelling deficit may not be a sufficient explanation to the difficulties observed in relation to the graphic side of writing.

5.3. Are Children with Dyslexia More Impacted by Orthographic Complexity of Words than the Typically Developing Children?

Data from the present experiment did not allow this question to be answered exhaustively. Indeed, as explained in the Results section (cf. 4.3), handwriting quality for the misspelled words could not be analysed, since it would bias our interpretations. Since our experiment led to a floor effect on orthographically complex words, the impact of orthographic complexity on handwriting quality could not be investigated. However, we can discuss the results insofar as the orthographic complexity of the words impacts on handwriting speed and on spelling accuracy. Regarding handwriting speed, DYS and CA children demonstrated faster handwriting for the orthographically simple words than for the orthographically difficult words, which is not surprising. This difference between the two conditions was not observed in the SA group. The explanation to this is that SA children were younger, with little experience in writing production. Thus, their handwriting was slow, whatever the level of orthographic complexity. For spelling accuracy, our experiment revealed that all children have lower spelling accuracy for orthographically complex words than for simple words, which was expected. The experiment also revealed DYS children, as well as younger SA children in Grade 2, were more negatively influenced by the orthographic complexity of words than CA children. This greater impact of orthographic complexity on spelling accuracy in the DYS group was also expected, since those children have lower spelling skills.

As a whole, our findings bring new elements to the investigation of of handwriting difficulties in dyslexia as well as their associated factors. Because DYS children did not show slower and poorer handwriting ability overall, our results cannot support the hypothesis of the presence of a global graphomotor deficit as such, along with dyslexia. This is in line with previous findings (Berninger et al., 2008; Sumner et al., 2014), supporting the idea that DYS children have writing difficulties because of their spelling deficit. However, this does not mean that their poor spelling abilities are the only cause of their handwriting difficulties. Indeed, this experiment demonstrated that DYS children faced more difficulties when the words were graphically complex than typically developing children, for both spelling and handwriting quality.

These findings support the idea that DYS children struggle with the graphomotor side of writing. However, their difficulties may not be as obvious as the motor hypothesis of dyslexia claims, since they appeared when the graphomotor demand increased. Moreover, the fact that their handwriting quality was even more impacted by graphic complexity than younger SA children is strong evidence that their spelling level cannot completely explain their handwriting performance. By including two typically developing groups matched to the dyslexic group on both age and orthographic abilities, our experiment aimed to determine whether DYS children show deviant or delayed handwriting acquisition. Our results demonstrated similarities in the way DYS children and younger SA children behaved, which highlights a delay rather than deviance. However, the fact that DYS children were more impacted than SA children by the graphic complexity of words for handwriting quality is a sign of deviant development.

DYS children were also more impacted by the orthographic complexity of words for handwriting quality than CA children. One possible explanation for these findings could lie in the concept of orthographic-motor integration, which was the focus of works conducted by Christensen (2005; Christensen & Jones, 2000; Jones & Christensen, 1999). Several studies have proved that children who have not reached sufficient level of automaticity in orthographic-motor integration face difficulties in text writing (Berninger & Swanson, 1994; Graham, 1990). Medwell and Wray (2007) defined orthographic-motor integration as “the ability to call to mind and write letter shapes, groups of letters and words efficiently and effectively without allocation of cognitive attention” (p. 12). The difficulties met by children with dyslexia on both spelling and handwriting could hamper the orthographic-motor integration processes. This would explain why, in the present study, their spelling difficulties were more prominent when they were asked to write graphically complex words compared to simple words.

In conclusion, even if spelling abilities are likely to explain to some extent handwriting outcomes, they may not be a sufficient explanation for the handwriting difficulties met by DYS children. These results highlight the need to keep exploring DYS children’s handwriting skills.

Finally, it is worth recalling that most of the studies reported in this discussion were conducted in English speaking contexts (Berninger et al., 2008; Graham, Harris, & Fink, 2000; Jones & Christensen, 1999; Sumner et al., 2014), while the present experiment occurred in a French-speaking context. However, it is worth considering generalising the present findings to other opaque orthographies, such as English. It is true that differences exist between French and English when it comes to development of literacy, especially in reading. Indeed, the direction spelling-to-sound is more predictable in French than in English. However, when it comes to spelling, those two languages are equally complex and opaque in the direction of sound-to-spelling (Ziegler et al., 1996). Therefore, from an orthographic perspective, we would expect a replication of this experiment in English to lead to similar conclusions. However, writing does not only depend on the orthographic characteristics of the language, but also on the graphic side of writing. Indeed, the present French-speaking context implied cursive handwriting style, unlike the UK and US English-speaking environments. Those two styles imply different graphomotor challenges (Anonymous, 2018; Paoletti, 1999). This diversity of handwriting instruction style could be at the source of different writing challenges for children with dyslexia across countries. Further investigation is needed to check whether such results can be generalised to other languages and outside of cursive handwriting contexts.

5.4. Limitations

Our experiment included some limitations, which are worth mentioning for future research. First, the sample size was relatively small, which can limit the extent to which the results can be generalised. Moreover, the DYS children came exclusively from Grades 3 and 4. Additional research with a larger sample of children are needed to further our understanding of DYS children’s difficulties and of the relationship between the orthographic and graphic processes involved in writing. Indeed, some differences between DYS children and typically developing peers could possibly arise in the late primary school years, when the performance gap between them gets even bigger. Second, we noticed a floor effect for the orthographically complex words. Indeed, the SA children in Grade 2 and the DYS children only wrote accurately a few words from those lists. Using target words more adapted to their spelling level could have led to more interesting results regarding the impact of orthographic complexity on handwriting outcomes, like those found by Sovik and Arntzen (1986), who demonstrated that DYS children produced better legibility when words were frequent compared to less frequent words. It would be interesting to replicate the present experiment either with older children, or less orthographically complex words to ensure a higher spelling success rate. The third limitation concerns the speed measure. It would be useful for future research to add a measure of latency and to take within-word pauses in consideration. Indeed, even if no difference in speed execution could be found between DYS children and CA typically developing children, we would expect longer latency durations before writing. Indeed, as shown in Sumner et al. (2013), DYS children need to take longer pauses between words in sentence writing. Higher latency durations before starting to write would confirm their slowness observed during writing, for instance by teachers. Finally, it is important to keep in mind that the present experiment was conducted in a single-word dictation context. In such context, the measure of handwriting speed relates to speed of retrieval of words characteristics (orthographic and graphic). Single-word writing is not as demanding as the tasks used in Sumner et al.'s (2013, 2014) studies which consisted in sentence and text writing. Compared to single-word writing under dictation, written composition involves more processes, such as generating and organising ideas (Flower & Hayes, 1980). Therefore, results from the present experiment and results from experiments on text writing in DYS children are complementary (Sumner et al, 2013). It would be of particular interest to investigate written composition abilities in DYS French-speaking samples to obtain a more comprehensive picture of writing difficulties among individuals with dyslexia, beyond the orthographic and graphic processes.

5.5. Educational and Clinical Implications

Our results convey relevant implications for practitioners, such as teachers and speech and language therapists. It is important to keep in mind that even if children with dyslexia may not show obvious handwriting difficulties, they seem to be more sensitive to graphic complexity than typically developing children, even younger ones. This means that the more difficult the task gets, the greater their writing difficulties will be in both spelling accuracy and handwriting quality. Our results highlight the importance of developing efficient handwriting abilities to cope with the graphomotor demand induced by word writing. Indeed, our results clearly indicate that word's graphic complexity influences children's spelling accuracy outcomes. In other words, when two words are equally demanding in terms of orthographic complexity, children will make more spelling errors on the graphically complex words compared to the graphically simple ones. This effect is stronger in children with dyslexia and younger typically developing children in Grade 2. Moreover, it is worth noting that it is still present in Grades 3 and 4 in typically children. This demonstrates that children aged around 9 to 10 years may not have reached graphomotor automatisation, which is congruent with previous findings (Graham et al., 1998). Despite this late automatisation, in European French-speaking contexts, teachers only focus on cursive handwriting and letter formation at the very beginning of primary school. While handwriting skills are not trained anymore after 1st grade, the present findings encourage teachers to continue working on letter formation after Grade 1. On a pedagogical perspective, these results highlight the need to consider writing as a pluri-skills activity, and that the motor side and the spelling side of writing can influence each other. Our findings provide interesting elements for a better understanding of children with dyslexia's writing difficulties, and they can open up new clinical perspectives. While the speech and language therapies usually focus on the orthographic side of writing, our results encourage an approach that better integrates handwriting to the spelling treatment. Future research should test the efficacy of interventions targeted at both handwriting and spelling to be in position to confirm the causal role of graphomotor abilities on spelling accuracy.

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